Title

Conceptual Ecologic Modeling in Regional Environmental Management and Land Planning: A Case Study of Lake Tahoe Water Color Transparency

Author

Schwarz, Charles F.

Publication Date

1982-06-01

INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.
2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.
3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.
4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.
5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University
Microfilms
International

300 N. Zeeb Road
Ann Arbor, MI 48106

8300644

Schwarz, Charles Fredrick

CONCEPTUAL ECOLOGIC MODELING IN REGIONAL ENVIRONMENTAL MANAGEMENT AND LAND PLANNING: A CASE STUDY OF LAKE TAHOE WATER COLOR TRANSPARENCY

University of California, Berkeley PH.D. 1982

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

Conceptual Ecologic Modeling
in Regional Environmental Management and Land Planning:
A Case Study of Lake Tahoe Water Color Transparency

By

Charles Fredrick Schwarz

B.L.Arch. (University of California) 1965

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Wildland Resource Science

in the

GRADUATE DIVISION

OF THE

UNIVERSITY OF CALIFORNIA, BERKELEY

Approved: Don C. Erman May 13, 1982
Chairman Date
Paul J. Zinke May 20, 1982
Robert [illegible] 5-8-82

DOCTORAL DEGREE CONFERRED
JUNE 19, 1982

I dedicate my dissertation to Pat, my wife, for her
continuous encouragement, assistance and personal
sacrifices to insure that I finished.

ACKNOWLEDGMENTS

Most of all I thank my chairman, Professor Don Erman, for his patience, his time and his thoughts. Next I thank my other committee members, Professors Paul Zinke and Robert Twiss, for their timeliness and comments in the final months. I thank Professor Lee Wensel for his appropriate threats at crucial times. I thank Terry Mollica for his competence and dedication in entering and retrieving my dissertation from a sometimes temperamental word processor. For their understanding, patience and support, I thank my present and former Research Project Leaders, J. Alan Wagar and Gary Elsner, Director Robert Callaham, Deputy Director Paul Guilkey and Assistant Director Benjamin Spada.

PREFACE

Overall Organization

In the first chapter, I point out that rarely are natural science information (e.g., knowledge about nutrient cycling, sediment transport) and analysis techniques (e.g., ecologic modeling, ecosystem analysis) used in land use planning decisionmaking. These products of science can significantly improve the technical quality of resource use allocations developed by land use planners and recommended to decisionmakers--particularly when the condition of a large portion of the planning area is controlled by natural processes. The complexity and technicality of scientific resources contributes to their infrequent use. Some planners have scientific backgrounds but none are broadly enough trained to use the plethora of diverse, scientific information commonly available on their planning areas and problems. Planners' training and function is to organize and to direct the process producing for decisionmakers a set of well evaluated alternative plans and/or to recommend a best plan. Their role is not to be or become scientific experts. However planners need to be able to work with scientific experts when such information is needed to analyze important problems.

Conceptual ecologic models (CEM) and ecologic simulation models (ESM) can be used to organize and integrate a broad diversity of natural science information for analyzing the problems of planners which have important scientific components. I note that the frequently encountered task of developing a land capability classificaton (LCC) for a regional planning area can be greatly improved by using CEMs to establish which variables and values define capability classes. I examine the use of CEMs as an analysis approach for developing technically improved and scientifically supported LCC by application to a case study.

In Chapter 2, I outline the general advantages of using scientific information and scientific analysis approaches, such as ESMs, for decisionmaking, and how to decide when they are appropriate tools for specific types of planning problems. I then present a general procedure for determining which analysis technique to use. The best scientific technique for analyzing a problem is determined by: (1) availability of data, equipment, skills and other analytic needs; (2) dominance of the problem by scientific and/or quantitative information; (3) working behavior of the planners (e.g., the relative consideration they give to formal analysis, expert judgment, public preference); and (4) working environment constraints within which the plan must be developed (e.g., time and funds available for analysis, political considerations, type of decisions to be made, size of the area for which decisions are to be made). In Chapter 3, from these four considerations I develop and explain a set of guidelines for deciding whether ESM is the most appropriate analysis technique. In Chapter 4, I develop a planning problem of the Lake Tahoe Basin region as an example of using the guidelines to assess the feasibility of CEM and ESM for developing a LCC for protecting the water color and transparency of the lake. In Chapter 5, I develop an overall CEM of the system of variables controlling water color and transparency as affected by suspended sediments and nutrients from watershed lands. In accord with the assessment guidelines, I also discuss the availability of adequate levels of scientific principles and data to enable construction of an ESM. I then divide the overall system CEM into a series of subsystems, subsequently developing CEMs for each in Chapters 6 through 10 and 13 through 16. Chapter 6 presents a CEM of the factors controlling the water color portion of the system model.

In subsequent chapters I present CEMs of subsystem variables controlling: biotic production and distribution of substances affecting water color and transparency (Chap. 7); transport of suspended sediment by overland flow and stream flow processes (Chap. 8); release, transport and delivery of nitrogen (Chap. 13) and phosphorus (Chap. 14); and suspension of particles in lake waters and retention once settled on the lake bottom (Chap. 16). In Chapters 11 and 12, respectively, I develop estimates of the quantities of nutrients and potential suspended sediment particles on watershed sites. In Chapter 17, I develop a LCC scheme based upon the information in the preceding subsystem CEM chapters and discuss various mapping and procedural decisions needed for its implementation. In the last chapter (18), I evaluate CEM use as an analysis technique likely to increase area planners' use of scientific information and analysis techniques. I also discuss why, in spite of their consider- able promise, I think scientific information and analysis techniques will not be used more widely by land use planners.

Accomplishment Criteria

The broad, complex problems I study do not lend themselves to hypothesis testing and quantitative evaluation. However, from the perspective of land use planner's needs, it is large, system-wide problems which most need study. Broad problems are difficult research topics because of the diversity of information and number of disciplinary skills needed for interpretations. I expect to increase understanding of the capabilities and limitations of a method for ameliorating the problems I describe in the first Chapter. Limitations of time and the breadth and depth of my technical skills and inclinations hamper attainment of a complete solution. No completely satisfactory solution exists for problems planners experience with scientific information and analysis techniques. Consequently, I attain my goals whether CEMs are shown to be useful, worthless or of indeterminate value for reducing problems of information use by planners--given our present state of knowldge and the small amount of use and testing of CEMs, ESMs and/or ecosystem analysis in real planning situations.

Because my purpose is general, the criteria for judging my accomplishments must also be general. At their most basic level, the judgement criteria are whether I have shown in the study that CEM is or is not a good technique for: (1) analyzing and possibly solving certain types of planners' problems; (2) providing a systematic method for selecting the best variables for LCC; (3) displaying the scientific basis of a LCC system; (4) organizing scientific and related information for analyzing a specific problem; (5) helping establish which information is relevant, which more important and which needed but absent; and (6) encouraging planners to make fuller use of scientific information when it is important for problems they must resolve.

Definitions

Planning

In this study I concentrate solely on land use allocation types of planning--the process whereby decisions are made about what type, mixture or juxtaposition of human uses of land areas should occur where, how, when, for how long, in what temporal sequence, etc. My use of "regional planning" in the text is merely to refer to the size of land use planning areas and I use "planning" simply for brevity purposes.

Throughout the study, "regional planning" refers broadly to land use regulation decisions for any area larger than a single city (Friedman 1963). I do not refer to the administrative regions of government land management agencies, but rather to those supraurban planning areas encompassing functionally integrated natural or economic systems, such as large ecosystems, river or lake basins, or metropolitan areas (McCloskey 1971). In U.S. Forest Service terms, my usage of "regional planning" closely coincides with their plans for individual National Forests.

Planners

I always use the term "planners" to refer to land use planners, and especially to planners with formal, professional training on how to manage an overall land use planning effort, rather than extensive training in geology, hydrology, ecology, sociology or other scientific fields. Sometimes I broaden my use of "planner" to include all those serving on the interdisciplinary planning team. These planners usually have extensive individual training in a particular discipline important for some aspect of the overall planning task, though seldom in planning *per se*. When the distinction between professionally trained planners and other members of the planning team is important, I include the appropriate modifiers. The main role of professionally trained planners is to coordinate the overall planning operation to efficiently and expeditously identify issues, direct analyses, assign responsibilities to other team members and consultants, set work priorities, budget finances and time, arrange for public involvement and perform other tasks needed to develop alternative resource allocation plans and make rational, substantiated, recommendations to decisionmakers. It is important to realize that planners only shape the recommendations and do not make the ultimate resource allocation decisions. The actual decisonmakers are elected or politically appointed individuals (e.g., planning commissions, governing boards), or in the case of government land management agencies, high level administrators.

Ecologic

Throughout this study, I use the term "ecologic" in a broad sense, referring to all natural factors--abiotic as well as biotic--rather than limiting its meaning to the relations between a living organism and its environment.

Ecologic Simulation and Conceptual Models

Models are idealized representations of reality--simplified portrayals of the relationships controlling the behavior of a system. They contain only the relationships of primary importance to the problem or process being studied (Woodmansee 1974). Ecologic simulation models represent the dynamic relationships of ecosystems. Fully operational ecologic simulation models mimic the dynamics of a system by showing how selected characteristics change through time or in response to some perterbation. Conceptual ecologic models are graphic representations of the conditions, substances, organisms and processes controlling or controlled by ecosystem dynamics.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

APPENDIX TABLES

LIST OF ILLUSTRATIONS

CHAPTER 1

LAND USE PLANNING: UTILIZATION OF SCIENTIFIC KNOWLEDGE FOR PROBLEM ANALYSES AND DECISON FORMULATION

Chapter Scope

In this chapter I point out that, while some planners are interested in using scientific information and analysis techniques, generally the amount of use is low. In particular, unmapped scientific information and ecologic models (EM) are rarely employed land use planners. Next, I suggest that EM are particularly useful for analyzing some problems regional planners encounter. Then I discuss a case study approach for examining the practicality of such models for analyzing an environmental problem dominating land use planning for a particular wildland region. Lastly, I review instances where land use planners have employed scientific information and EMs to help regional land use allocation decisions.

Extent and Problems of Scientific Knowledge Use

Formal studies of what types of information and analysis techniques planners use for decisionmaking are lacking (Seidel 1968). Clark (1978), in a study of the role of science in the California coastal zone planning process, found that professional planners seldom use scientific information and also are unreceptive to increasing scientist participation in planning. Some land use planners are intrigued by the potential use of scientific knowledge in their development of plans. However, even they still rarely use it because of (1) difficulty determining what scientific information they need or (2) whether it is available, because it is often (3) difficult to understand and interpret for their needs, etc. My own training in environmental planning and experiences working on two regional planning efforts (Tahoe Regional Plan, 1970-1; California Coastal Zone Plan, 1973-4) convince me that planners could profit greatly from increased use of scientific information and the analysis techniques of natural science.

Planners are less likely to use scientific information available only in written or numeric forms. They more frequently use the comparatively small quantity of scientific information available in mapped form for a planning area. The use of maps illustrating the distribution of natural factors throughout the planning area--e.g., types of soil, vegetation, geologic materials or annual rain and snow fall, land surface elevations--has become increasingly common in the United States since about 1963, when Ian McHarg began widely promoting natural factor maps as aids to the spatial allocation decisionmaking.

Mapped information relevant to planners' formulation and analysis of alternative decisions is far less available than unmapped information. However, planners tend to not use scientific information not already expressed in mapped form or that cannot readily be converted to such a format. The time and skills necessary to assemble and interpret such information for planners' use often are not available. The frequently greater difficulty of using written or numeric scientific information should not totally discourage planners from using it. Such information is no less relevant or valuable for planners' studies than information already displayed in map form. Planners readily use many other factors not readily displayed in mapped form--e.g., political awareness, social and economic data to develop and assess alternative decisions. I believe that a major reason unmapped scientific information relevant to planning areas and specific planning problems is often not used is the lack of an overall framework for organizing and recognizing the relative usefulness of many different kinds of information.

As part of regional planners' assistance to decisionmakers allocating resources among competing user groups, they must collect and analyze tremendous amounts of information. Despite the intensive information collection and analysis characterizing regional land use planning, planners rarely take advantage of even readily available scientific knowledge in the deliberations. This low use of scientific information is typical even in regional environmental planning and in wildland planning areas, settings where natural science information and analysis techniques should be particularly useful because so much of what society finds valuable in those areas is a product of natural processes.

Collecting available data is a logical step in the analysis of any planning problem and can be started without a great deal of forethought. Consequently and routinely, very early in most land use planning efforts, an inventory and collection of all information on the planning area are begun. However, an inventory effort which is not carefully thought out and directed frequently causes serious problems later in the planning process. Retrieval and use of the abundance of information commonly available on regional planning areas creates a major problem for planners studying the effects of alternative land use allocations.* Consequently planners also need methods for organizing and deciding what portion of the information is most useful for analyzing problems.

Any technique which can be used to analyze large, complex problems is of interest as a possible tool for land use planning (Bottoms and Bartlett 1975). Complex ecosystem interactions control the natural ability of wildlands to produce continually that which human users value. These interactions also control the ability of an ecosystem to respond to management actions intended to adjust the rate or type of that productivity. CEM and ESM are the best (and perhaps only) techniques for studying such complex interactions. I believe that CEM and ESM are useful for developing the systematic, comprehensive frameworks for fitting together the diverse scientific knowledge needed to study certain problems planners must resolve to make technically sound recommendations on the division of an area's land use resources. Once developed, CEMs will also assist planners in

---

*This plethora of information on the planning area is never all the information needed to analyze all problems (Lang 1979). However, the quantity available is always more than can be readily managed. Consequently, planners tend to ignore much scientific information because it usually contains terminology, symbolic logic, and technical information they do not readily understand, nor does their professional training prepare them to understand and evaluate such information. Their primary role is to lead the planning team. No individual is or can become an expert in all the types of information and skills needed to do land use planning. But professionally trained planners must still be able to direct an interdisciplinary team which may have to deal with important information beyond the expertise of any of its members.

their management of consultant experts (probably performing in most technical analyses) to most efficiently and assuredly obtain from them needed findings. In spite of these potential advantages, EM is an analysis technique rarely used by professional planners.

Case Study

Though the general problems examined by this study need not be tied to a specific geographic area or planning problem, the case study approach maintains a pragmatic perspective by providing a concrete geographic problem area and planning problem. Generalizations can then be developed from this specific example.

Since I have extensive experience with land planning problems in the Lake Tahoe Basin of California and Nevada, I have chosen it as the setting for this study. While any watershed could be used, the basin is a good choice because there are few other examples of actual planning areas which have been defined on an ecosystem basis. About seventy-five percent of the basin's land area is owned by state and federal agencies, making it a good example of planning for publicly owned wildlands.

The basin has been the subject of extensive scientific study, with at least 10 million dollars of state and federal funds spent on scientific research in the past 18 years. Additional millions continue to be spent each year on such work (Jones 1976). Much of the public funding has been granted under the assumption that the research findings will assist land planners, but little planning use has been made of this scientific knowledge.

In October 1976, the now defunct Lake Tahoe Area Research Coordinating Board published a bibliographic inventory of 1600 research publications based on studies in the Basin (Jones 1976). There appears to be more scientific information available on the Tahoe Basin than on any other wildland planning area of similar size. If scientific knowledge will aid planners, it ought to be demonstrable in the Lake Tahoe Basin!

Of the various multiple use problems facing Basin land planning, protection of the quality of the water in the lake is always a central theme. Since most of the scientific research has been conducted to gain an understanding of the lake and how changing land use may affect it, water quality is a logical central planning problem for this study.

My study is most clearly illustrated in terms of the specific regional context of the case study. A major legislative intent in creating the Tahoe Regional Planning Agency was to protect the quality of the basin's natural environment from the adverse effects of increasing urbanization. More precisely, the intent can be viewed as regulating land use to maintain the very high quality of the water in the lake. For example, the second sentence in Public Law 96-551 states "...That in order to encourage the wise use and conservation of the waters of Lake Tahoe and of the resources of the area around said lake, the consent of the Congress is hereby given to the Tahoe Regional Planning Compact..." The first "finding" (third sentence) in Public Law 96-551 (I(a)(1)) states "It is found and declared that: (1) The waters of Lake Tahoe and other resources of the region are threatened with deterioration or degeneration,...", and the fifth finding states "Increasing urbanization is the threatening the ecological values of the region." Other environmental concerns are important at Tahoe--concerns not protected by preserving the lake's extremely pure water (c.f. Chapter 4). However, no other concern is so important, as central and as continuing a theme of all Tahoe planning efforts as protecting this unique quality of the lake.

For my study purposes, this objective of protecting water purity may be more specifically restated as maintenance of Lake Tahoe's water color and transparency. My examination of the value of scientific analysis technique and information for analyzing a problem planners must resolve consists of studying how readily and how well CEMs can be used to describe the complex of factors controlling nutrient and sediment flows into the lake, and their effect on its water color and transparency. My test of CEM utility continues by using the models to propose a LCC scheme for zoning watershed lands according to their potential for producing substances causing such changes in the lake.

The context of Tahoe Basin regional planning efforts is a useful arena in which to examine the capability of scientific information and ecologic modeling to forecast environmental impacts because there, more clearly than in most current planning contexts, retention of natural environmental quality is a dominate, mandated goal of planning efforts (Public Law 96-551 I, a, 10). Also new legislation revising the Tahoe Regional Planning Agency's organization and mission specifically mandates that "environmental threshold carrying capacities" be developed (op. cit. V, 1, b) and used as a prominent consideration in revising the regional land use plan for the Basin (op. cit. V, 1, c). Public Law 96-551 also requires the Tahoe Regional Planning Agency to "Initiate and utilize ecological information in the planning and development of resource-oriented projects." (op. cit. VII, 5). These tasks cannot be satisfactorily accomplished without making extensive use of scientific knowledge.

Advantages of Modeling Approaches for Planning

The process of land use decisionmaking essentially involves social, not technical or scientific, choices (Behan 1971). Hence, only certain problems within any overall planning context are suited to resolution in the rational, objective and quantitative sense that makes scientific solutions so attractive (Nelkin 1979). Science contains no panacea for planners' problems. However certain activities planners engage in can be greatly aided by using ecologic models. Some of these are pointed out in the second section.

Environmental impact assessment problems are particularly well suited for analysis using scientific information and modeling techniques (Gilliland & Risser 1977). Simulation models can provide planners with an analytic tool for overcoming the inability to physically experiment with the possible consequences of alternative plans (Swank & Waide 1979 p. 154).

Individual scientific studies of the more traditional observational and experimental types are usually too limited in scope and purpose to make significant contributions to regional land use planning. In general, planners have more need for a method synthesizing and facilitating evaluation of already available data than they do for more data on the planning area. Again, modeling is an analysis technique particularly useful for such organization tasks. However models also can be used to show what types of additional information are most needed for the analysis of problems (Swank & Waide 1979 p. 152), if the time and resources are available to generate new data. Modeling may also reveal that additional effort to more precisely resolve issues is uneconomical, as the costs of thorough analysis may exceed the relative importance of many problems. Such a conclusion concerning lake water quality protection seems improbable at Tahoe.

In summary, the justification for my choice of ecologic modeling is the need of planners for comprehensive and integrative methods to manage, evaluate, and use scientific information for assessing alternative decisions coupled with evidence that modeling is the technique best possessing those attributes.

Research Approach

As a first step in the case study portion, I develop a general overall conceptual model (Chapter 5) showing the broad categories of ecosystem processes controlling water color and transparency. In an actual planning effort, the interdisciplinary planning team would develop the overall conceptual system model, occasionally consulting with experts on certain topics. This step establishes: (1) the ecosystem framework showing how a wide diversity of scientific knowledge fits together to describe the planning problem; (2) the system boundaries for the categories of scientific information needed for analyzing the problem; and, (3) the subsystem boundaries of more specific subproblems.

Next I develop more detailed, conceptual models for each of the subsystems identified by the overall conceptual model (e.g., one for nitrogen release and transport, one for sediment transport). In these steps, I more explicitly point out the scientific information needed and clarify those aspects of the planning problem which must be studied in greater depth. Accompanying development of each CEM, I review some scientific information on the relative quantitative and qualitative importance of processes and materials potentially affecting water color and transparency. For the purposes of this study, it is not necessary to conduct an exhaustive literature search and state-of-the-art write-up on each subsystem.

Using important, mappable controlling factors identified in each subsystem conceptual model as the parameters of land capability zones, I discuss how to develop a map of the relative potential of watershed lands to yield sediments or nutrients producing water color and transparency changes in the lake.

Finally, I assess CEM and ESM as decision guiding tools for wildland planning applications. To illustrate the present potentials of EM as a practical tool for analyzing regional planning problems, I use the successes, difficulties and failures of my efforts to; (1) construct the CEMs, (2) establish the important variables in each subsystem, and (3) identify and map important controlling variables.

Conceptual Modeling

In this study I proceed with ESM development only through the "conceptualization" stage. It is not necessary to develop the model further to analyze the problems being studied. For example, it is not necessary to produce a working model to show how the use of EM can bring about better use of scientific information by land use planners.

A conceptual model can display how relevant aspects of the ecosystem affect a particular planning problem. To date, ESMs have not been conceptualized in a manner making apparent to planners their usefulness for analysis of land use planning problems. Many planners have not recognized the potential utility of ESMs because those values have been concealed by the extensive use of ecologic, modeling and systems analysis jargon, theory and symbolic logic.

Proceeding with model development to the next "formulation" stage and through the subsequent "programming" stage (at which point quantitative output could be generated) is a formidable task for one person. The modeling experiences of others have shown that at least a small team of scientists is needed to carry development of most ecologic models to full working status (Holcomb Research Institute, 1976). Working alone, I can develop a model through the conceptualization stage.

Another reason to terminate development of the models at the conceptualization stage is that new data is not collected and analyzed to fill in the quantitative information needed for their working ESM versions. Collection of such data would greatly lengthen this study, one of the purposes of which is to examine the extent to which scientifically supported answers for the problems of planners can be provided using scientific knowledge already existing on a planning area.

If ESM is to significantly contribute to planners' decisions, the conceptualization stage usually determines its success or failure. Planner and modeler must work closely together during early development stages of an ESM--especially through the model conceptualization stage. This is the stage where planners' problems are articulated in a manner that can be modeled and where planners come to understand what type of aid modeling can and cannot deliver, enabling them to assess whether ESM will provide good enough analysis of a planning problem to make further advancement into the modeling process worthwhile.

Thus, by the end of the conceptualization stage, most of the benefits EMs are attained; i.e., possessing a method for: utilizing scientific knowledge for planning decisions, sorting useful from irrelevant scientific information, perceiving how diverse scientific information is integrated for analyzing a problem, illustrating graphically the complexity and the interrelatedness of factors in the planning area ecosystem and understanding the processes maintaining natural balances.

Review of Ecologic Modeling for Regional Planning

A number of studies are described below from a thorough review of modeling and planning literature. The review revealed no attempts to develop CEMs or ESMs to establish the variables of a special purpose LCC map which planners could use to protect an important planning area attribute by regulating land uses (Bowie & Schwarz 1978, Frenkiel & Goodall 1978, Hall & Day 1977, Holcomb Research Institute 1976, Holling 1978, Kracht 1971, Meshenberg 1976, Meyers 1973, Neivelt & Schwarz 1978, Schwarz 1974, Yeilding & Schwarz 1978). A few efforts come close to performing what I propose (Lyle & von Wodtke 1974, Fabos & Caswell 1977), but much more commonly, some develop capability classifications according to ecologic principles (e.g., Hills 1961, Lacate 1969, Rowe 1979); others develop ESMs of planners' problems but do not attempt to use them for classifying planning area lands (e.g., Boynton et al. 1976). Others attempt to directly use, translate or reinterpret readily available natural factor maps to establish land capability zones (McHarg 1969). This latter approach has become particularly common in regional environmental planning. Some government planning agencies, particularly in Canada and Australia (e.g., Rubec 1979, Thie and Ironside 1976), have established and extensively used a standardized set of information and mapping procedures to describe LCC for agricultural development, forestry and a few other uses. However, no one seems to have used or advocated the particular combination of ecologic modeling and land capability zoning I develop in this study.

City and urban region planners have long used quantitative models as part of their problem analysis techniques (e.g., Wilson 1974, Isard 1969, Kracht 1971), though a long lasting debate over their value continues to rage (Lee 1972, Sayer 1976, Batty 1979). But these are housing, transportation and other socioeconomic models, not ecologic models. Reviews and syntheses of the scientific knowledge on regional plan elements have also occurred in a few isolated instances (San Francisco Bay Conservation and Development Commission 1966-8, Tahoe Regional Planning Agency 1971, California Coastal Zone Conservation Commission 1973-5, Clark 1974). However, this information has never been used to develop CEMs or ESMs for analyses of the problems of planners.

Systems models have also been developed to describe factors affecting and affected by regional public policy decisions (Odum 1971, House & McLeod 1977); but these are not ESMs, nor are they designed to be used by land use planners for spatial use allocation decisions. A few ESMs have been developed for planning area ecosystems to give planners an understanding of how ecosystem interactions affect valuable system products (e.g., Boynton et al. 1976). However they are not used to develop a spatial capability classification system for the planning area.

ESMs have been developed and used for site and project planning (Swartzman 1979) and for guiding the management of special natural resources (Hilborn 1979, Holling 1978, Russell 1975). The latter use is not, of course, strictly a land use planning application, and analysis of planning problems at the site or project planning level is significantly different from that needed for regional planning.

Isard et al. (1972) derive an input-output matrix of linkage coefficients to assess the effects of urbanization on ecologic productivity. For example, they quantify the specific food input requirements and environmental conditions necessary to produce local fish species and quantitatively relate this fish production to the size of local sportfishing facilities and fish catch. Then they develop another set of input-output relations between urban development of marshland (a principal food chain starting point) and its water pollution effects and the size of the local sport fish population. They use these relationships to show the potential adverse effects of alternative new town development schemes on sportfish and the fishing industry.

Isard et al. believe that a use of input-output modeling to evaluate ecologic-economic interactions is valuable for assessing regional planning policy alternatives. The accounting framework of this model is a very large 500 row x 500 column matrix--potentially

250,000 interactions to evaluate--indicating the huge effort typically needed to develop complex input-output models. Their use to assess potential regional impacts is a data- and skilled labor-intensive process. Hence, it is expensive and economically justifiable only for the planning of very costly projects, such as oil refineries or nuclear power plants.

Ecologic models have been used in conjunction with functional planning for single resource uses (e.g., timber production), but no multiple use planning effort has truly used ecologic modeling as one of its decisionmaking tools. The closest any multiple use planning effort has come is the work of the California State Polytechnic University Laboratory for Experimental Design (1972, Lyle & von Wodtke 1974), for nine watersheds in the coastal area of San Diego County. The documents from this work prominently display conceptual energy circuit model diagrams of the general ecosystem processes controlling material and energy flows through that regional ecosystem. They attempt to show how broad categories of land use activities generally affect these natural processes. This effort was not carried far enough to bridge the gap between the ecologic models and the decisions which land use planners must make.

For a bay-estuary-urban area system, Boynton et al. (1976) constructed an analog computer simulation model of some relationships between the urban area's economy and the bay's oyster production industry. The latter is affected by the influence of the river and urban area on the suspended sediment, salinity, toxic substances, nutrients and organic matter in the bay water. These relationships were quantified and supplied to a planning agency. This model is essentially an analysis tool for evaluating a single resource use--i.e., oyster production. It does not seem to help land use planners deciding which use goes where in the planning area.

SVEN is a well documented group of computer simulation models which are purported to be a "forest land use allocation" system (Schreuder 1976). However, the SVEN models are really management models whose potential utility is for making such decisions as how to grow and harvest trees, manage logging slash, and estimate timber management practice effects on deer populations, stream flow, suspended sediment production, air pollution, etc. The models seem unable to provide the type of information planners need to allocate land uses. These models do not seem to have been developed in conjunction with any specific land use planning effort or for any specific users (Fleming 1976).

The six SVEN models produced to date were built to operate independently of each other, being linked only by their use of a common geographic data base. The models are valid for only a very limited number of situations; e.g., the forest stand model "Timber" is limited to second growth, even-aged stands of Douglas fir. Therefore, the SVEN models are not general enough to be used for establishing the type of large area, relative capability assessments needed by planners.

The Holcomb Research Institute (1976, p. 56) reports use of an ESM of a proposed river reservoir to estimate algal growth, the effects of various strategies for reducing available nutrients, and fish population changes. Reportedly this model contributed to the eventual decision by the State governor and the Congress to withdraw support for the project.

Mapped Ecologic Information in Planning

While mapping of natural factor information obviously is not ecologic modeling, I discuss it here because maps are the most common form in which ecologic information is included in planning decisions. Traditionally, planners have compiled maps of readily available natural factor information (e.g., rainfall distribution, geology, soils, and air temperature) as part of the planning area resource inventory. However, only since the ascendance to prominence in planning of the techniques of G. Angus Hills (1961), Philip Lewis (1961) and especially Ian McHarg (Wallace-McHarg Assoc. 1963, McHarg 1969) has mapped natural factor information been widely used in planning area decisionmaking.

Carefully selected natural factor maps are of great value as an analysis tool for planners when accompanied by clear interpretations of their significance for planning decisions. However, a map represents an inherently static view of an ecosystem dominated by dynamic processes. These dynamic processes cause constant change in many mapped biotic characteristics, though most abiotic characteristics are reasonably stable. For example, the distribution of vegetation types occupying a planning area is determined by a complex set of dynamic relationships. Those using mapping approaches to land planning commonly include a map of existing vegetation types in the planning area and occasionally a map of the potential vegetation (i.e., climax vegetation). Neither of these maps adequately communicates the instability of those vegetation types; e.g., a wildfire may eradicate much of what is shown on the existing vegetation map. Similarly, knowledge of the potential climax vegetation is of little significance to planning decisions, since it usually will be aborted by destructive natural events and human activities. It is more important for planners to understand natural successional tendencies, the rates at which changes occur and factors controlling the manner in which vegetation cover tends to change with time.

The block and arrow diagram of a CEM best communicates the complexity of potential vegetation succession pathways and the variable environmental factors controlling the destiny of vegetation types in a planning area. Only an ecologic model can clearly illustrate the cause and effect mechanisms in a form so expressive of the dynamic natural tendencies that planners will be aware of the potential consequences of alternative land use allocations. Other dynamic processes which cannot be adequately communicated by mapping are hydrologic and nutrient cycles and energy flow through ecosystems. It is impossible to clearly show three-dimensional relationships which change through the fourth dimension of time using the two-dimensional limitations of a map.

Though mapping approaches to land use planning are increasing in sophistication and comprehensiveness in their portrayal of the natural decision factors affecting spatial use allocation decisions (e.g., Wallace, et al. 1972), there remain many important ecologic planning considerations which cannot be represented in that manner. It is also much easier to relate and integrate the scientific knowledge contained in literature into an ecologic modeling framework than it is to see how such document information relates to maps.

CHAPTER 2

GENERAL ADVANTAGES OF SCIENTIFIC ANALYSIS APPROACHES FOR LAND USE PLANNING

Many planners are eager to use scientific information to analyze problems and formulate recommendations, but they lack the training needed to do so directly or to direct those with the expertise to do so. Thus this general problem hampers planners' use of ecologic modeling. Dickey and Watts (1978 p. xiii), in the preface to their book, Analytical Techniques in Urban and Regional Planning, point out that planners generally receive little training in quantitative analysis. They speculate that this makes planners reluctant to use such techniques; I believe it will make them particularly reluctant to use a fairly complex technique such as EM. Certainly most problems planners encounter cannot be resolved solely by using scientific information and quantitative analyis; but if better defined and broken into subproblems, many could be partially analyzed using those tools.

Since land use planners for years have produced plans with minimal use of scientific analysis techniques and scientific information, why should they now begin using them? Planners' decisions are more complicated now (Rittel and Weber 1973, Applegate 1978, Thurow 1979). They are expected to resolve conflicts between user groups competing for limited resources, to increase social equity in their decisions, to attain meaningful public participation in decision making processes, to comply with complex legal requirements and to operate in a manner defensible against probable court challenges of their decisions.

Given the increasingly difficult decisionmaking environment in which planners must work, they must take advantage of any analytic tools and information for shaping and supporting their recommendations (Bottoms & Bartlett 1975). When they can be used to substantially resolve issues, scientific information and quantitative analysis approaches provide the most incontrovertible evidence and analyses.

Better plans, more expeditiously arrived at, would also result if planners made more use of quantitative analysis techniques (Mackett, 1977, 1978). What constitutes a good or better plan is largely philosophic and relativistic, and can be argued endlessly without achieving general agreement. The irresolvable differences of opinion are based upon fundamental disagreements over which quality criteria are most important. Those most concerned with long range implementation of planners' allocation recommendations measure "goodness" in terms of political and administrative viability. Those most concerned with distributive justice measure "goodness" in terms of improving social equity. I am most concerned that planners' allocations reflect sound use of scientific information and analysis techniques to help shape rational, objective, comprehensive decisions. It is this criterion I employ when questioning the quality of land use plans developed with minimal use of scientific analytic techniques. Hence, one reason I believe planners should ensure that more use is made of quantitative analysis techniques is to produce plans with the aid of sound analysis of scientific information relevant to land use allocation decisions.

Increased objectivity of analyses is another advantage of quantitative analysis procedures. Much of the substance of problems faced by land use planners are (and perhaps will always be) difficult to analyze quantitatively. Consequently, most allocation decisions are based upon largely subjective assessments by planners. This subjectivity makes it unclear what factors, factor weightings, tradeoffs, etc., contribute to decisions.

Quantitative analysis techniques were developed and are regularly used by analysis experts--people with the special knowledge needed to avoid fundamental technical and conceptual mistakes. The strengths and weaknesses of such techniques are commonly reported in specialized scientific literature and are well known to analysts. Much experience has been gained from repeated use of scientific techniques, so expert assistance is usually available to assess their usefulness for, and aid their application to planners' problems.

Planners will find it easier to enlist participation of scientists in analyses of problems and support of conclusions when the latter are conducted in manners familiar to scientists. Scientists are reluctant to participate in studies of problems which cannot be analyzed by established quantitative means because they do not wish to endanger their scientific reputations. Thus, by using familiar scientific techniques, planners are better able to communicate with and exploit the skills of scientists and other technical experts.

A further advantage of using established quantitative analysis techniques is that decisions based, in part or in full, upon such analyses are more defensible in court should legal challenges arise

(Loucks 1972). Use of scientifically reputable analysis techniques such as ecologic simulation modeling does not decrease the likelihood of court challenges, but scientists are more willing to testify as expert witnesses in support of conclusions reached by using them. As legal challengers can also hire scientific experts, it is important to take care that the right techniques are used and that their results are interpreted correctly.

Oddly enough, rather than driving planners to make more use of quantitative analysis techniques to improve any technical reasons for land use allocations, generally court decisions have had the opposite effect. In the landmark decision of Citizens to Preserve Overton Park v. Volpe (401 U.S. 402, 1971), the U.S. Supreme Court held that the reasons for government agency decisions (such as land use regulations) do not have to be absolutely, technically, or scientifically correct; they must only not be arbitrary, capricious, an abuse of discretion, contrary to law, or clearly give insufficient weight to relevant factors (Kramer and Fox 1980, Applegate 1978 p. 454). In the long run, the consequence of such decisions, I believe, is to remove the incentive for planners to improve the technical quality of their decisions. As Applegate (1978 p. 453) states,

> The courts contribute to the problem by generally refusing to substitute their judgment for that of the agency's unless the agency record is hopelessly flawed in some way. This situation causes a decline in the quality of agency judgments.

Thus, as long as planners make a reasonable analysis effort before recommending land use regulations, decisionmakers' choices are protected from legal challenges.

Bronstein (1980) and Korwek (1980) point out other probable reasons there have been few successful legal challenges of plans based on the scientific incorrectness of any reasons used in their formulation. Courts are not likely to accept scientificly reasonable levels of statistical significance (even .001) as adequate evidence proving causality (Bonstein 1980 citing Pfennigstorf 1979 and Borgo 1979). If applied to ESM, the scientifically impossible requirement for absolute proof of causality eliminates any legal advantages of using that technique for decisionmaking. Cumulative errors in ESM always result in a large degree of uncertainity about analytic conclusions. Courts also often decide scientific cases on procedural grounds, avoiding the substantive issues (Korwek 1980, Jasanoff and Nelkin 1981).

However, these tendencies of the courts are not so immutable that technical correctness is legally unimportant. Loucks (1972) cites several court cases where decisions were based upon the scientific substance of the litigants' arguments. In these cases, systems analysis was used successfully to show how diverse scientific testimonies fit together to prove contentions. Thus, planners' use of ESMs to shape allocation decisions ought to provide a useful background for a legal defense, should the need arise. In some cases, the courts have insisted that agency decisions be based upon a thorough scientific knowledge review (e.g., Skopil 1977). Hence, planners should not consider present court tendencies to be an overriding reason for not increasing use of scientific analysis techniques.

Another reason planners should increase their use of scientific analysis techniques is that with them analyses of some types of problems can be conducted in a fairly routine manner. Technicians can perform much of the analytic work, freeing planners to concentrate on other tasks. Computerized statistical and data analysis programs are widely available for many quantitative techniques. Their use could considerably expedite analysis of well-selected planning problems.

In summary, planners ought to use quantitative analysis techniques for analyzing their problems because they increase legal defensibility, encourage scientific participation in planning efforts, increase the overt objectivity of planners' decisions, and may reduce individual problem analysis time.

Choosing the Appropriate and Best Problem Analysis Technique

Most scientific analysis techniques are best suited for studying only certain types of land use planner problems. Some techniques are subtly inappropriate, and their use may result in misleading conclusions. Where the same types of problems can be analyzed by several techniques, all may not be equally capable or efficient at producing analytic results. Others are inappropriate for any problems planners face.

Given the obviously different abilities of scientific analysis techniques, how should planners decide which to use for different types of problems? More specifically, which types of planning problems are most appropriately studied using ecologic modeling? The latter question is the topic of the next chapter. Choosing the best analysis technique is a problem that seems to have been neglected by planning researchers and theorists. I found no literature on the subject, though Cartwright (1973) gives some generic guidance but does not refer to specific techniques. In comparing analysis techniques, planning reasearch has concentrated on finding those best for evaluating entire alternative land use plans (e.g., Litchfield 1975 pp. 48-77.) It is possible to conceive of large simulation models encompassing many of the problems planners must study for a single plan, but this has been recognized as an inappropriate use of simulation modeling (Lee 1973, Mar 1974).

Planning researchers and theorists have not been overly concerned with the problem of pairing analysis techniques with appropriate planning problems; why therefore is it important to make good matches? Several of the more obvious reasons have been alluded to in the opening paragraph: avoiding incorrect conclusions drawn from incorrectly applied analysis techniques, using the most cost-effective analysis technique, and using the most analytically efficient techniques.

The traditional professional training of planners is weak in mathematics and quantitative and statistical analysis techniques (Dickey and Watts 1978). Lack of these skills necessary for deciding which analysis technique is appropriate for a problem may also result in misuse of basic mathematical principles and techniques for conducting analyses. Probably the most common mistake is misuse of measurement scales, as in performing multiplication and division operations on the sums of numerals corresponding to rankings. Subjective assignment of numeric weights also occurs frequently in approaches using composite overlays of maps to determine land capability classification (Grant 1974.) Regression equations have also been derived from mathematically incompatable data (e.g., Jacobs and Way 1968).

Many of the more sophisticated modern analysis techniques can be very expensive to use, needing special scientific and computer programming assistance, access to large digital computers and much computer time. Hence, as planning funds are usually marginally adequate, planners must spend their analysis budgets wisely and appropriately when techniques such as systems analysis and simulation modeling are being considered.

Planners should resist the tendency to "play it safe" by routinely eliminating consideration of unfamiliar analysis techniques, thus avoiding the risk of failure inherent in their initial use. Newer, unfamiliar techniques may be capable of providing the best analysis of a problem. They may even be the only technique capable of analyzing it (e.g., Swank & Waide 1979).

Planners must deal with a vast diversity of subjects and information to formulate and evaluate alternative plans. No single or few techniques are best, or even technically appropriate, for analysis of the range of problems that planners encounter. As planning is often a hectic job, it is unreasonable to expect planners, with their other duties and professional training, to make expert judgments about the comparative appropriateness of quantitative analysis techniques. However, it is reasonable to expect planners to ensure that someone with the necessary expertise determines which analysis technique is best for each problem.

While no quantitative analysis technique is a panacea for all, or probably even very many different types of planning problems, there are good techniques available for most. The problem facing planners is to develop and approach assuring that the best techniques are used to analyze planning problems. This study concentrates on an exploration of the potential role of a pair of modern quantitative analysis techniques--CEM and ESM.

General Procedure for Determining Analysis Approaches

The selection of quantitative analysis techniques for different problems planners must analyze is a much broader, more important decision than determining only those problems where ecologic modeling is the appropriate technique. Planners are unable to devote a large segment of time checking problems they must study for ones that should be analyzed using any particular technique. Thus, an examination of the potential applications of CEM and ESM is likely to be part of a larger screening operation wherein all the discrete problems identified by planners and other members of an interdisciplinary planning team are evaluated to determine how each can be analyzed, where quantitative analysis can be used and which technique is best for each problem.

The use of scientific analysis techniques can best be increased by adopting a structured evaluation approach for matching techniques with problems. This evaluation must be a joint effort of the planning team and a group of others collectively familiar with most analysis techniques. The group of analysis technique specialists might be a small consulting firm specializing in such services (none of which now exists to my knowledge), or an <u>ad hoc</u> group of experts from one of the large consulting research firms (e.g., SRI, Rand, Battelle), or it might be assembled from (or one of the others groups supplemented by) the faculty of nearby universities and professional offices. This latter approach would require considerable effort and special skills to identify and assemble a group of individuals collectively having the needed expertise on a broad array of analysis techniques. No one individual or area of expertise can possibly make such determinations. Ecologic modeling and other analysis technique specialists are unfamiliar with the temporal, budgetary and other constraints of the planning environment. Similarly, planners are not trained to judge the needs and appropriateness of ecologic modeling and other scientific analysis techniques and other members of the interdisciplinary team are only trained on the techniques of their particular expertise.

A general procedure for deciding which analysis techniques to use for different problems is illustrated in Figure 1. The numerals in the following text point out the particular step(s) in that diagram being discussed.

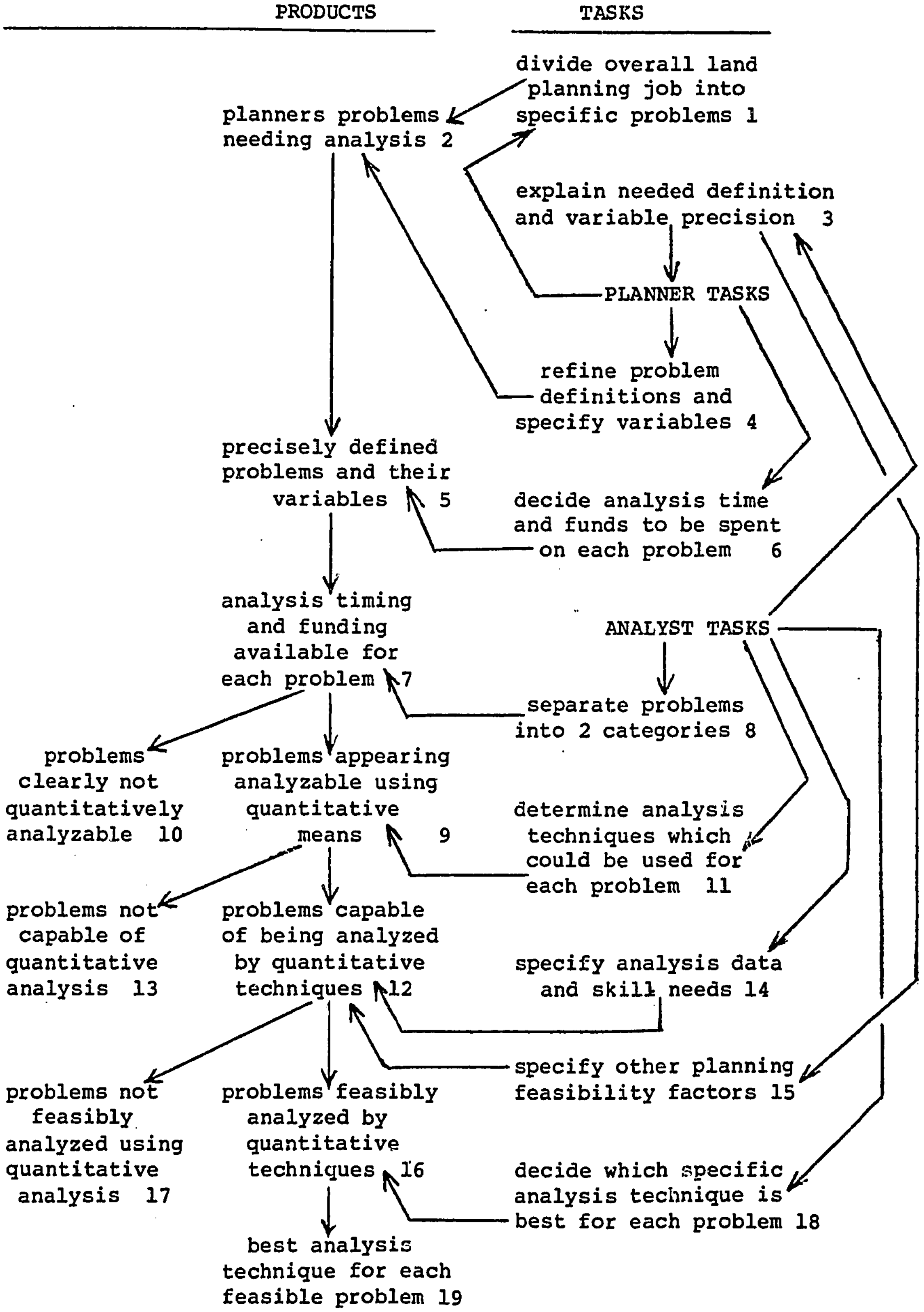
Initially (1 & 2) working alone, members of the planning team identify any analytically discrete problems in the overall planning task. Each problem must require individual study if planners are to formulate rationally and evaluate a set of alternatives and recommend decisions on the resource use demand issues responsible for the need to plan. Inevitably some planning problems will be difficult to define, especially in terms of quantifiable variables. However, in all land use planning processes it is necessary to break down the overall planning task into broad areas of analysis, such as the plan elements, and within these identify and study discrete issues and potential problems. As problem identification is a normal part the planning team's duties, no new effort should be required for the first part of the procedure. For CEM & ESM purposes, more precise definition of problems greatly aids location of scientific literature and expert advice on the subject.

Next (3), analysis technique specialists explain to the planning team the degree of problem and variable specification needed (8) to determine which problems appear analyzable using quantitative methods. Under the general procedure I outline, a precise definition of individual problems and variables must take place very early to enable analysis technique specialists to make their recommendations.

Logically, planning team members should also perform Task 4, describing each problem in detail, identifying factors thought to be controlling variables. Later interaction with the analysis technique specialists will stimulate further refinement and specification.

In Step 5 the director of the planning team specifies analysis fund allocations and due dates; this step could occur before or after Step 6. I think it is best done before, because the clearer understanding resulting from having to more precisely define problems and variables aids funding decisions. The members of the team with professional training in planning have special roles in keeping this (and subsequent formal analyses) problem analysis task forcused on producing something that planners need to know, something that can be used in shaping and implementing the plan. To accomplish this focus they must continually evaluate suggestions and recommendations generated by this analysis technique effort by questioning what is

Figure 1 A General Procedure for Matching Analysis Techniques with Planners' Problems



going to be (or can be) done with the results of individual analyses.

In Steps 6 & 7, planners decide the relative importance of each problem and accordingly determine the amount of time and funds to be allocated for work on each. Again, this is a task which can best be performed by the professionally trained planners. Due dates are determined by when particular answers are needed to keep the planning process proceeding in a timely and uninterrupted manner. Knowledge of deadlines and available funds is crucially needed by analysis technique specialists for deciding the feasibility of using specific techniques to study particular planning problems.

On the basis of the now refined statements of problems and their variables and the time and funds available for their analysis, analysts next (8) divide planners' problems into those which appear to be analyzable using quantitative techniques (9) and those which clearly are not (10). This stage separates fundamentally unquantifiable problems from quantifiable ones. These categorical decisions need only be gross judgments at this stage, because those problems initially placed in the latter category receive more thorough screening in Step 11.

Placement of planners' problems in the "clearly not quantitatively analyzable" category (10) is based on analysts' judgment that, for example, a particular problem largely involves social value conflicts, or that it is still too vaguely defined in terms of controlling variables. In the list of evaluation guidelines for ESM (Chapter 3, Table 1), questions such as numbers 22 and 24 are aimed at the objective of Step 8--i.e., separating nonquantitative from quantitatively analyzable problems. The purpose of guidelines such as numbers 13 and 14 is to establish properties of the planning environment determining the feasibility of using quantitative analysis methods for particular planning problems.

In the next step (11), analysts determine the capability* of quantitative analysis techniques for "problems appearing analyzable using quantitative means" (9). The analysis technique specialists make a preliminary match of planning problems with one or more analysis techniques capable of performing such analysis (12). The additional scrutiny in this process undoubtedly will result in some problems being recategorized as incapable of being analyzed by quantitative methods (13).

Next, the analysts divide those planning "problems capable of being quantitatively analyzed" into feasible** (16) and unfeasible (17) to analyze categories. To perform this catagorization analysts use: information on the dimensions of individual problems, an understanding of available funds, due dates, and other feasibility constraints (15); knowledge of the time and funds needed to perform analyses, and knowledge of the data and skills (14) needed to use different analysis techniques. The next task (18), deciding which

---

*Here I use the term "capability" when referring to specific techniques fully able to analyze the technical aspects of particular planning problems--ignoring any practical constraints on analysis imposed by analysis funds, due dates, available data and other necessary analysis resources.

**Here I use "feasibility" when referring to a technique which can be conducted within the resource constraints of a specific planning effort. Thus, "feasible" analysis techniques are both technically and practically performable.

specific analysis technique is best for each planning problem, is appropriately the responsibility of the analysis specialists. In deciding, they would use such criteria as relative analytic ease, efficiency and precision. For problems which ESM is capable of analyzing, Table 1 guidelines such as 5 and 27 are designed to determine that technique's appropriateness.

CHAPTER 3

DETERMINING THE APPROPRIATENESS OF ECOLOGIC MODELING AS AN ANALYSIS TECHNIQUE

Sources of Determining Factors

Four factors interact to determine the appropriateness of any technique for analyzing particular land use planning problems:

1. the characteristics of the working environment within which plans are prepared (e.g., deadlines, budgets, staffing, workloads, and technical abilities);
2. the working behavior of planners (e.g., attitudes toward the usefulness of formal analysis techniques, relative import attached to expert judgment vs. formal analysis);
3. characteristics of the specific problem (e.g., its relative import, technical complexity, relative dominance of social vs. scientific parameters); and
4. the needs associated with conducting analysis with a specific technique (e.g., types of data, special analysis skills, computing equipment).

Of these four, the planning environment is most commonly the source of impediments to routinely using an analysis technique such as simulation modeling.

A list can be made of the constraints or opportunities existing for each of the above four factors. Merging those lists creates a set of guidelines useful for evaluating whether, for example, ESM is an appropriate quantitative analysis approach for a particular planning problem. Only when a largely favorable response is obtained to the questions posed by the evaluation guidelines should EM be seriously considered as an analytic technique.

Characteristics of the Guideline List

Table 4 lists considerations to guide selection of the problems of planners best analyzed using ESM. Each guideline is derived from one or more of the four sources of analysis constraints; working environment of planners, working behavior and attitudes of planners problem characteristics particularly favorable for ESM, and circumstances facilitating development of a simulation model.

While the list is lengthy, it is not exhaustive. Other considerations could be added, and some in the present list could be subdivided into more specific points to be evaluated. However, the particular points included and the amount of subdivision is adequate for most purposes and particularly for mine. Its lengthiness reflects the many different points which should be evaluated to obtain a good match of ESM with problems of planners.

The list contains many guidelines for determining the technical appropriateness and pragmatic feasibility of ESM analysis techniques. The guidelines are distinctly slanted toward pointing out those characteristics of planning environments, planner behavior, planning problems and analysis techniques which are particularly important for deciding when to use ESM. It is not adequate for evaluating the appropriateness of other types of analysis techniques. However, the list should prove useful as a starting point for developing the questions needed for evaluating other quantitative analysis techniques.

Since the considerations in the list are slanted toward the public land planning working environment, some points are relevant only for governmental or other public agency planning applications of ESM. In the land planning environments of public agencies, hiring, contracting and purchasing constraints and delays can adversely affect the feasibility of simulation modeling as an analysis option. Yet public agency planning, particularly for wildlands, is a context where ESM is most likely to be of use. Nongovernmental planners would need to substitute a set of operational constraint considerations unique to their working environments. Slanting the selection considerations toward public land planning is justified in this study because: (1) the case study area is made up largely of public lands; (2) wildland planning is the most appropriate opportunity for applying ESM, and wildland planning is done largely by public agencies for public lands; and (3) my experience is with public land planning research and public planning agency operations.

Relationship of Guidelines to Procedures for Matching Analysis Techniques with Problems

The considerations listed in Table 1 specify in more detail the questions planners and analysts must ask in portions of the stepwise matching and decisionmaking tasks listed in Figure 1, "A General Procedure for Matching Analysis Techniques with Planning Problems."

Not represented in Figure 1 are the portions of the Guidelines aimed at assessing the constraints imposed by planners' working behavior. The Guidelines are more explicit statements of those considerations which must be evaluated to competently complete the tasks of the Procedures. The Guidelines begin explicitly meshing with the Procedures after Step 6 of the latter is completed--i.e., once the relative priority of different problems of planners is, in effect, established by allocation of analysis funds.

The next Procedure step obviously related to the Guidelines (Guideline 6) is number 11, where possible analysis techniques are determined for each problem. Guidelines 18 to 27 expand on Procedure Step 12, which isolates problems capable of being analyzed quantitatively. Guidelines 32 to 42 and 52 to 56, respectively, are examples of points evaluated in Procedure Step 14 specifying data and skill needs, and Step 15 specifying other planning environment factors affecting the feasibility of analysis. Guidelines 6 to 12 coincide with Procedure Step 18, i.e., deciding the best specific analysis technique for each problem.

Organization of Guidelines List

Awareness of the organizational logic of a long list is necessary for understanding. The general logical order of the Guidelines is not readily apparent because of their diversity. Crucial evaluation points are interspersed throughout the list, some occurring under most headings; accordingly, the relative importance of guidelines as determinants is unrelated to major headings.

It is desirable to list the guidelines in chronologic order or the order of their relative importance, but the guidelines are too diverse to allow this. Such a continuous order is only possible when guidelines can be ranked according to a single criterion. Such rigid consistency to aid comprehension is also unattainable because of the strongly interdependent relationships among many individual guidelines. To facilitate comprehension and application of this list, I believe it is more important to organize the guidelines under several headings rather than to maintain strict internal consistency among all guidelines. It is also more feasible to arrange guidelines under individual headings and subheadings in some logical order. However, the mixture of two or even three types of guidelines under one heading again usually prevents strictly logical ordering. This problem could be avoided by doubling or tripling the number of headings, but that would have complicated rather than simplified understanding.

Under headings, individual guidelines are listed in the approximate order in which they should be considered during the evaluation. However, this arrangement is not strictly maintained as evaluation of earlier steps sometimes depends upon the results of some later ones. The logic behind the order is varied to fit the different perspective of various headings.

Some guidelines are listed in more than one category; this reflects my desire to display a complete list within categories, not to imply that such guidelines are more important than those occurring only once. Some guidelines are essentially restatements of others, either using different emphases (e.g., 42 and 49) or stating the obverse case (e.g., 62 and 63). Such restatements emphasize ramifications particularly relevant to the perspective of different categories.

Some guidelines are essentially paired; accordance with one is a necessary precedent for possible conformity with others (e.g., 62 and 64). Accordance with some guidelines excludes conformity with others. For example, a favorable evaluation response to 73, "low levels of uncertainty are associated with analysis results" precludes conformity with 74, "high uncertainty is inherent in numerous variables, accumulating errors." Analogously, a favorable evaluation of 69, "reliability of results can be checked by direct measurements," makes it unnecessary to evaluate 71, analysis and results can be defended on theoretical grounds." Such interlocking guideline relationships are included to provide backup levels of evaluation when the most desirable attributes cannot be satisfied.

The specificity of evaluation considerations varies considerably. This lack of evenness is not related to relative importance, but rather to the relative difficulty of developing the information needed to evaluate different considerations. Evaluation considerations that can be answered quickly and precisely are asked very specifically (e.g., 1, 27). Less specific evaluation considerations can only be answered in general terms, even after considerable investigation (e.g., 64).

Reading the Guidelines

Each guideline should be read as the statement of an evaluation criterion to satisfy if ESM is a viable candidate technique for analyzing a particular problem. For example, ESM is an appropriate technique to use if..."planners are willing to use an unfamiliar analysis technique," or if..."analysis can be completed in about six months."

Table 1 Simulation Modeling of Planning Problems: Selection Guidelines

Attitudes of Planner's Toward Quantitative Analysis

1. analysis of problem is crucial for planning effort
2. planners are willing to use an unfamiliar analysis technique
3a. despite their high uncertainty, results are useful for decisions
4. planners are willing to deal with problem's natural complexity
5a. planners accept exclusion of social science variables by analysis

Comparison to Other Analysis Technique Capabilities

6. a simulation model can analyze the planning problem
7. confidence exists that simulation model can be fully completed
8. problem complexity exceeds capabilities of familiar techniques
9. complexity exceeds capabilities of easier, unfamiliar techniques
10. modeling is most efficient technique for this type of problem
11a. better quality analysis is needed than other techniques provide
12. type of analysis needed cannot be provided by other techniques

Funding of Planning's Analysis Stage

13. foreseeable modeling costs do not exceed total analysis budget
14. planners are willing to allot a large share of budget to modeling

Information Characteristics of Problem's

15. information on problem is too technical for planners
16a. information on problem is technically diverse
17. technical information on problem is very abundant

Suitability of Problem for Systems Analysis

18. problem variables are numerous and their interactions are complex
19. information organization, screening and synthesis is badly needed
20. system boundaries of problem coincide with these of planning area
21. problem is quantitatively independent of other planning problems
22. analysis and resolution of problem are essentially quantifiable
23. problem is describable as a system of interacting variables
5b. system's simplification of problem is acceptable to planners
24. cause-effect relationships of variables are quantifiable
25. variables are precisely definable
26. variables are quantifiable

Essentially a Natural Science Problem

27. natural science information dominates system variables
5c. social science aspects of problem are not crucial to analysis

Complexity Characteristics of Problem

28. problem not so complicated that conceptual modeling is difficult
29. conceptual model is adequate for a thorough and complete analysis
5d. reducing complexity does not ruin utility of analysis for planners
30. thorough analysis of problem does not require a large scale study
16b. model does not call for excessively diverse scientific information
31. thorough analysis does not need many diverse scientific specialtys

Availability of Information for Analysis of Problem

32. scientific principles governing the problem are well developed
33. scientific knowledge breakthroughs are not needed
34. planning area natural science information inventory is completed
35. natural science information is abundant for planning area
36. scientific literature is abundant on the specific planning problem
37. planning area analogs exist as sources of supplemental information
38. much scientific information exists on planning area analogs
39. strategies are known for overcoming major information gaps
40a. need for new data collection is foreseen as minor
41. scientific consultation on problem is readily available
42a. planning area natural science data are largely computerized
42b. mapped data is largely computerized into a geographical data base

Timeliness of Analysis Results

43a. simulation model analysis can be completed by planners' deadlines
43b. analysis can be completed in about six months
44. analysis has support needed to expedite staffing and purchasing
45a. no large team needs to be assembled for the analysis
46. extensive outside consultation or review is not forseen as needed
47. nonagency personnel are not needed
48. agency scientific experts are readily available to assist analysis
40b. only minor, short term data collection is needed
49. computerization of extensive data is not needed
50a. acquisition of expensive equipment is not needed
51a. useful analysis software is compatible with available hardware

Extraordinary Support Needs for Analysis

Scientific Expertise Needs

45b. a large team of nonagency scientific specialists is not needed
52. paid, outside specialists are needed only for advice and review
53. access to outside experts available informally, at no cost
54. agency already employs needed scientific specialists
45c. a big team of in-house scientific specialists is not needed
48b. agency scientific specialists are readily available
55. specialists needed only on a short term or intermittent basis
56. specialist consultations accomplishable by telecommunication

Computer Hardware Needs

57. computer hardware is largely on hand, or remotely accessible
50b. no expensive hardware must be purchased or leased
58. hardware not on hand can be leased rather than purchased
59. computer access and response time is good

Computer Software Needs

60. programming breakthroughs are not foreseen as needed
61. good agency programming assistance is readily available
51b. useful software is compatible with available hardware
62. need for development of complicated new programs not foreseen
63. needed complicated programs exist or can be adapted
64. needed new programming is foreseen as simple, straight forward

Reliability of Analysis Technique and Results

Reputation of Analysis Technique

65. analysis technique has a well established favorable record
66. technique has proven useful in planning problem contexts
67a. openness to scrutiny and participation communicates objectivity

Technical Challenges and Defense of Analysis

68a. openness of analysis procedure facilitates challenges
68b. visible analysis decisions will stimulate technical challenges
69. interpretation of results is open to technical challenges
70. reliability of results can be checked by direct measurements
71. analysis and results can be defended on theoretical grounds
72. analysis defendable because it uses best available information

Technical Quality of Analysis

5e. nothing of practical significance omitted to simplify analysis
11b. analysis procedure provides best solution for complex problem
73. assumptions effects, relative import of variables is estimatable
74. low levels of uncertainty are associated with analysis results
75. high uncertainty inherent in many variables, accumulating errors
3b. planners can understand and accept high uncertainty of results
3c. decision value of results remains despite their high uncertainty

Openness of Analysis to Scrutiny

67b. openness to scrutiny and participation communicates objectivity
76. structure of analysis and data assumptions fully open to scrutiny
77. planning decisions are obviously derivative of analysis results

Openness of Analysis to Participation

67c. participation in analysis process increases confidence in results
78. public can participate in significant portions of analytic process
79. planners can significantly participate in analytic process
80. public can contribute information needed for analysis
81. planners can contribute information needed for analysis

Communicability of Analysis Process and Results

82. analysis process is portrayable graphically to aid communication
83. planners can readily understand entire analysis process
84a. planners can gain enough understanding to publicly defend results
84b. planners can gain enough understanding to explain process to others
85. public can essentially understand entire analysis process
86. deriviation of answers from analysis are generally understandable
3d. answer's uncertainty communicable without damaging their value
5e. results readily relate to public concerns about problem

Reasons for Individual Guidelines

In the following section I give the main reason(s) I included each guideline for deciding whether ESM is an appropriate technique for analyzing a particular problem. Because there are so many guidelines, I have kept my statement of the reasons for each brief.

Any analysis time-frame or staff size figures I give are for illustrating my points by providing an estimate of the magnitudes involved; they are not based upon established data.

From the statement of most reasons for individual guidelines, it is obvious whether that guideline originates from some characteristic of the typical working environment of planners, or from planners' working behavior or common attitudes, or from characteristics of problems favoring use of ESM, or from some conditions propitious for developing an ESM. Whether a particular guideline is included specially to emphasize a constraint peculiar to the working environment of public agency land use planning is also usually obvious.

All guidelines are not equally important determinants of whether ESM should be used. The importance of each guideline as well as its origin and special orientation are summarized in Table 2.

Attitudes of Planners Toward Quantitative Analysis

1. Analysis of Problems is crucial for planning effort.

   ESM typically costs more than planners are used to budgeting for analysis of single, routine problems. Hence, that approach is feasible only for problems planners consider very important to resolve.

2. Planners are willing to use an unfamiliar analysis technique.

   Planners may be reluctant to use unfamiliar analysis techniques. ESM is an analysis technique unfamiliar to few land use planners.

3a. Despite their high uncertainty, results will be useful for decisions.

   In their decisionmaking, planners tend to depend upon information in proportion to its degree of certainty. Because of the numerous variables commonly included in ESM's, operational versions are likely to produce results with high levels of uncertainty. If its results are going to be discounted, ESM is futile.

4. Planners are unwilling to deal with the natural complexity of the problem.

   Some planners may look for simple analyses and resolutions for all problems, ignoring their true complexity even when it must be considered for reaching well-founded decisions. One of ESM's great advantages is its ability to explicitly recognize and deal with and illustrate variable interaction complexities when they are essential to understanding and analyzing a problem.

5a. Planners accept exclusion of social science variables by analysis.

   Social variables are usually so poorly established quantitatively that it is undesirable to include them in an ESM. The latter is analytically most powerful when used for problems where social variables are relatively unimportant, and so may be omitted. If planners and modelers disagree upon the importance of social variables, planners will oppose use of ESM, push for inclusion of social variables in them or discount model results. This guideline is a special case of guideline 5b.

Comparison to Other Analysis Technique Capabilities

6. A simulation model can analyze the planning problem.

   ESM is not a good quantitative technique for many problems of planners because most are not scientifically analyzable.

7. Confidence exists that the simulation model can be fully completed.

   Planners do not want to waste their time and budgets on techniques that may not be able to produce the analysis they need.

8. Problem complexity exceeds capabilities of familiar techniques.

   Because ESM is comparatively more costly and technically difficult to use than quantitative analysis techniques familiar to planners, ESM ought to be used only when the complexity necessary to the analysis exceeds the ability of more familiar techniques.

9. Complexity exceeds capabilities of easier, unfamiliar techniques.

   ESM should be used only if less costly quantitative analysis techniques are not capable of analyzing problems.

10. Modeling is most efficient analysis technique for this type of problem.

Modeling should be chosen when it is more analytically and economically efficient than other approaches to analysis.

11a. Better quality analysis is needed than other techniques can provide.

No easier, cheaper, or more effective quantitative analysis approach than ESM is capable of producing the quality of results desired.

12. Type of analysis needed cannot be provided by other techniques.

If only ESM is capable of producing the desired type of analysis, it is the logical choice.

Funding of Planning's Analysis Stage

13. Foreseeable modeling costs do not exceed total analysis budget.

Obviously, the cost of using ESM as an analysis technique must be affordable by a regional planning effort.

14. Planners [illegible] to allot a large share of budget to modeli[illegible]

ESM is [illegible]pensive analysis technique. If planners are not willing to spend enough of their analysis budget for analyzing the particular problem under consideration, ESM should not be contemplated.

Information Characteristics of Problems

15. Information on problem is too technical for planners.

The typically busy schedules and nonscientific backgrounds of planners do not allow them to acquire the technical background of planners necessary to understand most scientific information. Bringing into the analysis process individuals who can understand and make applied sense of scientific information is an integral part of using ESM.

16a. Information on problem is technically diverse.

"Technically diverse" refers to information from two or more fields having significantly different jargons, measurement systems, analysis or experimental techniques and scientific theory. Planners are faced with a particularly difficult analysis task when one of their planning problems can only be understood and analyzed using technically diverse scientific information. This situation is an ideal opportunity for considering ESM, since its development involves bringing in sufficient expertise to integrate such scientific information diversity into a problem application framework.

17. Technical information on problem is very abundant.

"Abundant" refers to large quantities of information, not necessarily technically diverse, relevant for analyzing a problem. This condition is an ideal opportunity for considering ESM.

Suitability of Problem for Systems Analysis

18. Problem variables are numerous and their interactions are complex.

ESM is a systems analysis technique. It is also an analysis approach inherently suited for analyzing problems with these characteristics.

19. Information organization, screening and synthesis is badly needed.

    ESM is inherently suited for analyzing problems with these kinds of characteristics.

20. System boundaries of problem coincide with those of planning area.

    To effectively use a systems analysis approach such as ESM, the boundaries of the problem ought to encompass all significant factors affecting or controlling system behavior. This problem characteristic facilitates control of the problem by planners and analysis by modelers.

21. Problem is quantitatively independent of other planning problems.

    To effectively use systems analysis approaches, the system boundaries of a problem must encompass all important variables. If the problem is inextricably mixed with others, it cannot be resolved as the system is defined. Enlarging system boundaries may make the analysis of the problem so complicated that using ESM is no longer feasible.

22. Analysis and resolution of problem are essentially quantifiable.

    ESM only works for problems which can be analyzed quantitatively. CEMs can be used when some variables are not quantitatively well understood.

23. Problem is describable as a system of interacting variables.

    This is a characteristic of problems suited to ESM.

5b. System's simplification of problem is acceptable to planners.

    Modeling always involves some simplification of reality. To facilitate development of a working ESM, variables that can be shown to have little quantitative effect on the problem must be omitted. Planners must accept the usefulness of analysis results when such minor variables are ommitted.

24. Cause-effect relationships of variable are quantifiable.

To take full advantage of ESM's analytic capabilities, the exchanges between variables must be expressable in quantitative terms.

25. Variables are precisely definable.

The first step in quantifying variables is to identify and describe them as distinctly discrete entities.

26. Variables are quantifiable.

To be able to develop a working ESM, the problem's variables must be quantifiable.

Essentially a Natural Science Problem

27. Natural science information dominates system variables.

ESMs most competently analyze problems dominated by natural variables and processes. The technique was conceived for studying ecosystem operations.

5c. Social science aspects of problem are not crucial to analysis.

ESM is best suited for analyzing problems with natural science variables rather than social ones. Simulation modeling is not a good analysis technique for most social science problems as the latters' variables are typically too poorly understood to permit competent quantification. An ESM's analysis will not be valid if significant variables are omitted or are artifically valued.

Complexity Characteristics of Problem

28. Problem is not so complicated that conceptual modeling is difficult.

While ESM is a good analysis technique for complicated problems, they must not be so complex that successful analysis is difficult and uncertain. If it is difficult to develop a CEM, it will be more difficult to develop a working version of the model.

29. Conceptual model is adequate for a thorough and complete analysis.

If the conceptual model excessively simplifies the complexity of the problem, its superficial framework for analysis makes results worthless and misleading.

5d. Reducing complexity does not ruin utility of analysis for planners.

Some simplification of the true complex of variables and their interactions always occurs when developing models. It must be possible to develop a feasible ESM of a problem without so simplifying its complexity that analysis of aspects of the problem specially needed by planners are seriously compromised or so that the model's operations inadequately mimic the behavior of the real system.

30. Thorough analysis of problem does not require a large scale study.

If large scale studies are needed to develop an adequate ESM of a problem, the approach is infeasible because of the planning environment's characteristically short analysis periods and budgetary limitations on the scope of individual analyses.

16b. Model does not call for excessively diverse scientific information.

While ESM is useful when scientifically diverse information is needed for analyzing a problem, it becomes increasingly difficult for a small team of specialists to integrate many different kinds of technical information.

31. Thorough analysis does not need many diverse scientific specialties.

It is financially infeasible and managerially difficult to develop an ESM when many specialists are needed for building the model.

Availability of Information for Analysis of Problem

32. Scientific principles governing the problem are well developed.

Development of an ESM is greatly facilitated if the scientific theory and principles governing factors controlling a problem are thoroughly understood.

33. Scientific knowledge breakthroughs are not needed.

ESM is infeasible if a significant scientific knowledge breakthrough is needed to develop the model. Time and funds are not available for overcoming such gaps during the planning effort. It is inappropriate to conduct a basic research effort as part of the analysis of planners' problems.

34. Planning area natural science information inventory is completed.

Possessing the information available on a planning area, one can evaluate its adequacy for developing an ESM.

35. Natural science information is abundant for planning area.

Abundant natural science information for the planning area greatly contributes to development of an ESM analyzing a problem.

36. Scientific literature is abundant on the specific planning problem.

If scientific literature is abundant on a type of problem, e.g., eutrophication, it is likely that the information needed to develop an ESM is also available, and that gaps in scientific knowledge on the planning area can be overcome.

37. Planning area analogs exist as sources of supplementary information.

The existence of areas or situations which are ecologically similar provides a good source of supplementary information to fill gaps in knowledge needed for ESM.

38. Much scientific information exists on planning area analogs.

The availability of such alternate sources of information increases the likelihood that the information needed to develop an ESM already exists in the scientific literature.

39. Strategies are known for overcoming major information gaps.

Ordinarily, an ESM is considered infeasible when any important information needed for its development does not exist. However, if a good strategy exists for compensating for the missing crucial information, ESM is not automatically eliminated.

40a. Need for new data collection is foreseen as minor.

The need for minor effort or expense to collect or develop new field or experimental data seldom renders ESM infeasible.

41. Scientific consultation on problem is readily available.

If scientific assistance needed to develop an ESM is not readily available, that analysis approach usually should be considered infeasible.

42a. Planning area natural science data are largely computerized.

If most or all of the information needed for the model is computerized, development of a working ESM is greatly expedited.

42b. Mapped data are largely computerized into a geographic data base.

Same reason as for 42a, of which this guideline is a special case.

Timeliness of Analysis Results

43a. Simulation model analysis can be completed by deadlines of planners.

ESM is the wrong approach if it cannot produce an analysis when planners need it.

43b. Analysis can be completed in about six months.

This is a reasonable approximation of the time available to analyse an individual planning problem--given two years as a common span available to develop a plan and the trend to complete plans in half that time so that the last year can be used to meet legal requirements for public hearings on the proposed plan, environmental impact statement, public comment time, etc.

44. Analysis has support needed to expedite staffing and purchasing.

Development of an ESM will probably take the full span of the planning effort's analysis stage. Thus, the decision to use ESM must be made very early and modeling started quickly. In government agencies, it commonly takes months to purchase major equipment and hire or transfer new personnel. High level administrative support for the planning effort can minimize routine delays.

45a. No large team needs to be assembled for the analysis.

ESM is usually infeasible when a large team is needed because of procedural delays and financial difficulties associated with hiring or assembling such a group of specialists.

46. Extensive outside consultation or review is not foreseen as needed.

Same reason as 45a plus additional delays commonly associated with contracting by government agencies.

47. Nonagency personnel are not needed.

In government agency land use planning, it is much easier to obtain special ESM staffing when individuals with the needed skills already work for the agency.

48a. Agency scientific experts are readily available to assist analysis.

ESM is probably not feasible if the special assistance needed to develop a model is not quickly available.

40b. Only minor, short term data collection is needed.

For ESM to be feasible, development must begin early and proceed rapidly without delays. Such models are likely to be infeasible if more than a minor amount of new information has to be collected.

49. Computerization of extensive data is not needed.

Unless data are already computerized or computerization help is readily available, the delay associated with computerizing an extensive set of data needed for an ESM may make that technique infeasible.

50a. Acquisition of expensive equipment is not needed.

ESM must deliver analysis results in a timely manner. In government agencies, purchase of expensive equipment usually involves extensive delays.

51a. Useful analysis software is compatible with available hardware.

It frequently is difficult and time consuming to convert existing computer programs useful for developing an ESM to a new computer hardware system.

Extraordinary Support Needs for Analysis

Scientific Expertise Needs

45b. A large team of nonagency scientific specialists is not needed.

Same as 45a and 46.

52. Paid, outside specialists are needed only for advice and review.

Same reasons as 46. If nonagency scientists are needed to only a limited extent, ESM is a feasible analysis technique.

53. Access to outside experts is available informally, at no cost

Availability of assistance needed from outside scientists without agency hiring or contracting delays adds to the feasibility of ESM.

54. Agency already employs needed scientific specialists.

Same reason as 47.

45c. A large team of in-house scientific specialists is not needed.

Identifying many individuals with needed skills and obtaining their participation usually is difficult and time-consuming. If more than a few such persons are necessary, ESM is probably infeasible--though not so clearly as when a large team of nonagency scientists is needed.

48b. Agency scientific specialists are readily available.

If either the needed specialists, their supervisors or agency administrators resist their participation, such assistance is, for all practical purposes, unavailable. If ESM development is entirely dependent upon internal agency technical assistance that is not readily available, the technique is infeasible.

55. Specialists are needed only on a short-term or intermittent basis.

When developing an ESM it is much easier to obtain outside scientific assistance on a short-term or intermittent basis. Participating individuals and administrators are much less resistent to such interruptions of normal job responsibilities.

56. Consultation with specialists can be accomplished by telecommunication.

This is the least costly, physically disruptive and organizationally cumbersome way to obtain outside scientific assistance. Administrators and especially scientists seldom resist requests for this type of assistance. If only this kind of limited consultation with others is needed during development of an ESM, feasibility is increased.

Computer Software Needs

60. Programming breakthroughs are not foreseen as needed.

ESM is an infeasible analysis technique if any programming technique breakthroughs are needed for the development of a model.

61. Good agency programming assistance is readily available.

Computer programming is one of the major tasks for developing a working ESM. If programming assistance is available, conditions are favorable for using ESM.

51b. Useful software is compatible with available hardware.

Same reason as 51a.

62. Need for development of complicated new programs is not foreseen.

It takes much time to develop a complicated computer program for an ESM. If the amount of time needed to complete such a task is more than is available for analysis of a planning problem, use of ESM is contraindicated.

63. Needed complicated programs exist or can be adapted.

Computer programs exist for many ecologic models. If a usable one can be identified and adapted to a planner's problem, ESM is a more feasible candidate analysis approach.

64. Needed new programming is foreseen as simple and straightforward.

If the new computer programming needed to develop a working ESM is fairly simple, such modeling is feasible.

Reliability of Analysis Techniques and Results

Reputation of Analysis Technique

65. Analysis technique has a well-established favorable record.

Planners are (or ought to be) reluctant to use unknown analysis techniques. Only techniques having a good reputation for delivering timely results should be considered for use.

66. Technique has proven useful in planning problem contexts.

Previous success in analyzing planning type problems and delivering results in a timely fashion is a favorable characteristic.

67a. Openness to scrutiny and participation communicates objectivity.

The public tends to be suspicious of the avowed reasons for governmental decisions. Thus, it is desirable to choose analysis techniques permitting interested parties to see how information affecting decisions was developed, and further, to choose analysis techniques in which the public can participate.

Technical Challenges and Defense of Analysis

68a. Openness of analysis procedure facilitates challenges.

Because analysis technique openness facilitates technical challenges, an approach must be chosen which is capable of being well executed to discourage challenges which may totally undermine the model's validity in the mind of the public.

68b. Visible analyses for decisions are likely to stimulate technical challenges.

The reasons for this guideline are similar to those for 68a. However, here there is more emphasis on choosing analysis approaches which can be executed in a patently objective manner by making good use of scientific data and by not requiring analysts to make many judgmental decisions or assumptions to fill in for missing data or incomplete scientific understanding.

69. Interpretation of results is open to technical challenges.

Choose the analysis approach capable of providing the most definitive, unequivocable analysis results--results most stable and defendable when challenged. Its decisionmaking and public confidence value is then unlikely to be undermined by generating scientific controversy or pickiness.

70. Reliability of results can be checked by direct measurements.

Planners and the public have the most confidence in an analysis approach when its predictions can be substantiated by direct measurement of field conditions. ESMs fare poorly on this selection criterion, as there are substantial reasons to expect that their analytic results cannot be validated by field measurements. However, they are usually a superior analysis approach for complex ecosystem problems when compared to most approaches capable of producing results that can be validated.

71. Analysis and results can be defended on theoretical grounds.

If analysis results cannot be substantiated by measuring predicted changes, backup criterion for selecting techniques is that the relationships used in the analysis be in accordance with the preponderance of scientific principles and theory.

72. Analysis defendable because it uses best available information.

When analysis technique results cannot be supported by direct measurements of their predictions or cannot be irrefutably shown to be supported by the preponderance of scientific knowledge (as when significant scientific controversy exists), a last backup selection criterion exists. An analysis technique may still be acceptable if its results can be defended as making the best use of available information --even though the latter is incomplete or not of as high a caliber as desired.

Technical Quality of Analysis

5e. Nothing of practical significance is omitted to simplifv analysis.

Same reasons as 5c.

11b. Analysis procedure provides best objective solution for complex problem.

Same reasons as 11a.

73. Assumptions effects, relative import of variables can be estimated.

The quantitative effect of procedural decisions (eg., assumptions) on analysis results should be establishable in an objective analysis technique. Similarly, the relative effect on analysis results of the different variables used in the analysis should be establishable. All variables are not of equal quality; and if a poorly known one greatly affects analysis results, analysts and decisionmakers ought to be made aware and be wary. Identifying the most important variables in a complex problem points out to decisionmakers potential ways to manage the problem.

74. Low levels of uncertainty are associated with analysis results.

Planners and other public decision makers greatly favor analysis techniques capable of producing results with only a small chance that they are inaccurate, accompanied by only small error terms.

75. High uncertainty is inherent in many variables, accumulating errors.

The purpose of this guideline is to emphasize to evaluators the dilemma that uncertainty of analytic results is likely to be high for any technique for analyzing a complex problem by explicitly including most of the variables affecting it. Lower uncertainty occurs in the results of analysis techniques using fewer variables; but there is much covert uncertainty in the aggregation of variables by those approaches.

3b. Planners can understand and accept high uncertainty of results.

Same reasons as 3a.

3c. Decision value of results remains despite their high uncertainty.

Same reasons as 3a.

Openness of Analysis to Scrutiny

67b. Openness to scrutiny and participation communicates objectivity.

Same reason as 67a.

76. Structure of analysis and data assumptions are fully open to scrutiny.

Selecting analysis techniques which are fully open to inspection enables the public to understand the means by which information leading to agency decisions is developed.

77. Planning decisions are obviously derivative of analysis results.

If agency decisions do not have any readily apparent relationship to the substance of analysis technique results, then choosing an analysis technique for its openness is unimportant.

Openness of Analysis to Participation

67c. Participation in analysis process increases confidence in results.

It is a good general principle to choose analysis approaches which can include decisionmakers and the public as substantial participants. Under such circumstances, they are more likely to accept and use analysis results and believe the objectivity of decisions based upon them.

78. Public can participate in significant portions of analytic process.

Same reasons as 67c.

79. Planners can significantly participate in portions of analytic process.

Choosing an analysis technique in which planners can actively and meaningfully participate increases the likelihood that they will gain enough understanding and confidence in those results to use them in shaping their decisions.

80. Public can contribute information needed for analysis.

If the public can participate in no other more substantial manner, an analysis technique should at least be capable of involving them in data collection.

81. Planners can contribute information needed for analysis.

If they can participate in no other, more substantial manner, they ought to at least be solicited as important sources of data inputs to an analysis approach.

Communicability of Analysis Process and Results

82. Analysis process is portrayable graphically to aid communications.

Graphics is the most readily understood of all communication media. Therefore, it is desirable to choose an analysis technique whose process is readily portrayed using a graphic display.

83. Planners can readily understand entire analysis process.

Understanding creates insight, acceptance and confidence. Hence, it is most desirable to choose a technique whose analysis process can be understood by the decisionmakers expected to use its results.

84a. Planners can gain enough understanding to publicly defend results.

Since planners must explain and defend their decisions publicly, it is desirable to select a technique for which the planners can understand the analysis process well enough to explain any scientific bases upon which the decisions may be based.

84b. Planners can gain enough understanding to explain process to others.

Same reasons as for 84a, but it takes significantly more understanding to be able to explain and defend an analysis technique at public meetings.

85. Public can essentially understand entire analysis process.

Understanding should increase acceptance and confidence in objectivity. Hence, it is most desirable to choose a technique for which the analysis process can be understood by those potentially affected by decisions based on results.

86. Derivation of answers from analysis are generally understandable.

If planners and the public cannot understand the entire analytic process, they ought to at least be able to gain a general understanding of how those results were obtained.

3d. Answers' uncertainty can be communicated without damaging their value.

Planners tend to discount the value of analytic results with high uncertainty. If they cannot accept that such levels of uncertainty always exist for complex problems and that such analysis results still are of value for decisionmaking, then it is futile to attempt such techniques.

5e. Results readily relate to public concerns about problem.

Techniques should be avoided which produce analytic results in a form or with a degree of abstractness which makes them difficult to relate to the topical quantities or qualities of planning problems.

Deciding Whether Guidelines are Crucial, Important or Desirable

Before ESM is attempted, a favorable assessment of some Guidelines is crucial; for others, only important; and for some, merely desirable. In the column under the heading "Importance" in Table 5, I indicate my rating of the relative importance of each guideline. Two different ratings are needed; one for development of a CEM of the planners' problem and another for the development of a fully functional model. The analytic resources needed to develop a CEM are considerably less than for a fully operational ESM.

Table 2. Summary of Guidelines' Origins, Importance, Special Emphases.

No.	Origins	Importance		No.	Origins	Importance		Special Characteristics Affecting Any Analysis Technique's Appropriateness		
		CESM	WESM			CESM	WESM	No.	Origins	Importance
1	PE	C	C	35	ESMN		D			
2	PB	I	I	36	ESMN		D			
3a	PB	C	C	37	ESMN		D			
4	PB	D	D	38	ESMN		D			
5a	PB	I	I	39	ESMN	I	C	65	PB-PE	I
6	PC	C	C	40a	ESMN(PE)		C	66	PB-PE	D
7	PE(PC)	C	C	41	ESMN(PE)	I	I	67a	PE	I
8	PE(PC)	I	I	42a	ESMN(PE)		D	68a	PB-PE	UD
9	PE(PC)	I	I	42b	ESMN(PE)		D	68b	PB-PE	UD
10	PE(PC)	I	I	43a	PE	C	C	69	PB-PE	UD
11a	PE	I	I	43b	PE	I	I	70	PE	D
12	PE	I	I	44	PLPE	I	I	71	PE	D
13	PE	C	C	45a	PE	C	C	72	PE	D
14	ESMN	D	C	46	PLPE	I	I	5e	PE	I
15	PC	D	D	47	PLPE	I	I	11b	PE	I
16a	PC	D	D	48a	PLPE	D	I	73	PE	D
17	PC	D	D	40b	PE		C	74	PB-PE	D
18	PC	D	D	49	PE		I	75		UD
19	PC(PE)	D	D	50a	PE		I	3b	PB-PE	C
20	ESMN(PC)	I	I	51a	PE		I	3c	PE	C
21	ESMN(PC)	I	I	45b	PLPE	C	C	67b	PE	D
22	ESMN(PC)	D	C	52	PLPE	D	D	76	PE	D
23	ESMN(PC)	C	C	53	PLPE	D	D	77	PE	D
5b	ESMN-PB	C	C	54	PLPE	D	D	67c	PE	D
24	ESMN(PC)		C	45c	PLPE	I	I	78	PE	D
25	ESMM(PC)		C	48b	PLPE	D	D	79	PE	D
26	ESMN(PC)		C	55	PE	D	D	80	PE	D
27	ESMN(PC)	D	I	56	PE	D	D	81	PE	D
5c	ESMN(PC)	D	I	57	PE		I	82	PE	D
28	ESMN(PE)	I	I	50b	PE		I	83	PE	D
29	ESMN(PE)	I	I	58	PE		D	84a	PE	D
5d	ESMN(PE)	C	C	59	ESMN(PE)		D	84b	PE	D
30	PE-PC	C	C	60	ESMN(PE)		C	85	PE	D
16b	ESMN(PC)	I	I	61	ESMN(PLPE)		D	86	PE	D
31	ESMN(PE)	C	C	51b	ESMN(PE)		D	3d	PB-PE	C
32	ESMN(PC)	C	C	62	ESMN(PE)		I	5e	PE	I
33	ESMN(PE)	C	C	63	ESMN(PE)		I			
34	ESMN(PE)	D	D	64	ESMN(PE)		D			

Origins column legend
ESMN = modeling need
PLPE = public land planning environment
PB = planner behavior
PC = problem characteristic
PE = planning environment
( ) = in context of PC, PE or PLPE
- = joint origin

Importance column legend
CESM = conceptual model
WESM = working model
D = desirable
C = crucial
I = important
UD = undesirable

To decide ratings, I asked myself, "In the context of typical planning environments or planner behavior, is this Guideline a desirable, important or crucial reason to use ESM, and/or if the conditions stated in this Guideline are not present, is ESM still possible?"

Crucial Rating. ESM is infeasible if these Guidelines cannot be satisfied.

Important Rating. Failure to satisfy "important" Guidelines can eliminate ESM if no strategy can be thought of for overcoming the associated difficulties. For example, for Guideline 47, given the typical short and rigid time delays in hiring nonagency personnel, I believe it is "important" that nonagency personnel not be needed. However, if they were needed, it is conceivable that strongly supportive agency administrators could quickly find a way to surmount hiring or contracting difficulties. An "important" rating is also used when satisfactory attainment of a Guideline is not judged to be imperative, but is certainly more necessary than would be indicated by a "desirable" rating.

Desirable Ratings. The factors these Guidelines call for are useful, but not major determinants of the feasibility of using ESM. Under marginal feasibility circumstances, unsatisfactory assessment of a "desirable" Guideline could make ESM impossible. Thus, a favorable rating on "desirable" Guidelines increases the feasibility of using ESM as an analysis technique.

CHAPTER 4

ASSESSING A TAHOE CASE STUDY USING THE GUIDELINES

Not all of the Guidelines are directly relevant to assessing Tahoe as a favorable planning environment for using ESM. Nor are all Guidelines relevant for determining whether studying the system of factors affecting water color and transparency is a problem well suited for using ESM. Many that are relevant cannot be discussed in a substantial manner because that would require detailed knowledge of planning agency budgets (Guidelines 13, 14), planning staff attitudes (Guidelines 2-4) and technical skills (e.g., Guideline 83), political and administrative support (Guideline 44), government agency scientific personnel and agency willingness or ability to provide (e.g., Guidelines 47, 48a) technical or extraordinary support needs (Guidelines 52-64) for planning.

Rather than discussing all Guidelines relevant to assessing the choice of the Tahoe Basin and water color and transparency, I concentrate discussion on those related to evaluating the availability of scientific information useful for studying this problem facing Tahoe's planners. I also concentrate discussion on those Guidelines related to the appropriateness of water color and transparency as a subject for an ESM. My discussion emphasizes: whether that problem is important enough to Tahoe planning to justify development of an ESM (Guideline 1); whether it can be considered an essentially physical-biological problem with some rather unimportant social components (Guidelines 27, 5c); the ability of that problem to be successfully represented by an ESM (Guidelines 20, 26), and whether enough scientific information exists to express the quantitative relationships of water color and transparency to controlling variables (Guidelines 32-33, 36-38). With respect to Tahoe regional planning, I discuss only Guidelines 1, 20 and 35.

As I do not specifically develop an ESM of land capability classification, the appropriateness of that portion of this study cannot be discussed in terms of the Guidelines. Discussion of the importance and appropriateness of land capability classification for application of ESM results by regional planning and planners is concentrated in Chapter 17, where I develop a land capability classification zoning map is developed using the understanding gained from the EM. However, that classification is not the problem being modeled.

The Relationship of Water Color and Transparency to Tahoe's Regional Planning

Guideline 1, in effect, requires that ESM be used as an analysis technique only for high priority problems. In this section I provide evidence that in Tahoe's planning environment, the problem of preserving water color and water transparency, is so important that it fully meets this criterion.

I believe water quality is the key environmental protection problem facing Tahoe Basin planners--whether for public or private land planning efforts. My assessment is supported by the identification and rating of Tahoe Basin land use problems by others (U.S. For. Serv. Region 5 1978, U.S. Env. Protect. Agency 1974, U.S. Dept. Interior 1973, U.S. Western Fed. Reg. Council 1979.) The uniqueness of that very large, highly pure water body and the knowledge that it will retain for a very long time (Crippen and Pavelka 1970) any substance entering it has been a major impetus for planning and the rationale for threatened direct federal intervention in basin activities. The general public and environmentalists are most concerned about the adverse effect of land uses on the lake, and this concern has been the key public issue responsible for initiating and continuing to drive regional land use planning efforts in the basin.

Of course there are other public concerns about what has, is, and may happen in the basin. For example, the lake would not be the unique national resource it is if it were sitting out on a vast plain without its scenic backdrop of mountainous surroundings. In fact, its color would be modified by a change in surroundings, as the apparent deep blue water color is partially due to the close high mountains cutting off reflection of the lighter blue sky that exists near the horizon (Hulburt 1934). However, the scenic splendor of the surrounding mountains is not seriously threatened, as they are nearly all in public ownership.

The problems associated with urbanization of wildlands in scenic areas occur in many mountainous regions experiencing development pressures (e.g., Lynch and Broome 1973). However, they have seldom stimulated and focused the kind of nationwide public concern that forced interstate regional planning in the Tahoe Basin. Planners at Tahoe must acknowledge and respond to these other public concerns.

But evidence indicates that the single most important planning issue is protection of the lake's uniquely pure water quality.

Preservation of water color and transparency is not a common land planning problem, though it is more common than is realized. Cultural eutrophication is a common land planning issue in many areas containing lakes. The vast amount of literature produced on this subject since the mid-1960s is convincing evidence of its social importance. For example, a winter 1979 computer search of the WRSIC (Water Resources Scientific Information Center) computerized bibliographic file yielded 3315 references on eutrophication.

Many reasons cause the general public's negative reaction to cultural eutrophication: e.g., offensive odors, unsightly scum, slippery rocks, bad taste, fear of health hazards, and decreased fishing quality. I believe that concern over changes in the optical properties of the water would rank high on any such list.

Measures of changes in optical properties have long been used and are still widely advocated as good indicators of trophic status and hence, of eutrophication (Carlson 1977). Thus, whether changes in the optical properties of water are, explicitly or implicitly, a topic of great public concern, those qualities are good indicators of the status of most other problems caused by cultural eutrophication.

Water color and transparency are two qualitative variables which effectively capture those attributes about which the public cares most at Tahoe. People care more about the visual appearance of the lake (and therefore its water) than any other quality aspect, even though most do not express their aesthetic concerns with these exact words. Water clarity (a synonym for transparency) is explicitly recognized to be a matter of great public concern in several basin planning documents (Tahoe Regional Planning Agency 1971, U.S. For. Serv. Region 5 1978 p. 81, U.S. Western Fed. Regional Council 1979). Protection of water transparancy also results in protection of water color, as the latter is largely a product of the effect of the former on sunlight in water.

Water Color and Transparency as Environmental Management Symbols

While of central and perhaps paramount importance among regional the goals of planners, preservation of Lake Tahoe's water purity (as epitomized by its color and transparency) would not represent attainment of a solution to all environmental management problems in the basin. Other environmental concerns were initially and continue to be stimuli for regional planning activities. Preservation of the lake's purity is symbolic of what regional land use planners are expected to accomplish. Preservation of the lake's water quality is an easily understood goal and is the most frequently vocalized concern of those seeking to protect the entire basin from further urban development. Thus the "preserve the lake" battle cry is more symbolic of what is at stake than it is the sole purpose of environmental planning efforts. The large, pure, high elevation lake is internationally unique in many respects, while what is happening to basin lands is a relatively commonplace problem.

In terms of the comparative sensitivity to degradation of other environmental conditions in the basin, lake water quality is not a good overall indicator. Large quantities of pollutants over many years are needed to cause prominent, long duration changes--an undesirable reponse characteristic for a good indicator of environmental problems (Lenhard and Witter 1977).

The visual conditions of the lake's waters are relatively unresponsive to assaults on its purity. This slow response time is to be expected given that each year the lake receives only about 1/400th* of its volume from stream inflows and only about 1/700th** of its volume is displaced down the Truckee River. Hence any increasingly polluted waters flowing into the lake are greatly diluted by its current store of very pure waters. Gradual water color changes over the years are unlikely to be noticed by most of the general public (Smith et al. 1973 p.197).

The great depth of the lake also contributes to its inherently slow response time to pollutant increases. About 75 percent of its waters are below the 80 m deep compensation point (Richerson et al. 1978). Hence they are at depths where light levels are theoretically too low to enable water coloring and transparency-reducing phyto-

---

*The average annual total streamflow is 307,900 acre-feet (AF) and the lake's volume is 122,000,000 AF (McGauhey et al. 1963 p.59). Water diversions from streams are 5131 AF (Crippen and Pavelka, 1970). 122,000,000 - 302,796 = 403 years.

**The mean outflow to the Truckee River is 171,000 AF (Crippen and Pavelka 1970). 122,000,000 - 171,000 = 713 years. The discrepancy detween 403 and 713 years is due to direct precipitation additions to the lake and evaporative losses from its surface.

plankton to grow and reproduce.* The volume of waters out of the growth zone is probably even greater than 75 percent** because the top 15 m is so strongly lighted that phytoplankton photosyntesis, and hence growth and reproduction, is greatly inhibited (Tilzer et al., 1975). Also inhibiting phytoplankton biomass growth is the perpetual cold of the waters below 30 m., averaging about 4-5°C (Richerson et al. 1978, McGauhey et al. 1963 table 11-IX).

As a consequence of the dilution abilities of its great volume and the darkness and coldness of three-fourths of its waters, the lake is buffered from many nutrient pollution additions. Because any obvious water quality changes will appear at a greatly delayed time, the degradation of the lake's water quality could become a classic example of the consequences of cumulative impacts--if present land use development amounts and patterns continue to be inadequately controlled by regional land use planning. By the time the lake's water color and transparency show obvious changes, it will probably be too late to reverse the consequences of a many year degradation process. The properties of the watershed that maintain water quality would already have been devasted by land use changes. Especially because of this long delayed response time, preservation of the lake's water color and transparency may be more a symbolic objective than the only and best objective of basin environmental management.

A historic perspective also supports the symbolic nature of

---

*However, sessile aquatic plant populations have been observed at much greater depths in Tahoe; c.f. Kiefer et al. 1972, Frantz and Cordone 1967.

**About 4.5% of the lake's volume is in this photoinhibition zone when estimated from the data in McGauhey et al. 1963 p.59, Table 11-V.

preservation of the lake's water color and transparency. The lake was not always as clear as it now is. During periods of glaciation, the lake was the milky blue-green color typical of lakes fed by glacial melt waters containing glacial flour. Glacial melt water last poured into the lake less than a thousand years ago (Birman 1964, Matthes 1942 p. 197, 210-214). Theoretically glacial flour particles should remain in suspension forever because of their colloidal size. Yet the lake recovered from such highly turbid conditions to become one of the world's most transparent large lakes. However, the water coloring agent was only finely ground rock dust, containing no more nutrients than the basin's generally infertile rocks. Hence this nutritionally sterile influx only temporarily colored the waters. Glacial melt waters are also very pure, containing low dissolved nutrient concentrations.

In addition to the expected unfavorable nutrient supply conditions during glacial periods, the lake's water must have been unable to sustain a conspicuous phytoplankton population because sunlight penetrates only a few inches into flour-laden lakes. Hence the compensation depth is practically coincidental with the surface, and their waters are very cold throughout with not even a heated surface layer (epilimnion) forming during the summer months. All three conditions are unsupportive of algal biomass growth.

The mechanisms of water clarification from such conditions are unknown. Most glacial flour probably flocculated and settled to the lake's bottom. Perhaps it was merely the passage of many thousands of years with the accompanying flushing of the lake's basin which accomplished this clarification. The lake's water retention time must have been much shorter than its present 700 years because it was receiving great quantities of glacial meltwater.

Tales also exist of the lake being muddy brown following the almost total deforestation of the basin by logging and wildfires during the Comstock mining era (ca. 1870). Erosion in the basin during those times must have been much worse than anything that has happened in the last 20 years. Most likely such stories arose from sightings of the muddy waters in the nearshore zone at stream mouths--a scene seen today during flood flows which can in a single event when mudflows occur deliver 10 to 100 times the entire basin's average annual sediment inflow (Glancy, 1969). Also land-based observers, no matter what their elevation in the watershed, cannot directly see the true color of the lake's waters for more than a short distance in the lake, beyond which they are mostly seeing reflected sky colors. The earth's curvature and atmospheric refraction make it impossible for an observer from one point on the shoreline to see waters more than three miles distant;* thus about 90 percent of its surface waters are out of sight.** However, if those stories are essentially correct, the lake received, absorbed and recovered from the muddy and nutrient-rich water inputs so rapidly that when Le Conte (1883) took the first measurements of its transparency, that parameter was as great as has ever been recorded.

---

*Assuming a 270° maximum pan. The area seen by a three mile, 270° pan is (3.14)(3)^2(.75) = 21.2 mi^2. The lake's surface area is 191 mi^2. 21.2 - 191   100 = 11.1%.

**Assuming an eye-level of 5.5 ft. above the lake's surface. Maximum seen distance (miles) = eye-level (feet)/0.574. To see all the way across the 12 mile maximum width. Viewers must be 87 feet above its shoreline and 278 feet for the 22 miles length.

While the lake recovered from such large polluting events, it is important to understand that they endured for a relatively short number of years compared to those produced by urbanization. Natural revegetation typically begins to occur within several years after fire and logging. Once the timber was gone there was no longer any reason to extensively redisturb the vegetation cover. Logging operations were also the major originators of wildfires, though some attempts at converting land to hay production probably continued to be a source of ignition in later years. Once burns took place, it was many years before enough fuel accumulated to again support intensive and extensive wildfires. On lands not further disturbed by human activities, natural revegetation probably progressed far enough in 4 to 7 or 11 years (Anderson et al. 1976 p. 37-48) that terrestrial production of and fluvial release and transport of nutrients and erosion products had returned to near predisturbance levels. Revegetation at high elevations undoubtedly took much longer, as did the return of channels to their former hydraulic geometry.

In contrast, water pollutant production by urban areas will continue as long as lands are kept cleared of forest cover; are covered by asphalt, concrete pavement and tar and gravel, composition or wood shingle roofs; as long as motor driven vehicles continued to be run, parked, leak oil, washed or produce organic particulates from their exhaust and tires; as long as lawns and gardens are fertilized and sprayed with pesticides; etc. Even lands cleared and heavily graded incidental to accomplishing some project may continue eroding and show no sign of natural revegetation 15 to 30 years later (Leiser et al. 1974)--a degree of ground disturbance conditions never created by early logging. Once lands have been urbanized, the economic and sociologic costs and impacts of their reclamation are so great that urbanized, can be considered an irreversible change. Consequently the inadvertant contribution of pollutants from urban areas will continue for the foreseeable future.

Though unlikely, it is also conceivable that urban development could become much more extensive in the basin without further harming the water color and transparency of the lake. The only sewage still being released in the watershed is that escaping in accidental spills and abandoned septic field leaching (Cal. SWRCB 1980). All sewage is now exported from the basin rather than dumped into the lake or allowed to eventually seep in from waste ponds or septic fields. The typical highly polluted urban storm runoff from pavements (Gupta et al. 1981) and other impervious surfaces could be captured from the storm drains, treated and exported. Soil erosion on disturbed sites could be prevented or the suspended sediment captured in settling ponds or by some other means. These options are possible, but they are not likely to by achieved even by parties with the best intentions. Many control and prevention options are costly, require drastic changes from the standard procedures for accomplishing tasks, and the best planned precautions still exhibit failures--as attested to by occasional raw sewage spills,* and failure of settling ponds (Reed, 1978).

Saving the lake while permitting the continued degradation of the terrestrial portions of the basin is certainly not a goal of

---

* San Francisco Chronicle, February 20, 1980, p. 5, January 13, 1982, p.7.

environmental managers. While the lake and its qualities are unique and therefore the most important attribute of the region, without protection of its wildland surroundings the aesthetic and recreational value of the lake will be seriously jeopardized--possibly to such a degree that it would no longer be worth protecting. Protecting the lake's water quality while allowing the basin lands to become highly urbanized would be an ironic acknowledgement of the ultimate failure of all regional planning efforts.

The Level of Scientific Knowledge on Water Color and Transparency

Once it has been established that a particular problem facing planners is sufficiently important for them to allocate enough resources to make development of an ESM a possibility, the next most important screening criterion is that the scientific principles governing the problem be well developed (Guideline 32). Without adequate, existing resources of knowledge and data, ESM is an impractical analytic approach for planning. The planning environment is not the place to work on issues not thoroughly understood by science. Certainly anathema are problems needing scientific discoveries for their successful analysis (Guideline 33). This problem selection criterion for many scientists creates a disincentive to work on an ESM for land planning. The inclinations, work responsibilities and reward systems of many scientists are strongly oriented toward discovering new knowledge, not synthesizing or applying already existing knowledge (McEvoy 1972). Thus, assuring that existing scientific principles are adequate is a pragmatic necessity for choosing problems where ESM is likely to be a successful analysis tool.

Both water transparency and color appear to be well understood natural phenomena. They are two of the first properties of water bodies studied by the physical sciences. The basic physical principles governing water transparency and color were established between 1850 and 1930 by such historically prominent physicists as Rayleigh (1871, selective scattering of light by particles), Tyndall (1872, colloidal scattering of light), Mie (1908, particle size-light wave length scattering), and C.V. Raman (1928, light absorption and scattering by water molecules). The basic physical factors controlling water color and transparency (e.g., light extinction coefficients, refraction, reflection, selective absorption and scattering by molecules, suspended particles, or dissolved organic matter) appear to be clearly understood, for they are dogmatically stated in every major limnology textbook; e.g., Cole 1975 p. 110-122, Hutchinson 1957 p. 366-425, Reid 1961 p. 93-107, Reid & Wood 1976 p. 131-148, Ruttner 1963 p. 12-23, Welch 1952 p. 73-87, Wetzel 1975 p. 42-65.

At least two physical oceanography reference books are devoted solely to summarizing our scientific knowledge of the optical properties of water, with considerable space devoted to water color and transparency (Jerlov 1968 p. 15-44, 141-152, Jerlov 1976 p. 13-45, 163-174). A six-volume treatise on water optics also exists (Preisendorfer 1976a-f). Scientific journal literature and reports on water color and transparency are also impressively abundant. A computer search of the Water Resources Scientific Information Center's three-quarter million reference file yielded 900 citations containing information on water color. Jerlov's (1976) most recent book, Marine Optics, cites about 450 references, 17 of which are in the chapter on water color and 50 in the chapters relating to water transparency.

Given the existence of such an extensive amount of specialized literature and a well-established set of governing scientific principles, the completeness of our understanding of water transparency and color seems extremely good. Water color and transparency certainly appear to be prime subjects for developing an ESM and a subject that will not be stymied by inadequate scientific understanding.

Water Color and Transparency as a Function of a System of Quantitative Variables

Guideline 25 screens for problems with precisely definable variables. To satisfy this guideline, a problem must be describable in terms of a manageable number of quantifiable dependent and independent variables effectively expressing the relationship between a system's outputs (i.e., Lake Tahoe's water color and transparency) and factors controling the state of those outputs. In this section, I examine water color and transparency as visual entities which can be defined in a precise enough manner to enable quantification.

First, I examine the qualities water color and transparency as dependent variables (Guideline 25). Second, I assess the extent to which water color and transparency can be described as a function of some discrete set of independent controlling variables (Guidelines 23, 24). Third, I assess our ability to quantify those dependent and independent variables.

Water Transparency as a Dependent Variable for ESM

In its most general sense, water transparency refers to the ability of light to move through water. Two significantly different concepts of water transparency exist: apparent (perceptual) water transparency, and true (optical) water transparency. The former refers to the depth an observer can see into water. It is a function of those processes and objects within water limiting light transmission, an observer's angle of vision to the water surface, the presence of submerged objects visible through the water, the relative brightness of those objects, and surface water reflections.

The presence of surface reflections usually prevents perception of transparency by blocking vision into the water. Viewing angle also affects our ability to see into (or more accurately, the ability to see light coming out of) the water column because of the refraction of light at the air-water interface. For example, as a consequence of light refraction, the brightness of the light reflected from an underwater object decreases rapidly as the viewing position departs from directly overhead. As a consequence of light refraction, observers cannot see into the water when viewing at angles of less than 49°.

Apparent water transparency is determined by our ability to see objects through a thickness of water (Metelli 1974 p. 91) This perceptual phenomenon is readily seen in the startling pictures we frequently see of boats appearing to float on air above tropical seas, and the classic photos used to illustrate lake Tahoe's great transparency by showing the large underwater boulders along its northwest shore (e.g., U.S. Western Fed. Reg. Council 1979 p. 16). As a consequence of this perceptual phenomenon of the eye-brain system, the tranparency of waters identical in all other respects appears to be different because of differences in the size of objects seen on the bottom--boat shadows, cobbles, boulders, periphyton patches. The water over fine-textured sandy bottoms on which no details can be detected appears less transparent than if the bottom were strewn with large boulders casting shadows. Thus, apparent water transparency is dependent upon the coarseness and albedo variations of lake bottom sediments and other features.

Apparent water transparency is the water quality actually seen by the general public. However, it is not a reasonably manageable quantitative variable because of the infinite number of viewing positions, sun angles, ephemeral surface reflections, and cloud shadows. Changes in true water transparency constantly affect whether and where bottom details are visible. The zone of most public concern for apparent water transparency consists only of a relatively narrow band along the shallow shore. Thus, for ESM purposes, the ephemeral factors controlling water transparency must be dismissed. True water transparency must be the dependent variable used for ESM purposes. Subsequently in this study I use the term water transparency to refer only to true water transparency unless otherwise noted.

True Water Transparency

True (optical) water transparency is altered only by substances affecting light transmission in water, and processes operating within water. True water transparency is measured from two different perspectives: 1) light intensity and spectral composition changes with depth, and 2) the visibility of submerged objects viewed through a thickness of water.

The first approach measures downwelling light using submerged photometers (e.g. Jerlov 1976 p. 101-117) to determine underwater light conditions. The second approach measures upwelling light, and its most commonly used tools are the Secchi disk and turbidity meters. These latter tools are not as precise as photometers, but their measurements are accurate enough for ESM and public policymaking purposes. However, turbidity meters are designed for measurement of stream water, where suspended sediment concentrations are relatively high; they do not work well in the low concentrations common in Lake Tahoe. The Secchi disk is not subject to this drawback.

The Secchi disk approach is a standard measurement technique effectively capturing the main aspects of water transparency which concern the general public, and therefore, planners. This measurement of water transparency has been so widely used and studied that water quality factors and measurement conditions affecting readings are well understood (e.g., Tyler 1968). Secchi disk measurements of water transparency have been collected since 1866, and LeConte in 1873 made the first such measurements in Lake Tahoe (Juday 1906). Hence, an extensive historical record exists for Lake Tahoe and other waters. Thus this measurement of "true water transparency" is an especially appropriate dependent variable to use for developing an ESM.

Water Color as a Dependent Variable for ESM

In its most general sense, water color refers to the spectral distribution and intensity of light emanating from a water surface (Hovis et al. 1980). As in the case of water transparency, two significantly different concepts exist; apparent water color and true water color. The latter refers to the quality and quantity of light determined by light's interactions with water molecules and dissolved substances. The former consists of a combination of the light moving upward from below the water surface with other light of external origin reflecting from the water surface. On undulating water surfaces, the lights from each source have quantitatively different roles in the mixture of light we see as the color of each separate water surface plane. When seen from a distance exceeding our eyes' ability to distinguish objects of small apparent sizes, these differently colored surface planes are blended by a perceptual process--mosaic fusion (Rainwater 1971 p.109)--and appear as one color.

Apparent water color is the type most commonly seen by the general public under normal viewing conditions. However, it is subject to the same sort of quantification difficulties (especially influences by ephemeral independent variables not related to water quality conditions) which make apparent water transparency an unmanageable dependent variable for ESM.

Neither apparent water color nor true water color sufficiently captures those aspects of the water quality parameters which are of public concern and which planners must understand. Neither light's reflection, absorption or alteration by bottom materials or suspended particulates can be excluded from a definition of water color useful for ESM analysis of this particular problem; both of those color-affecting variables are particularly affected by land use impacts.

The primary effect land uses have on water color and transparency occurs by increasing nutrient and suspended sediment input to the lake. Increased nutrients affect water color only by increasing epiphytes and other bottom color altering and obscuring aquatic growths, and by increasing the abundance of phytoplankton. Similarly, increased sediment inputs affect water color primarily by reducing the depth to which light penetrates and is subject to quantity and quality-altering processes in the water. To a lesser extent, they alter water color by decreasing bottom visibility or bottom color.

Quantification of water color

Despite the lack of a standard definition, and therefore an accepted measure of water color which coincides with the needs of this planning problem, I do not seriously doubt that water color can be treated as a quantitative variable. However, in quantitative terms, the variable water color is unusual because it cannot be expressed as a single measurement; at least three principal independent dimensions of color must be recorded: hue (dominant wave length) saturation (purity of hue) and brightness (luminous flux) (Optical Soc. of Amer. 1953 p. 86).

Because water colors are primarily due to the transparency of that medium, they are not well represented by any of the existing color chip systems, such as those of Ostwald and Munsel. Several colored glass, plastic and chemical solutions (Wetzel 1975 p. 62) have been developed specifically for recording water color by comparison. All color sample approaches are unsatisfactory because of the small number of possible water colors represented by their samples, and most importantly because they do not provide a quantitative measurement of that variable.

A quantitative technique which can be used to mathematically record water color has been developed by the Commission Internationale de l'Eclairage (International Committee of Illumination, usually referred to as CIE.) The CIE technique has been used for characterizing water color variations (e.g., Thomson and Jerome 1975.) The CIE color measurement and recording techniques possess the type of quantification characteristics needed for using water color as an ESM's dependent variable.

Exclusion of Psychosocial Factors: Effect on ESM Acceptabiliy for Planning Applications

Three obvious, potentially significant social science aspects of the water color and transparency system exist. First, there is a psychologic question about the extent of perceptual agreement on water color and transparency among observers. This question is relevant to defining water color and transparency and to assessing the ability of observers to detect changes in these factors. A second psychologic question concerns the acceptability of limiting the problem to variables affecting water color and transparency as seen by an observer looking vertically down through a flat water surface. Does that constrained definition of water color and transparency capture sufficiently the essence of public concerns about degreadation of those qualities of the lake water? Last is the sociologic question of what the public's preferences are for water color and transparency and their sensitivities to changes of these qualities.

My main reason for believing that a system model of factors affecting water color and transparency is best developed without including any social science considerations is that planners are expected to generate a plan which will retain the lake's present water quality levels. If the planning objective is preservation of existing water color and transparency, then these psychosocial factors are irrelevant. Even the acceptability of using a definition of those variables which eliminates significant factors affecting apparent water color and transparency is an irrelevant question.

The omission of psychosocial independent variables is further defensible because our ability to remember colors is very weak (Wetzel 1975 p. 62, Kornerup and Wanscher 1967 p. 7). Relying on memory alone, we cannot recall the quality of water colors we have seen well enough to make the comparisons needed to detect changes. Photographs are not necessarily a solution, for different films have different color fidelities and weaknesses under varying conditions. The organic dyes used to reproduce colors gradually break down, further frustrating attempts to record water color for posterity. Only the ability to take and record the physical dimensions of water color offers a means for obtaining records which remain unchanged by time.

Perceptual Agreement on Color and Transparency

The quality and quantity of light we see as water color can be precisely specified in psychophysical measurement terms. However, the ability to distinguish between colors varies somewhat within a human population as does the ability to detect faint or small objects--a necessity for perceiving water transparency. This perceptual variability is of concern to planners only if color discrimination and object resolution acuity vary to a significant degree. If frequent disagreements occur on the water color specified by a set of psychophysical dimensions, obviously a satisfactory quantitative measurement of water color is lacking. If variations in the visual perception of color and transparency are great, large differences in individual abilities to detect change occur. Under such circumstances, planners are faced not only with the problem of setting acceptable levels of water quality change, but also with the dilemma of whether to set those levels according to the limits of detectable and offensive changes of sensitive, average, or insensitive individuals.

Of the three types of psychosocial variables not considered by an ESM of factors affecting water color and transparency, of the least significant is the known variation in perceptual agreement among the public. The amount of perceptual variation in object resolution acuity among those with normal vision is so small (Optical Soc. of Amer. 1953 p. 83) that disagreement on water transparency is insignificant. The amount of variation in color distinction acuity has been expressed a confidence limit elipses or circles about loci on

CIE chromaticity diagrams (MacAdam 1971, Judd and Wyszecki 1975 p. 301-313). What those variations mean in terms of a range of colors which will be perceived as one color is difficult to tell from the illustrations and text. Little variability exists between individuals' ability to perceive differences between two colors varying in brightness, hue, saturation or some combination thereof (Optical Soc. of Amer. 1953 p. 121, 226). However, large differences exist between individuals' ability to detect spectral distribution differences in polychromatic light (Optical Soc. of Amer. 1953 p. 251).

The eye is a very sensitive detector of color differences, being able to distinguish between hundreds of thousands (Optical Soc. of Amer. 1953 p. 129, Strandberg 1968) of slightly different light wave length intensity-brightness combinations. Given this extremely powerful color discrimination ability, it is reasonable to assume that the amount of perceptual disagreement is not large enough to cause significant problems. Certainly the small amount of this perceptual disagreement is insignificant in comparison to the amount of disagreement occurring as a result of different public preferences for and tolerances of water color and transparency changes.

Effect of Exclusion of Apparent Water Color and Transparency Variables on ESM Utility

An analysis approach excluding some variables affecting the perceptual reality of a public issue may produce results irrelevant to planners' understanding of crucial public concerns. Have I excluded so much that the remaining abstraction has lost essential characteristics of water color and transparency which stimulate the public's concern? This is the most important of the three social science considerations possibly limiting the utility of the system of variables I defined.

Significance of Water Transparency Deviation Resulting from Reducing Independent Variables

The perceptual fidelity question is not equally important to my definition of the system of independent variables controlling water transparency and color. Water color is the result of a more complex system of interacting variables than water transparency; hence more were eliminated to make it a more feasible dependent variable for an ESM. True water transparency is not significantly changed from apparent water transparency by limiting the former to the depth observers can see by looking vertically down through a smooth water surface on sunny days to a just-visible white bottom. The independent variables I removed are: (1) light refraction, (2) surface reflections, (3) bottom material color variations, (4) bottom material albedo variations, (5) bottom material size variations (the Secchi disk becomes a standard size bottom object), and (6) the possibility that the bottom is not visible. I only eliminated variables which reduce the magnitude of apparent water transparency.

Inclusion of some perceptual variables results in some rather preposterous characterizations of the lake's water quality conditions. For example, perception of transparency is dependent upon the ability to visually detect the overlapping of two objects seen as separate entities (Metelli 1974). Hence, those portions of a lake where bottom materials are no longer visible have no perceptual transparency. Thus an "apparent water transparency" does not exist over the vast majority of Lake Tahoe's surface, for its bottom is almost never visible. In some intermediate depth areas with sandy bottoms, water transparency is only distinguishable by the increased brightness of water color. In other areas, the bottom fleetingly vacillates between being visible and invisible for much of the shore zone, as suspended sediments and plankton concentrations change. By using the independent variables controlling Secchi disk visibility depth as the variables controlling the water transparency of an ESM, I am, in effect, using a lake bottom which shifts so that it is always barely visible. This avoids the logical absurdities which result if "perceptual water transparency" is used as the dependent variable. It also avoids a dependent variable which is analytically difficult to use as a basis for planners' design of land use regulations.

To more closely simulate the variables affecting perceptual water transparency, the distribution of bottom objects of different sizes could be included in a simulation model. Such information is available in a very general form in Orme's text (1971 p. 5-6) and map (p. 23). However, his bottom material categories do not usefully represent the real variation that exists; e.g., cobbles are lumped with boulders, and the map is exceedingly small (scale = 1:168,215).

An interesting implication of the existence of prominent variations in bottom material sizes is that the same increase in suspended sediment concentration produces different decreases in apparent water transparency in different areas of the lake. For example, the apparent water transparency of sandy bottom areas, such as Baldwin Beach, is more readily affected by changes in suspended particulate concentrations than are the bouldery bottoms of the northeast shoreline in Nevada.

Thus, perceptually real "apparent water transparency" has several strange quirks which render it an undesirable variable for planners' analysis of water quality problems and for development of an ESM. Water transparency as defined for an ESM relates well to water color as I have limited definition of that variable. Secchi disk determined water transparency shows the maximum depth from which upwelling light originates. Processes occurring further down have no effect on water color. Using Secchi disk depth to measure water transparency also includes the effect of the increased brightness of water color over white, sandy bottoms too deep to be actually seen.

CHAPTER 5

A SEDIMENT-NUTRIENT, WATER COLOR AND TRANSPARENCY SYSTEM MODEL

Chapter Scope

In this Chapter I discuss a schematic conceptual model of the processes and substances controlling lake water color and transparency beginning with the rationales for an ecosystem analysis approach. Then I present and discuss the process-place oriented conceptual framework with which I initially subdivide and organize the system of factors controlling sediment and nutrient movement. I use this framework to develop a schematic box and arrow model of the ecosystem processes generally controlling water color and transparency. Next I describe, in general terms, the processes illustrated in the schematic model diagram. I divide the schematic model into subsystems which are conceptually modeled and discussed in more detail in subsequent chapters. Finally, I give my reasons for the order in which those subsystems are investigated.

The Ecosystem Concept and Analysis Approach

An often stated tenet of ecologic and ecosystem analysis is that everything is connected to everything else (Odum 1971 p. 9). While this dictum is hyperbole, the property of connectedness makes ecosystems fascinating and complex to study. That which ecosystems possess and produce of value to us is somehow a product of the complex interactions characteristic of ecosystem functioning.

We seldom possess a complete understanding of how ecosystems produce what we value, but we do understand that these products are rarely a consequence of a very simple chain or network of factors. We know that fairly complex interactions are the general rule, and great care must be taken not to oversimplify analysis of ecosystem problems. However, analytic difficulty increases and feasibility decreases as the number of variables increase (Pimental 1966). Therefore, a balance, sometimes delicate and difficult to achieve, must be sought between including enough of the complexity which truly exists and not including so much that analytic solutions become difficult, or even infeasible (Van Dyne and Abramsky 1975). Attainment of this balance is a dilemma facing all attempting to conduct ecosystem analysis . Thus, the initial analysis task all ecosystem modelers must accomplish is to decide which independent variables must be included. Deciding how much detail to add to a conceptual model of an ecosystem problem is as crucial an early task as deciding how to add that detail.

Material Cycling and Flows: Key Connecting Ecosystem Concepts

Most, if not all, properties of ecosystems are connected by the fundamental ecologic concepts of flows of energy and cycles of matter, including nutrients. These principles provide a basis for organizing all ecosystem models around movements of matter and transformations of energy.

Very seldom is matter created or destroyed by natural, earthly processes. Hence, tracing its movement through ecosystems is one ready way of detecting relationships and organizing information concerning the complexity of ecosystem functions. The ecosystem factors affecting water color and transparency consist of interactions among four cycles--hydrologic, sediment, nitrogen and phosphorus. While truly part of complete cycles, the movement of sediment and nutrients in the Tahoe Basin ecosystem can be treated as open-ended flows because closing the cycles of those substances takes eons. Only the hydrologic cycle is completed on an annual basis. As the lake has at least a 700 year retention time for dissolved substances entering it (Crippen and Pavelka 1970), processes operating entirely within it could, from a water quality management standpoint, also be considered as operating on a closed cycle basis.

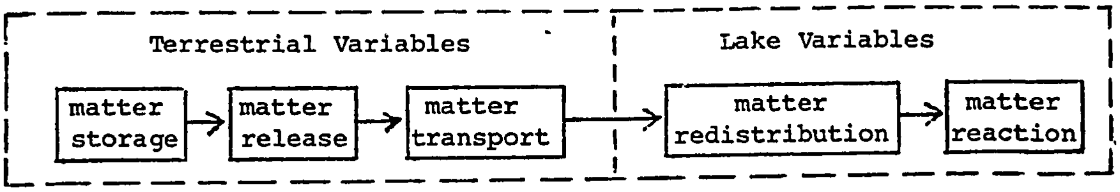
Thus, for practical and modeling purposes, sediment, nitrogen and phosphorus cycles can be considered open flows. The number of factors involved can appear to be hopelessly abundant and disorganized unless we see how they are organized. Tracing material flows provides this initial organization of diverse information.

Levels of Elaboration

One strategy for deciding how much detail to include in a simulation model based on ecosystem processes is to develop the conceptual model of the problem in stages introducing increasing detail. Thus, for example, I begin development of a CEM of the factors that affect water color and transparency by using a very simple concept that involves only five general stages: storage, release, transport, redistribution and reaction of nutrients and sediments. The first three stages occur in the terrestrial environment and the latter two in the lake. These five stages form an overall system framework for the conceptual model. They can be thought of as macrosubsystems, and further levels of elaboration as subsystems. This conceptual framework is a slight elaboration of the storage, release, transport, desposition framework used to study sediment cycles (Anderson 1971).

The "storage" stage includes all variables related to the quantitative amount and degree of immobility of some substance at a given location. All variables loosening a substance from its stored forms comprise the "release" stage. The "transport" stage consists of all variables removing a substance from its initial storage location and moving it to the lake. The "redistribution" stage includes all variables affecting the spread of a transported substance around the ecosystem sink. The "reaction" stage includes all variables controlling how the transported substance affects some condition in the ecosystem sink--i.e., water color and transparency, in this study.

This simple framework of the flow of matter within an ecosystem and its effects on conditions in the place of concern provides the initial representation of the conceptual ESM.



I then increase the complexity by adding within this initial conceptual framework the most basic processes and conditions operating in each stage of the schematic model. I also use arrows to indicate the most important relationships among independent variables in these intermediate detail compartments. The resulting schematic model is shown in Figure 2. That model indicates which general nutrient and sediment variables affect water color and transparency and how the effect occurs. Minor relationships are omitted from the schematic model at this stage to simplify graphic presentation. Their existence is referred to in the accompanying text discussion of each macrosubsystem's variables and relationships.

In subsequent chapters, I increase by one more level my elaboration of factors and processes affecting water color and transparency. Still further increasing levels of detail can be identified; in some cases, it appears details could be listed ad infinitum. However, generally by the third level of complexity, the independent variables are sufficiently detailed. For simple ecosystem problems, elaboration of most detail might be stopped after the second level of CEM development, elaborating further only a few parts of the system.

In proceeding through these successive levels of elaboration of the independent variables affecting water color and transparency, I continue to make the same assessment of the adequacy of existing scientific knowledge as I did for the independent variables in the last chapter. I watch especially for information gaps which may prevent ESM development.

Independent Variable Emphases

In the last chapter, I evaluate water color and transparency as suitable water quality parameters and as dependent variables for an ESM. I demonstrate that those qualities are essentially a function of the dissolved substances and suspended particles present in lake waters. For Lake Tahoe, the effects of the former can be ignored; direct water color and transparency influences by optically active dissolved matter are not a problem, nor are they likely to subsequently become one.

Two basically different types of suspended particles affect water color and transparency: suspended sediments originating from basin lands and streams, and endogenously generated lake plankton and their remains. The amount of suspended detached lake periphyton and their remains is an insignificant source of suspended particulates compared to the lake's suspended phytoplankton biomass and its debris. The amount of particulates contributed by stream periphyton debris is also negligible because the that total annual stream flow volume is only one-seven hundredth (Crippen and Pavelka 1970) of the lake's volume.

Land use effects on water color and transparency are all likely to occur by increasing or decreasing the rates of natural processes controlling those water qualities. The nonindustrial land developments occurring in the basin seldom affect water quality by introducing any totally new stimulatory or depressive process or substance. The terrestrial land uses are most likely to affect the lake by increasing the amount of suspended sediments and nutrients entering it. Thus, it is logical to orient an ESM around processes controlling those inputs and their effect on lake plankton populations.

Figure 2 Schematic Model of Nutrient-Sediment-Water Color-Transparency Interactions

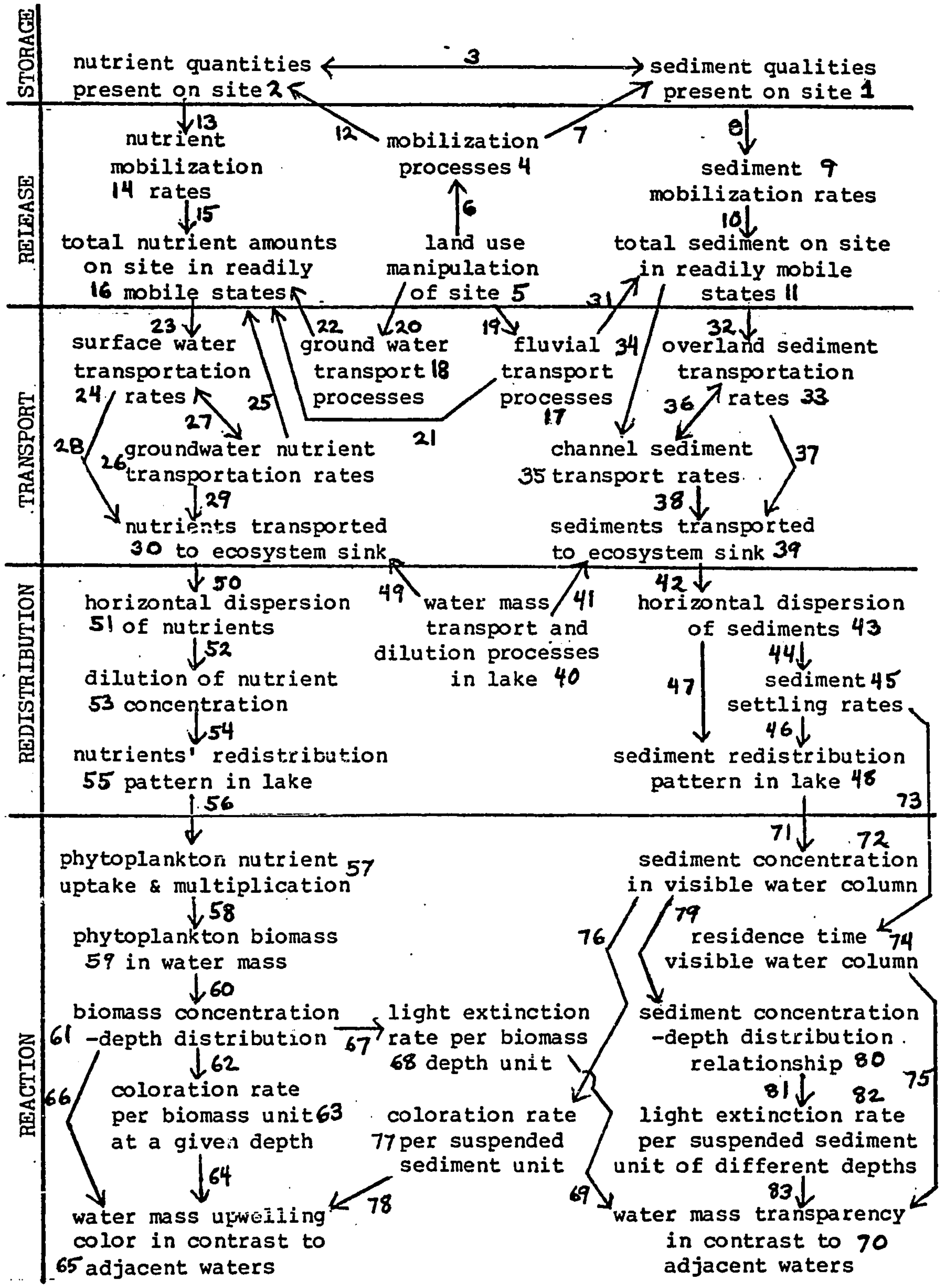


Table 3. Legend for Nutrient-Sediment-Water Color Schematic Model

Number	Description
	Storage
1.	Total quantitiy of potential suspended sediment on different watershed locations.
2.	Total quantity of phytoplankton growth stimulating nutrients on different watershed locations.
3.	Stimulating nutrients intimately attached to sediments.
	Release
4.	Processes loosening sediments and nutrients from their stored states.
5.	Land use actions affecting watershed locations.
6.	Effect of land use actions (on processes mobilizing sediments and nutrients).
7.	Mobilization processes acting on sediments stored on watershed locations.
8.	Effect of mobilization processes on stored sediments.
9.	Rates at which stored sediments are loosened by mobilization processes.
10.	Effect of sediment loosening rates on increasing the amount of readily mobile, stored sediment.
11.	Total amount of stored sediment in readily mobile form.
12.	Mobilization processes acting on nutrients stored on watershed locations.
13.	Effect of mobilization processes on stored nutrients.
14.	Rates at which stored nutrients are released by mobilization processes.
15.	Effect of nutrient release rates on increasing the amount of readily mobile stored nutrients.
16.	Total amount of stored nutrients in readily mobile forms.
	Transport
17.	Flowing surface water processes which remove and transport sediments and nutrients.
18.	Subsurface flowing water processes which remove and transport dissolved nutrients.
19.	Land use actions affecting fluvial removal and transportation processes.
20.	Land use actions decreasing or increasing affecting subsurface flowing water nutrient removal and transportation processes.
21.	Flowing surface water actions on stored but mobile nutrient supplies.
22.	Flowing subsurface water actions on stored but mobile nutrient supplies.
23.	Removal of dissolved and particulate nutrients by flowing surface waters.
24.	Rates at which mobile nutrients are being transported by surface flowing waters.
25.	Removal of dissolved nutrients by subsurface flowing waters.

26. Rates at which mobile nutrients are being transported by subsurface flowing waters.
27 Subsurface flowing waters joining surface flowing waters and vice versa.
28. Surface flow movement of nutrients from storage site to lake.
29. Groundwater flow movement of nutrients from storage site to lake.
30. Total amount of nutrients entering the ecosystem sink.
31. Actions of flowing surface water on stored but mobile sediment supplies.
32. Removal of mobile sediments by overland flowing surface waters.
33. Rates at which mobile sediments are being removed and transported by overland fluvial processes.
34. Direct removal of stored but mobile sediments by stream channel processes.
35. Rates at which mobile sediments are being removed and transported by channel fluvial processes.
36. Overland flowing waters joining flowing waters in channels or overbank channel flows rejoining overland flows.
37. Overland flow transport of sediments from site directly to lake.
38. Fluvial channel movement of sediments from storage site to lake.
39. Total amount of suspended sediments entering the ecosystem sink.

Redistribution

40. Influent water mass circulation and dilution processes occurring in lake.
41. lake circulation and water mass mixing processes acting on suspended sediments in influent water masses.
42. Influent suspended sediments moving out into lake.
43. Horizontal movement of inflowing suspended sediments in lake.
44. Sediment particles sinking as they spread out in lake.
45. Rates at which sediment particles sink.
46. Effect of sediment sinking rates on the distance they travel in lake's photic zone.
47. Effect of horizontal dispersion of fluvial sediments on their ultimate redistribution in lake.
48. Ultimate suspended sediment redistribution pattern at visibility-affecting depths in lake.
49. lake circulation and water mass mixing processes acting on nutrients in influent water masses.
50. Influent nutrients moving out into lake.
52. Horizontal spreading of inflowing nutrients in lake.
53. Dilution of nutrient concentration in influent water mass by lake waters.
54. Sinking of nutrient rich influent waters.
55. Redistribution pattern of ultimate stream-water mass-borne nutrients in water color-affecting depths in lake.

Reaction

56. Effect of ultimate nutrient redistribution on phytoplankton uptake and multiplication.
57. Phytoplankton uptake of nutrients and their concomitant population growth.
58. Effect of influent nutrient stimulation on total phytoplankton biomass.
59. Total phytoplankton biomass at water color affecting depth.
60. Effect of increased total phytoplankton biomass on its depth distribution.
61. Water depth distribution of phytoplankton biomass.
62. Effect of water depth on influence of phytoplankton biomass on water color.
63. Water color as a function of phytoplankton biomass concentration.
64. Contribution of phytoplankton biomass to upwelling water color.
65. Upwelling water color of lake water mass affected by influent stream's suspended sediment load and the phytoplankton bloom resulting from its nutrient load enrichment of lake waters.
66. Effect of upwelling water color of concentrations of phytoplankton at different depths.
67. Light extinction by phytoplankton biomass.
68. Light extinction rate per unit of biomass concentration at different depths.
69. Net effect on water transparency of light extinction by phytoplankton.
70. Water transparency of lake water mass affected by influent stream's suspended sediment load and the phytoplankton bloom resulting from its nutrient load enrichment of lake waters.
71. Effect of ultimate suspended sediment pattern on suspended sediment concentration at visible depths in affected areas of the lake.
72. Suspended sediment concentrations in visible portions of the water column.
73. Effect of suspended sediment settling rates on how long they remain at visible depths.
74. Length of time stream borne suspended sediments remain at visible depths.
75. Effect of suspended sediment settling rates on changes in water transparency.
76. Effect of suspended sediment concentration on upwelling water color.
77. Rate at which upwelling water color is affected by different concentrations of suspended sediment.
78. Net effect of suspended sediment on upwelling water color.
79. Effect of water depth on suspended sediment concentration variability.
80. Water depth distribution of suspended sediments.
81. Effect of depth distribution of suspended sediments on light extinction.
82. Upwelling light extinction per unit of suspended sediment at different depths.
83. Net effect of suspended sediment on water transparency.

The Schematic Model and Its Independent Variables

Storage

The site storage portion of the schematic model consists of a conceptually simple summation of the amount of nutrients and suspended sediment-size particles existing in any form on watershed locations. These quantities can be estimated from a knowledge of such factors as the nutrient content of the litter, vegetation, and soil (e.g., Rogers 1974 p. 75-78); and from a knowledge of the particle size contents of soils at various depths (e.g., Rogers 1974 p. 40-51, 73-74) and the amount of soil organic matter and litter present on a site.

I chose the nutrient cycles of nitrogen and phosphorus for modeling because of the well documented roles of these elements as key limiting nutrients in many lake ecosystems (e.g., Likens 1972, National Academy of Sciences 1968), and particularly Lake Tahoe's waters (e.g., Leonard et al. 1979 p. 281; Paerl, Richards et al. 1975.) Other nutrients, notably iron (Elder et al. 1976), at certain times and places play a controlling role in phytoplankton growth in Lake Tahoe. The chemistry of iron affecting its solubility, and hence availability to phytoplankton, is very complex and much less thoroughly understood than the chemical availability of phosphorus or nitrogen. Thus, I omitted iron. The scientific literature on the roles of nitrogen and phosphorus in controlling phytoplankton abundance is plentiful (e.g., Meals and Cassell 1978, Keeney 1972, Brezonik 1973, Stewart and Rholich 1967).

Release

The operation of processes acting in the "release" and "transport" compartments frequently are continuous and covariant under natural conditions. However, this is not their common relationship when land use alterations of sites occur. In this latter instance, release may, and usually does, occur quite apart from the temporal occurrence of transport mechanisms. Nutrients and sediments may be loosened and be present in readily mobile states on a site for considerable periods of time before transport actually occurs. Therefore, it is conceptually useful to treat these phases in matter cycles as essentially being discrete.

The key objective of the "release" compartment is the identification of the processes by which, and the rates at which nutrients and sediments are converted to readily mobile states. I assume process rates are the probable major point of interaction between manipulation of sites by land uses and increases of nutrient and sediment flows to the lake.

Factors controlling mobilization can reasonably be approximated from a knowledge of such onsite and offsite properties as revegetation rates (Nakao et al. 1976), soil mass and stream bank stability characteristics (e.g., Richert et al. 1978 p. 37-42, 117; Kelsey 1975), frost heaving, rainfall intensities and susceptibility of those factors to rate changes when alteration occurs in vegetation cover, soil consolidation and slope support, drainage efficiency and surface permeability.

Transport

This stage contains independent variables affecting the rapidity and efficiency with which the available nutrients and mobile sediments are removed from a watershed site and moved to the ecosystem sink. I assume all significant amounts of transport occur via fluvial processes; atmospheric, pure gravitational, and biotic transport processes are relatively unimportant.

Nutrients and sediments sometimes are deposited in semipermanent sinks (e.g., smaller lakes or reservoirs) along the route to the lake. As such conditions only rarely exist, this consideration usually presents only minor difficulties for analyzing transport. Temporary storage more frequently occurs in the process of movement to or in channels. Such temporarily stored matter moves along the transport system in pulses covariant with high stream flows. Thus sediments and nutrients stored in such states are totally flushed from temporary deposits during extreme flow events.

Transport process functions can be approximated in a satisfactory manner from a knowledge of such factors as average and maximum annual precipitation (Tahoe Reg. Plan. Agency 1971h), average maximum and 25 year maximum snowpack (U.S. Soil Conser. Serv. 1970), maximum precipitation intensities (e.g., U.C. Agr. Ext. Serv. 1967), maximum stream flows (e.g., Butler et al. 1966) and flow durations, watershed slope steepness and drainage density (from U.S. Geol. Survey topographic maps), and selected channel characteristics.

Land use modifications of sites also affect the magnitude of the "transport" stage's outputs (e.g., Lull and Sopper 1969), though to a lesser extent than they affect the output of the "release" stage. Increasing surface imperviousness and improving site drainage efficiency result in predictable increases in the amount, duration and peaking characteristics of water flowing in channels, and ultimately in the readjustment of channel geometry to accommodate these changed flow characteristics (e.g., Leopold 1968).

Most transport--especially of sediments--occurs as a result of temporally and spatially unpredictable stochastic events such as summer cloudbursts, sudden snow melts, or landslides and bank collapse into stream channels (e.g., Kelsey 1977, Glancy 1969). The occurrence of these random catastrophic events could be incorporated as averages if long-term records were available--but they are not. Flood event approaches and concepts are used (e.g., Dunn & Leopold 1978; Kochel & Baker 1982) in other contexts to obtain usable approximations of such randomly occurring events. Such concepts can be used to handle similar problems in this stage. However, any predictions using such approaches cannot be expected to be amenable to validation by field measurements.

Redistribution

In evaluating the impact of land use actions it is inadequate to stop at quantification of the amount of onsite alteration occurring, since many effects will be offsite. It is also inadequate to stop with quantification of the amount of on- or offsite materials converted to mobile states, because this does not necessarily tell us how much of those materials actually reach the lake. Likewise, knowing the amount of materials flowing into the lake at stream mouths does not necessarily tell us what is going to happen to the quality of the water. To answer this final question we need to know not only the concentrations of substances being put in by stream plumes, but also the spatial and temporal aspects of their bio-stimulant properties and/or resident times in the visible portions of the water column. From this information we can forecast the water color and transparancy in the water masses during those times.

On theoretical as well as evidential grounds, lakes such as Tahoe--i.e., with great volumes of water in very deep basins--have a great ability to absorb and sequester such inputs (Mortimer 1941, Schindler 1974). While responding by altered water colors and decreased transparencies as expected during the time of active input, these water quality properties essentially return to their previous status after nutrient and suspended sediment inputs return to their former levels (Vallentyne et al. 1970, Edmondson 1972). For example, during glacial periods Lake Tahoe must have been the powder blue color typical of lakes receiving melt waterfall of glacial powder. At times the entire lake probably was muddy brown (Tahoe Research Group 1975 p. 66) when basin lands were being stripped of forest cover to provide timber for the Comstock mines and by the frequent wildfires occurring in those days. I describe as model outputs the change in degree, spatial extent and duration of water color and transparency in influent water masses until such time as they merge to imperceptability with the lake proper's water mass. I recognize that these high inflow events are relatively ephemeral; but this is the only attainable "quantification" of current concerns about the lake's water quality. Quantification of the extent to which the oligotrophic "life" of the lake has been shortened and the extent to which the path of irreversible degradation has been traversed is a less attainable and less meaningful goal for planners' purposes.

I assume that sediment and nutrient inputs, once they sink below the visible zone of the water column, do not reenter inflowing water masses in significant amounts. This assumption is reasonably sound for sediment particulates--except for those deposited in waters so shallow that they are subsequently resuspended by wave induced bottom surge. It is a more questionable assumption for nutrients, since evidence exists in many lakes that considerable amounts of nutrients are subsequently released by bacterial activities in the bottom sediments. However, Tahoe's bottom waters are always aerobic (Western Fed. Reg. Council 1980 p. 118-119). Hence the continually forming oxidized microzone might reasonably be assumed to tie up permanently most nutrients deposited in bottom sediments--and certainly iron and phosphate, for they become the cementation matrix of that formation.

In Tahoe there are probably no significant mechanical forces operant to break up this oxidized microzone at the great depths at which most of its bottom sediments lie. Occasionally slumping of sediments from littoral bottom deposits (Hyne et al. 1973) break up large patches of the microzone, and stream sediment turbidity slows may abrade through it. Bioturbation is a significant force returning nutrients to overlying waters from ocean bottom sediments (Aller 1979, Nixon et al. 1979) and a large freshwater lake. However, most recycled bottom sediment nutrients become a part of the background concentrations in the lake water mass and are not added preferentially to influent water masses.

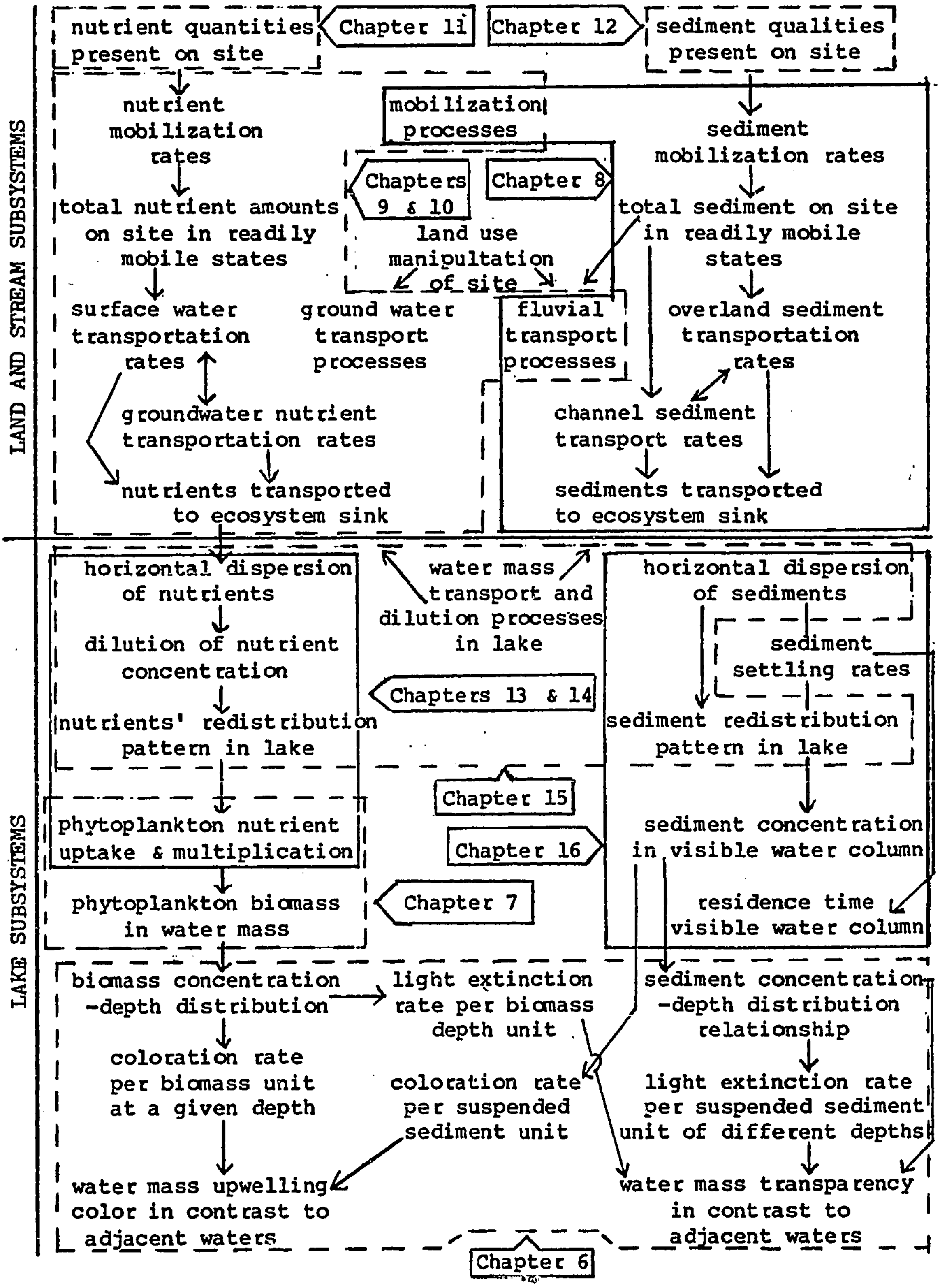
Definition of Subsystem

The overall nutrient-sediment-water color and transparency relationships are not sufficiently detailed in my system diagram for adequate analysis. Not enough specific independent variables are shown to enable meaningful analysis of the problem or to facilitate organization and exploitation of scientific knowledge. Most scientific literature tends to be on such specific topics that it is difficult to realize how it relates to general independent variables.

No more detailed specification of variables and their interactions can be crowded into the system diagram. Beyond a certain point, increasing the complexity of that diagram impedes communication and perception of the whole system rather than aiding it. More detailed specification requires development of a set of subsystems. To retain the organization and perspective advantages obtained from development of a system diagram, delineation of the subsystems must occur within the context of the system's diagram. Figure 3 shows my delineation of the subsystems. The order in which they are developed and discussed is: (Chapter 6) upwelling water color, (Chapter 7) phytoplankton biomass production, (Chapter 8) land and stream sediment routing, (Chapter 9) land and stream nitrogen routing, (Chapter 10) land and stream phosphorus routing, (Chapter 11) nutrient storage, (Chapter 12) sediment storage, (Chapter 13) lake nitrogen cycling, (Chapter 14) lake phosphorus cycling, (Chapter 15) water mass mixing, and (Chapter 16) lake particles.

The criteria used to establish these subsystem boundaries are: (1) biologic or physical functional unity, (2) minimizing overlap with other subsystems, (3) coinciding with system compartment boundaries; and (4)

Figure 3 Schematic Model Showing Division into Subsystems



minimizing the number of subsystems. The first criterion is the basis for defining any system of variables controlling an output.

The purpose of the second criterion is to avoid redundancy. Any repetitive use of the same scientific knowledge wastes time and other analysis resources. The subsystem overlaps in Figure 3 represent different emphases of the same general scientific subjects.

The purpose of the third criterion is to take advantage of and preserve the compartment's rational subdivision of the system by keeping subsystem boundaries parallel and coincident. Subsystems do not have to stay within single compartments. However, they should begin and end at the boundaries of system compartments (fourth criterion).

The overlapping of system compartments in Figure 3 is partially an artifact of the very general nature of the independent variables shown in the system diagram. To a larger extent, overlapping of compartment boundaries is due to criterion 4: establish only the number of subsystems absolutely needed. The amount of analysis detail and effort is directly proportional to the extent of subsystem subdivision.

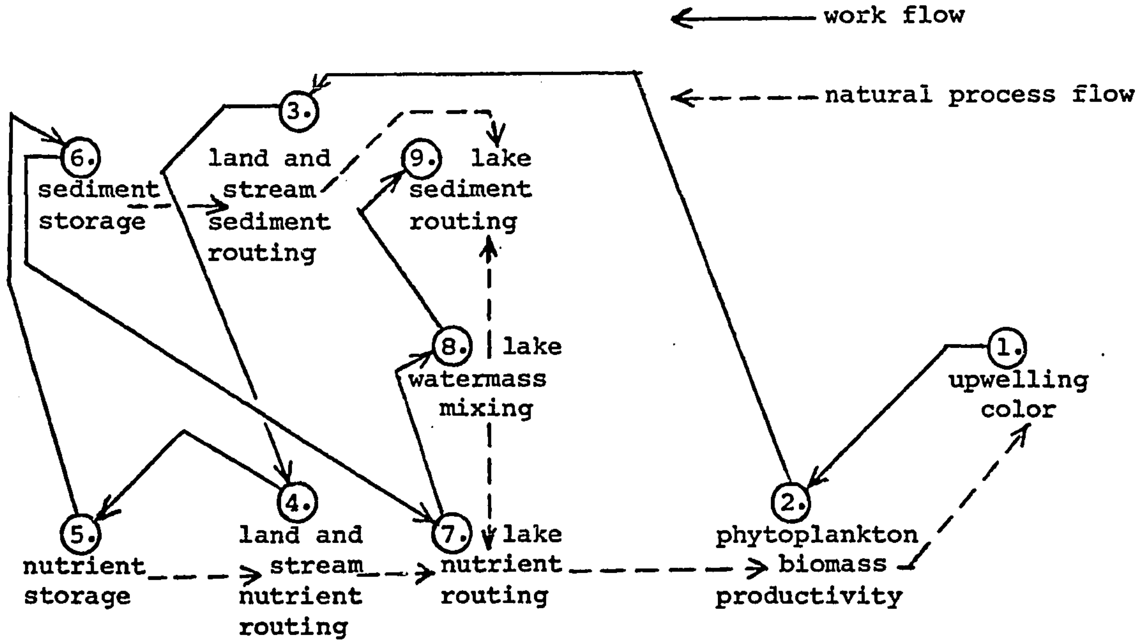
Order of Analysis of Subsystems

In subsequent chapters, I do not study subsystems in the order of their occurence in the system diagram. I begin at the end of the system diagram and then skip around to the other subsystems as shown in Figure 4.

The order of subsystem assessments reflects the relative import of early detection of information gaps blocking model completion and of knowledge of the different subsystems to analyze the system. For example, the most crucial relationships to develop are the effect of phytoplankton and of suspended sediment concentrations on water color and transparency. If those relationships are not well enough known, there is no sense in proceeding with development of other subsystems.

The logic of subsystem ordering is also dictated by my need to know certain facts before being able to proceed efficiently with development of other subsystems. Identifying a few key variables in one subsystem more sharply focuses subsequent information development in others. For example, the first subsystem--upwelling water color--seeks to establish which sizes and types of suspended sediments most affect water color and transparency. This identification provides a focus for all the sediment subsystems so that they concentrate only on what happens to a few particle sizes and types.

Figure 4. Subsystem Development Sequence



CHAPTER 6

THE UPWELLING WATER COLOR SUBSYSTEM

Chapter Scope

In this chapter I first give a diagrammatic representation of my conceptual model of the factors controlling upwelling water color; then I briefly explain the sequence of factors and interactions shown in the illustrated model. A detailed discussion of each of the 80 steps in the conceptual model would be too lengthy. Therefore, I next selectively discuss in detail the most important groups of factor interactions illustrated: the selective scattering of light by water molecules (interactions 18-22) and the effect of suspended particle size, concentration and depth distribution on upwelling water color (30-43).

Figure 5, Conceptual Model of Upwelling Water Color Subsystem

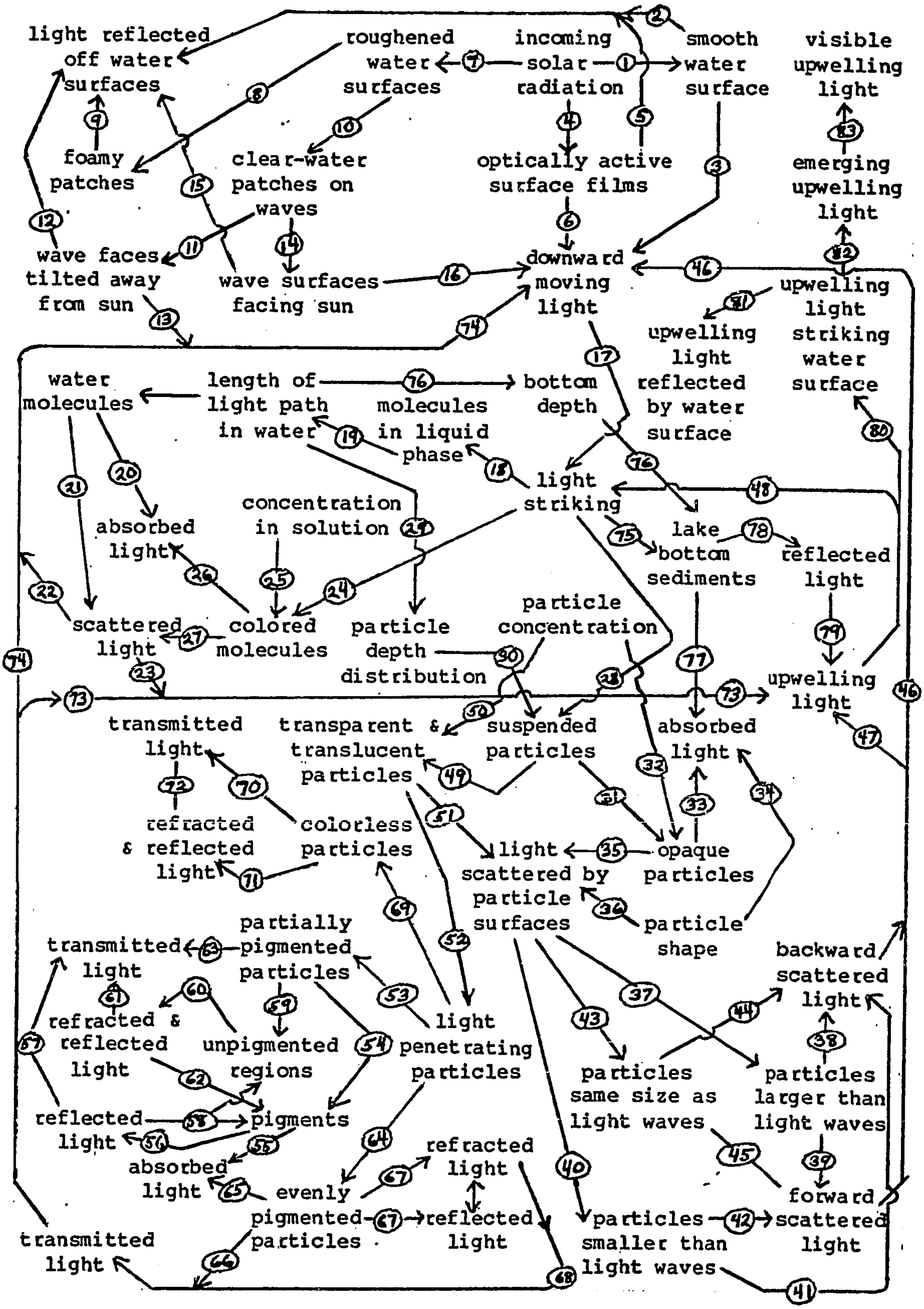


Table 4. Actions and Interactions of Conceptual Model of Water Color Due to Upwelling Light

Arrow No.	Description
1.	Solar radiation (insolation) striking level, smooth water.
2.	Insolation reflected from level, smooth water.
3.	Insolation penetrating level, smooth water.
4.	Insolation striking optically active substances concentrated on the water surface.
5.	Insolation reflected from optically active surface films.
6.	Insolation penetrating surface films.
7.	Insolation striking roughened water surfaces.
8.	Insolation striking foamy patches on water surface.
9.	Insolation reflected from foamy patches.
10.	Insolation striking clear water patches.
11.	Insolation striking clear water on wave surfaces tilted from sun.
12.	Insolation reflected from clear water on wave faces tilted from sun.
13.	Insolation penetrating clear water on wave faces tilted from sun.
14.	Insolation striking clear water on wave faces tilted toward the sun.
15.	Insolation reflected from clear water on faces tilted toward sun.
16.	Insolation penetrating clear water wave faces tilted toward the sun.
17.	Downward moving (downwelling) light striking liquid molecules or dissolved matter.
18.	Downwelling light striking water molecules.
19.	Light path length controls number of light-water molecule collisions.
20.	Light absorbed by water molecules.
21.	Light scattered by water molecules.
22.	Light scattered downward by liquid molecules and dissolved colored matter.
23.	Light scattered upward by liquid molecules and dissolved colored matter.
24.	Light striking dissolved colored matter.
25.	Colored molecule concentration controls light collision frequency.
26.	Light absorbed by dissolved colored matter.
27.	Light scattered by dissolved colored matter.
28.	Light striking particles suspended in water.
29.	Effect of depth on quality of light striking suspended particles.
30.	Depth distribution of suspended particles.
31.	Light striking suspended opaque particles.
32.	Opaque particle concentration controls frequency of light ray collisions.
33.	Light absorbed by opaque particles.
34.	Effect of particle shape on light absorption.
35.	Light scattered by opaque particles.
36.	Effect of particle shape on light scattering.
37.	Light scattered by particles larger than its wave length.
38.	Light scattered backward by particles larger than its wave length.
39.	Light scattered forward by particles larger than its wave length.
40.	Light scattered by particles smaller than its wave length.
41.	Light scattered backward by particles smaller than its wave length.
42.	Light scattered forward by particles smaller than its wave length.

43. Light scattered by particle sizes approximately equal to light wave lengths.
44. Light scattered backward by particle sizes approximately equal to its wave length.
45. Light scattered forward by particle sizes approximately equal to its wave length.
46. Light scattered downward by particles.
47. Light scattered upward by particles.
48. Upward scattered light striking other molecules and suspended particles.
49. Light striking transparent and translucent suspended particles.
50. Transparent and translucent particle concentration controls frequency of light ray collisions.
51. Light scattered by transparent and translucent particles.
52. Light penetrating transparent and translucent particles.
53. Light penetrating partially pigmented particles.
54. Light striking pigments.
55. Light absorbed by pigments.
56. Light reflected by pigments.
57. Light leaving particles after reflecting from pigments.
58. Light reflected from pigments striking other internal portions of particles.
59. Light striking unpigmented, internal inhomogeneities and particle walls.
60. Light refracted by and reflected from unpigmented internal irregularities and particle walls.
61. Light leaving particles after striking unpigmented internal surfaces and irregularities.
62. Refracted and reflected light striking pigments.
63. Light passing directly through particles.
64. Light entering evenly pigmented, translucent suspended particles.
65. Light absorbed by pigments.
66. Unabsorbed light passing directly through evenly pigmented particles.
67. Light reflected by pigments and side walls or refracted by internal irregularities.
68. Reflected and refracted light leaving evenly pigmented particles.
69. Light entering colorless suspended particles.
70. Light passing directly through colorless particles.
71. Light refracted and reflected by internal irregularities.
72. Light leaving particles after being refracted and reflected.
73. Upward moving (upwelling) light leaving transparent and translucent particles.
74. Downwelling light leaving transparent and translucent particles.
75. Light striking lake bottom materials.
76. Effect of depth on quality of light striking bottom materials.
77. Light absorbed by bottom materials.
78. Light reflected from bottom materials.
79. Light reflected upward by bottom materials.
80. Upwelling light striking underside of water surface.
81. Upwelling light reflected downward by underside of water surface.
82. Upwelling light passing through water surface.
83. Upwelling light reaching (seen by) viewer.

Explanation of Conceptual Model of the Upwelling Light Subsystem

The amount of sunlight entering a lake is initially affected by water surface conditions. Sunlight may strike three functionally different types of water surfaces. It may strike (1)* smooth water, with some being (2) reflected and some entering the water to become (3) downward moving light.

Sunlight may also strike a water surface covered by a film affecting the amount of light penetration. Some sunlight striking such (4) optically active surface films is (5) reflected, and some (6) enters the water. The relative proportion going in the two directions is controlled by the film's chemical composition, its thickness and its horizontal continuity. The persistence and continuity of such films is largely controlled by water surface turbulence, but they may also be blown ashore by winds, concentrated into surface streaks by Langmuir currents and water mass fronts, decompose or sink.

The most commonly encountered surface condition is one (7) roughened by winds. Sometimes the water surface is so rough that whitecaps and other wave turbulence-generated air bubble patches form. Sunlight (8) encountering foamy patches is (9) totally reflected.

Usually the water surface is not rough enough to form abundant foamy patches; even on very rough water, most of the surface is clear. Hence sunlight most commonly (10) strikes clear water patches on wavy water. Some strikes (11) wave faces tilted away from the sun, with most (12) being reflected and less (13) entering the water. Some

---

*Numbers in parentheses refer to arrows in the conceptual model diagram.

sunlight strikes (14) wave surfaces facing the sun with a portion being (15) reflected but most (16) penetrating to become downward moving light.

Downward moving light most commonly strikes (17) molecules which are part of the liquid phase. (18) Water molecule collisions vastly dominate light-object encounters in the water column; their number is governed by the (19) light path length. Water molecules (20) absorb some of the striking light, but most is (21) scattered (22) downward or (23) upward.

Occasionally downward moving light strikes (24) dissolved or liquid molecules which selectively reflect light of different wave lengths--i.e., different colors. The number of these encounters is dependent upon the (25) concentration of such "colored" molecules and ionic species. Most of the light striking colored molecules is (26) absorbed but some is (27) scattered.

The second most common light collisions are with (28) suspended particles. The qualities of light striking particles depends on the length of the path of light in water (29), hence on the depth distribution of particles (30). Some light strikes (31) opaque particles at a frequency determined by their (31) concentration. Opaque particles (33) absorb some light depending upon their shape (34) and other qualities. However, most is (35) scattered by their surfaces according to their characteristics such as shape (36).

The way light is scattered by particles depends upon their size relative to light wave lengths. Most suspended particles are considerably (37) larger than light wave lengths (38), and scatter much less light backward than (39) forward. Particles (40) smaller than light waves are second in abundance. Some of the light striking these relatively small particles is (41) scattered backward,* but about four times more is (42) scattered forward. Particles about (43) the same size as light waves are least abundant and scatter as much light (44) backward as (45) forward.

Whether the light scattered by a particle subsequently moves up or down in the water column depends upon the relative direction of the impacting light ray and the angle at which it strikes a particle's surface. Thus some of the forward and backward scattered light leaving particles will (46) move in downward directions, subsequently striking other molecules and particles, and some (47) moves upward, (48) striking other objects in its path.

Downward moving light also (49) strikes transparent and translucent particles, with the incidence of such events being controlled by (50) their respective particle concentrations. Some light striking such particles is (51) scattered by their surfaces according to the same principles governing light scattering by different sized opaque particles. The remaining light (52) penetrates into the transparent and translucent particles.

Most light passes into (53) unevenly pigmented particles, e.g., phytoplankton, as these are most abundant. Some of this entering light

---

* I use the terms forward, downwelling, backward, backscattering, upwelling and upward in a relative sense to describe the direction of light movement with respect to the water surface. The first two refer to light generally moving downward, the latter four refer to light generally moving back toward the surface--but not necessarily going straight up or down. Technical literature on light-particle interactions describes the effects relative to the direction of incident light; hence the terms forward and backward are used.

strikes (54) the pigmented portions and is (55) absorbed or (56) reflected. The reflected light is either (57) transmitted out through the particle wall or strikes (58) unpigmented internal inhomogeneities. Some of the entering light initially strikes (59) unpigmented areas and is (60) refracted and reflected before being (61) transmitted out of the particle or striking (62) pigmented areas. A relatively small portion of the light penetrating unevenly pigmented particles (63) passes directly through without being altered or diminished.

A small portion of downward moving light penetrates (64) particles having evenly distributed pigments, e.g., a tiny carnelian grain. This light is either (65) absorbed by the pigments, (66) passes directly through, or is (67) refracted and reflected by internal discontinuities before eventually passing (68) out of the particle.

Occasionally, downward moving light penetrates colorless suspended particles (69). Most of this light is (70) transmitted directly through, but some is initially (71) reflected and refracted by internal inhomogeneities before (72) transmission.

Depending upon the direction in which transmitted light leaves a particle, it becomes either (73) upwelling or (74) downwelling light. If the water is shallow or very transparent, downward moving light eventually (75) reaches the bottom sediments [its qualities determined by water depth (76)], where some is (77) absorbed and some (78) reflected, becoming (79) upwelling light. Upwelling light not directed nor absorbed on its upward journey (80) strikes the underside of the water surface. Depending upon surface conditions and the angle at which upwelling light strikes this undersurface, some is (81) reflected back downward and the remainder (82) passes through into the air. This upwelling light is (83) subsequently seen by viewers as one of the components of apparent water color.

Particle Size Effects on Upwelling Light

The quantitative effect of suspended particles on the amount of downwelling light they intercept and turn back upward frequently is not a simple function of their geometric cross sections. The size of suspended particles relative to light wave lengths is a critical dimension determining net effect of many particles on upwelling light. Table 5 lists examples of some types of particles commonly present and graphically shows the relationship of their size to light wave lengths.

Particles may reflect, absorb or scatter incident light. Scattering is a mixture of reflection, diffraction (bending), interference (superimposition of light waves), and for translucent particles, refraction of incident light waves (Jerlov 1976 p. 26, Rainwater 1971 p. 50). In multiparticle suspensions, scattering results in the random deflection of light rays, changing only the direction of photons (Yura 1971 p. 114). Particles about the size of light waves or smaller affect incident light more by scattering than by reflection or absorption. The amount of light scattering by particles is a function of their size, refractive index and the wave length of incident light (Burt 1956). Burt (1956 p. 78) gives a nomograph showing these relationships.

Molecules as well as tiny particles much smaller than light wave lengths affect incident light according to Rayleigh's principle (see Jerlov 1976 p. 19-20). These tiny particles and molecules

Table 5. Comparative[1] Sizes of Suspended Particles to Light Wave Lengths

water molecule's diameter[2] = .00000028

small montmorillonite crystal[3] = .00001 mm.

small illite and kaolinite crystals[3] = .0001 mm.

smallest colloids[4] = .0002 mm.

violet light wavelength[5] = .00041 mm.

indigo light wavelength[5] = .00044 mm.

blue light wavelength[5] = .00047 mm.

green light wavelength[5] = .00052 mm.

yellow light wavelength[8] = .00058 mm.

orange light wavelength[5] = .0006 mm.

red light wavelength[5] = .00065 mm.

bacteria[6], large montmorillonite crystal[3], or largest colloid[4] = .001 mm.

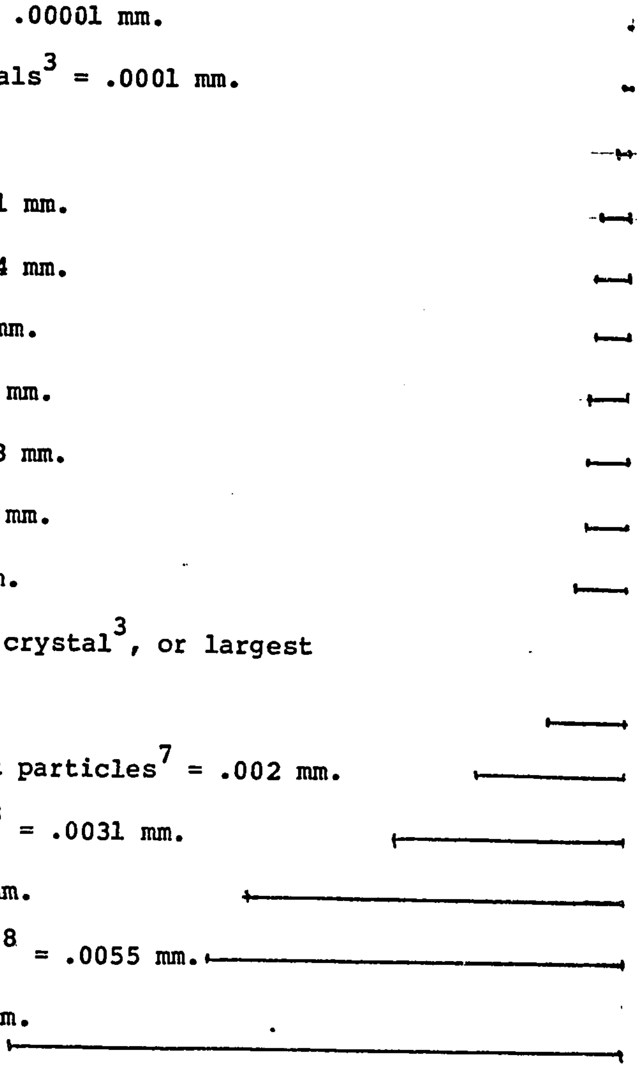
large illite crystal[3] finest silt particles[7] = .002 mm.

chlorella ellipsoidea, dark cell[8] = .0031 mm.

large kaolinite crystal[3] = .005 mm.

chlorella ellipsoidea, light cell[8] = .0055 mm.

flagellate phytoplankton[6] = .01 mm.



---

1. multiplication factor of graphic representation = 10,160x
2. Hutchinson 1957 p. 198
3. Buckman & Brady 1969 p. 79
4. Ibid p. 70
5. American Optical Society 1953 p. 41
6. Ruttner 1963 p. 107, 109
7. Buckman & Brady 1969 p. 43
8. Fogg 1965

differentially scatter light in proportion to the fourth power of its wave length (Reid 1961 p. 101, Jerlov 1976 p. 20). Consequently, short wave lengths (blue-violet) are scattered much more than long ones. As particles of such very small sizes are relatively rare, nearly all Rayleigh scattering is by water molecules (20). This selective back scattering causes the dominantly blue color of waters with low concentrations of suspended particles (Ruttner 1963 p. 19, Jerlov 1968, Kalle 1938, 1939). Particles in this size range are not optically efficient at scattering light. For example, at the upper end of the range where their scattering is strongest, a small clay crystal only scatters 1/20th of the red light and 1/8th of the incident blue light (Burt 1956 p. 78).

Transparent or translucent particles much smaller than light waves scatter as much light forward (downwelling) as in an upwelling direction (Shoulejkin 1924 p. 310-11, Kerker 1974 p. 93). However, highly reflecting or tiny opaque particles scatter nine times as much light in backward (upwelling) directions as downward (Kerker 1974 p. 95). In terms of their ability to contribute to upwelling light, these small particles are not very important because of their rarity and optical inefficiency.

The smallest particle sizes commonly found in water are about the same size as light wave lengths--e.g., the smallest colloids and clay crystals. Particles of these sizes affect light more strongly than others (Kerker 1974 p. 94). They scatter from about 2.5 to 3.5 times as much light as strikes their cross sections (Burt 1956 p. 78, Jerlov 1976 p. 31). This counterintuitive phenomenon occurs because the only downwelling light actually reflected upward is that striking the particle's geometric cross section, while the diffraction and interference effects of the particle affect light for a greater distance around the particle. These particles also selectively scatter light according to its wave length. For example, a .001 mm. clay crystal scatters blue light 30 percent more intensely than red (Burt 1956 p. 78). These wave length sized particles scatter much more light in downwelling (forward) direction than in upwelling (backward) ones. For example, particles equal to light wave lengths (e.g., small bacteria) scatter 11 times more light forward than upward (loc. cit.) Downward (forward) scattering dominates all particles about the size of light waves, whether they are transparent, absorbant or highly reflective of incident light (Kerker 1974 p. 94).

Given the powerful light-scattering ability of particles approximately the size of light wave lengths, the movement of these materials into the lake's waters is of special concern. They are also of special concern because they will remain in suspension unless flocculating forces cause their aggregation, hastening settlement.

All phytoplankton are much larger than light wave lengths (see Table 6), and particles in this size range affect downwelling light by simple geometric blocking proportional to their cross sectional area (Kerker 1974 p. 93).

Table 6. Sizes of Common Lake Tahoe Phytoplankton

	Diameter or width X length, mm
Chlorophyta, (division)	
Elakatothrix gelatinosa[1]	
Chrysophyta (division)	
Bacillariophyceae (class-diatoms)	
Centrales (order)	
Cyclotella[2] stelligera[3]	.005 - .025[4]
Melosira crenulata[1,5]	.005 - .021[4]
Stephanodiscus rotula[1]	.010 - .030
Pennales (order)	
Asterionella[2] formosa[1,6]	.001 - .002 X .03 - .14[4]
Fragilaria crotonensis[1,7]	.002 - .003 X .04 - .15[4]
Navicula[2] hungarica[8]	.004 - .007 X .01 - .03[4]
Nitzschia[2] acicularis	.003 - .004 X .04 - .154
Thalassionema[2]	
Chrysomonadian (order)	
Dinobryon sociale[1,9]	

---

1. The six dominant phytoplankton species found in Lake Tahoe.[10]
2. The genera most frequently found in Lake Tahoe water samples.[10]
3. Dominates phytoplankton in Lake Tahoe by late September[11] and consistently dominates the epilimnion.[12]
4. U.S. Federal Water Pollution Control Administration 1966.
5. Dominates region of chlorophyll maximum.[12] Frustules are usually united into long filaments.[4]
6. Typically forming stellate colonies.[4]
7. Form 60% of phytoplankton volume in 350 m layer.[12] Forms colonial stacks.[4]
8. Usually solitary but occasionally forming irregular, ribbon-like chains or stellate colonies.[4]
9. Flagellated.[4]
10. Goldman, C. R., Moshiri, G. A., and de Amezaga, E. 1970.
11. Powell, T., Richerson, P., Dillon, Agee, Golden and Myrup, L. 1975.
12. Richerson, P. Lopez, and Coon 1978.

Particles much larger than light wave lengths scatter an even larger portion of incident light forward than upward (Kerker 1974 p. 94-5, Shoulekin 1924 p.318-19, Burt 1965 p. 79). Most of the light scattered forward by relatively large transparent particles, such as small crustacean zooplankton (Mellanby 1963 p. 73), is not diffracted from their surfaces, but rather is refracted light that has passed through them (Shoulekin 1924 p. 318).

Particles much larger than light wave lengths scatter about twice as much light as is directly incident on their cross sections (Burt 1965 p. 79, Jerlov 1976 p. 31). They do not selectively scatter light according to its wave length (Raman 1922, Rainwater 1971 p. 50). If pigmented they affect water color by altering the spectral composition of upwelling light via selectively reflecting wave lengths not absorbed by their pigments. Light scattering by these relatively large particles is accurately described by Mie (for nonabsorbing particles), and van de Hulst's (for absorbing particles) diffraction equations (Bryant et al. 1969, Kiefer & Austin 1974, Latimer et al. 1968) provided they are at least three times their radii apart (Jerlov 1976 p. 28).

Upwelling Water Color

All the upwelling color we see on looking vertically down into water is light reflected or refracted (bent) until it is going in the opposite direction from which it initially traveled upon entering the water. The amount of returning light responsible for water color is basically a function of water transparency as affected by the color, concentration and depth distribution of suspended particles. Water without any particles looks inky black if the bottom is too deep to be seen (Reid 1971). Upwelling water color can be explained in terms of five independent variables: (1) selective scattering and absorption by water molecules, (2) unselective reflection by uncolored, suspended particles, (3) selected reflection by colored suspended particles, (4) selective absorption by colored dissolved organic matter and (5) reflection by bottom sediments. These interacting variables constitute the subsystem controlling upwelling water color. The unselective absorbers and reflectors affect only the quantity of light; the selective reflectors also affect the quality of upwelling light. Thus, the effect of selective absorbers, scatterers, and reflectors is to change the relative strength of different spectral wave lengths in upwelling light.

Table 7. Summary of Suspended Paricle Size Effects on Light

	Size's relation to light wave lengths		
	much less	about equal	much larger
Incident light scatter efficiency (optical : geometric x-section)	$<.1$	2.5 - 3.5	2
Upwelling light backscatter ratio (forescatter : backscatter)	1:1	11:1	52:1
Incident light backscattered	5%	23% - 32%	4%
Comparative upwelling efficiency (size class : about equal size)	.16x-.22x	1.0x	.13x - .17x
Typical example(s)	small clay crystals	colloids bacteria	phytoplankton large sediment
Typical diameter (mm)	.00001	.00052	.01
Typical cross-section area (mm^2)	$.785\mathrm{x}10^{-10}$	$2120\mathrm{x}10^{-10}$	$785000\mathrm{x}10^{-10}$
Incident light backscattered (mm^2 per cross-section)	$3.93\mathrm{x}10^{-12}$	$48800\mathrm{x}10^{-12}$ $67800\mathrm{x}10^{-12}$	$3140000\mathrm{x}10^{-12}$
Comparative upwelling backscatter strength	1.0x	12400x-17300x	799000x
Light wave length selective scattering	strongest blue and violet	strongest blue and violet	unselective

CHAPTER 7

LAKE PRODUCTION AND DISTRIBUTION OF ORGANIC SUBSTANCES AFFECTING WATER COLOR AND TRANSPARENCY

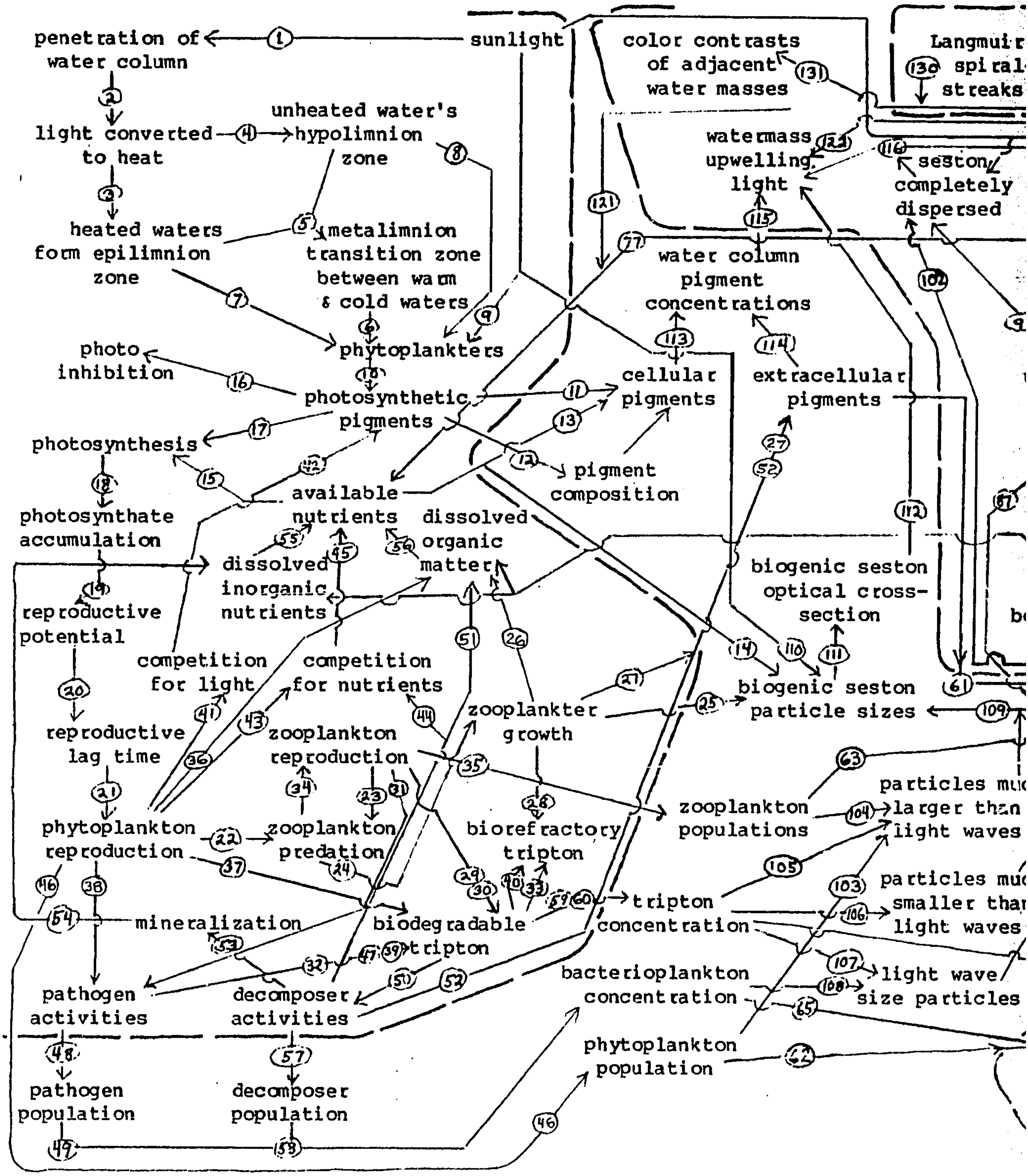
Chapter Scope

In this chapter, I first present a CEM of factors controlling lake production and spatial distribution of organic substances affecting water color and transparency (Figure 6). I then explain the model and discuss its relationship to the upwelling water color subsystem model (Figure 5).

Overview of Subsystem Model

The model has four sections: (1) factors controlling lake organic matter production, (2) quantities of various types of organic matter, (3) factors controlling the vertical distribution of such matter and (4) factors controlling its horizontal distribution. The sections are indicated by the dashed red lines on Figure 6. The upper left section represents factors affecting autochthonous production of seston (a collective term for all suspended particulates) and dissolved substances affecting water color and transparency. The central section represents the total quantities in categories of substances affecting water color. The section in the upper right represents lake circulation factors affecting the horizontal movement of water masses, and hence of their colored waters in the Lake. The lower right section represents vertical mixing processes affecting lake waters, and hence the distribution of seston and extracellular pigments in the water column.

Figure 6. Conceptual Model of Factors Controlling Lake Concentrations of Autochthono



ng Lake Concentrations of Autochthonous Biogenic Materials Affecting Water Color

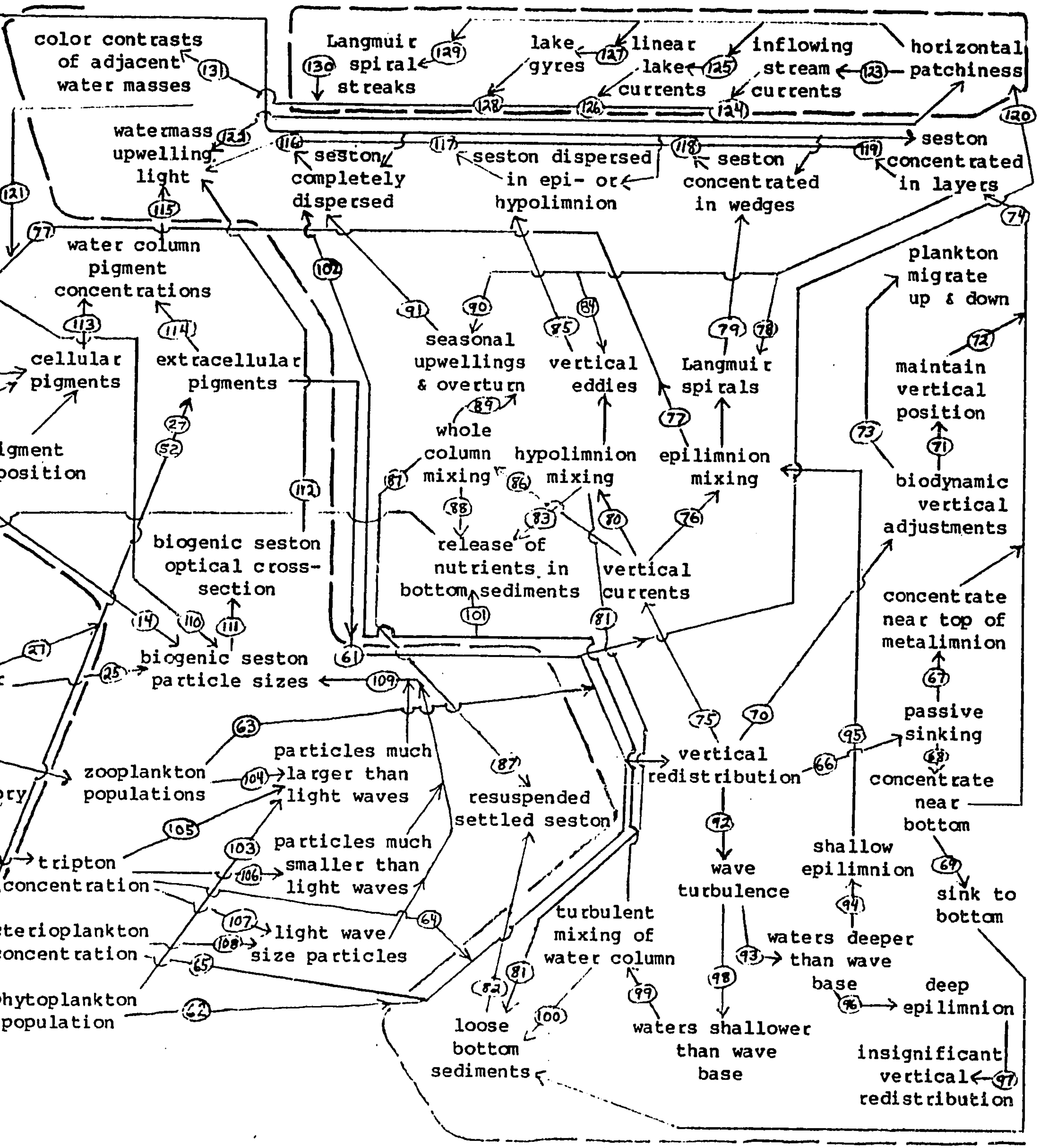


Table 8. Legend for the CEM of Factors Controlling Concentrations of Autochthonous Organic Matter Affecting Lake Water Color.

Number	Description
	Production of Particles and Pigments
1.	Sunlight moves through water column.
2.	Sunlight heats penetrated waters.
3.	Epilimnion zone is formed by warm upper waters.
4.	Hypolimnion zone is formed by cold deeper waters.
5.	Metalimnion zone forms where water temperatures change rapidly.
6.	Metalimnion phytoplankton.
7.	Epilimnion phytoplankton.
8.	Hypolimnion phytoplankton.
9.	Sunlight striking phytoplankters.
10.	Sunlight striking photosynthetic pigments in plankters.
11.	Pigment concentration in cells increases as light decreases.
12.	Pigment composition changes with decreasing light intensity.
13.	Pigment concentration increases with improving nutrition.
14.	Phytoplankter size increases with improving nutrition.
15.	Nutrient supply effects on production of photosynthate.
16.	Sunlight inhibition of photosynthesis in top few meters.
17.	Photosynthetic activity.
18.	Photosynthate accumulation effects on reproduction.
19.	Species-specific maximum reproductive potential.
20.	Lag time for improved nutrition to increase reproduction rates.
21.	Production of new plankters.
22.	Zooplankton predation of phytoplankton.
23.	Zooplankton predation of zooplankton.
24.	Zooplankter growth.
25.	Zooplankter size increases with growth.
26.	Zooplankton excretion of extracellular products.
27.	Phytoplankton pigments excreted in zooplankton wastes.
28.	Exoskeletons shed by crustacean zooplankton growth stages.
29.	Zooplankton fecal pellets added to biodegradable tripton.
30.	Zooplankton carcasses added to biodegradable tripton.
31.	Pathogen predation of zooplankton.
32.	Pathogen killed zooplankter carcasses added to tripton.
33.	Biorefractory portions of zooplankton carcasses added to tripton.
34.	Zooplankton reproduction.
35.	Zooplankton population size.
36.	Phytoplankton leakage of extracellular products.
37.	Phytoplankton carcasses added to biodegradable tripton.
38.	Pathogen predation of phytoplankters.
39.	Pathogen-killed phytoplankton carcasses added to tripton.
40.	Biorefractory portions of phytoplankton carcasses added to tripton.
41.	Phytoplankton competition for sunlight.
42.	Reduction of light intensity striking photosynthetic pigments.
43.	Phytoplankton competition for nutrient supplies.

Number	Description
44.	Decomposer competition for nutrient supplies.
45.	Nutrient competition constraints on phytoplankton population.
46.	Phytoplankton population size.
47.	Pathogen carcasses added to biodegradable tripton.
48.	Pathogen population size.
49.	Pathogen contribution to bacterioplankton population size.
50.	Decomposer breakdown of biodegradable tripton.
51.	Decomposer excretion of extracellular products.
52.	Phytoplankton pigments released by decomposition.
53.	Decomposer mineralization of biodegradable tripton.
54.	Dissolved inorganic minerals released by mineralization.
55.	Dissolved inorganic matter phytoplankton nutrients.
56.	Dissolved organic matter phytoplankton nutrients.
57.	Decomposer population size.
58.	Decomposer contribution to bacterioplankton population size.
59.	Biodegradable tripton contribution to total concentration.
60.	Biorefractory tripton contribution to total concentration.
	Distribution of Particles and Pigments
61.	Factors affecting vertical distribution of extracellular pigments.
62.	Factors affecting vertical distribution of phytoplankton.
63.	Factors affecting vertical distribution of zooplankton.
64.	Factors affecting vertical distribution of tripton.
65.	Factors affecting vertical distribution of bacterioplankton.
66.	Passive sinking of seston.
67.	Concentration of seston on top of metalimnion.
68.	Concentration of seston in near-bottom waters.
69.	Seston sinking to lake bottom sediments.
70.	Biodynamic adjustment of vertical distribution.
71.	Maintenance of vertical position by biodynamic actions.
72.	Biodynamic maintenance of plankton concentrations in layers.
73.	Biodynamic daily seasonal vertical migration of plankton.
74.	Seston concentrated in layers in water column.
75.	Vertical currents affecting distribution of seston, pigments.
76.	Vertical eddies mixing epilimnion.
77.	Mixing of available nutrients in epilimnion.
78.	Dispersal of seston layers by eddies.
79.	Langmuir cell concentration of seston into vertical wedges.
80.	Vertical eddies mixing hypolimnion.
81.	Hypolimnion eddies' stirring of loose bottom sediments.
82.	Resuspension of settled seston.
83.	Release of nutrients in bottom sediments by resuspension.
84.	Disruption of seston layers by hypolimnion eddies.
85.	Uniform vertical dispersion of seston in hypolimnion.
86.	Vertical mixing of entire water column.
87.	Resuspension of settled seston by mixing of water column.
88.	Release of bottom sediment nutrients by water column mixing.
89.	Breakup of water column stratification.
90.	Dispersion of seston by mixing of entire water column.

Number	Description
91.	Uniform vertical dispersion of seston.
92.	Wave turbulence effects on vertical distribution of seston.
93.	Wave turbulence in waters much deeper than wave base.
94.	Wave turbulence effects when epilimnion is shallow.
95.	Mixing of epilimnion.
96.	Wave turbulence effects when epilimnion is deep.
97.	Insignificant vertical redistribution by wave turbulence.
98.	Wave turbulence in waters shallower than wave base.
99.	Wave turbulence mixing of shallow water column.
100.	Wave turbulence resuspension of settled seston.
101.	Release of nutrients in bottom sediments by wave turbulence.
102.	Uniform vertical mixing of seston by wave turbulence.
103.	Phytoplankton portion of seston much larger than light waves.
104.	Zooplankton portion of seston much larger than light waves.
105.	Tripton portion of seston much larger than light waves.
106.	Tripton portion of seston much smaller than light waves.
107.	Tripton portion of seston about the size of light waves.
108.	Bacterioplankton portion of seston about the size of light waves.
109.	Size distribution of seston.
110.	Sunlight striking different sizes of seston.
111.	Seston's optical cross section.
112.	Seston's optical cross section effect on upwelling color.
113.	Pigments within cells' portion of total water column pigments.
114.	Extracellular pigment's portion of total water column pigments.
115.	Total water column pigment's effect on upwelling color.
116.	Water color effects of uniform vertical distribution of seston.
117.	Color effects of uniform distribution in epi- or hypolimnion.
118.	Effect of seston concentrated in wedges on upwelling color.
119.	Effect of seston concentrated in layers on upwelling color.
120.	Factors affecting the horizontal distribution of seston.
121.	Horizontal current redistribution of water mass nutrients.
122.	Upwelling color of individual water masses.
123.	Seston patches caused by inflowing stream water mass currents.
124.	Role of stream water mass in lake water color variations.
127.	Seston patches caused by lake gyres.
128.	Role of lake gyres in water color variations.
129.	Seston patches caused by Langmuir spirals.
130.	Role of Langmuir spirals in lake water color variations.
131.	Horizontal juxtaposition of different patches of water color.

Explanation of CEM Factors Controlling Concentrations of Autochthonous Organic Matter Affecting Lake Water Color

Production of Particles and Pigments

The first and most important factor controlling the amount of biologically produced, optically active materials affecting lake water color is the amount of (1)* sunlight in the water column. The large portion of that sunlight not eventually returning to the atmosphere is converted to other forms of energy by interactions with suspensoids, water molecules and dissolved substances. The amount of (2) water heated by such conversions is directly proportional to the intensity of penetrating sunlight. When in spring to late summer the sun remains high in the sky for long periods, lake waters experience a net gain of heat. The most intensely lighted and warmed surface waters form into a (3) relatively stable, low density layer termed the epilimnion. Waters deeper down are insignificantly heated by sunlight, and they form a stable, relatively cold water layer termed the hypolimnion. The transition zone between these top and bottom layers where (5) water temperature and density change rapidly is termed the metalimnion.

A favorable water temperature is the second most important factor controlling the autochthonous production of organic substances. Light and heat are such preeminant determinants of the biotic productivity of lakes (Smith 1980) that all other factors, no matter how favorable, are

---

*Numbers in parentheses refer to numbered arrows on the CEM.

inoperative when the former are unfavorable. Consequently, because the phytoplankton in the (6) metalimnion, (7) epilimnion, and (8) hypolimnion exists in very different light and temperature environments, their productive and reproductive potentials are significantly different. In each differing thermal environment, sunlight first strikes (9) phytoplankters, some penetrates cell walls, and subsequently strikes chloroplasts and their (10) photosynthetic pigments. Within limits, the (11) pigment concentration in phytoplankton cells increases as ambient light intensity decreases (Carlson 1977 citing Steele 1962, Fogg 1965 p.23) and as cell (13) nutrition increases (Ryther & Kramer 1961). Conversely, as light intensity increases, so does the pigment concentration in some zooplankters (Hairston 1980); but they are sun screening, not photosynthetic pigments. The phytoplankton found in different light environments have somewhat differing (12) pigment compositions (Jeffrey et al. 1975), (14) Phytoplankter size (and hence, light scattering ability), and ability to (15) produce photosynthate also increase with improved nutritional conditions.

In very clear waters, sunlight is so intense in the top few meters that (16) photosynthesis is greatly inhibited (Tilzer & Horne 1979 p. 163). At greater depths, the sunlight striking chloroplast pigments causes (17) photosynthetic activity, resulting in photosynthate production and accumulation, and ultimately (18) increasing (21) phytoplankton reproduction. The latter is constrained by (19) maximum reproduction rates of species and the (20) time it takes for increased reproduction rates to appear after environmental conditions improve.

Phytoplankton populations are to some extent controlled by (22) zooplankton. Larger zooplankton also (23) prey on smaller ones. As a result of the nutrition gained by feeding activities, zooplankters (24) grow in (25) size, excrete (26) dissolved organic matter, (27) undigested phytoplankton pigments and (29) fecal pellets. Crustacean species (28) shed exoskeleton debris. The latter two byproducts are added to the organic, nonliving suspensoids (tripton). Zooplankters are (31) attacked by pathogens and eventually die, either due to the (32) pathogens or (30) other causes, adding their carcasses to the tripton. The (35) zooplankton population size is the net result of the balance between (34) zooplankton reproduction rates and population control factors--e.g., (31) pathogen, invertebrate and vertebrate predation.

Tripton consists of two functionally different types: biodegradable and biorefractory. Portions of crustacean (33) zooplankters and diatom (40) phytoplankters become part of both the biorefractory and biodegradable tripton. Upon their death from (38, 39) pathogens or other (37) causes, phytoplankton carcasses become a part of the tripton, as do those of dead (47) pathogens.

When phytoplankton populations become dense enough, they are also limited by (41) competition for sunlight, because light interception by plankters above begins to (42) reduce the intensity striking the photosynthetic pigments of those below. Similarly, (45) phytoplankton populations are to some extent limited by (43) competition with other phytoplankton and with the population of (44) decomposer microorganisms for nutrient supplies. The (46) phytoplankton population size is the net result of the favorable light and water temperature conditions plus the effect of population controlling factors on reproduction and survival rates.

The (48) pathogen population size is determined by the availability of hosts. To the extent that they become detached from a host substrate, (49) pathogens are part of the bacterioplankton population.

Microorganisms largely (50) using dead organic matter as their source of nutrients and energy are termed decomposers. Dissolved organic matter, much of which is excreted by living (26) zooplankters, (36) phytoplankters (Tilzer & Horne 1979) and (51) decomposer bacteria, is used as a lesser source of nutrition by many decomposers. During cell lysis, or decomposition of phytoplankton tripton, much of the (52) pigments and protoplasmic fluids escape into surrounding waters, further adding to the dissolved organic matter supply. Decomposition of biodegradable tripton (53) breaks down (i.e., mineralizes) much of the organic matter into (54) inorganic forms primarily (55) used by phytoplankton and adds other partial breakdown products to the dissolved organic matter which phytoplankton may use (56) (Hellebust & Lewin 1977) as nutrition sources. The (57) decomposer population size is determined by the supply of tripton and dissolved organic matter, and by the abundance of attachment surfaces (Paerl & Goldman 1975) they need to capture and digest those foods. To the extent that they float freely detached from a substrate, decomposers (58) are the remaining, and in fact, major portion of the bacterioplankton population.

The total tripton concentration has a (59) biodegradable and a (60) biorefractory fraction. The sole biologic function performed by the biorefractory portion is as attachment surfaces from which bacteria can conduct their nutrition-scavenging activities.

Distribution of Particles and Pigments

Upwelling color is affected not only by the amount of particles and pigments present, but also by their depth (Lorenzen 1972) and density distribution (Kirk 1980). Thus, an adequate conceptual model must include factors affecting the vertical distribution of (61) extracellular pigments, (62) phytoplankton, (63) zooplankton, (64) tripton and (65) bacterioplankton.

Gravitational forces are always acting on seston in suspension. Thus, the predominant vertical redistribution force on most seston is an omnipresent tendency to (66) sink (Smayda 1970). Ultimately all but colloidal size seston (.0002-.001 mm.) (69) sink to lake bottom sediments and eventually even those sink.

In thermally stratified lakes, seston are typically found concentrated near the top of the (67) metalimnion (Harder 1968) where water's density most rapidly increases with depth, and in (68) waters close to the bottom. Many healthy plankters are able to (70) actively exert some control over their vertical distribution--zooplankters by swimming, and some phytoplankters by adjustment of their buoyancy or hydrodynamic shape (Smayda 1970). By such actions some plankters (71) remain at a relatively constant, environmentally favorable depth, resulting in (72) plankton being concentrated in layers. Many zooplankters are able to move so rapidly that they (73) daily migrate up and down as sunlight intensity decreases and increases. Some phytomeroplankton (Preston et al., 1980) seasonally migrate up and down as part of their life cycles. The net result of interactions between these properties, processes and forces is that (74) seston frequently occur concentrated in layers.

The (75) vertical distribution of seston and extracellular pigments is also affected by vertical currents. In a stratified lake, vertical (78) dispersion of seston and (77) nutrients most commonly occurs because of (76) eddies mixing the epilimnion. The most common epilimnion eddies are Langmuir spirals (Wetzel 1975 p. 100). They (79) concentrate seston, whether initially present in (78) layers or evenly dispersed into vertical wedges between the downwelling sides of adjacent spirals.

Occasionally, (80) vertical eddies occur which are confined to the hypolimnion (Powell & Jassby 1974). Such eddies (81) stir up loose bottom sediments, (83) releasing interstitial and some absorbed nutrients, (82) resuspending settled seston and (84) disrupting any seston layers by (85) uniformly dispersing them throughout the hypolimnion.

In late fall when the epilimnion layer has cooled enough that it is only slightly less dense than the hypolimnion, persistent, unidirectional winds (89) break up water column stratification, producing (86) vertical mixing of the entire water column. If extremely strong and persistant winds occur, such mixing may take place on a more limited scale (e.g., along one side of the lake) even when the lake is well stratified (Richerson et al. 1978). Such overturn and upwelling occurrences, as they are respectively termed, result in (87) resuspension of settled seston, (88) release of some bottom sediment nutrients, and (90, 91) uniform dispersion of seston concentrations. The (92) water column turbulence generated by waves is a commonly occurring vertical mixing force, albeit one whose effectiveness decreases rapidly with depth and consequently is much less thorough than Langmuir spirals, upwelling or overturn. The ability of wave-generated turbulence to affect significantly the vertical distribution of seston and extracellular pigments largely depends upon the mazimum depth of waters and of the epilimnion. When both are (98, 94) shallow compared to the maximum depth at which wave-generated turbulence is still great enough to cause mixing (termed "wave base" depth), stirring of the (99) water column or (95) of the epilimnion occurs. Consequently, when both are shallow, wave turbulence results in (100) resuspension of settled seston, (101) release of some bottom sediment nutrients and (102) uniform vertical dispersion of seston. When both (93) water depth and the (96) epilimnion are deeper than wave base, the amount of (97) vertical redistribution is insignificant.

As emphasized in the previous Chapter, the size of suspensoids relative to light wave lengths is an important characterization for estimating their effects on water color. Three relative size categories are significant for characterizing the optical effect of suspensoids. All (103) phytoplankton and (104) zooplankton and much of the (105) tripton originating as their carcasses are much larger than light waves. The only autochthonous biogenic contribution to suspensoids much smaller than light waves are the (106) broken off pieces of bacteria and other very tiny tripton particles. The bacterioplankton (108), their intact carcasses and the remainder of the (107) tripton (i.e. smaller fragments of zoo- and phytoplankton carcasses) are seston approximately the size of light waves.

The relative abundance of suspensoids in each optically significant size category determines the (109) size distribution of seston in the optical activity categories. The (110) sunlight striking the particles in each category results in (111) significantly different effects on that light. Consequently, the particles in each class have a different amount of (112) influence on upwelling color.

Water column pigments exist in two forms: confined (113) within plankton cells--such as in chloroplasts, or as (114) extracellular substances dispersed in the water, completely dissociated from their suspensoid origins. Regardless of their location, in aggregate these (115) pigments collectively affect upwelling water color.

Whether, where, and to what degree seston is concentrated in the water column greatly determines its effect on upwelling water color. The forces affecting the vertical location of seston produce four types of distributions having significantly different influences on the upwelling color of water masses: concentration in (119) layers, (118) in wedges, or uniform dispersal in (117) the epilimnion, in the hyplimnion, or in (116) the entire water column.

The water in large lakes seldom remains in the same horizontal position for long, being constantly moved by current systems. Consequently, when describing the system of factors controlling water color, I must also discuss factors affecting the horizontal mass movement of (122) waters having different upwelling color characteristics. To the extent that water masses retain their integrity during horizontal movement, they also carry with them their initial (120) seston and (121) phytoplankton nutrients. To the extent that they lose integrity by mixing with other waters, new water masses are formed with different upwelling color characteristics.

The horizontal variations in plankton density are commonly termed "patchiness." As the tripton's portion of the seston has planktonic origins, generally all seston show the same patchy distribution. The various types of seston patchiness occurring in large lakes and the consequent water color can be categorized according to the vertical moving force: i.e., patchiness and color variations associated with (123, 124) inflowing stream water masses, (125, 126) linear and (127, 128) gyre lake currents and (129, 130) Langmuir spirals. Only the latter vertical process actually alters seston distribution by concentrating it from its initial distribution in the water mass. All other processes only alter seston's horizontal position by moving their entire water mass environment.

A different upwelling water color experience occurs because of the close juxtaposition of (131) differently colored water masses. In such cases we see side by side waters with significantly different upwelling light characteristics. Such contrasts are more likely to attract public attention and generate outcrys than seeing only the upwelling light arising from a single, optically uniform water mass.

Relation to System Diagram

The "Lake organic matter production" section is an expansion of system Variable 57, "phytoplankton nutrient uptake and multiplication." The categories of the "autochthonous organic matters" section are an expansion of system Variable 59, "phytoplankton biomass in water mass." While emphasis is on phytoplankton biomass growth, that is somewhat a misnomer. Here I am more specifically concerned with all aspects of biomass affecting color and transparency, i.e., phyto-bacterio-zooplanktonic pigment concentrations and optical cross sections, and the depth distribution of those two quantities. Likewise, I am also concerned with extracellular pigments and dead organic suspended particles (tripton).

The population of zooplankton, bacterioplankton (Mitchel & Kiefer 1980), and the amount of tripton and extracellular pigments play some role in determining upwelling water color. I emphasize the role of phytoplankton biomass because it is the most abundant autochthonous product and the one whose importance in determining water color is most likely affected by increased of nutrient and sediment inflows caused by land use activities. Zoo- and bacterioplankton biomass are also a function of the abundance of phytoplankton food sources. However, zooplankters are ineffective controllers of the size of phytoplankton populations when the latter are as sparse as in Lake Tahoe (Richerson et al. 1978, Western Federal Regional Council 1979). The zooplankton biomass is sometimes greater than the phytoplankton biomass (Pennak 1955). However, it is largely and frequently so deep in the water column during daylight hours that it has little or no effect on the quality and quantity of upwelling light.

The processes in the "vertical and horizontal movement" sections are approximate expansions of system Variable 40, "water mass transport and dilution processes in the lake." The latter is a portion of the water mass mixing subsystem discussed in Chapter 15, where a more detailed CEM of these processes and their effects is presented. However, the emphasis of that chapter is on the movement and fate of stream-borne sediments and dissolved nutrients. Movement of autochthonous seston and extracellular pigments is not explicitly discussed, though the processes and effects are the same. It is useful to include here some discussion of vertical and horizontal transport of seston and pigments by lake water movement processes because they are crucial factors controlling concentrations of organic substances in the visible water column.

Relation to Upwelling Water Color Subsystem

The end products of this lake biotic products model (i.e., abundance and distribution of types of optically active organic substances) are basic information inputs to the upwelling water color model.

Relative Particle Sizes

Variables 103 and 104 of this model represent the abundance of particles much larger than light waves and are a elaboration of Variable 37 in the upwelling water color CEM. Variable 106 represents particles much smaller than light waves and is equivalent to Variable 40 in the upwelling water color CEM. Variables 107 and 108 represent particles approximately the size of light waves and are equivalent to Variable 43 in the upwelling water color CEM.

Translucent Particle Types

Some transformation is also needed to use the information developed on lake biotic product particles for the optical effect types of the upwelling water color model. All autochthonous particles are quite small. The largest individual phytoplankters are too small to be seen by the unaided eye (cf. Table 6). Even most Tahoe zooplankters are pinhead-sized or smaller. In accordance with their miniscule dimensions, all plankters' cell, frustule or exoskeleton walls are very thin, and consequently, translucent. Hence, all seston belong in either the colorless, partially pigmented or evenly pigmented particle categories of the upwelling water color model.

Most zooplankters are colorless (Mellanby 1963), and therefore are in the upwelling water color model's "colorless particles" category. The pigments in all diatoms and other abundant phytoplankton in Lake Tahoe are concentrated in chloroplast organelles. Therefore, these particles belong in the "partially pigmented particles" category of the upwelling water color model. The pigments in blue-green algal phytoplankton are not confined to chloroplasts but are disseminated evenly all around cell walls. Therefore they are evenly pigmented particles. Members of this phylum are not abundant in Lake Tahoe, though they are more common in some streams (Smith and Ludwig 1968a & b) and artificial embayments with poor circulation.

Some zooplankters contain pigments. Those with the greatest amount are likely to occur in the upper portion of the water column (Hairston 1980) where they may affect water color. Some of these pigments may be concentrated in internal structures, but most are dispersed in the exoskeleton epidermis (Ringelberg 1980). Thus those zooplankters are also part of the "evenly pigmented particles" category.

Cellular and Extracellular Pigments

The pigments existing within the phytoplankton are the upwelling color model's "pigments" within "partially pigmented particles" component. The relative importance of cellular pigments and the other optical effects of internal inhomogeneities on light passing through the water column is proportional to the number of phytoplankters. The extracellular pigments are the upwelling water color model's "concentration in solution" of "colored molecules" variable.

Depth Distribution

The vertical distribution of lake-produced organic particles and extracellular pigments provides information for evaluating the net effect of the upwelling water color model's "water molecules" as a function of the "length of light path in water." The differences in upwelling light due to the same substances at different depths is entirely a consequence of how water molecules change the quality and quantity of light before it arrives at those substances and as it returns to the surface.

Water Mass Upwelling Color

The aggregate effect of the amount, concentration and vertical distribution of autochthonous organic substances in a water mass make its upwelling color qualitatively and quantitatively different than if only the effects of pure water were present. In comparison, the first order effects of stream-borne sediments themselves are ephemeral, and therefore relatively unimportant. It is the secondary effects of suspended sediments (i.e., introducing nutrients and providing surfaces microorganisms use to speed up nutrient cycling) that increase the lake's production of biologic matter. That additional organic matter is a particularly significant factor affecting upwelling water color.

CHAPTER 8

THE LAND AND STREAM SEDIMENT TRANSPORT SUBSYSTEM

Chapter Scope

In this chapter I first present an overview of a CEM of factors generally affecting the release and transportation of sediment particles from watershed locations to the lake (Figure 8). I then present the full conceptual model and explain that complex model.

Overview of Sediment Transport Model

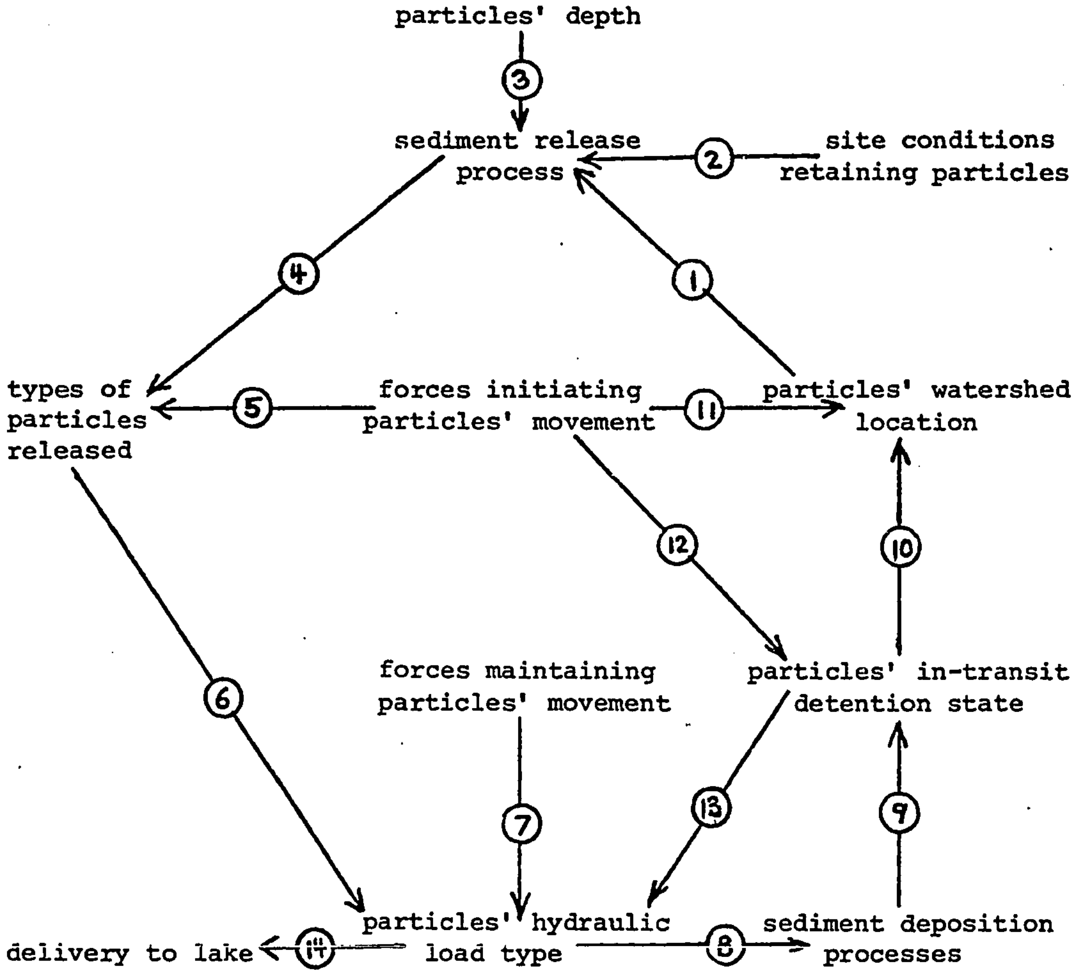
The particular release processes converting stored fine particles to a readily transported form depends upon the potential location of suspended sediments (1)* of in a watershed, (2) the tenacity of forces holding them to a site and (3) the depth of their burial. Some aspects of the latter are a special case of (2) site fixation, but it is useful to consider particle depth separately since it is particularly important in determining the probability of exposure to, and therefore, the effectiveness of many release processes.

As a consequence of release processes, certain portions of the particles on a site are (4) converted to readily transportable forms. The release forces acting on the transportable particles (6) usually also initiate their movement as sediments. For characterizing the

---

* Numbers in parentheses refer to numbered arrows in Figure 7.

Figure 7. General Organization of Sediment Transport Subsystem Model



relative transportability of particles, it is useful to (6) distinguish between different types of water-borne sediments, primarily a particle size based subdivision.

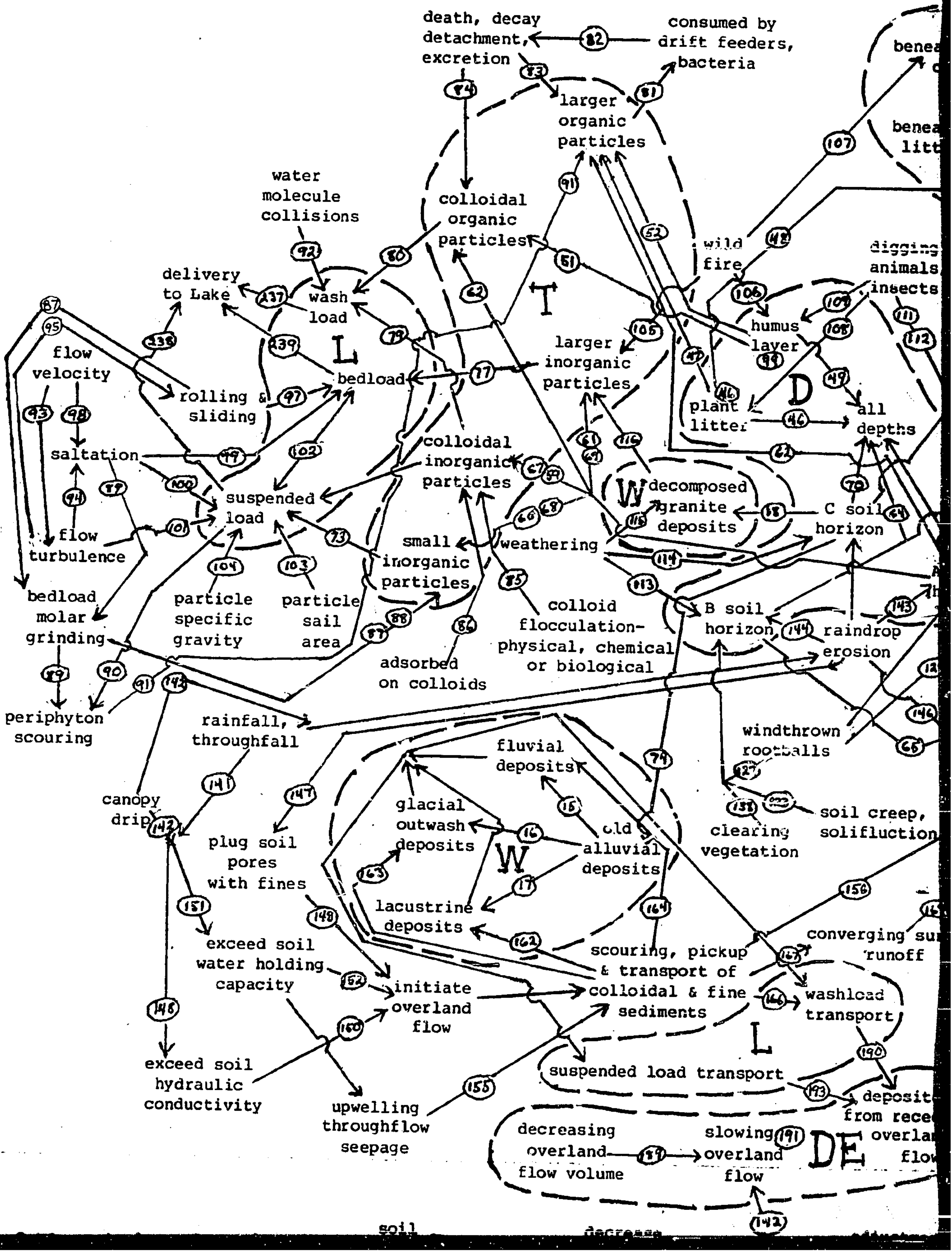
Certain hydrodynamic (7) forces act on fluvial sediment loads to maintain their movement. Other forces (8) acting on moving sediments cause their deposition before reaching the lake. As a consequence of the intervention of the depositional forces, some or all of the moving sediments are detained one or more times before their ultimate delivery to the lake. Depending upon the (11) location of this detention, (12) different resuspension forces act on the deposited sediments, again (13) returning them to the moving stream sediment load. After a few or many such transportation-detention-transportation sequences, particles originating from watershed sites eventually are (13) delivered to the lake.

The subsystem model diagram (Figure 8) presents an elaboration of the above sequences and the effects of location, depth, site fixation and motion predisposing states and initiating, suspending and deposition processes. This conceptual model emphasizes ecosystem processes controlling movement of inorganic sediments from watershed sites to the lake. The significant water color effects of organic particles is largely due to the biomass production stimulated by their contained nutrients. Therefore, transportation of organic particles is more thoroughly covered in Chapters 9 and 10, respectively, on nitrogen and phosphorus delivery to the lake.

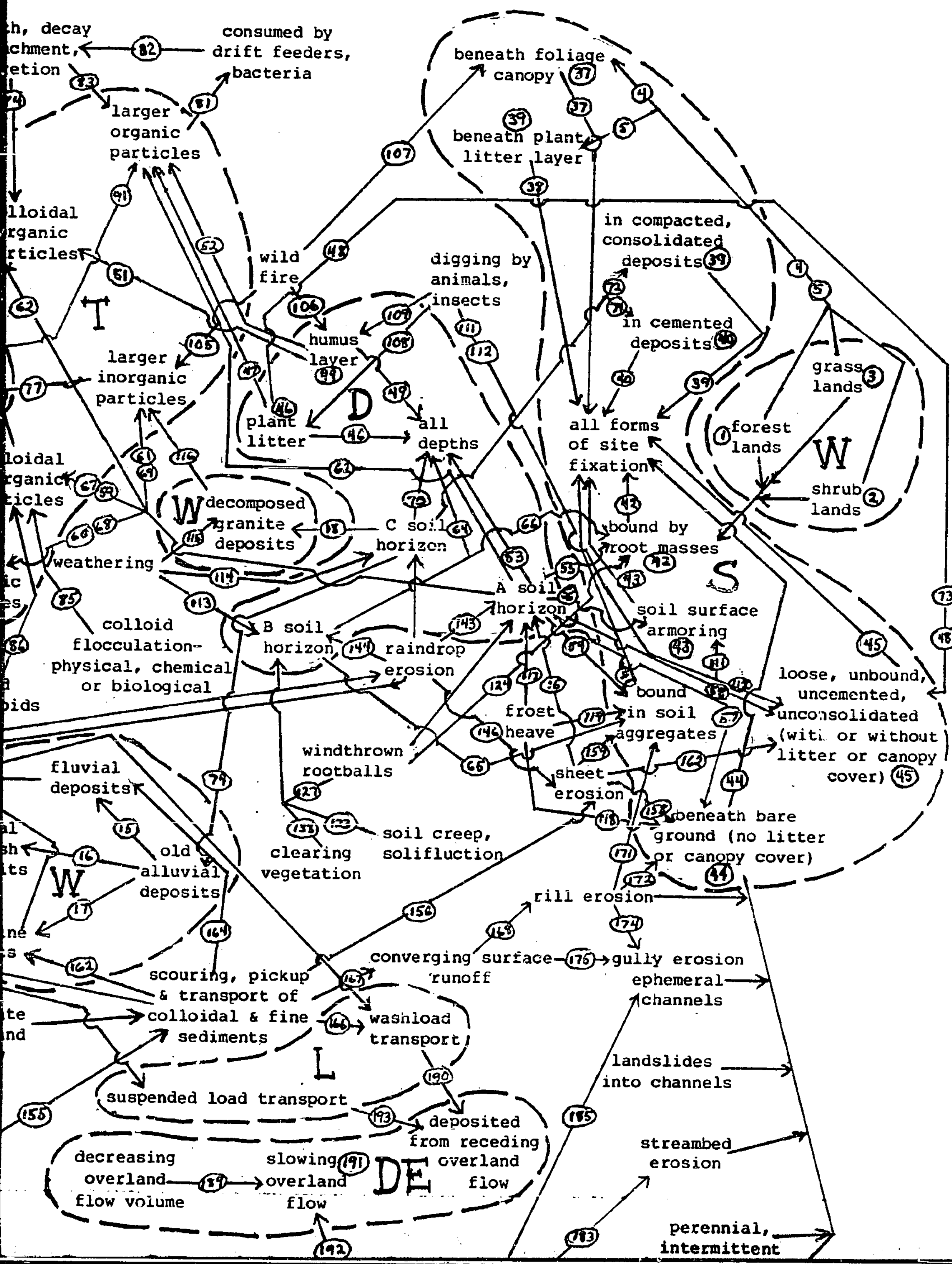
Terrestrial organic particles are greatly altered physically during their land and stream journeys. As their particulate nature changes greatly during their journey, so do their optical properties.

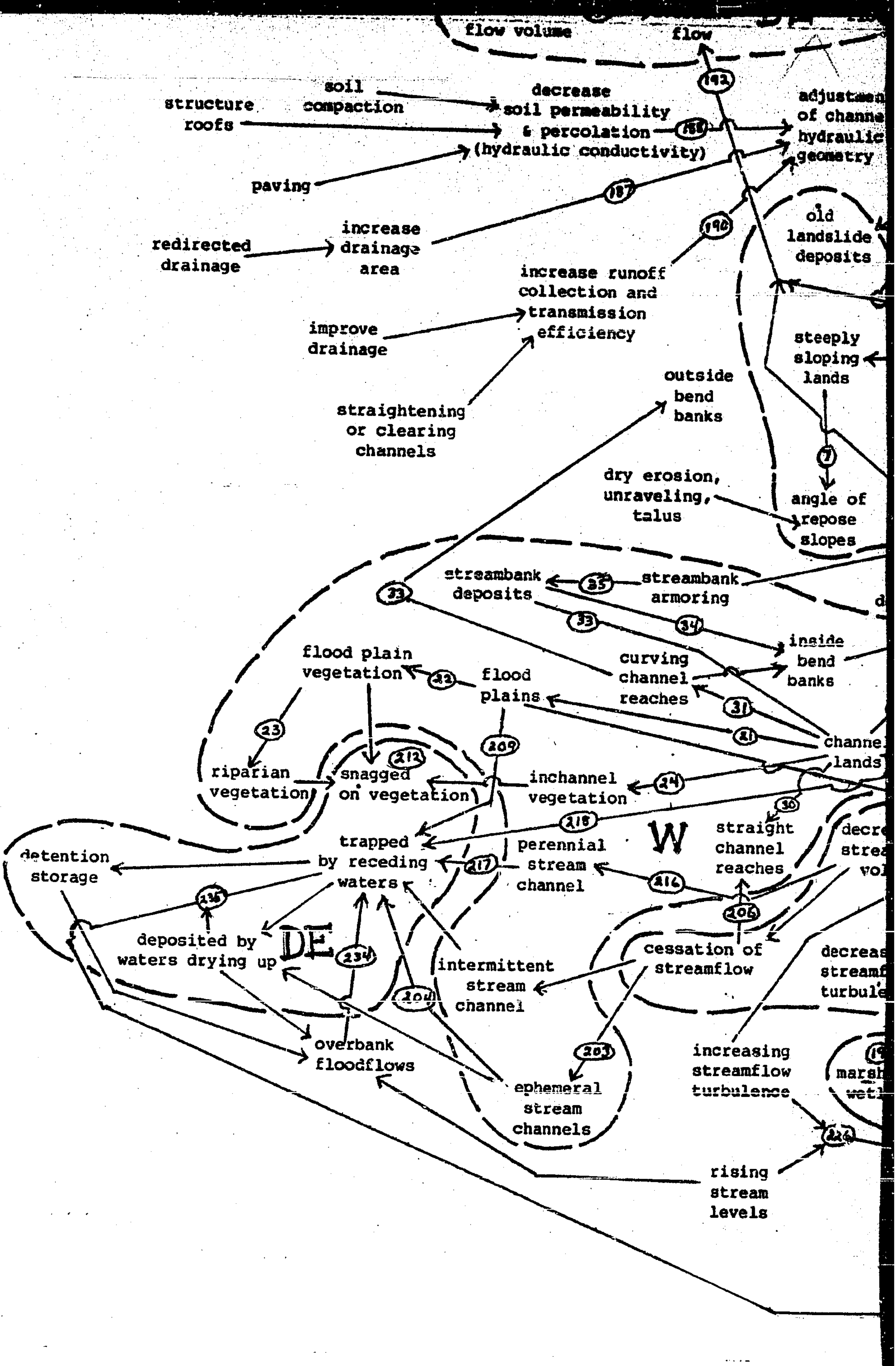
Therefore, it is futile to initially characterize them optically as particles on a watershed site and then trace their pathways to the lake. The organic particles arriving at the lake are optically unrelated to those which left the site.

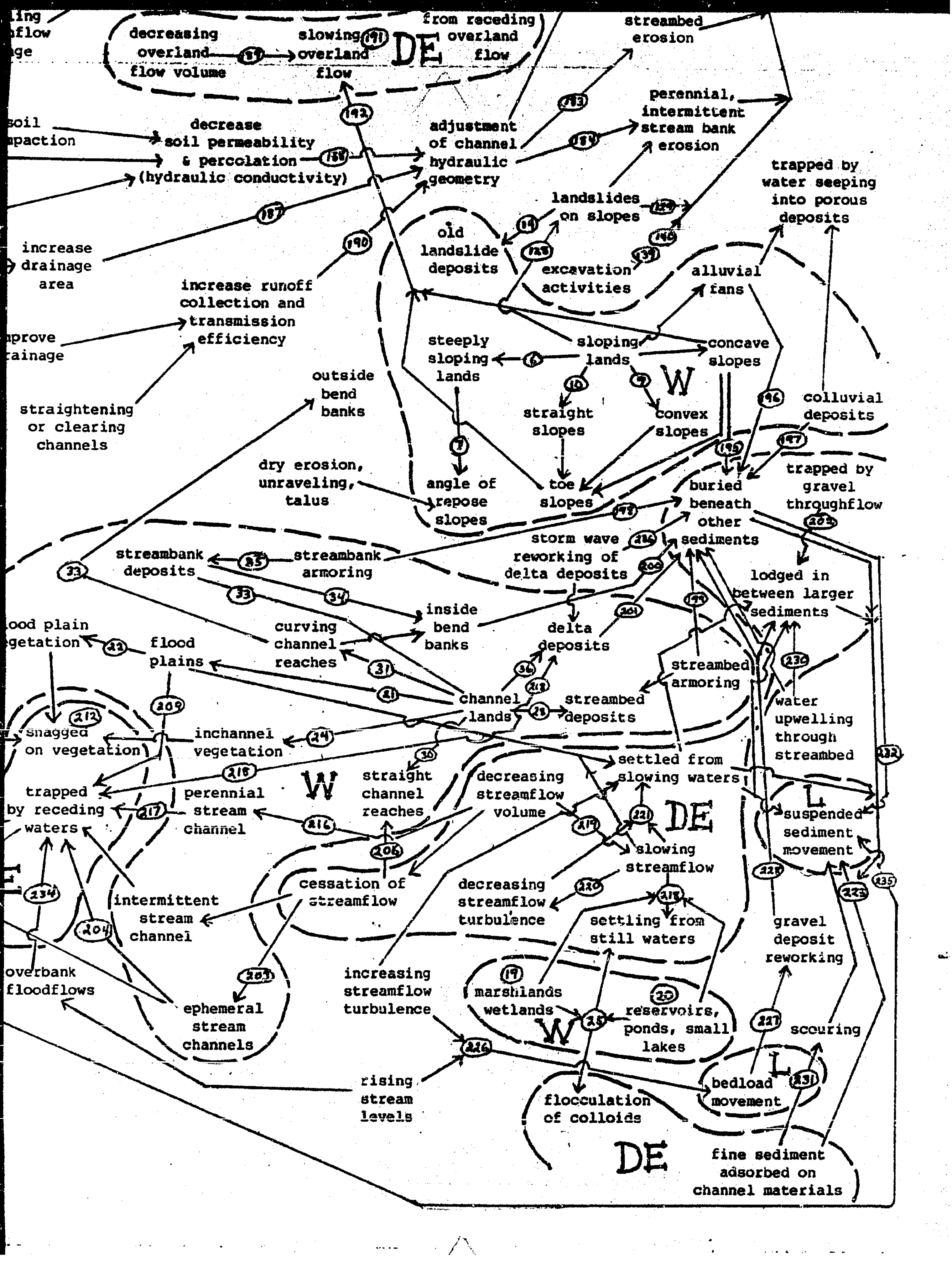
Figure 8. Conceptual Model of Land and Stream Sediment Transport Subsystem



m Sediment Transport Subsystem




flow volume
flow
192
soil compaction
structure roofs
decrease soil permeability & percolation (hydraulic conductivity)
188
adjustmen of channe hydraulic geometry
paving
187
190
old landslide deposits
redirected drainage
increase drainage area
increase runoff collection and transmission efficiency
improve drainage
straightening or clearing channels
steeply sloping lands
outside bend banks
7
dry erosion, unraveling, talus
angle of repose slopes
streambank deposits
35
streambank armoring
33
33
34
d
inside bend banks
curving channel reaches
flood plain vegetation
22
flood plains
31
21
channel lands
23
209
riparian vegetation
212
snagged on vegetation
inchannel vegetation
24
30
218
W
straight channel reaches
decre strea vo
trapped by receding waters
detention storage
217
perennial stream channel
216
206
235
deposited by waters drying up
DE
234
204
intermittent stream channel
cessation of streamflow
decreas streamf turbule
203
overbank floodflows
ephemeral stream channels
increasing streamflow turbulence
19
marsh wetl
226
rising stream levels



ling
flow
ge
decreasing overland flow volume
189
slowing overland flow
191
DE
from receding overland flow
streambed erosion
192
193
soil
paction
decrease soil permeability & percolation (hydraulic conductivity)
188
adjustment of channel hydraulic geometry
194
perennial, intermittent stream bank erosion
trapped by water seeping into porous deposits
187
landslides on slopes
129
increase drainage area
190
old landslide deposits
14
128
140
139
excavation activities
alluvial fans
increase runoff collection and transmission efficiency
prove
ainage
steeply sloping lands
6
sloping lands
concave slopes
outside bend banks
10
9
W
straightening or clearing channels
straight slopes
convex slopes
196
colluvial deposits
7
195
197
dry erosion, unraveling, talus
angle of repose slopes
toe slopes
198
buried beneath other sediments
trapped by gravel throughflow
205
streambank deposits
35
streambank armoring
storm wave reworking of delta deposits
236
33
200
lodged in between larger sediments
33
34
inside bend banks
201
199
ood plain
getation
22
flood plains
curving channel reaches
31
delta deposits
32
streambed armoring
230
21
channel lands
213
23
streambed deposits
water upwelling through streambed
209
212
snagged on vegetation
inchannel vegetation
24
30
232
218
settled from slowing waters
trapped by receding waters
217
perennial stream channel
W
straight channel reaches
decreasing streamflow volume
L
216
206
219
221
DE
suspended sediment movement
slowing streamflow
234
cessation of streamflow
decreasing streamflow turbulence
220
228
233
235
204
intermittent stream channel
215
settling from still waters
gravel deposit reworking
overbank floodflows
203
increasing streamflow turbulence
19
marshlands wetlands
20
reservoirs, ponds, small lakes
ephemeral stream channels
25
W
227
scouring
226
L
231
rising stream levels
flocculation of colloids
bedload movement
DE
fine sediment adsorbed on channel materials

Table 9. Legend for Conceptual Model of Land and Stream Sediment Transport

Number	Description
	Watershed Location Effects
1.	Particles on watershed locations covered by forests.
2.	Particles on watershed locations covered by shrubs.
3.	Particles on watershed locations covered by grasses.
4.	Watershed locations covered by foliage canopy.
5.	Watershed locations covered with plant litter.
6.	Particles on steeply sloping watershed lands.
7.	Particles on slopes steeper than the angle of repose.
8.	Particles on concave slopes.
9.	Particles on convex slopes.
10.	Particles on straight slopes.
11.	Particles on toe zones of slopes.
12.	Particles in colluvial deposits.
13.	Particles in alluvial fan deposits.
14.	Particles in old landslide deposits.
15.	Particles in old fluvial (stream) alluvial deposits.
16.	Particles in glacial outwash alluvial deposits.
17.	Particles in old lacustrine (lake) alluvial deposits.
18.	Particles in decomposed granite deposits.
19.	Particles on watershed wetlands.
20.	Particles in ponds, reservoirs or minor lakes.
21.	Particles in flood plain deposits.
22.	Particles in deposits under flood plain vegetation.
23.	Particles in deposits under riparian (stream bank) vegetation.
24.	Particles in deposits under plants growing within channels.
25.	Particles in ephemeral stream channels.
26.	Particles in intermittent stream channels.
27.	Particles in perennial stream channels.
28.	Particles in stream bed deposits.
29.	Particles in deposits under stream bed armor.
30.	Particles located along straight channel reaches.
31.	Particles located along curving channel reaches.
32.	Particles in stream bank deposits.
33.	Particles in stream banks on the outside of channel bends.
34.	Particles in stream banks on the inside of channel bends.
35.	Particles in deposits under stream bank armor.
36.	Particles in stream delta deposits.
	Detention Conditions
37.	Particles sheltered by plant foliage.
38.	Particles in or sheltered by plant litter.
39.	Particles in compacted or consolidated deposits.
40.	Particles bound in cemented deposits.

Number Description

41. Particles bound in soil aggregates.
42. Particles bound by root masses.
43. Particles sheltered by soil surface armoring
44. Particles in deposits not sheltered by plant foliage or litter.
45. Particles in loose, uncemented or unconsolidated deposits.

Initial Depth on Watershed Sites

46. Particles in plant litter layer.
47. Larger organic particles originating from the litter layer.
48. Loose particles present in litter layer.
49. Particles in humus layer.
50. Loose particles present in humus layer.
51. Colloidal organic particles originating from the humus layer.
52. Larger organic particles originating from the humus layer.
53. Particles in A soil horizon.
54. A horizon particles bound in soil aggregates.
55. A horizon particles bound by roots.
56. A horizon particles sheltered by surface armor.
57. A horizon particles beneath bare ground.
58. Particles in loose A horizons.
59. Colloidal inorganic particles originating from the A horizon.
60. Small inorganic particles originating from the A horizon.
61. Larger inorganic particles originating from the A horizon.
62. Colloidal organic particles originating from the A horizon.
63. Larger organic particles originating from the A horizon.
64. Particles in B soil horizon.
65. B horizon particles bound in soil aggregates.
66. B horizon particles bound by roots.
67. Colloidal inorganic particles originating from the B horizon.
68. Small inorganic particles originating from the B horizon.
69. Larger inorganic particles originating from the B horizon.
70. Particles in C soil horizon.
71. Particles in cemented fragipans of C horizons.
72. Particles in compacted or consolidated C horizons.
73. Particles in loose C horizon deposits.
74. Particles in C horizon deposits of alluvial origin.
75. Small inorganic particles in C horizon alluvial deposits.
76. Larger inorganic particles in C horizon deposits.

Types of Release and Transport

77. Larger inorganic particles are transported as bed load.
78. Smaller inorganic particles are transported as suspended load.
79. Colloidal inorganic particles are transported as wash load.
80. Colloidal organic particles are transported as wash load.
81. Larger organic particles consumed by drift feeders, decomposers.
82. Larger organic particles processed by filter feeders, decomposers.
83. Larger organic particles returned to suspension after processing.

Number Description

84. Colloidal organic biproducts of processing put into suspension.
85. Flocculated colloids converted to suspended sediment load.
86. Colloids adsorbed to larger particles, becoming suspended load.
87. Production of small particles by rolling and sliding bed load.
88. Production of small particles by bed & suspended load saltation.
89. Scouring of stream periphyton by bed load molar grinding.
90. Scouring of stream periphyton by suspended load.
91. Larger organic particles released by souring of periphyton.

Release and Movement Maintaining Processes

92. Water molecule collisions maintain suspension of wash load.
93. Flow turbulence is a direct function of stream flow velocity.
94. Portion of saltation due to flow turbulence.
95. Bed load rolling & sliding due to flow turbulence.
96. Portion of bed load rolling & sliding due to flow velocity.
97. Bed load moving by rolling and sliding.
98. Portion of saltation due to flow velocity.
99. Bed load moving by saltation.
100. Suspended load moving by saltation.
101. Particles suspended by flow turbulence.
102. Movement as suspended vs. bed load shifts with speed & turbulence.
103. Particle sail area effects on transport as suspended load.
104. Particle specific gravity effects on transport as suspended load.
105. Wildfire removal of litter layer sheltering soil particles.
106. Wildfire removal of humus layer sheltering soil particles.
107. Wildfire removal of plant canopy sheltering soil particles.
108. Animal displacement of litter layer containing and sheltering particles.
109. Animal displacement of humus layer containing and sheltering particles.
110. Animal digging activities in A horizon of soil.
111. Disruption of surface armor protection by digging animals.
112. Loosening of soil particles by digging animals.
113. Release of new particles in B horizon of soil by weathering.
114. Release of new particles in C horizon of soil by weathering.
115. Release of decomposed granite particles by weathering.
116. Decomposition of granite yields coarse sand size particles.
117. Frost heave loosening of A horizon particles of soil.
118. Frost heave loosening of particles in exposed bare ground.
119. Loosening of particles bound in soil aggregates by frost heave.
120. Disruption of surface armor shelter by windthrown tree rootballs.
121. Exposure of bare ground by windthrown tree rootballs.
122. Overturn of A horizon by windthrown tree rootballs.
123. Overturn of B horizon by windthrown tree rootballs.
124. Destruction of root binding of particles by windthrown rootballs.
125. Soil creep, solifluction occurring on sloping lands.
126. Soil creep, solifluction of A horizon soils.
127. Soil creep, solifluction of B horizon soils.

Number	Description
128.	Landsliding occurring on sloping lands.
129.	Release of particles by landslides on slopes.
130.	Landsliding occurring on slopes adjacent to channels.
131.	Release of particles by landslides into channels.
132.	Removal of foliage sheltering particles by clearing of vegetation.
133.	Removal of litter sheltering particles by clearing of vegetation.
134.	Removal of root binding of soil particles by clearing.
135.	Loosening of soil particles by clearing.
136.	Exposure of bare ground by clearing.
137.	Release of particles in the A horizon by clearing.
138.	Release of particles in the B horizon by clearing.
139.	Release of particles from all depths by excavation.
140.	Excavation releases particles from all forms of site fixation.
141.	Raindrops striking ground, releasing soil particles.
142.	Raindrops from plant canopy striking ground, releasing particles.
143.	Raindrop release of particles in A soil horizon.
144.	Raindrop release of particles from exposed B soil horizons.
145.	Raindrop release of particles from exposed C soil horizons.
146.	Sheet erosion resulting from raindrops striking ground.
147.	Raindrop erosion sealing of soil surface with fine particles.
148.	Overland flowing rainfall runoff resulting from surface sealing.
149.	Rainfall exceeding hydraulic conductivity of soil.
150.	Overland flow resulting from rainfall exceeding conductivity.
151.	Rainfall exceeding water holding capacity of soil.
152.	Overland flow resulting from exceeding soil water capacity.
153.	Upwelling throughflow seepage resulting from exceeding capacity.
154.	Release & transport of fine sediments by overland flow.
155.	Release, suspension of fine sediments by upwelling throughflow.
156.	Sheet erosion resulting from overland flow.
157.	Sheet erosion of soil particles on sloping lands.
158.	Sheet erosion release and transport of particles in bare ground.
159.	Sheet erosion release of particles bound in soil aggregates.
160.	Sheet erosion transport of loose particles.
161.	Sheet erosion release & transport of A soil horizon particles.
162.	Release & transport of particles in exposed lacustrine deposits.
163.	Release & transport of particles in exposed outwash deposits.
164.	Release & transport of particles in exposed fluvial deposits.
165.	Overland flow transport of suspended load particles.
166.	Overland flow transport of wash load particles.
167.	Converging & deepening overland sheet flow runoff.
168.	Initiation of rill erosion by converging sheet flow runoff.
169.	Rill erosion of soil particles on sloping lands.
170.	Rill erosion release & transport of A soil horizon particles.
171.	Rill erosion release of particles bound in soil aggregates.
172.	Rill erosion release & transport of particles in bare ground.
173.	Gully erosion of particles on sloping lands.
174.	Gully erosion initiated by converging rills.
175.	Gully erosion initiated by converging surface runoff.
176.	Gully erosion release of particles from all depths.
177.	Gully erosion of particles from all forms of site fixation.
178.	Stream bank erosion releases soil particles from all depths.

Number	Description
179.	Stream bank erosion releases particles from all fixation forms.
180.	Release of particles by erosion of stream bends' outside banks.
181.	Release of particles by stream banks collapsing into channels.
182.	Release of particles from all soil depths by stream bed erosion.
183.	Bed erosion caused by channel adjustment to land use actions.
184.	Bank erosion caused by channel adjustment to land use actions.
185.	Gully erosion caused or increased by land use actions.
186.	Channel enlargement due to site drainage speeded by use.
187.	Channel enlargement due to increased drainage area.
188.	Enlargement due to surface permeability lowered by use actions.
	Detention and Deposition Processes
189.	Decreasing overland flow volume.
190.	Deposition of wash load by decreasing flow volume.
191.	Slowing overland flow velocity.
192.	Slowing overland flow velocity due to decreasing slope steepness.
193.	Suspended load particles deposited by slowing overland flow.
194.	Particles deposited by runoff seeping into porous deposits.
195.	Particles buried by other sediments on concave slopes.
196.	Particles buried by other sediments on alluvial fans.
197.	Particles buried by other sediments in colluvial deposits.
198.	Particles buried beneath stream bank armoring.
199.	Particles buried beneath stream bed armoring.
200.	Particles buried in deposition occurring on inside bend banks.
201.	Particles buried in deltaic deposits.
202.	Particles trapped between larger sediments by gravel throughflow.
203.	Cessation of stream flow in ephemeral channels.
204.	Particles stranded in ephemeral channels by receding waters.
205.	Ephemeral channel particles deposited as pools dry up.
206.	Cessation of stream flow in intermittent channels.
207.	Particles stranded in intermittent channels by receding waters.
208.	Intermittent channel particles deposited as pools dry up.
209.	Particles deposited on flood plains by receding waters.
210.	Particles trapped in flood plain pools.
211.	Flood plain pool particles deposited as pools dry up.
212.	Particles trapped, adsorbed on plants in channels, flood plains.
213.	Particle deposition by water slowing on moving onto flood plain.
214.	Particles settling on entering still waters of wetlands, ponds.
215.	Colloid flocculation & settling from pond, lake still waters.
216.	Decreasing flow volume in perennial streams.
217.	Particles stranded in perennial stream channel by receeding flow.
218.	Particles stranded on deltas by receding stream flows.
219.	Slowing of stream flow speed due to decreasing flow volume.
220.	Decreasing flow turbulence due to decreasing flow volume.
221.	Particles settling from slowing and stilling waters.
222.	Suspended sediments settling between larger stream bed cobbles.
223.	Fine sediments, colloids adsorbed to channel materials.
224.	Rising stream flows increase flow speed & turbulence.
225.	Resuspension of settled particles.

Resuspension Processes

Number	Description
226.	Rising stream flow speed & turbulence movement of bed load.
227.	Bed load movement reworking of gravel deposits.
228.	Release of fines lodged in gravels by reworking.
229.	Release of deeply buried fine sediments by reworking.
230.	Resuspension of lodged & buried fines by upwelling bed interflow.
231.	Scouring of adsorbed fines by moving bed & suspended particles.
232.	Increasing suspended load.
233.	Rising stream flows overflowing onto flood plains.
234.	Flood flow scouring of particles deposited on flood plain.
235.	Flood flow resuspension of particles deposited on flood plains.
236.	Lake storm wave reworking of delta sediment deposits.
237.	Delivery of wash load to lake.
238.	Delivery of bed load to lake.
239.	Delivery of suspended load to lake.

Explanation of Land and Stream Sediment Model

Effects of Location in Watershed

The likelihood that particles of a size and density to become suspended sediments will be moved by natural processes depends on where they are located and how they are stored on watershed lands. Most of the potential suspended sediments are located on watershed land covered by forest (1), some by grasses (3) and least by shrubs (2). They are less likely to be released by natural processes from lands covered by a canopy of foliage (4) and/or plant litter deposits (5). Particles on steeply sloping lands (6), especially when greater than the angle of repose (7), are most likely to move. The curvature of slopes also affects the potential movement of particles. Those on concave slopes (8) are likely to be retained or rapidly redeposited; those on convex slopes (9) are more likely to be eroded. Straight slopes (10) indicate that released particles are being carried straight down hill from evenly erodable soils or geologic deposits.

The type of deposit in which particles are located indicates their likely relative abundance as a consequence of previous transport events and the likelihood that those processes will again move them. Thus they are likely to be concentrated at the base of slopes (11) in colluvial deposits (12) by slope wash and in the intersticies of alluvial fan deposits (13) by ephemeral and intermittent streams moving out onto flatter slopes. Particles in old landslide deposits (14) may be stable if located on gently sloping lands or if still on steeper lands subject to remobilization by mass movement processes triggered by unusually wet seasons, excavations or other circumstances. Fine particles are likely to be abundant in old fluvial (15), glacial outwash (16) and lacustrine (17) (U.S. Forest Service 1966 p.62) alluvial deposits and in areas of decomposed granite (18). Fine particles are likely to be especially abundant and stable in the deposits of wetlands (19), ponds, reservoirs and minor lakes (20) in watershed lands. They are likely to be abundant but unstable in alluvial deposits (15), on flood plains (21), underlying flood plain vegetation (22), stream bank plants (23) and vegetation growing channels (24).

Fine particles are likely to remain stored temporarily in stream channels for periods in proportion to the frequency, duration and volume of flow, residing for increasingly longer periods in ephemeral (25), intermittent (26) and perennial channels (27), respectively. Fine particles stored in the bed deposits of active streams (28), even when under the surface armor (29) of larger rocks, remain there for only short periods. The location of stored particles with respect to the configuration of channels also effects the tenactity of fine particles in deposits. Little deposition (and that being only short term) is likely to occur along straight reaches (30), while erosion occurs on one side and deposition on the other of curving channel reaches (31). Thus in this latter situation, fine particles in bank deposits (32) on the outside of bends (33) are likely to be released by erosion and be deposited on the inside of bends (34) downstream. The amount and size of stream bank armor (35), from rock slide or fluvial origins, also affects the mobility of fine particles in bank deposits. Considerable volumes of fine particles are present in delta deposits (36) where they remain until excavated by shifting or expanding channels, lake waves, or forever if buried sufficiently deep.

Particle Detention Conditions

The conditions under which fine particles are stored also affects their probability of detention. Those sheltered underneath plant foliage (37), plant litter (38) and/or a soil surface armor of loose rocks (43) are much more stable than those not (44) so protected. Fine particles in cemented deposits (40) are held more strongly than those in compacted or consolidated deposits (39), which are in turn more stable than those in deposits of loose earth materials (45). Fine particles, particularly clay and silt, may be stably bound in soil aggregates (41), and all sizes may be bound by root masses (42) (Gray 1981).

Storage Depth Considerations

The depth at which fine particles are stored on watersheds obviously effects the probability they will be released. Fine particles located in litter deposits are unlikely to become suspended sediments because of the deposits' extremely high infiltration rates and sheltered position under the vegetation canopy from which they originated. However, if subjected to release and transport by fluvial and mass movement processes, the upper, undecomposed portions (litter layer) (46) of those deposits are especially likely to become suspended sediments because they are exposed on the surface, where release and transport processes operate most strongly. Because litter layer materials have specific gravities and are loosely held (48) together, they are easily detached and transported when exposed to such forces.

Larger organic particles (47), such as limbs and cones, have a lesser tendency to move until reduced in size by decomposition processes.

Fine organic particles (or others readily rendered to such sizes during movement by physical forces) constitute nearly all of the fermented and humus layers (49) (partially and fully decayed, respectively) of litter deposits. Many of these fine particles are loose in the humus layer (50), though some, especially in the fermented layer, are bound together by fungal mycelia, bacterial nets and fine roots, or their wet surfaces stick together. Colloidal organic particles (51) in the humus layer are particularly transportable and capable of effecting lake water color, while large organic debris (52) remains in place until broken down to fine sizes by decomposition processes.

The group of fine particles next most exposed to erosional processes by virtue of their relatively shallow depth are those in the uppermost (A horizon) soil layer (53)--ranging to 28 to 53 cm deep on Ward Creek watershed soils. Some of these fine particles are of low inherent mobility because they are bound in soil aggregates (54) or by mats of roots (55); others are loose (58), hence readily mobilized. Fine particles in the A horizon are less vulnerable to erosion if located beneath a layer of surface armor (56) than if located below bare ground (57). Obviously the size of inorganic particles in the A horizon affects their transportability which increases from colloidal (59) to small (60) to large (61) particles, repectively, and similarly affects colloidal (62) to large (63) organic particles.

None of the soils mapped for the Ward Creek Watershed has yet developed B horizons, but they occur in seven of the other soil series in the Tahoe Basin. Some of the fine particles located in these next deeper layers (64) are also resistent to erosion even when exposed, because they are bound in soil aggregates (65) or by mats of roots (66). The potential mobility of inorganic particles generally increases with their decreasing size from colloidal (67) to small (68) to large (69), respectively.

Particles in the watershed's deepest soil layer (C horizon) (70) are the partially decomposed bedrock or alluvium from which the A developed (U.S. Forest Service 1966 p.78). Some of these have low mobility even if exposed, because they are in cemented layers (71); some are held more loosely in compacted or consolidated (72) parts of soil C horizons; others are in loose deposits (73) and hence readily mobilized on exposure. Fine particles, especially small inorganic ones (75), are very abundant in C horizons of alluvial deposit origin (74), while large inorganic particles (76) dominate C horizons of bedrock origin.

Types of Release and Transport

Larger inorganic particles are transported in water by rolling or bouncing along the bottom as bed load (77). Those of intermediate size spend most of their transit time up in the moving waters as suspended load (78). The smallest ones, particularly the inorganic (79) or organic (80) colloids, spend all their transit time in suspension moving as wash load.

Some organic particles larger than colloidal sizes are captured and removed from transit by drift, feeding aquatic insects (81), particularly during late spring and summer. They are physically broken down to smaller sizes, eaten, digested (82) and returned by excretion to suspension (83) after this period of biotic processing. Some of the returned particles are colloidal (84), and some of these flocculate or stick to larger particles (86), forming organic aggregates (85) large enough to be part of the suspended, rather than wash loads.

Some small inorganic suspended particles are produced by collisions between rolling and sliding bed load (87) and saltating (jumping) particles (88). The same grinding process (89) and scouring by suspended sediments (90) produces fine organic particles from periphyton growing on channel materials--sometimes removing them in large masses (91).

Release and Movement Maintaining Processes

The finest washload particles are maintained in suspension by collisions with water molecules (92), while flow turbulence (a direct function of flow velocity (93) is the main process keeping larger particles moving. Bed load particles move mainly by rolling and sliding (97), and to a lesser extent, by saltation (99). The former transport process is due to flow turbulence (95) and flow velocity (96). Saltation is caused more by flow velocity (98) than by turbulence (94). Suspended particles larger than colloids are raised and kept aloft mainly by flow turbulence (101), with the suspension of the larger ones sometimes aided by saltation (100). Whether particles of intermediate sizes move as suspended or bed load is determined by changes of flow speed and turbulence (102). It also depends upon their sail area (103) and specific gravity (104) interactions with flow speed and turbulence.

On the dry, nonchannel portions of the watershed, fine particles can be released from sheltered locations by wildfire destruction of plant canopies (107), litter layers (105) and fermented and humus deposits (106). Rooting and digging activities by animals may also shove aside the litter (108), fermented and humus (109) layers sheltering deeper particles. Their digging activities also can disrupt the protection afforded by a layer of loose surface rock (armor) (111), and in the soil A horizon (110), loosen and expose soil particles (112).

Chemical and physical weathering of partices in the B (113) and C (114) horizon of soils continually breaks them down to smaller sizes. The decomposition of granite by weathering (115) processes particularly yields an abundance of coarse sand-size particles (116) where that rock is common. The expansive force of water freezing in surface soils (117) loosens, and may expose on the surface, particles held in place by forces such as the silt and clay bound in soil aggregates (119). Such frost heave activity also releases particles held in areas of bare ground (118) where soils are not developed.

Over many years the loosening and heaving of soil materials by the uprooted stump and rootballs of blown-over trees can seriously disrupt surface armor layers (120), expose areas of bare ground (121) and the A (122) and B soil horizons (123) and loosen particles bound by root mats (124).

On sloping lands, soil materials, at imperceptable rates, move down slope by the creep of dry and damp materials and solifluction (flow) of soggy soil materials (125). These release and transport processes move the materials in the A horizon of soils (126) downslope faster than those in the B horizon (127). Other mass movement processes--particularly landsliding--may play a major role in exposing, releasing, (129) and sometimes transporting the particles on watershed lands to channels, (130) where they are exposed to flowing waters (131). Landslides are particlularly important mass movement processes on sloping watershed lands (128) and occur with increasing frequency as steepness increases until slopes are so steep that their surface is largely bedrock.

Clearing the vegetation covering watershed lands removes the foliage sheltering fine particles (132) from rain, also removing litter coverings (133) and exposing bare ground (136) to erosional processes which release fine particles from the A (137) and B (138) horizon depending on the depth of disturbance. Clearing also kills and may uproot the rootmass binding soil particles (134) and physically loosens soil particles (135). Excavation activities associated with development may release soil particles at any depth (139) from all forms of site fixation (140), expose bare areas to erosion by rain drop (141) and plant drip (142), releasing fine particles from attachments they may have in the A (143), B (144) and/or C soil horizons (145) if they are exposed by the digging.

The pounding of raindrops may loosen and remove an even sheet of soil materials (146) and break apart the aggregates of clay and silt particles in soils. The latter situation may destroy the infiltration capacity of the surface by sealing its pores with fine particles (147), creating conditions favorable for subsequent production of overland flowing waters (148). Rainfall intersities exceeding the capacity of soil infiltration and percolation rates to conduct water (149) also produce overland flow (150). Rains falling on already salturated soils

(151) also produce surface runoff (152). Waters percolating downslope through soils may also be forced to the surface upon encountering saturated, shallower or less permeable soils (153) or steeper gradients. They can release and even suspend fine sediments, depending upon the force with which they well up through the surface (155). The overland flowing waters from these causes may release and transport additional fine sediments (154) as they flow down slope and into channel.

Detachment and movement of particles on a sloping surface (157) by raindrops and/or thin sheets of water flowing over the surface (156) releases and transports fine particles on bare, nonsoil areas (158), releases particles bound in soil aggregates (159), and by most other fixing forces, readily transports those with no binding forces (160) especially moving A soil horizon particles (161). Where lacustrine (162), glacial outwash (163) or fluvial deposits (164) are, exposed raindrops and overland flow especially erode and transport large amounts of fine sediments. Overland flowing waters move both suspended (165) and wash load particles (166).

When overland flows deepen (167), erosive powers greatly increase and soon dig out small rills (168) where channel release and transport processes first begin acting on fine particles. Gradually the network of rills lengthens and spreads over sloping watershed lands (169), loosening and transporting soil particles, particularly from the A horizon (170), breaking apart silt and clay aggregates (171) and removing the particles in unvegetated, nonsoil areas in a similar manner (172). Further downslope (174), rills merge with other rills and surface runoff (175), forming larger channels (gullies) where fluvial processes are stronger and release particles held by all forms of site fixation (177) in their beds, banks and head walls (173) to whatever depth they have cut into soils or other earth deposits (176). Further downslope gulleys merge or flow into yet bigger stream channels where fluvial erosion processes are much stronger, and again particles are released from all forms of fixation (179) at all depths (178) exposed in the bed (182) and banks, particularly those on the outside of bends (180) and especially from portions of the bank which collapse into channels (181).

Certain land use activities result in increased amounts of runoff into channel systems receiving the drainage from affected areas. For example, speeding site drainage (186), increasing the drainage area by altering surface drainage patterns (187) or increasing runoff by reducing watershed surface permeability (188) all necessitate enlargement of gully (185) or stream drainage to accommodate the added flow. Enlargement of channels by bed (183) and/or bank erosion (184) releases (182) and transports more fine particles.

Detention and Deposition Processess

Detention processes typically interrupt the journey of fine particles to the lake for short or long periods. As the velocity of overland flowing waters slows (191) because of decreasing volume (189), slope steepness (192), or increasing ground surface roughness, suspended particles are deposited (193). Both suspended and wash load particles are deposited (190) when the overland flow volume decreases by seeping into porous deposits (194). These and other fine particles deposited on land surfaces may be buried for long periods by the deposition of other sediments on concave slopes (195), alluvial fans (196) or in the colluvial deposits at the base of slopes (197).

In channels, fine particles may be deposited and buried beneath stream bank (198) and bed armoring (199), in the sediment deposits which grow on inside bend banks (200) or in delta deposits (201). The mechanisms by which fine particles are redeposited in channels include lodging between gravels by waters flowing through them (202). However, more commonly they are stranded in ephemeral (204) and intermittent channels (207) as waters cease flowing (203) (206), and gradually dry up in their pools (205, 208).

The flow velocity and turbulence of waters moving onto flood plains decreases; consequently larger size suspended particles drop to the bottom (213). All sizes of suspended particles are deposited on flood plains and in their pools (210) as waters recede (209), seep in and/or evaporate (211). Some particles are also trapped in clumps of plants growing on flood plains and in channels or stick to their surfaces (212).

In the channels of perennial streams, suspended particles larger than wash load size begin settling as waters slow and still (221) in wetland, ponded (214), particularly voluminous reaches or as flow volume (216) velocity (219), and hence turbulence decreases (220). In wetlands or ponded portions along perennial streams, settling of colloidal wash load particles may be significantly accelerated by particle flocculation processes (215).

Particles are also stranded in the high water areas of perennial stream channels (217) and in their deltas (218) as waters recede. In perennial streams, some suspended sediments settle in the intersticies and sheltered areas between larger cobbles (222), and some by sticking to the surface of channel materials (223).

Resuspension Processes

In addition to the initial release mechanisms previously mentioned, usually the next high stream flow or flood will begin moving most of the particles which settled during the decline of previous such events. Rising stream flows increase flow speed, and hence turbulence (224), readily resuspending particles which settled on top-most surfaces (225). Rising flows may again initiate movement of bed load deposits (226), and shifting of the gravels and stones (227) releases fine particles lodged between (228) or buried under them (229). Some lodged or buried fine particles may also be resuspended by ground waters welling up through the bed (230). Fine particles stuck to rocks and plant materials in channels are released and resuspended by the grinding and scouring action of moving bed load and passing suspended sediments (231). All these fluvial channel processes increase the suspended load by resuspending fine particles previously deposited in channels (232).

Increasing stream flows may rise so far as to overflow onto flood plains (233) where their flowing waters may scour loose (234) and resuspend fine particles previously deposited on those lands (235) by the receding phase of the last flood. At its mouth, rising stream waters pour wash load (237), suspended load (239) and bed load (238) sediments into the lake waters, and storm waves reworking older delta deposits (236) introduce more fine sediment into the lake waters.

CHAPTER 9

NITROGEN RELEASE, TRANSPORT AND DELIVERY BY LAND AND STREAM PROCESSES

Chapter Scope

In this chapter I first introduce the general organization of my CEM of land and stream processes controlling delivery to the lake of incoming nitrogen and stored nitrogen on watershed lands. I then give my conceptual model and explain the numbered steps and processes shown in the model.

Overview of Subsystem Model

The model has four major sections: (1) above ground (bulk precipitation, standing vegetation and plant litter) processes introducing and releasing nitrogen; (2) below ground (soil) processes converting nitrogen from gases and solids to forms readily moved by water; (3) nutrient cycling processes in streams delaying the delivery of water-borne nitrogen to the lake; and (4) the land (above and below ground) and stream hydrologic processes ultimately delivering nitrogen to the lake from the watershed, frequently in annual spasms. The section locations are indicated by the dashed red lines in Figure 10.

I include more detail than strictly needed for the stream portion of the nutrient cycling to show the complex of factors controlling stream nitrogen delivery, as worked out by Cummins (1974) and others.

Information on the relative roles and importance of different types of terrestrial litter-processing by organisms is less well synthesized and not as important for understanding watershed nitrogen delivery. Overland flow in litter-covered forest lands is unusual on undisturbed areas (Harr 1977). Hence, nitrogen transport from litter deposits not immediately adjacent to channels or on flood plains is almost entirely as dissolved organic and inorganic nitrogen moving in interflow and ground waters (Vitousek et al. 1979, Vitousek & Melillo 1979). In contrast, the nutrient cycling controlled by stream invertebrates greatly delays the efficient delivery of instream dissolved or particulate nitrogen to the lake--at least until annual high snow melt or stormflows flush out channel deposits, organic debris dams and invertebrate organisms.

Figure 9. General Organization of Land & Stream Nitrogen Transport Subsystem Model.

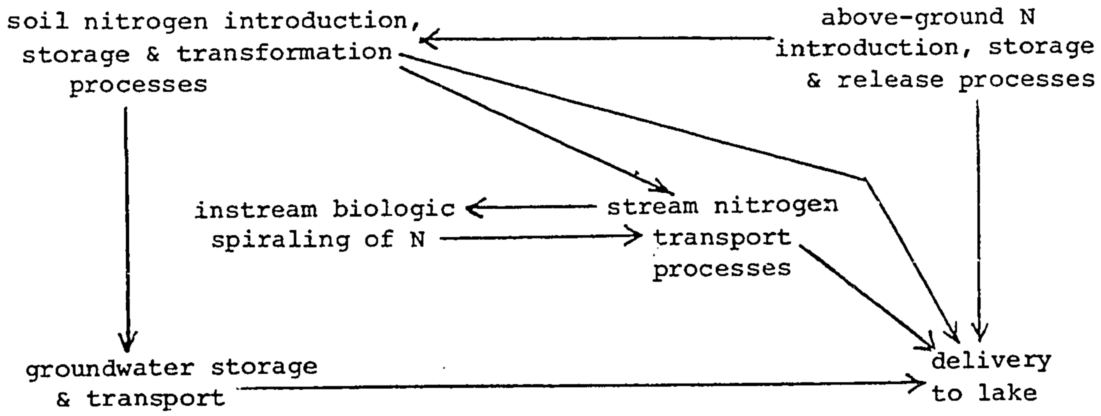
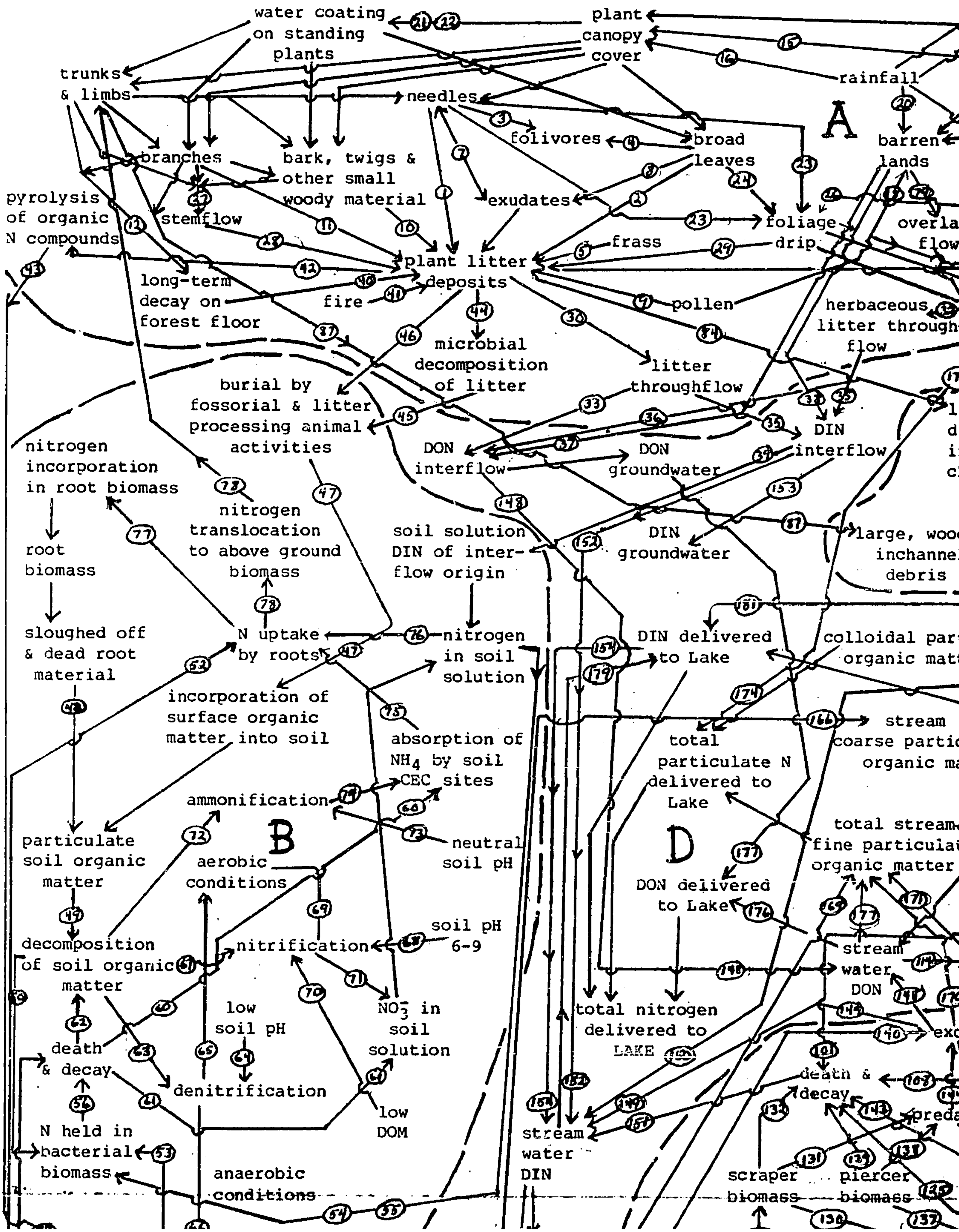
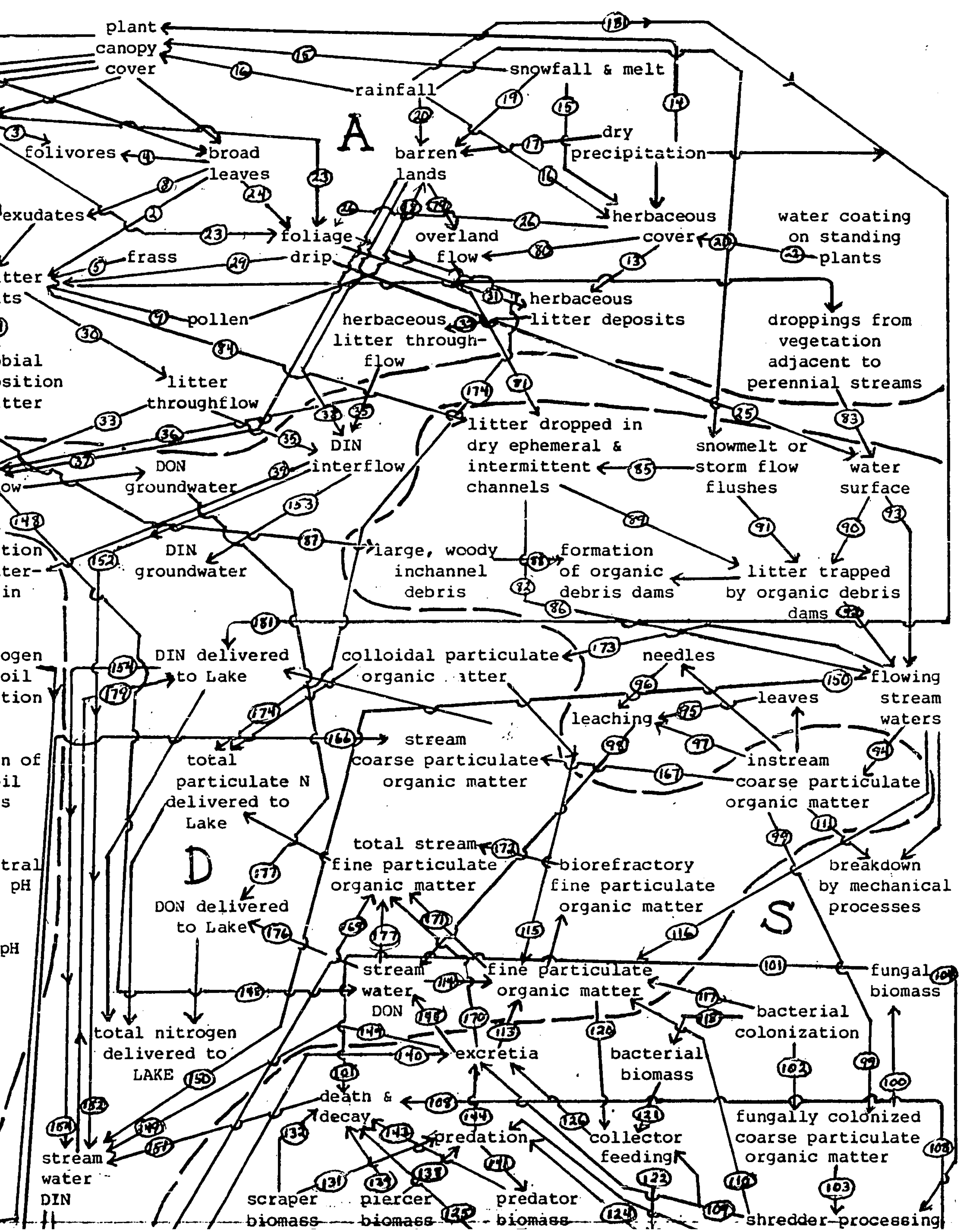
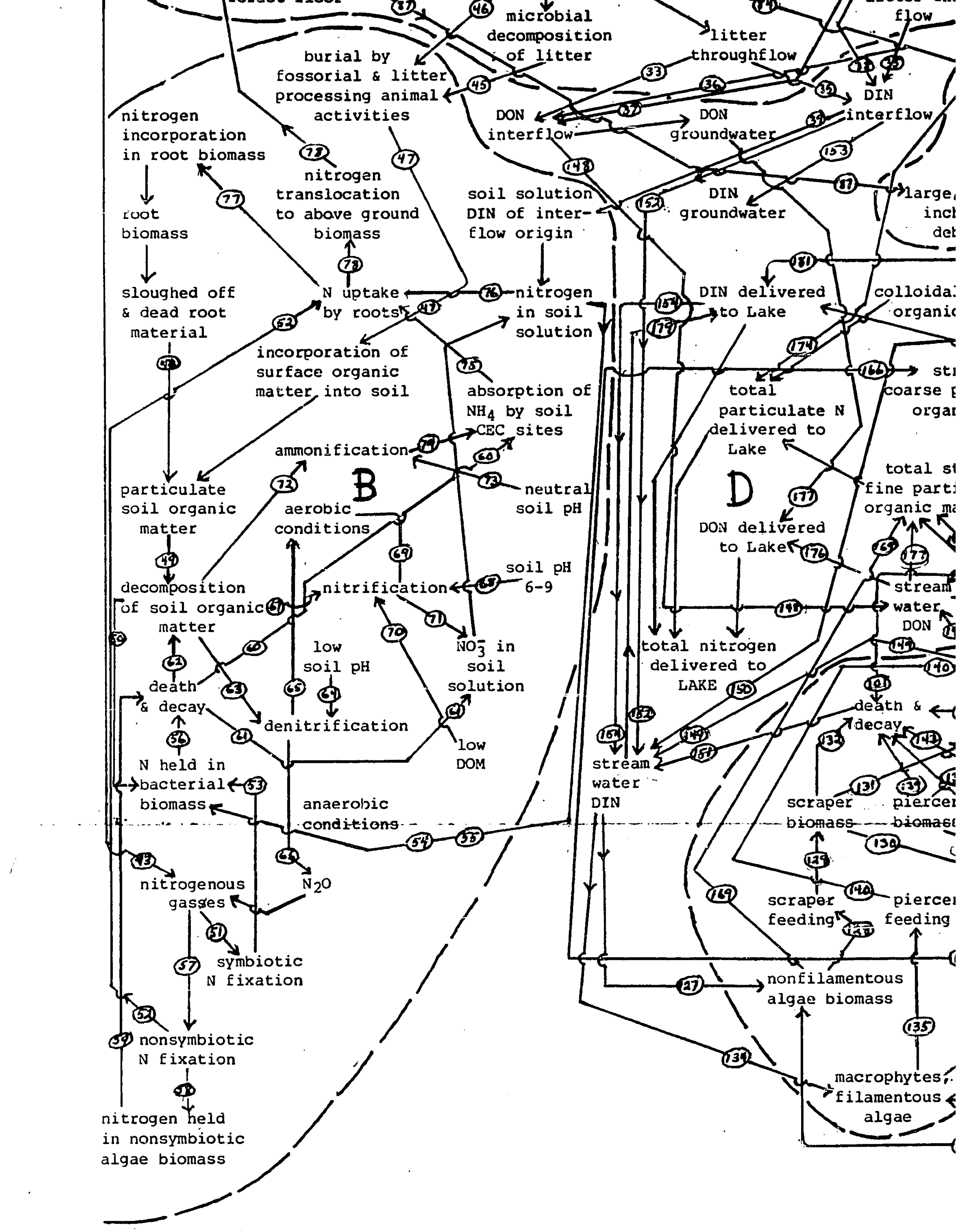


Figure 10. Conceptual Model of Land & Stream Nitrogen Release & Transport Subsystem



itrogen Release & Transport Subsystem




microbial decomposition of litter
burial by fossorial & litter processing animal activities
litter throughflow
flow
nitrogen incorporation in root biomass
DON interflow
DON groundwater
DIN interflow
root biomass
nitrogen translocation to above ground biomass
soil solution DIN of interflow origin
DIN groundwater
large, incl deb
sloughed off & dead root material
N uptake by roots
nitrogen in soil solution
DIN delivered to Lake
colloidal organic
incorporation of surface organic matter into soil
absorption of NH4 by soil CEC sites
total particulate N delivered to Lake
coarse organ
ammonification
neutral soil pH
total st fine parti organic ma
particulate soil organic matter
aerobic conditions
B
D
DON delivered to Lake
decomposition of soil organic matter
nitrification
soil pH 6-9
stream water DON
low soil pH
NO3 in soil solution
total nitrogen delivered to LAKE
death & decay
denitrification
low DOM
death & decay
N held in bacterial biomass
anaerobic conditions
stream water DIN
scraper biomass
piercer biomass
nitrogenous gasses
N2O
scraper feeding
piercer feeding
symbiotic N fixation
nonfilamentous algae biomass
nonsymbiotic N fixation
macrophytes, filamentous algae
nitrogen held in nonsymbiotic algae biomass
46
45
33
36
35
37
39
153
148
152
87
181
154
179
174
166
78
77
79
76
47
75
74
68
73
72
69
65
67
70
71
60
62
63
65
64
66
61
177
176
146
150
149
151
162
164
140
141
131
132
139
130
129
128
169
127
135
134
53
54
55
56
57
58
59
51
52
48
49

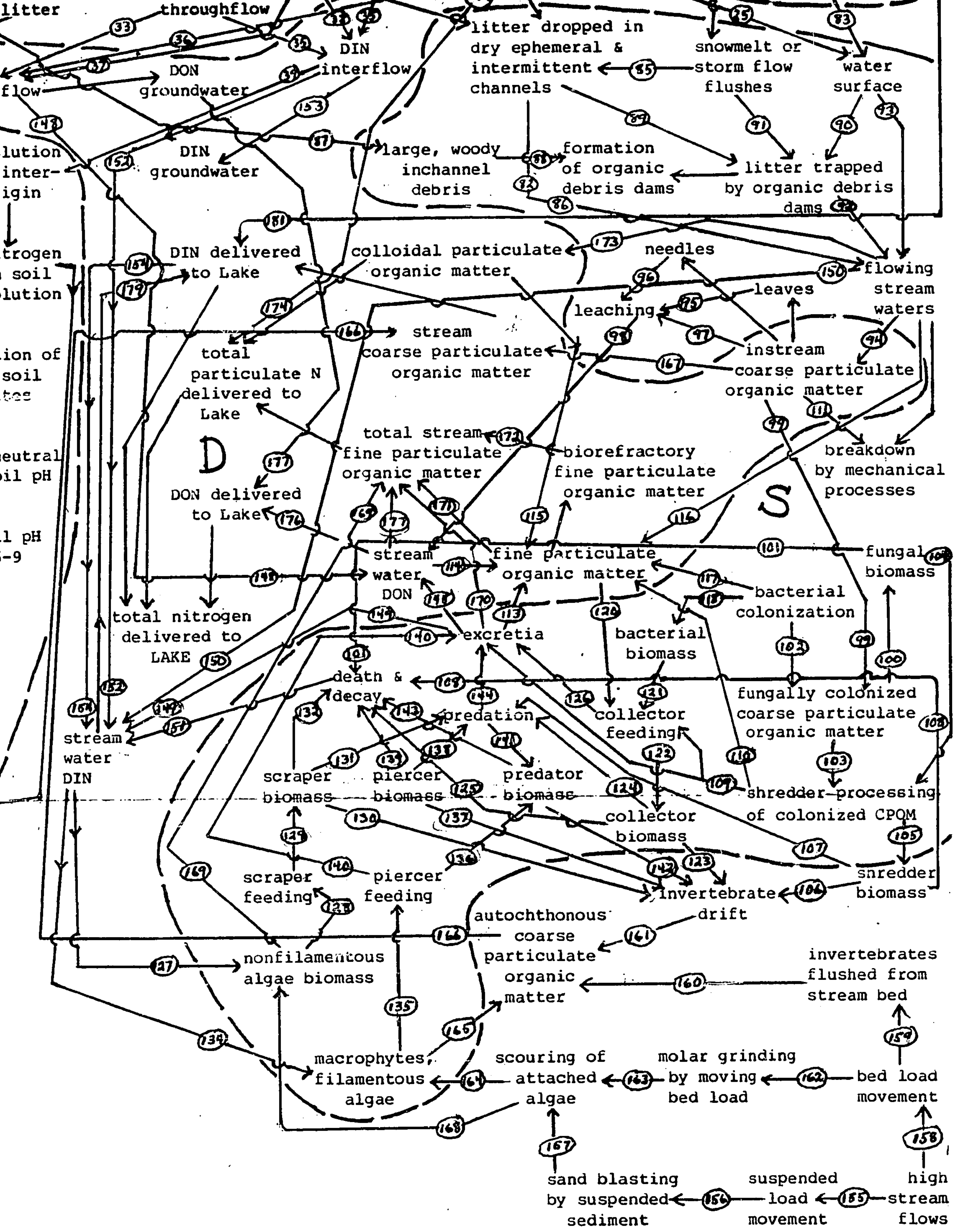

litter
throughflow
DIN interflow
DON groundwater
flow
litter dropped in dry ephemeral & intermittent channels
snowmelt or storm flow flushes
water surface
lution inter- igin
DIN groundwater
large, woody inchannel debris
formation of organic debris dams
litter trapped by organic debris dams
trogen soil lution
DIN delivered to Lake
colloidal particulate organic matter
needles
flowing stream waters
leaves
leaching
ion of soil tes
total particulate N delivered to Lake
stream coarse particulate organic matter
instream coarse particulate organic matter
eutral il pH
D
total stream fine particulate organic matter
biorefractory fine particulate organic matter
breakdown by mechanical processes
DON delivered to Lake
S
l pH -9
stream water DON
fine particulate organic matter
fungal biomass
bacterial colonization
total nitrogen delivered to LAKE
excretia
bacterial biomass
death & decay
fungally colonized coarse particulate organic matter
predation
collector feeding
stream water DIN
scraper biomass
piercer biomass
predator biomass
shredder processing of colonized CPOM
collector biomass
scraper feeding
piercer feeding
invertebrate drift
shredder biomass
autochthonous coarse particulate organic matter
nonfilamentous algae biomass
invertebrates flushed from stream bed
macrophytes, filamentous algae
scouring of attached algae
molar grinding by moving bed load
bed load movement
sand blasting by suspended sediment
suspended load movement
high stream flows

Table 10. Legend for Nitrogen Transport Model

Number	Description
	Above Ground Release Processes
1.	Nitrogen in conifer needles falling to litter deposits.
2.	Nitrogen in broad leaves falling to litter deposits.
3.	Foliage feeder consumption of live needles.
4.	Foliage feeder consumption of live broad leaves.
5.	Nitrogen in fecal pellets dropped by foliage feeders.
6.	Nitrogen in exudates from foliage feeders.
7.	Nitrogen in exudates from needles.
8.	Nitrogen in exudates from broad leaves.
9.	Nitrogen in pollen deposited on plant litter.
10.	Nitrogen in bark, twigs & other small, woody deposited litter.
11.	Nitrogen in branches deposited on litter.
12.	Nitrogen in trunks & limbs deposited on forest floor.
13.	Nitrogen in herbaceous plant litter.
14.	Nitrogen in dust deposited on woody & herbaceous plants.
15.	Nitrogen in snow deposited & melting on woody & herbaceous plants.
16.	Nitrogen in rain falling on woody & herbaceous plants.
17.	Nitrogen in dust deposited on barren lands.
18.	Nitrogen in pollen deposited on barren lands.
19.	Nitrogen in snow deposited & melting on barren lands.
20.	Nitrogen in rain falling on barren lands.
21.	Leaching of nitrogen from standing plants by water films.
22.	Leaching of nitrogen from dust coatings on standing plants.
23.	Nitrogen in water dripping from needles.
24.	Nitrogen in water dripping from broad-leaved foliage.
25.	Nitrogen in water dripping from foliage into streams.
26.	Nitrogen in water draining from herbaceous plants.
27.	Nitrogen in water draining from bark, branches, limbs & trunks.
28.	Water draining from woody plants into litter.
29.	Woody plant foliage drip into litter deposits.
30.	Nitrogen in waters draining from woody litter deposits.
31.	Water draining from herbaceous plants into litter.
32.	Nitrogen in waters draining from herbaceous plant litter.
33.	Dissolved organic nitrogen (DON) in woody plant litter drainage.
34.	Dissoved inorganic N (DIN) in woody plant litter drainage.
35.	DIN in waters draining from herbaceous plant litter.
36.	DON in waters draining from herbaceous plant litter.
37.	DON in interflow waters draining from barren lands.
38.	DIN in interflow draining from barren lands.
39.	Interflow DIN remaining in soil solution.
40.	Trunk & limb nitrogen become litter after long decay periods.
41.	Burning of litter deposits.
42.	Pyrolysis of organic nitrogen compounds.
43.	Nitrogen returned to atmosphere by pyrolysis.
44.	Breakdown of nitrogen-containing litter materials.

Number	Description
	Below Ground Release Processes
45.	Burial of decomposed litter by animals & litter processors.
46.	Burial of unprocessed litter by digging animals.
47.	Nitrogenous litter incorporated into soil organic matter.
48.	Nitrogenous soil organic matter originating from roots.
49.	Decomposition of nitrogenous soil organic matter.
50.	Soil nitrogen held in decomposer biomass.
51.	Nitrogen gas converted to organic N by symbiotic bacteria.
52.	Root uptake of symbiotically fixed nitrogen.
53.	Fixed nitrogen held in symbiotic bacterial biomass.
54.	Nitrogen from soil solution held in bacterial biomass.
55.	Nitrogen from soil cation exchange sites held in biomass.
56.	Nitrogen released by death & decay of bacteria.
57.	Nitrogen gas converted to organic N by nonsymbiotic organisms.
58.	Fixed nitrogen held in nonsymbiotic organism biomass.
59.	Nitrogen released by death & decay of nonsymbiotic organisms.
60.	Ammonium ions released by death & decay of microbes.
61.	Nitrate ions released by death & decay of microbes.
62.	Organic nitrogen released by death & decay of microbes.
63.	Microbial conversion of nitrate to nitrogen or nitrous oxide.
64.	Slightly acid soil conditions favoring microbial denitrification.
65.	Anoxic conditions needed for microbial denitrification.
66.	Nitrous oxide gas released by microbial denitrification.
67.	Bacterial production of nitrate from other nitrogen compounds.
68.	Slightly acid to alkaline conditions favoring nitrification.
69.	Oxic conditions favoring bacterial nitrification.
70.	Low dissolved organic matter quantities favoring nitrification.
71.	Nitrate added to soil solution by nitrifying bacteria.
72.	Microbial production of ammonium ions from dead organic matter.
73.	Neutral acidity conditions favoring ammonification.
74.	Microbially produced ammonium ions on cation exchange sites.
75.	Root absorption of ammonium ions from cation exchange sites.
76	Root absorption of nitrate ions from soil solution.
77.	Nitrogen incorporated into root biomass.
78.	Nitrogen translocated to above ground biomass.
79.	Nitrogen in surface runoff from barren lands.
80.	Nitrogen in surface runoff from herbaceous vegetation lands.
81.	Nitrogen in surface runoff into ephemeral & intermittent streams.
82.	Nitrogen in perennial streams from barren or herbaceous lands.
	Instream Spiraling Processes
83.	Plant litter falling or blown into perennial streams.
84.	Plant litter dropping into dry stream channels.
85.	Snowmelt or storm flows in ephemeral or intermittent streams.
86.	Litter flushed into perennial streams by snowmelt or storm flows.
87.	Large woody debris dropping into stream channels.

Number	Description
88.	Formation of organic debris dams behind large, woody debris.
89.	Litter trapped behind debris dams in dry stream channels.
90.	Litter trapped behind debris dams in perennial streams.
91.	Snowmelt or storm flow washout of debris dams.
92.	Debris dam deposit is flushed into perennial streams.
93.	Untrapped litter moving downstream and/or sinking to bottom.
94.	Breakdown of coarse particulate organic matter (CPOM) in stream.
95.	Stream water leaching of organic matter from broad leaves.
96.	Stream water leaching of organic matter from needles.
97.	Leaching of organic matter from other plant litter in stream.
98.	Dissolved organic nitrogen (DON) from instream litter leaching.
99.	Stream fungi colonization & processing of CPOM.
100.	Litter nitrogen converted to stream fungal biomass nitrogen.
101.	Nitrogen released by death & decay of fungi.
102.	Bacterial colonization & processing of litter occupied by fungi.
103.	Stream invertebrate shredder processing of litter occupied by fungi.
104.	Shredder consumption of fungal biomass.
105.	Litter & fungal nitrogen held in shredder biomass.
106.	Invertebrate drift movement of shredder biomass nitrogen.
107.	Consumption of shredder biomass by predators.
108.	Nitrogen released by death & decay of shredders.
109.	Nitrogen transferred in shredder excretia.
110.	Fine POM (FPOM) produced by shredder processing of litter.
111.	Breakdown of CPOM by stream mechanical processes.
112.	FPOM produced by mechanical breakdown of CPOM.
113.	Stream invertebrate fecal pellets added to FPOM.
114.	Formation of FPOM from dissolved organic matter.
115.	Formation of FPOM by flocculation of colloidal organic particles.
116.	Allochthonous FPOM in stream waters.
117.	Bacterial colonization & processing of FPOM.
118.	FPOM nitrogen converted to bacterial biomass nitrogen.
119.	Nitrogen released by death & decay of bacteria.
120.	Collector invertebrate consumption of FPOM.
121.	Collector consumption of bacterial biomass.
122.	FPOM & bacterial nitrogen held in collector biomass.
123.	Invertebrate drift movement of collector biomass nitrogen.
124.	Consumption of collector biomass by predators.
125.	Nitrogen released by death & decay of collectors.
126.	Nitrogen transferred in collector excretia.
127.	Dissolved inorganic nitrogen uptake by nonfilamentous algae.
128.	Scraper invertebrate consumption of nonfilamentous algae.
129.	Algal nitrogen held in scraper biomass.
130.	Invertebrate drift movement of scraper biomass nitrogen.
131.	Consumption of scraper biomass by predators.
132.	Nitrogen released by death & decay of scrapers.
133.	Nitrogen transferred in scraper excretia.
134.	Dissolved inorganic nitrogen (DIN) uptake by filamentous algae.
135.	Piercer invertebrate consumption of filamentous algal fluids.

Number	Description
136.	Algal nitrogen held in piercer biomass.
137.	Invertebrate drift movement of piercer biomass nitrogen.
138.	Consumption of piercer biomass by predators.
139.	Nitrogen released by death & decay of piercers.
140.	Nitrogen transferred in piercer excretia.
141.	Nitrogen held in predator biomass.
142.	Invertebrate drift movement of predator biomass nitrogen.
143.	Nitrogen released by death & decay of predators.
144.	Nitrogen transferred in predator excretia.
	Land & Stream Delivery Processes
145.	DON coming from excretia.
146.	Stream DON coming from death & decay of aquatic organisms.
147.	Stream DON coming from ground water inflow.
148.	Stream DON coming from soil interflow waters.
149.	Stream DIN coming from excretia.
150.	Stream DIN coming from surface drainage.
151.	Stream DIN coming from death & decay of aquatic organisms.
152.	Stream DIN coming from soil interflow waters.
153.	Interflow DIN entering ground waters.
154.	Stream DIN coming from groundwater inflow.
155.	Suspended sediment movement by high stream flows.
156.	Sand blasting of instream surfaces by moving suspended sediment.
157.	Algae scoured from rocks by moving suspended sediment.
158.	Movement of stream bed deposits by high stream flows.
159.	Displacement of stream invertebrates by moving bed materials.
160.	Displaced invertebrates added to stream flow CPO nitrogen load.
161.	Invertebrate drift additions to stream flow CPON load.
162.	Molar grinding of stream bed surfaces by moving bed material.
163.	Algae scoured from rocks by molar grinding.
164.	Filamentous algae scoured from attachment by molar grinding.
165.	Scoured filamentous algae added to stream flow PON load.
166.	Autochthonous stream CPON delivered to lake.
167.	Incompletely processed FPON added to stream flow load.
168.	Nonfilamentous algae added to stream flow FPON load.
169.	Scoured nonfilamentous algae added to stream flow FPON load.
170.	Invertebrate excretia added to stream flow FPON load.
171.	Incompletely processed FPON added to stream flow load.
172.	Biorefractory FPON added to stream load.
173.	Colloidal organic particle nitrogen in stream flow load.
174.	Pollen particulate nitrogen added directly to lake.
175.	Total particulate nitrogen added to lake.
176.	Stream water DON delivered to lake.
177.	Groundwater DON delivered directly to lake.
178.	Precipitation DON delivered directly to lake.
179.	Stream water DIN delivered to lake.
180.	Groundwater DIN delivered directly to lake.
181.	Precipitation DIN delivered directly to lake.
182.	Total nitrogen delivered to lake.

Explanation of Land and Stream Nitrogen Release and Transport Model

Above Ground Release Processes

Geologic materials are seldom important sources of nitrogen, and Tahoe Basin rocks are not exceptional in this respect. Therefore, rock weathering as a source of released nitrogen is not considered in this conceptual model. The shedding of needles (1)* from conifers and broad leaves (2) from other plants may be considered the major initial source of nitrogen release from the numerous locations in which it is stored in the land ecosystem. Dominance of shed foliage remains even though most nutrients are translocated back into the perennial portions of the plant prior to leaf and needle shedding (Ryan & Bormann 1982). The amount of nitrogen in needles and broad leaves, and the rates at which they decompose and yield leachates is so different that they are treated as separate variables until broken down by stream invertebrates. Foliage eaters, mainly insects, consume living needles (3) and leaves (4) before nutrient translocation occurs, speeding the release of foliar nitrogen. However, most leaf and needle biomass is shed by plant processes in a relatively short seasonal period. Folivore fecal pellets (frass), rich in released nitrogen, drop to the ground (5). During certain times of the year this is the dominant process depositing foliar nitrogen in the plant litter.

Nonfecal exudates, emanating from folivores (6), or needles (7) or leaves

---

*Numbers in parentheses refer to numbered arrows on the conceptual model diagram.

(8), release more nitrogen from foliar storage. Some exudate droplets fall directly to the ground, and others are detained by adhering to foliage surfaces, not falling until their substrate falls.

Shedding and dispersal of pollen grains (9) are other seasonal processes releasing minor amounts of nitrogen from plant nutrient pools. With irregular and lesser frequencies, smaller quantities of bark, twigs and other small woody nitrogen-containing plant debris(10) are shed and become part of plant litter deposits. As trees and large shrubs grow, branches are shaded, die, decay, eventually break off (11) and add their nitrogenous contents to the plant litter. Infrequently, larger limbs and whole tree trunks die, decay and fall (12) to the forest floor, gradually adding their remaining nitrogen content to plant litter deposits. On watershed lands covered by herbaceous plants (e.g., grasses), their debris and its nitrogen contents are also deposited (13) on herbaceous litter.

Liquid (16), frozen (15) and dry (14) precipitation are major sources of external nitrogen inputs to watershed lands and are also mobilizers of stored nitrogen. All nitrogen delivered by atmospheric processes is in a highly mobile state. Wind-blown watershed dust and atmospheric dry fallout are not considered as sources of released nitrogen, though much of them must fall directly into the lake. The former has not been evaluated. The latter is an insignificant source when compared to wet precipitation. The atmospheric dust, settling on plant canopies (14) or herbaceous cover, contains some nitrogen in its fine particulate matter. Snow (15) and rain (16) also contain some dissolved forms of nitrogen. The nitrogen deposited on barren lands (e.g., talus slopes) by dust (17), pollen (18), snow (19) and rain (20) undergoes much less alteration and detention by biotic processes before reaching fluvial waters. Water films form on plant surfaces and leach nitrogen from them (21), and from any dust, pollen, or exudate coatings (22) on the wet surfaces. Some of those waters drip from needles (23) or leaves (24). Some drain down the stems of herbaceous plants (26) or across bark of branches, limbs and trunks (27), leaching even more nitrogenous substances. Some of these nitrogen-carrying waters drip directly into streams (24) from overhanging vegetation. But as only a small portion of watershed vegetation cover overhangs channels, most such waters drain into woody (28) or herbaceous (31) plant litter deposits or drip onto them (29).

The nitrogen held in litter is mobilized more slowly than leaching by throughflow by several processes. Fine plant litter breaks down and loses its nutrient contents rapidly when moisture and temperature conditions are favorable. For example, all the nitrogen is released from pine needles after a single winter under a snow pack (Stark 1972). The decay rate of larger woody litter is directly proportional to size and the extent of direct contact with soil or other moist substrates. Hence, the decay and release of all nitrogen stored in large limbs and trunks can require several hundred years (40) (Triska & Cromack 1979). Most nitrogen held by litter is released by soil flora and fauna litter-processing activities (44).

Wildfire can also play a role in releasing nitrogen held in litter deposits (41). Pyrolysis of organic nitrogen compounds (42) results in the conversion of most nitrogen to a gaseous state which returns it to the atmosphere (43). However, the residual ash commonly raises the typically low pH of forest soils to levels (pH 6-9) (64) favoring nitrifying bacterial activities (Tidemann et al. 1979 citing Rode 1955).

Consequently, wildfires commonly result in an increase in the inorganic nitrogen concentration in streams (Tidemann et al. 1979 citing Fredricksen 1971, Kimms & Feller 1976, Helvy 1976 and Tidemann et al. 1978).

Below Ground Release Processes

Plant litter, whether fresh (46) or in various stages of decomposition (45), gradually becomes mixed with mineral soil materials by the digging of animals and the ingestion, excretion, growth, multiplication, death, decay and burrowing activities of litter dwelling invertebrates. These biotic processes gradually result in all litter particles not totally consumed by some process becoming soil organic matter (47). Additional particles are added to soil organic matter and particulate nitrogen pools by the death and decay of roots (48). Gradually the remaining nitrogen held by soil organic particles is released by their decay (49). Much of the nitrogen released in the soil (and litter) is taken up and held in the biomass of decomposers (50).

Frequently the amount of root and litter particulate organic nitrogen in soil is added to in the form of symbiotic bacteria which convert the nitrogen gas present in the soil atmosphere into particulate organic nitrogen (51). Some of this fixed atmospheric nitrogen is taken up by the roots (52) and used to build new above and below ground plant biomass.

Some of the fixed nitrogen remains held in the symbiotic bacteria biomass (53) until translocated or until released by their death and decay. The nitrogen held in the biomass of bacteria unable to fix gaseous nitrogen is obtained from dissolved inorganic nitrogen (DIN) in the soil solution (54) or from ammonium ions adsorbed on soil cation exchange sites (55). Some nonsymbiotic microorganisms also fix nitrogen gas, converting it to organic nitrogen (57). Most fixed nitrogen remains in the biomass of organisms (58) until released by their individual death and decay. Nitrogen stored in bacterial biomass is released by their death and decay (59), though it is rapidly taken up and held by the growth and multiplication of others of their kind. Eventually the conditions favoring large bacterial populations worsen, causing their decline and a permanent release of nitrogen held in their biomass. The death and decay of microbes releases their biomass nitrogen and it is converted to ammonium (60) and nitrate (61) ions. Most of the former is soon held against flushing waters by adsorption to cation exchange sites, and the latter migrates into the soil solution.

When the conditions for soil organic matted decomposition are anoxic (65) and slightly acid, certain microbes rapidly denitrify released nitrate ions, converting them (63) to nitrous oxide gas (66). If soil conditions are anoxic and pH is neutral to alkaline, this denitrification process proceeds slowly. Alternatively, when the conditions for soil organic matter decomposition are slightly acid to alkaline (68) and oxic (69) and low concentrations of dissolved organic matter (DOM) (70) are in the soil solution, bacterial nitrification occurs, resulting in the conversion of other nitrogenous compounds to nitrate (67). Because nitrate is highly mobile, nitrification releases nitrogen to the soil solution (71) where it is subject to flushing by throughflow waters.

A third, alternative nitrogen microbial conversion process may occur when soil pH is neutral (73) and the organic matter is rich in nitrogen. Under these conditions, microbes convert organic nitrogen to ammonium ions (72). They are adsorbed promptly onto soil colloid cation exchange sites (74), from which many are subsequently absorbed by roots (75). Some of the nitrogen that roots absorb (ammonium from exchange sites and nitrate from the soil solution) is held by incorporation into root biomass (77), and the rest is translocated to and becomes incorporated into the above-ground plant biomass (78). With the passage of time, it is again released in the shedding and subsequent decay of foliage, bark, twigs or falling limbs or trunks.

Because of the extensive litter deposits on forest lands, surface runoff rarely occurs (Anderson et al. 1976 p. 11-12). But litter deposits are less well developed under herbaceous cover and obviously totally absent on lands which are essentially barren of plant cover. Hence, on barren or sparse litter areas, when rainfall or snowmelt is sufficiently intense, runoff waters flow across the ground surface, releasing and transporting nitrogenous inorganic and organic particles and soluble substances (79, 80). Typically waters do not flow very far over the ground surface before encountering an ephemeral or intermittent stream channel (81). Subsequently, the nitrogen in surface waters draining from barren or herbaceous vegetation-covered lands moves into the perennial streams draining such lands (82).

Instream Spiraling Processes

Some plant litter falls or is blown directly into perennial stream waters (83), a particularly common occurrence for riparian vegetation. Other plant litter is dropped into dry ephemeral or intermittent channels (84) and onto dry portions of perennial channels. Subsequently, usually on at least an annual basis, snowmelt or rainstorms generate flows in ephemeral or intermittent channels (85) that flush litter in them into perennial streams (86).

Any large wood debris falling into wet or dry channels (87) is sooner or later moved by flowing waters and commonly becomes the framework of organic debris dams (88) or is trapped in the pools formed behind them (89, 90). These debris dams are important traps for instream litter in small streams (Bilby 1981, Triska & Cromack 1979 p. 178). At least annually, debris dams are washed out by the high waters of snowmelt or storm flows (91), flushing their organic deposits into (and usually largely down) perennial stream channels (92).

Litter never trapped or freed from debris dams floats or is carried downstream until it sinks to the bottom (93). The coarse particulate organic matter (CPOM), introduced by the addition and movement of undecomposed plant litter, then undergoes a process of breakdown in the stream (94). When litter enters water, nitrogenous organic matter quickly and thoroughly leaches from broad leaves (95) and FPOM, more slowly from needles (96), and even slower from other plant litter (98)--particularly large woody debris. Dissolved organic nitrogen (DON) is released into the stream as a consequence of the leaching of litter (98).

Soon after entering stream waters, plant litter CPON is colonized by fungi which rapidly invade and spread throughout particles and begin breaking them down (99). Consequently, some of the litter nitrogen is converted to fungal biomass nitrogen (100) where it is held until released by the death and decay of fungi (101). Following initial processing of CPOM by fungi, bacteria colonize and begin decomposing instream plant litter (102).

Simultaneously or subsequently, certain types of stream invertebrates (shredders) begin chewing and eating the litter occupied by the fungi (103), primarily to consume the fungal biomass (104). Consequently fungal biomass and CPOM nitrogen become concentrated and held in shredder biomass (105). Some of this nitrogenous biomass is transported downstream in a stepwise manner by the invertebrate drift of litter shredders (106). Other nitrogen is transferred to predators of shredders (107), and the remainder is released by their death and decay (108).

A portion of the nitrogen contained in shredder-ingested CPOM is released from organic nitrogen forms but unabsorbed during passage through their digestive tracks and released in shredder excretia (109). Their excretia add partially digested fine POM to stream waters (110) as well as dissolved organic and inorganic forms. Stream mechanical processes also add to the FPOM load by breaking down CPOM (111)(112), as do the fecal pellets of all stream invertebrates (113). Some FPOM also forms from DOM (114) and flocculation of colloidal organic particles (115). Yet other stream FPOM originates entirely from outside the stream (116).

Fine POM is quickly colonized and digested by bacteria (117), shifting the of nitrogen held in its biomass to bacterial biomass (118). The FPOM nitrogen assimilated into bacterial biomass is eventually released by death and decay (119). Some stream invertebrates collect passing FPOM by filtering water through nets or by similar means. These collectors consume the snared FPOM (120), primarily for the food content of the attached bacteria (121). By digestion and assimilation, some of the FPOM and bacterial nitrogen is transferred to collector invertebrate biomass (122), and some is released in their excretia (126). Some of the collector invertebrates gradually drift downstream (123) in a stepwise manner; some are consumed by predators (124). Other species mature to a reproductive stage, emerge from the water and fly upstream to reproduce. All eventually release all their nitrogen by death and decay (125).

Algal Scrapers and Piercers

The nonfilamentous algae (mainly epiphytic diatoms) coating rock and other hard substrates in streams take up dissolved inorganic and organic nitrogen from streamwater (127). Certain invertbrates feed by scraping algae from rocks and other surfaces, assimilating some algal nitrogen into their biomass (129) and releasing the rest in their excretia (133). Some of the assimilated nitrogen is moved downstream as those invertebrates drift (130), a portion is consumed by predators (131), and all their nitrogen is released by their death and decay (132).

Filamentous algae and aquatic macrophytes also take up dissolved inorganic nitrogen from stream waters (134), and some of this is sucked from their protoplasmic fluids by invertebrates which feed by piercing cell walls (135). Some of the transferred algal nitrogen is converted to piercer biomass (136), and the remainder is released in their excretia (140). Some piercer biomass is consumed by predators (138) and converted to their biomass (141); the remainder is released upon their death and decay (139). Some piercer biomass nitrogen is again carried upstream by winged reproductive stages, and some downstream as these invertebrates drift (137).

Predators

Vertebrate and invertebrate predators of stream invertebrates convert only a part of their ingested organic nitrogen to new biomass (140), and the rest is released in their excretia (144). Also, predatory invertebrates drift downstream with their nitrogen (142), some have an adult winged stage whose reproductive flights result in upstream movement of nitrogen. The nitrogen in all preditors is released by their death and decay (143).

Delivery Processes

Nitrogen is delivered to the Lake by the stream system in four functionally different forms: dissolved organic or inorganic nitrogen, and fine or coarse particulate organic matter. The dissolved organic nitrogen (DON) in streams comes from four sources: the excretia of aquatic organisms (145), death and decay of aquatic organisms (146), groundwater seepage into channels (147) or from soil interflow waters (148). The latter two are a product of the leaching of decomposed, digested or excreted organic matter in the above or below ground terrestrial watershed lands. Dissolved organic nitrogen is then delivered to the lake by stream water (176) or directly into the lake by ground water seepage (177) or precipitation (178).

In summary, stream water dissolved inorganic nitrogen (DIN) comes from aquatic organism excretia (149), surface drainage into channels (150), death and decay of aquatic organisms (151), soil interflow waters (152), and ground water seepage into channels (154). The latter initially comes from interflow additions to the ground waters (153).

Channel Flushing Processes

Most particulate organic nitrogen (PON) in streams is annually flushed into the lake by high stream flows. Rising stream flows produce increased concentrations of suspended sediments (155) and movement of larger streambed materials (158). Algal coatings on channel materials are added to the stream FPON load (168)(169) when they are scoured or ground off by abrasive suspended sediments (157) and the molar grinding (162) of larger streambed materials (163), respectively. The latter process also scours off (164) most filamentous algae and adds them to the coarse PON of the stream (165). Shifting streambed materials also displace streambed invertebrates (159), adding them to the CPON load flowing in stream water (160). During normal stream flow periods, invertebrate drift (constant and behavioral) adds CPON to the stream load (161). Thus the delivery of CPOM by streams to the lake is produced either in the stream (166), or is terrestrial plant litter (167).

To summarize, the sources of FPON delivered to the lake are stream invertebrate excretia (170), incompletely processed biodegradable fine particles of terrestrial origin (171), biorefractory FPON of stream or terrestrial origins (172) and colloidal-sized nitrogen particulates (173). The lake also receives PON directly from watershed lands as windblown dust and pollen (174). It also receives PON as general atmospheric dry precipitation. However that source is not significantly affected by basin land use changes and, being evenly dispersed across the lake surface, is much less likely to cause offending shoreline algal blooms. The significance of wind-blown basin dusts as nitrogen transporters has not been assessed. The total particulate nitrogen delivered to the lake (175) comes from those sources. The sources of DIN delivered to the lake are streams (179), directly inflowing groundwaters (180), and precipitation (181). Taken together, the previously enumerated nitrogen forms and sources constitute the total nitrogen delivered to the lake (182).

CHAPTER 10

PHOSPHORUS RELEASE, TRANSPORT AND DELIVERY BY LAND AND STREAM PROCESSES

Chapter Scope

In this chapter I introduce the general organization of my conceptual CEM of land and stream processes controlling delivery of incoming and stored watershed phosphorus to the lake. I then give my conceptual model (Figure 11) and explain the numbered steps and processes shown in the model.

Overview of Subsystem Model

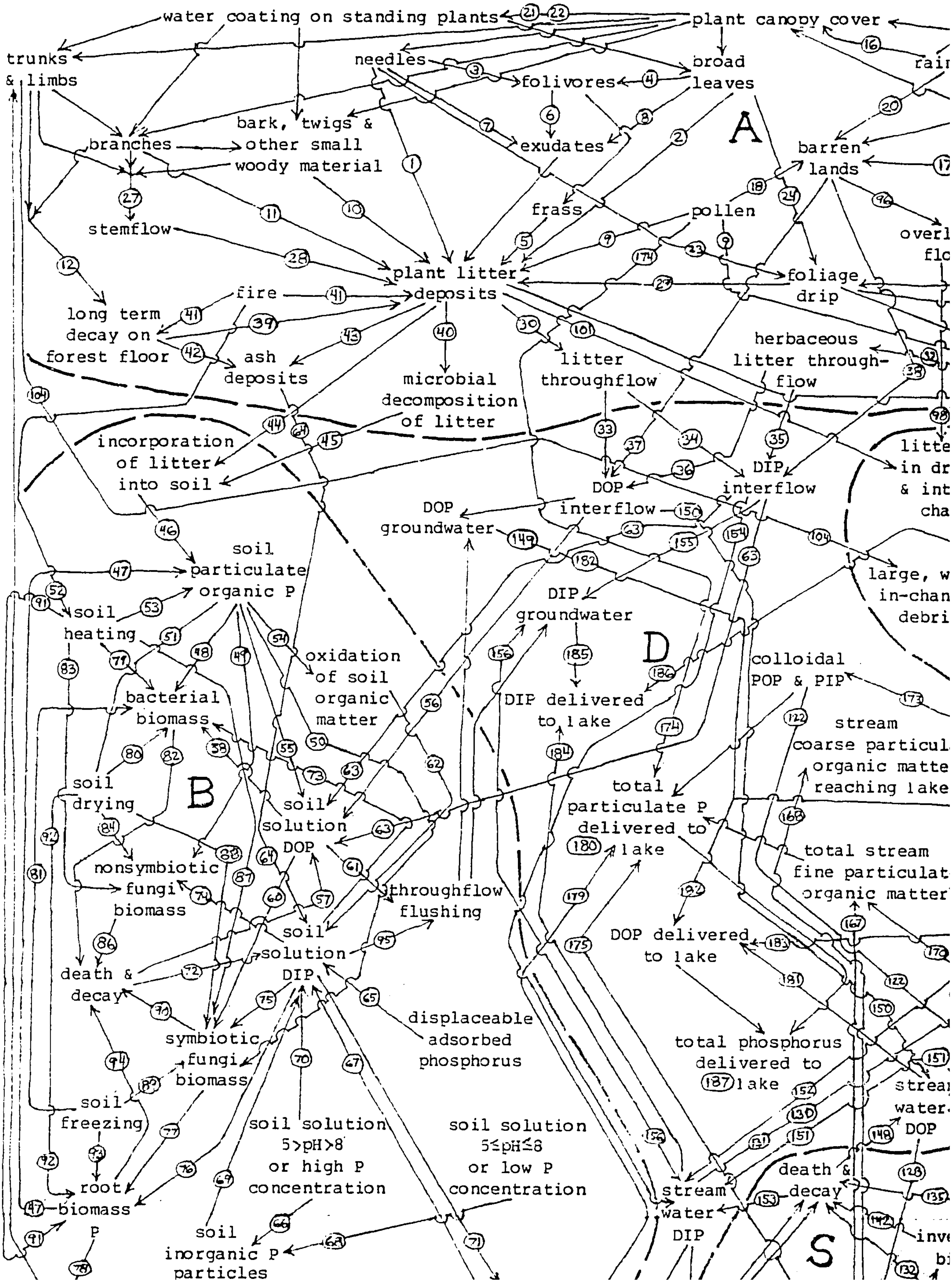
The model has four major sections: (1) above ground influx (bulk precipitation) processes releasing phosphorus from standing vegetation and plant litter; (2) below ground (soil) processes converting phosphorus to forms more or less readily moved by water; (3) nutrient cycling processes in streams delaying the delivery of water-borne phosphorus to the lake; and (4) the land (above and below ground) and stream hydrologic processes ultimately, though frequently in annual spasms, delivering phosphorus to the lake from the watershed. The locations of these sections are indicated by the dashed red lines in Figure 11.

The phosphorus and nitrogen release and transport models strongly resemble each other. This is not surprising as both elements are important components of all living matter. Hence, living (and dead) matter is a dominant storage place for both, and living matter possesses many processes for concentrating those nutrients from dilute solutions and for retaining them by tight recycling. The first 45 steps (above ground input and release processes) of the two models are virtually identical. Their stream cycling and delivery process sections look considerably different, but the differences are superficial and reflect my choice to simplify the treatment of the stream invertebrates in the phosphorus model. In the latter, I merge all invertebrate feeding types together, rather than explicitly showing the processing by each. Consequently the 46 invertebrate processor steps (99-144) shown in the nitrogen model are reduced to 31 (116-146) in the phosphorus model. The sections on hydrologic delivery process also have identical delivery categories and processes. However, four steps are added to the phosphorus model to display the important role of suspended inorganic sediments in delivering phosphorus to the lake.

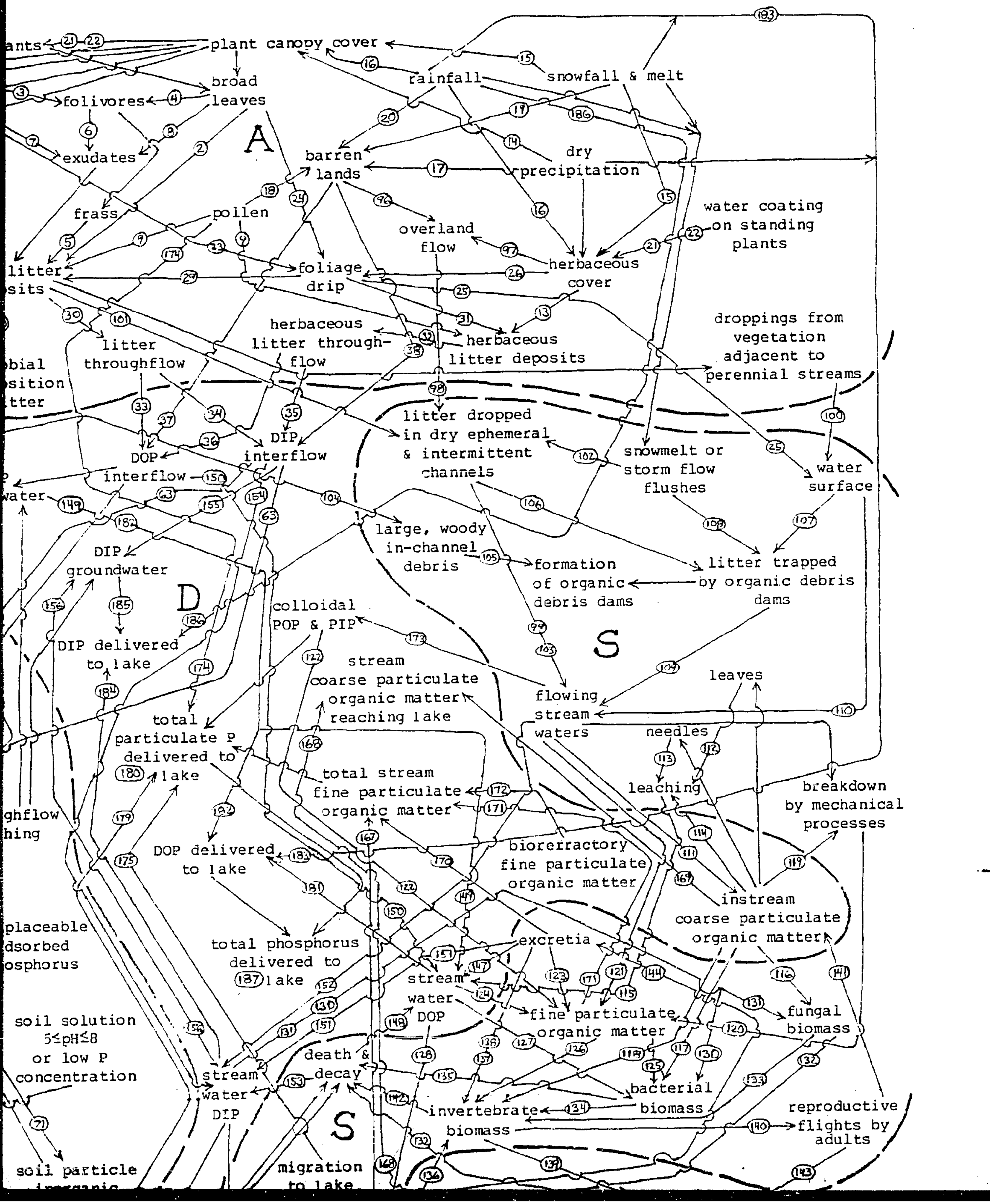
The below ground release and conversion process portions of the two models are completely different. The most important below ground processes affecting the biologic availability of nitrogen are the redox reactions which change its gases to soluble solids and organic forms to inorganic forms which are highly soluble, and hence very mobile. Only the mobility of ammonium ions is still somewhat retarded by its weak adsorption to cation exchange sites in soils. Nitrogen compounds are thousands of times more soluble than phosphorus compounds. Some phosphorus enters an ecosystem with wet, frozen and dry precipitation.

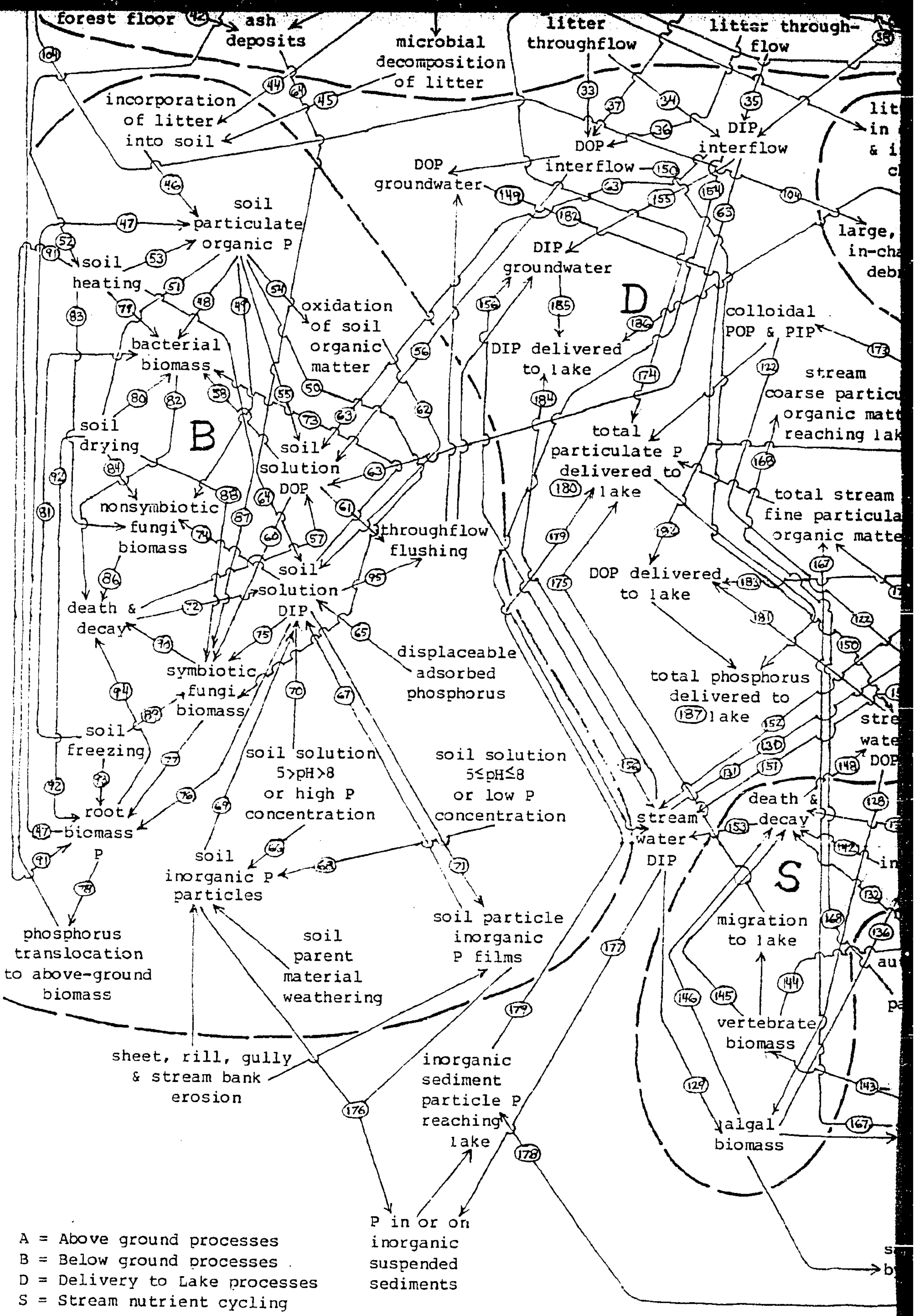
However, its main source is weathering of geologic materials. As a consequence of its very low solubility, the conversion of phosphorus to forms readily moved by ground or stream waters is largely controlled by the factors affecting the solubility equilibria between phosphorus minerals and the soil solution. The very different phase, form and solubility controlling factors are the reason for the great difference between the below ground process sections of the nitrogen and phosphorus models.

Figure 11. Conceptual Model of Land & Stream Phosphorus Release & Transport Subsystem



am Phosphorus Release & Transport Subsystem




forest floor
ash deposits
microbial decomposition of litter
litter throughflow
litter throughflow
incorporation of litter into soil
DOP interflow
DIP interflow
DOP groundwater
soil particulate organic P
DIP groundwater
soil heating
large, in-cha debr
D
oxidation of soil organic matter
bacterial biomass
DIP delivered to lake
colloidal POP & PIP
stream coarse partic organic matt reaching lak
B
soil drying
soil solution DOP
total particulate P delivered to lake
nonsymbiotic fungi biomass
total stream fine particula organic matte
throughflow flushing
soil solution DIP
DOP delivered to lake
death & decay
displaceable adsorbed phosphorus
symbiotic fungi biomass
total phosphorus delivered to lake
soil freezing
soil solution 5>pH>8 or high P concentration
soil solution 5≤pH≤8 or low P concentration
stream water DIP
stream water DOP
death & decay
root biomass P
soil inorganic P particles
S
soil particle inorganic P films
migration to lake
phosphorus translocation to above-ground biomass
soil parent material weathering
vertebrate biomass
sheet, rill, gully & stream bank erosion
inorganic sediment particle P reaching lake
algal biomass
P in or on inorganic suspended sediments
A = Above ground processes
B = Below ground processes
D = Delivery to Lake processes
S = Stream nutrient cycling

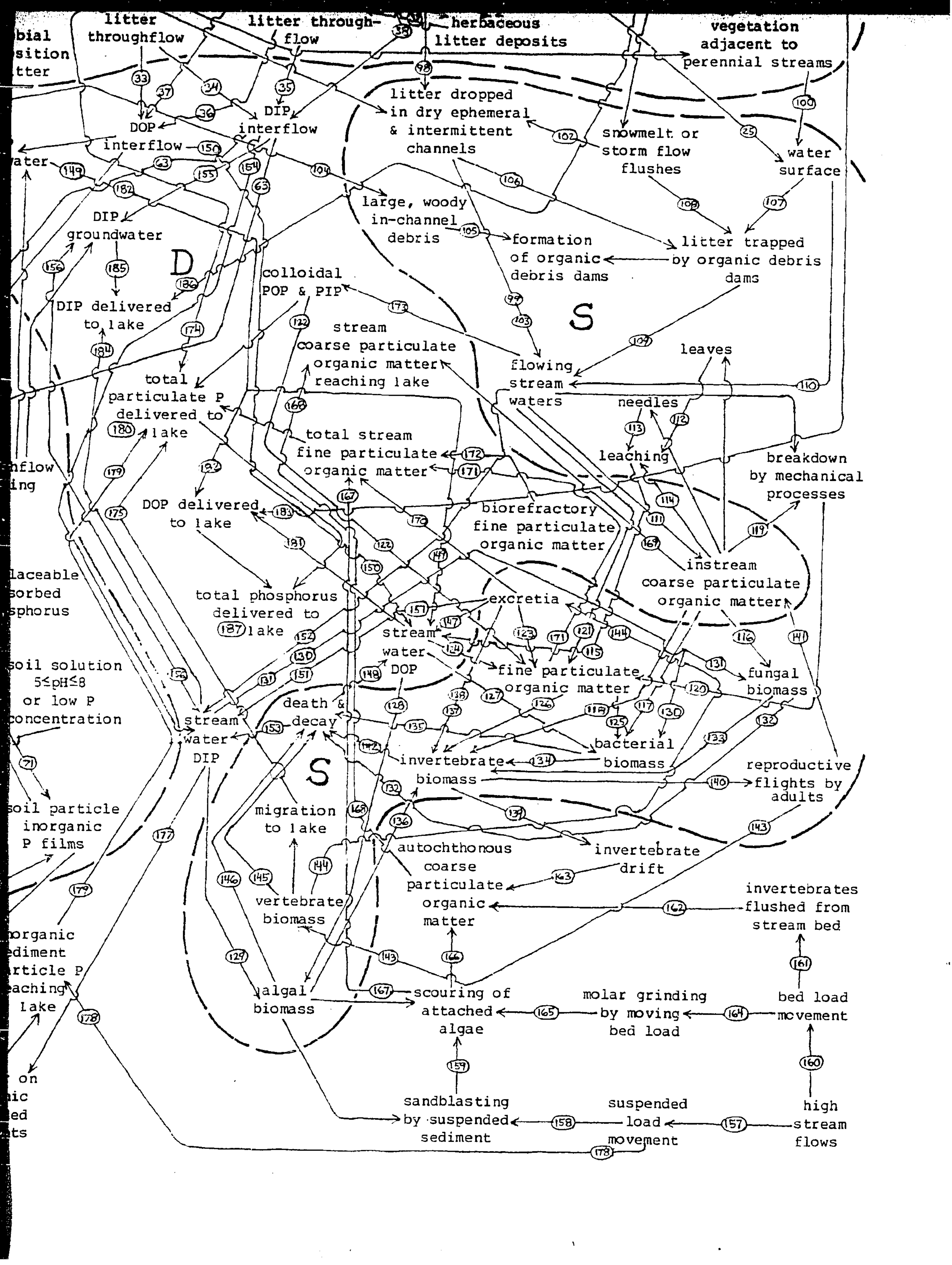

bial
sition
tter
litter
throughflow
litter through-
flow
herbaceous
litter deposits
vegetation
adjacent to
perennial streams
33
37
34
36
35
98
100
25
DOP
interflow
DIP
interflow
litter dropped
in dry ephemeral
& intermittent
channels
102
snowmelt or
storm flow
flushes
water
surface
ater
149
150
63
155
154
63
104
106
182
DIP
groundwater
large, woody
in-channel
debris
108
107
105
formation
of organic
debris dams
litter trapped
by organic debris
dams
156
185
D
186
DIP delivered
to lake
colloidal
POP & PIP
173
99
103
S
174
184
122
stream
coarse particulate
organic matter
reaching lake
109
leaves
flowing
stream
waters
110
total
particulate P
delivered to
180
lake
168
needles
112
113
leaching
total stream
fine particulate
organic matter
172
171
breakdown
by mechanical
processes
nflow
ing
179
192
114
DOP delivered
to lake
183
175
170
biorefractory
fine particulate
organic matter
111
119
181
122
149
167
instream
coarse particulate
organic matter
laceable
sorbed
sphorus
150
total phosphorus
delivered to
187
lake
excretia
151
147
stream
123
171
121
144
152
124
water
DOP
fine particulate
organic matter
115
116
141
130
131
151
148
131
fungal
biomass
soil solution
5≤pH≤8
or low P
concentration
156
stream
water
DIP
death &
decay
138
128
127
126
118
117
130
120
137
125
135
153
bacterial
biomass
132
133
71
142
invertebrate
biomass
134
S
reproductive
flights by
adults
140
soil particle
inorganic
P films
177
migration
to lake
132
168
139
136
143
autochthonous
coarse
particulate
organic
matter
invertebrate
drift
163
144
146
145
179
vertebrate
biomass
invertebrates
flushed from
stream bed
162
organic
ediment
rticle P
aching
lake
143
166
161
129
algal
biomass
167
scouring of
attached
algae
165
molar grinding
by moving
bed load
164
bed load
movement
178
159
160
on
ic
ed
ts
sandblasting
by suspended
sediment
158
suspended
load
movement
157
high
stream
flows
178

Table 11. Legend for Phosphorus Transport Model

Number	Description
	Above Ground Release Processes
1.	Phosphorus in conifer needles falling to litter deposits.
2.	Phosphorus in broad leaves falling to litter deposits.
3.	Foliage feeder consumption of live needles.
4.	Foliage feeder consumption of live broad leaves.
5.	Phosphorus in fecal pellets dropped by foliage feeders.
6.	Phosphorus in exudates from foliage feeders.
7.	Phosphorus in exudates from needles.
8.	Phosphorus in exudates from broad leaves.
9.	Phosphorus in pollen deposited on plant litter.
10.	Phosphorus in bark, twigs & other small woody deposited litter.
11.	Phosphorus in branches deposited on litter.
12.	Phosphorus in trunks and limbs deposited on forest floor.
13.	Phosphorus in herbaceous plant litter.
14.	Phosphorus in dust deposited on woody & herbaceous plants.
15.	Phosphorus in snow deposited & melting on woody & herbaceous plants.
16.	Phosphorus in rain falling on woody & herbaceous plants.
17.	Phosphorus in dust deposited on barren lands.
18.	Phosphorus in pollen deposited on barren lands.
19.	Phosphorus in snow deposited & melting on barren lands.
20.	Phosphorus in rain falling on barren lands.
21.	Leaching of phosphorus from standing plants by water coatings.
22.	Leaching of phosphorus from dust coatings on standing plants.
23.	Phosphorus in water dripping from needles.
24.	Phosphorus in water dripping from broad-leaved foliage.
25.	Phosphorus in water dripping from foliage into streams.
26.	Phosphorus in water draining from herbaceous plants.
27.	Phosphorus in water draining from bark, branches, limbs & trunks.
28.	Water draining from woody plants into litter.
29.	Woody plant foliage drip into litter deposits.
30.	Phosphorus in waters draining from woody litter deposits.
31.	Water draining from herbaceous plants into litter.
32.	Phosphorus in waters draining from herbaceous plant litter.
33.	Dissolved organic phosphorus (DOP) in woody plant litter drainage.
34.	Dissolved inorganic P (DIP) in woody plant litter drainage.
35.	DIP in waters draining from herbaceous plant litter.
36.	DOP in waters draining from herbaceous plant litter.
37.	DOP in interflow waters draining from barren lands.
38.	DIP in interflow draining from barren lands.
39.	Trunk & limb phosphorus released over long decay period.
40.	Breakdown of phosphorus-containing litter materials.
41.	Phosphorus released by burning of litter deposits.
42.	Trunk & limb organic P transformed by fire to inorganic P.
43.	Transformation of organic P in litter to inorganic P in ash.
44.	Undecomposed litter mixed with soil by fauna.
45.	Decomposed litter mixed with soil by fauna.

Number	Description
	Below Ground Release Processes
46.	Incorporated litter becomes soil particulate organic matter (POM).
47.	Dead root materials contribution to soil POM.
48.	Soil particulate organic P (POP) transformed to bacterial P.
49.	Soil POP transformed to nonsymbiotic fungal biomass P.
50.	Soil POP transformed to symbiotic fungal biomass P.
51.	Conversion of soil POP to soluble P by drying of soil.
52.	Heating of surface soil by fire or hot sun.
53.	Conversion of soil POP to soluble P by heating of soil.
54.	Oxidation of soil POP by heating & drying.
55.	Soil solution DOP leached from soil POP.
56.	Soil solution DOP coming from interflow.
57.	Soil solution DOP coming from decaying soil organisms.
58.	Soil solution DOP transformed to bacterial biomass P.
59.	Soil solution DOP transformed to nonsymbiotic fungi biomass P.
60.	Soil solution DOP transformed to symbiotic fungi biomass P.
61.	Soil solution DOP flushed from root zone by throughflow waters.
62.	Soil solution DIP coming from oxidation of particulate IP (PIP).
63.	Soil solution DIP coming from interflow waters.
64.	Soil solution DIP coming from litter ash leachates.
65.	Soil solution DIP coming from displaceable adsorbed P.
66.	Dissolving of IP films by soil pH or low DIP conditions.
67.	Soil solution DIP from dissolved IP films on particles.
68.	Dissolving mineral particle P by soil pH or low DIP conditions.
69.	Soil solution DIP coming from dissolved mineral particles.
70.	Soil solution DIP precipitation by pH or high DIP conditions.
71.	Formation of soil particle films by precipitating DIP.
72.	Soil solution DIP coming from decaying soil flora & fauna.
73.	Soil solution DIP transformed to bacterial biomass P.
74.	Soil solution DIP transformed to nonsymbiotic fungi biomass P.
75.	Soil solution DIP transformed to symbiotic fungi biomass P.
76.	Soil solution DIP transformed to root biomass P.
77.	Symbiotic fungi biomass P transformed to root biomass P.
78.	Translocation of root biomass P to above ground plant biomass.
79.	Bacterial biomass killed by soil heating.
80.	Bacterial biomass killed by soil drying.
81.	Bacterial biomass killed by soil freezing.
82.	Bacterial biomass P release by decay.
83.	Nonsymbiotic fungal biomass killed by soil heating.
84.	Nonsymbiotic fungal biomass killed by soil drying.
85.	Nonsymbiotic fungal biomass killed by soil freezing.
86.	Nonsymbiotic fungal biomass P release by decay.
87.	Symbiotic fungal biomass killed by soil heating.
88.	Symbiotic fungal biomass killed by soil drying.
89.	Symbiotic fungal biomass killed by soil freezing.
90.	Symbiotic fungal biomass P release by decay.
91.	Root biomass killed by soil heating.
92.	Root biomass killed by soil drying.
93.	Root biomass killed by soil freezing.

Number	Description
94.	Root biomass P release by decay.
95.	Soil solution DIP flushed from root zone by thoughflow waters.
96.	Phosphorus in surface runoff from barren lands.
97.	Phosphorus in surface runoff from vegetated lands.
98.	Phosphorus in surface runoff into ephemeral & intermittent streams.

Stream Cycling & Transport Processes

Number	Description
99.	Phosphorus in perennial streams from barren or vegetated lands.
100.	Plant litter falling or blown into perennial streams.
101.	Plant litter dropping into dry stream channels.
102.	Snow melt or storm flows in ephemeral or intermittent streams.
103.	Litter flushed into perennial streams by snow melt or storm flows.
104.	Large woody debris dropping into stream channels.
105.	Formation of organic debris dams behind large, woody debris.
106.	Litter trapped behind debris dams in dry stream channels.
107.	Litter trapped behind debris dams in perennial streams.
108.	Snow melt or storm flow washout of debris dams.
109.	Debris dam deposits flushed into perennial streams.
110.	Untrapped litter moving downstream and/or sinking to bottom.
111.	Breakdown of coarse particulate organic matter (CPOM) in stream.
112.	Stream water leaching of organic matter from broad leaves.
113.	Stream water leaching of organic matter from needles.
114.	Leaching of organic matter from other plant litter in stream.
115.	DOP leached from instream litter.
116.	Stream CPOP transformed to fungal biomass P.
117.	Stream CPOP transformed to bacterial biomass P.
118.	Stream CPOP transformed to stream invertebrate biomass P.
119.	Physical breakup of coarse POM by stream.
120.	Fine POM (FPOM) produced by mechanical breakup of CPOM.
121.	Allochthonous FPOM in stream waters.
122.	Formation of FPOM by flocculation of colloidal organic particles.
123.	Stream invertebrate fecal pellets added to FPOM.
124.	Formation of FPOM from dissolved organic matter.
125.	Fine POP transformed to bacterial biomass P.
126.	Fine POP transformed to collector invertebrate biomass P.
127.	Stream DOP transformed to bacterial biomass P.
128.	Stream DOP transformed to algal biomass P.
129.	Stream DIP transformed to algal biomass P.
130.	Stream DIP transformed to bacterial biomass P.
131.	Stream DIP transformed to fungal biomass P.
132.	P released by death & decay of fungi.
133.	Fungal biomass P transformed to stream invertebrate biomass P.
134.	Bacterial biomass P transformed to invertebrate biomass P.
135.	P released by death & decay of bacteria.
136.	Algal biomass P transformed to scraper & piercer invertebrate P.
137.	Excreta P transformed to collector invertebrate biomass P.
138.	Phosphorus transferred in invertebrate excretia.

Number	Description
139.	Down stream transport of invertebrate biomass P by drift.
140.	Invertebrate biomass P leaving stream with flying adults.
141.	P returned to stream by eggs & carcasses of adults.
142.	P released by death & decay of invertebrates.
143.	Invertebrate biomass P transformed to vertebrate biomass P.
144.	P transferred in vertebrate excretia.
145.	P released by death & decay of vertebrates.
146.	P released by death & decay of algal biomass.
	Land & Stream Delivery Processes
147.	Stream DOP coming from aquatic organism excretia.
148.	Stream DOP coming from death and decay of aquatic organisms.
149.	Stream DOP coming from groundwater inflow.
150.	Stream DOP coming from soil interflow waters.
151.	Stream DIP coming from aquatic organism excretia.
152.	Stream DIP coming from surface drainage.
153.	Stream DIP coming from death & decay of aquatic organisms.
154.	Stream DIP coming from soil interflow waters.
155.	Interflow DIP entering groundwaters.
156.	Stream DIP coming from groundwater inflow.
157.	Suspended sediment movement by high stream flows.
158.	Sandblasting of instream surfaces by moving suspended sediment.
159.	Algae scoured from rocks by moving suspended sediment.
160.	Movement of stream bed deposits by high stream flows.
161.	Displacement of stream invertebrates by moving bed materials.
162.	Displaced invertebrates added to stream flow CPOP load.
163.	Invertebrate drift additions to stream flow CPOP.
164.	Molar grinding of stream bed surfaces my moving bed materials.
165.	Algae scoured from rocks by molar grinding.
166.	Scoured filamentous algae added to stream CPOP load.
167.	Scoured nonfilamentous algae added to stream FPOP load.
168.	Autochthonous stream CPOP delivered to lake.
169.	Incompletely processed litter CPOP delivered to lake.
170.	Aquatic organism excretia added to stream FPOM load.
171.	Incompletely processed FPOP added to stream flow load.
172.	Biorefractory FPOP added to stream load.
173.	Colloidal POP & PIP in stream water load.
174.	Pollen POP added directly to lake.
175.	P transported into lake by vertebrate migrations.
176.	Inorganic sediment P released & transported by erosion.
177.	Precipitation of stream DIP on sediment particles.
178.	Inorganic suspended sediment load transported by stream.
179.	PIP reaching lake in or on suspended inorganic sediments.
180.	Total particulate phosphorus added to lake.
181.	Stream water DOP load delivered to lake.
182.	Groundwater DOP delivered directly to lake.
183.	Precipitation DOP delivered directly to lake.
184.	Stream water DIP load delivered to lake.
185.	Groundwater DIP delivered directly to lake.
186.	Precipitation DIP delivered directly to lake.
187.	Total phosphorus delivered to lake.

Explanation of the Conceptual Model

Above-Ground Release Processes

In the above-ground terrestrial portions of watersheds, the nutrient phosphorus is stored in or on living plant and animal biomass, their excretia, exudates and remains--whether liquid or solid, upright or on the ground. The potential for release of phosphorus varies throughout the watershed ecosystem depending upon in which forms and positions it is present. One form of initial release of phosphorus from living woody plants to litter deposits is by annually shed needles (1), leaves (2), pollen (9), bark, twigs, cones and other small woody material (10). Pollen is also readily and widely spread by winds and deposited on water and barren land (18) surfaces. The less frequent shedding of branches (11), and over many years, by the death and decay and fall of tree trunks and major limbs (12) releases more standing biomass phosphorus to litter deposits. In similar manners, the phosphorus stored in herbaceous plants is transferred to litter deposits (13). Some woody and herbaceous plants also release phosphorus as exudate from their needles (7) and leaves (8). The phosphorus held in living plants may also be released by the consumption of needles (3), leaves (4), and other plant parts by foliage feeders and subsequently dropped to the litter by their fecal pellets (5) and other exudates (6) and eventually by their carcasses.

In addition to its primary initial source as the weathering products of watershed geologic materials, phosphorus is carried into the ecosystem by dry (dust), frozen and wet precipitation which is deposited on plants (14)(15)(16), plant litter deposits and on barren lands (17)(19)(20). When in a fluid phase, precipitation waters leach some phosphorus (though much less than nitrogen) from plant tissues (21) and dust coatings (22), as well as wash most of the latter from those surfaces. The phosphorus-enriched leachate drips from needles (23), leaves (24) and other portions of standing plants into streams (25) and litter deposits (29). Some of these waters drain down the continuous, vertically inclined bark, branches and stems of woody (27) and herbaceous plants (26), leaching more phosphorus from them in passing (while losing a lesser amount to epiphytes) and flows into litter deposits (28)(31).

Some of the phosphorus in waters draining into litter deposits is rapidly removed by and stored in bacteria and fungi biomass. However, when litter deposits become saturated, the waters draining through them pick up some phosphorus from slowly decaying woody (30) and much more from rapidly decaying herbaceous (32) materials. The phosphorus in water draining from woody and herbaceous plant litter materials and barren lands is either dissolved inorganic (DIP) (34)(35)(38) or dissolved organic phosphorus (DOP) (33)(36)(37). These two forms have significantly different biologic availability and mobility characteristics.

The particulate organic phosphorus (POP) held in standing dead trunks and limbs is gradually released over periods of a hundred or more years by decay (39), or more precipitously by fire, which converts it to particulate inorganic phosphorus (PIP) in ash (42). The POP held in litter deposits is released from storage by draining waters, by decay (40) and/or by burning (41)--with the latter process converting it to PIP in ash (43). Some of the partially decomposed (45) and undecomposed (44) litter deposit materials are directly incorporated into the upper layers of soil by digging fauna, and become subject to below-ground release processes acting on soil particulate organic matter (POM) (46).

Below-Ground Release Processes

Soil POP originates from incorporated litter organic matter (46) and dead and rotted root materials (47). Some soil POP is consumed by soil arthropods and insects, but most is consumed by bacteria and fungi (nonsymbiotic and symbiotic) and converted to biomass P in their respective bodies (48)(49)(50). Some soil POP is also oxidized to soluble phosphorus (54) by the heating (53) and drying (51) of surface soils caused by dry periods, sun and ground fires (53). Some phosphorus is also released from soil POP by leaching by soil solution and throughflow waters (55). The free water existing between soil particles in termed the soil solution and its DOP content comes from POP leachate (55), carried in by percolating waters, (56) and from decaying soil organisms of all types (57).

Some soil solution DOP is taken up by bacteria and fungi (nonsymbiotic and symbiotic) and converted to their respective biomass phosphorus (58)(59)(60). Rain storm and snow melt waters percolating through soils flush the existing soil solution with its DOP content ahead of them. The DIP in soil solutions comes from oxidation of PIP (62), percolating waters (63) carrying DIP from above ground sources (such as leachate from litter ashes (64)), displacement of phosphorus absorbed on the surface of soil particles (65), dissolving of inorganic phosphorus (IP) in films on particles (66)(67) or in their constituent minerals (68)(69) by conditions of near neutral soil pH, and/or compensating actions of solubility equilibria caused by low DIP concentrations. Some soil DIP also is released by the decaying biomass of soil organisms (72).

Soil solution DIP is stored by its precipitation as films on soil particles (71) at high or low pH conditions or to reestablish solubility equilibria disrupted by excessively high DIP concentrations (70). Some soil solution DIP is also stored by uptake and conversion to the biomass phosphorus of bacteria (73) and fungi (nonsymbiotic and symbiotic) (74)(75). Some is also removed by roots which may convert phosphorus from symbiotic fungi (77) to their biomass phosphorus (77) or translocated it to above-ground plant biomass phosphorus (78).

Phosphorus held in the biomass of soil bacteria, fungi (nonsymbiotic and symbiotic) and roots is released by their decay (82)(86)(90)(94) following killing by soil heating (79)(83)(87)(91), soil drying (80)(84)(88)(92), soil freezing (81)(85)(89)(93) or other causes.

Phosphorus (DIP and DOP) is released from the below ground storage in the root zone by flushing by throughflow waters (95) into water tables, eventually draining into the lake or stream channels. Throughflow waters also surface down slope in swales, at banks, or where slopes steepen, soils become shallower, less permeable or are saturated. Phosphorus (largely PIP and POP, but also some DIP and DOP) is also released and initially moved from land surfaces by occasional, patchy surface runoff on vegetation-covered lands (97), more commonly on barren lands (96) and most commonly in and along emphemeral and intermittent stream channels.

Stream Cycling and Transport Processes

Another means of transfer of terrestrial POM into perennial streams is by small woody and herbaceous plant litter falling or being blown directly into them (100). Some of these materials initially drops into dry (ephemeral or intermittent) channels (101) and then is carried into perennial channels by snowmelt or storm flows (102)(103). Large woody debris may also fall directly into or be carried into stream channels (104) and may become lodged and piled into debris dams (105)--trapping herbaceous and smaller woody materials on them or in the permanent or ephemeral pools that form behind them (106)(107). Subsequently the POM materials detained by these debris dams is released by snowmelt or storm flow washouts (108) which carry it into and down perennial streams (109).

Terrestrial plant litter released by the rupture of debris dams or that was never trapped floats downstream, some becomming waterlogged and sinking to the bottom (110). On contact with water, much of the organic matter containing phosphorus and other nutrients is leached rapidly from leaves (112) and more slowly from needles (113) and other larger herbaceous and woody plant litter (114) and is added to the DOP in stream waters (115).

In streams, CPOM is broken down (111) by physical forces (119) and biologic processes, with some being colonized and digested in sequence by fungi, bacteria, and invertebrates and converted to their biomass phosphorus (116)(117)(118). The fate and rate of conversion of fine POM (.00045-.075 mm) is significantly different from that of CPOM (Cummins et al. 1972). Some CPOM is reduced to FPOM by abiotic mechanical forces in stream waters (120). Other FPOM is produced by allochthonous biotic and abiotic processes in streams (121)--some by flocculation of colloidal particles (122), some by invertebrate fecal pellets (123) and some from chemical transformation of dissolved organic matter (124). During cold seasons and high stream flows, nearly all CPOM, FPOM, DOP and DIP is transported directly to the lake. When stream waters are warmer and flows slower, much of the FPOM is transformed to bacterial and collector invertebrate biomass phosphorus (125)126), and most DIP is directly taken up and converted to algal, bacterial and fungal biomass phosphorus (129)(130)(131).

In addition to above and below ground terrestrial and aquatic leachate sources, stream water DOP is produced by allochtonous biotic processes, as from aquatic organism excreta, decay and excretion of extracellular organic matter. Some of the stream water DOP is directly taken up by bacteria and algae and phosphorus converted to their respective biomass phosphorus (127)(128).

Some transfer of biomass phosphorus from one type of aquatic organism to another occurs via predation, digestion and assimilation. Thus some: fungal and bacterial biomass phosphorus is transformed to stream invertebrate biomass phosphorus (133)(134); algal biomass phosphorus is transformed to the biomass phosphorus of aquatic invertebrates which feed by scraping and piercing (136); and aquatic invertebrate biomass phosphorus becomes aquatic or terrestrial invertebrate biomass phosphorus (143).

Some of the phosphorus in the excretia from invertebrates (138) and vertebrates (144) is transformed to the biomass phosphorus of invertebrates which feed by collecting passing organic particulates (137).

Some biomass phosphorus is transported downstream or into the lake by drifting invertebrates (139) and by swimming invertebrates and vertebrates. Some biomass phosphorus is shifted to dry land by the emergence from the stream of winged adult invertebrates (140) and some is moved and deposited upstream by them in the form of eggs and their carcasses (141). The swimming and spawning activities of vertebrates similarly moves, deposits and releases some biomass phosphorus upstream. The death and decay in the stream of aquatic fungi (132), bacteria (135), algae (146), invertebrates (142) and vertebrates (145), releases biomass phosphorus to stream waters in the form of CPOM, FPOM, DOP and DIP.

Land and Stream Delivery Processes

All delivery processes are strongest during high stream flows; hence all forms of phosphorus are delivered most rapidly and thoroughly during these times. The DOP in stream waters originates from aquatic organism excretia (147) and decay (148), inflowing groundwaters (149) and soil interflow waters (150). Similarly the DIP in stream waters comes from aquatic organism excretia (151), decay (153) directly entering surface runoff (152), soil interflow (155) or ground waters (156)--with the latter being a product of soil interflow waters (155).

The unattached store of POP in streams is augmented during high flows by the abrasive actions of high concentrations of inorganic suspended sediments which scour algal periphyton from the surface of instream materials (157)(158)(159). High flows also move larger stones in stream beds (160) adding drifting, displaced cryptic stream invertebrates to the stream's load of CPOP (161)(162)(163). The rolling, sliding and bouncing stones also grind against each other and stable materials in channels (164), grinding off addition attached algae--adding FPOM from nonfilamentous epiphytic algae (167) and CPOM and FPOM from filamentous epiphytic algae (166).

Most of the unattached autochthonous (168) and allochthonous (169) CPOM in stream channels is released by the increased intensity of abiotic mechanical forces during high flows (168)(169). The biologically processed (170) biodegradable and biorefractory (172) autochthonous FPOP and unaltered FPOP (171) in stream channels are simultaneously and similarly released. During high flow events, nearly all of the CPOP and FPOP stored in perennial stream channels and the colloidal POP and PIP (173) in their waters are delivered to the lake. Some stream and land biomass phosphorus is also delivered directly to the lake by drifting pollen (174) and the downstream migration of aquatic vertebrates (175).

Some phosphorus is directly delivered to the lake by, in or on particles of suspended inorganic sediments (179). These may be released initially by soil erosion (176) or by channel erosion and abrasion processes. Some small proportion of released (or created) phosphorus containing inorganic particles reach the lake directly in unchanneled waters flowing over the land, but the vast majority reaches the lake as the suspended sediment load of streams (178). Some of the phosphorus content in the latter phosphorus is enriched by precipitation of stream DIP films on the particles (177).

Taken in aggregate, all these phosphorus sources and forms constitute the grand total particulate phosphorus delivery to the lake from watershed lands and streams (180).

Most of the total DOP and DIP entering the lake is delivered by stream waters (181)(184); some unknown but probably much lesser amount by groundwaters (182)(185) and also some small amount by wet and dry precipitation falling into the lake (183)(186). Taken as a whole, all the watershed land stream and atmospheric delivery processes are the source of phosphorus entering the lake (187).

CHAPTER 11

NUTRIENT QUANTITIES ON WATERSHED SITES

Chapter Scope

In this chapter I review my reasons for using the total amount of nutrients stored on watershed locations as a land capability indicator of the potential water quality effects of land use actions. I then present a conceptual framework for their quantification and discuss some theoretical and practical problems of my approach. Then I develop estimates of the concentration of nutrients present in the dominant tree species, their litter deposits and soil types of the watershed. Finally I use these estimates to quantify the nutrient mass on map units of different soil, land and forest cover types.

Reasons and Exceptions

The nutrients released by land use activities, and ultimately affecting lake water quality, must already be present on the site. Nutrients other than those initially present may also be released by land use activities. Some nutrient additions associated with land use may be due to direct importation of new nutrients. An obvious example is fertilization to establish or maintain landscape plantings or golf courses. Land use alteration of sites may also cause synergistic and indirect off-site situations which add other nutrients to waters. For example, increasing the quantity of or decreasing concentration time of runoff waters from a site results in enlargement of downstream channels (Leopold 1972) with attendant bank erosion and release of the nutrients in bank soils.

More subtle on-site and off-site conditions created by land use actions may release nutrients not represented in my simple quantification of those initially present. For example, the concentration of nitrogen and phosphorus in precipitation is frequently greater than their concentration in Lake Tahoe. The concentration of nutrients in precipitation falling on well-developed forests is commonly greater than their concentration in waters draining from those lands (Coats 1975, Kirchner 1975). Such forests pick up and store in their biomass some of the nutrients brought in by precipitation. Consequently, removal of forest cover may result in an increase of the nitrogen and phosphorus in waters reaching the lake which is unrelated to quantification of the stock of nutrients initially present on watershed sites.

Some of the effects of added nutrients undoubtedly will occur with alteration of site conditions by land use. Obviously, therefore, quantification of nutrients present on a potential development site does not produce a comprehensive evaluation of the total nutrient release potential of land use activities.

Assessment of the potential release of nutrients from on-site stocks by land use disturbances can recognize that some of the initial quantities can be prophylactically removed during construction.For example, land grading, paving and building structures always result in removal of original vegetation cover. If cleared plant debris is removed form the basin, its nutrient contents are prevented from entering its aquatic nutrient cycles. If the cleared plant debris is wholly or partially disposed of by burning on the construction site, much of its nitrogen is removed from basin nutrient cycles by volatilization (Powers 1979), but most of the phosphorus remains. Plant litter deposits also are easily gathered and removed for disposal where their nutrients cannot cause water quality problems. However, they are more typically mixed with the soil by grading activities and subsequently release their nutrients to the soil and throughflow waters.

Studies have shown that in forest lands three to six times as much nitrogen is stored in the soils as in the plant and litter cover (Cole et al. 1967, Mitchell et al. 1975, Waide & Swank 1977). An even larger portion of site phosphorus is stored in soils, though much of it is not as biologically available nor as readily transported as nitrogen. Yet site soils are much more difficult to remove, and to minimize ecosystem disturbance it is undesirable to do so. Hence their initial nutrient contents are likely to remain on site and be leached by throughflow waters or carried away by soil erosion.

In this study I chose to examine the potential effects of land uses only in terms of those quantities of nutrients already present on a site prior to use activities. Therefore I ignore the consideration of nutrient importation, stimulated site nutrient production (e.g., microbial nitrogen fixation activity), decreased nutrient retention, and off-site, downstream releases of other nutrients as a consequence of land use alteration of watershed sites. My consideration of only the release of on-site nutrient stocks by land use results in a conservative estimate of their potential nutrient enrichment consequences.

Conceptual Framework for Quantification

The nutrients of a site may be usefully considered to exist in three fundamentally different locations--living vegetation, plant litter deposits and soil deposits. Thus, a simple quantitative tabulation of the amount of nitrogen and phosphorus present in each location on watershed sites establishes an estimate of the total amount of those nutrients present. Only three other locations of site nutrients are omitted by this simple subdivision of the nutrient stock: the fauna, dry precipitation films, and standing dead vegetation. Quantitative information on the amount of nutrients stored in these locations is sparse. Mitchell et al. (1975) found that herbivores contained less than 0.1 percent of the nitrogen stock on an undisturbed oak-hickory forest. Voegtlin (Carroll 1980 p. 104) found that caterpillars ate less than 1 percent of the new foliage each year in a douglas fir forest. The amount of nutrients held in caterpillar biomass must be much less than 1 percent of the new foliage biomass. These few reported values indicate that fauna located on and/or feeding on vegetation probably contain an insignificant amount of a forest nutrient stock. The mass of dust coatings relative to that of plants is very small; consequently I also expect that it contains a relatively insignificant portion of the nutrients of a site. Franklin and Waring (1980 p. 77) report that standing dead snags contain only 5-7 percent of the biomass in douglas fir stands of the same age as Tahoe forests (about 100 years old). Trunk wood contains the lowest concentration of nitrogen and phosphorus. Hence, the amount of nutrients held in standing dead vegetation is probably much less than 5 percent of the total.

Forest Biomass Estimation

Figure 12 shows the distribution of major vegetation cover types in the Ward Creek Watershed as determined by recent (1980) U.S. Forest Service mapping based on interpretation of aerial photos. I use the mapping specification* information on tree species composition, total canopy density and most common crown diameter (see Table 12 and Appendix Table A1) and biomass estimation equations (Appendix Table A2) to estimate the above-ground tree biomass in each forested cover type. My assumptions, detailed procedures, calculations, results and comparisons to the data of others are given in Appendix A.

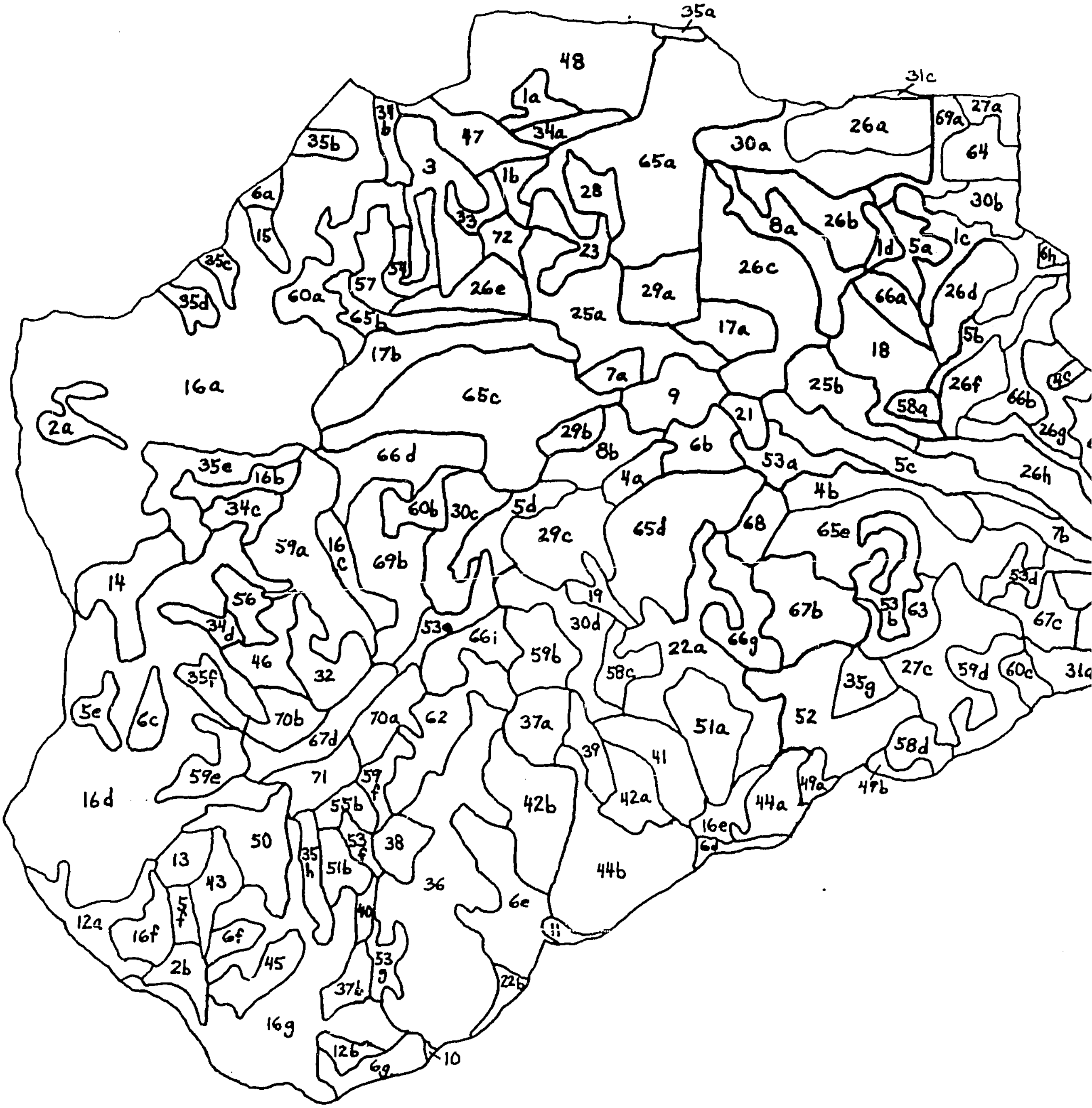
Nutrient Mass in Tree Biomass

Using reported values (Appendix Table A3) for nitrogen and phosphorus concentrations in foliage, trunk wood and bark and branch wood and bark, I develop estimates of their concentration in the forest cover tree species of the Ward Creek watershed (Appendix Table A9). Multiplying those concentrations by the estimates of tree above-ground biomass developed in the preceding section (Appendix Table A5), I obtain estimates of the mass of nutrients, by species, in the various portions of trees on each map unit and the total nutrient mass of whole units (Appendix Tables A7 and A8).

---

* USDA Forest Service, Tahoe National Forest. 1981, June Planning file; standards, instructions and coding definitions p.74-80. (Unpublished document).

FIGURE 12. Vegetation Cover Types of Ward Creek Watershed



r .Types of Ward Creek Watershed

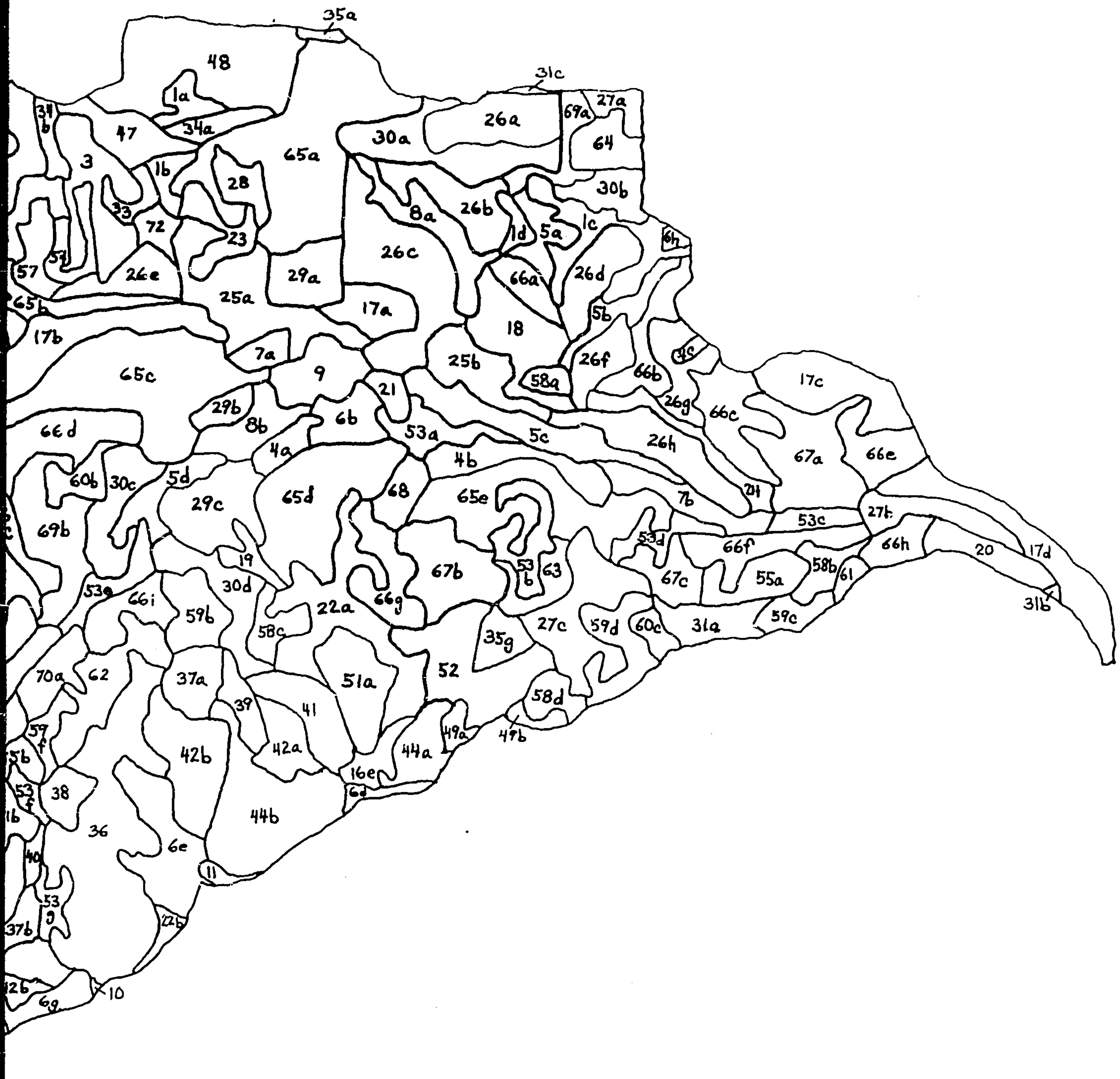


Table 12. Legend for Tree Species, Size and Density Map

Map Symbol	Type Label	Map Symbol	Type Label	Map Symbol	Type Label
1	GL	25	PPWF3G	49	RFWF4G
2	LP2P	26	PPWF3N	50	RFWF4N
3	LP2S	27	PPWF3P	51	RFWP3P
4	LP3G	28	PPWF3S	52	RFWP4N
5	LP3N	29	PPWF4G	53	SR
6	LP3P	30	PPWF4N	54	WF1N
7	LP3S	31	PPWF4P	55	WF2N
8	LP3S/SR	32	PPWF4S	56	WF2P
9	LPPP3N	33	RF2N	57	WF2S
10	LPRF3N	34	RF3G	58	WF3G
11	LPRF3P	35	RF3N	59	WF3N
12	MH2N	36	RF4G	60	WF3P
13	MH3P	37	RF4N	61	WF2S/SM
14	MHLP2P	38	RF4P	62	WF3S/SR
15	MHLP3N	39	RF4P/SR	63	WF4N
16	NB	40	RF4S	64	WFPP2P
17	ND	41	RFLP3G	65	WFPP3G
18	PP3P	42	RFLP3N	66	WFPP3N
19	PP4S/SR	43	RFMH2P	67	WFPP3P
20	PP6G	44	RFMH3G	68	WFPP3S/SR
21	PPLP4N	45	RFMH3P	69	WFPP4G
22	PPRF4P	46	RFPP3N	70	WFPP4N
23	PPWF2P	47	RFPP4N	71	WFPP4P
24	PPWF2S/NG	48	RFPP4P	72	WFRF3N

GL= grasslands
LP= lodgepole pine
PP= ponderosa pine
RF= red fir
MH= mountain hemlock
NB= barren
ND= urbanized
WF= white fir
WP= western white pine

1= 0-5 foot crown diameter
2= 6-12
3= 13-24
4= 25-40
5= 40+
6= 2-storied stands

S= 10-20% canopy cover
P=20-39%
N= 40-69%
G=70+%

For a more detailed explanation, see Appendix Table A1.

N and P Mass Classes

The 69 forest tree biomass units (3 types shown on the map are non-forest) combine into 62 and 46 units of nitrogen and phosphorus, respectively, with differing values. Nitrogen mass values range from 124 to 2452 kg/ha and phosphorus from 11 to 204 kg/ha. These value levels are arranged in Tables 13 and 14 respectively, in the order of increasing values. Also shown are differences between adjacent and cumulative values on an absolute and percentage basis--information I used to help decide where to divide classes. From comparison of the locations where values change by large amounts, where class line boundaries should be to obtain fairly even regular value intervals ranges within classes, I establish six value classes for each nutrient. For nitrogen mass they are 115-228, 229-369, 370-591, 592-790, 791-1119, 1120-2669 kg/ha, and for phosphorus mass 10-30, 31-47, 48-79, 80-99, 100-123, and 124-240 kg/ha. Their areal distribution in the watershed is shown in Figures 13 and 14 for nitrogen and phosphorus, respectively.

Litter Deposit Nutrient Storage

In Appendix Table A10 I estimate the amount of nitrogen and phosphorus stored in litter deposits from reported values for concentrations in litter and litter deposit weights (Appendix Table A11) under the major forest tree species in the watershed. To simplify my estimation task and mapping of the results I treat each forest type as if it consists of only one species--that indicatedly by the first species code in map unit labels.

Table 13. Nitrogen in Tree Biomass: Ranking and Class Groupings

Map Unit Number	N Mass	Differences				Class Groupings
		absolute		cumulative		range (interval)
	kg/ha	kg/ha	%	kg/ha	%	
43	124					
41	128	4	3	4	100	115-228 kg/ha (113)
3	137	9	7	13	69	
40	148	11	7	24	46	
57	167	19	11	43	44	
7,8,51	172	5	3	48	10	
45	177	5	3	53	9	
24	178	1	1	54	2	
68	194	16	8	70	23	
14	214	20	9	90	22	
33	216	2	1	92	2	
23	240	24	10	116	21	229-369 kg/ha (140)
19	242	2	1	118	2	
61,62	248	6	2	124	5	
28	257	9	4	133	7	
35	262	5	2	138	4	
2	270	8	3	146	5	
18	271	1	0	147	1	
11	280	9	3	156	6	
38,39	290	10	3	166	6	
13	296	6	2	172	3	
48	303	7	2	179	4	
64	314	11	4	190	6	
46	322	8	2	198	4	
56	329	7	2	205	3	
42	336	7	2	212	3	
6	341	5	1	217	2	
12	342	1	0	218	0	
27	344	2	6	220	1	
54	394	50	13	270	19	370-591 kg/ha (221)
22	412	18	4	288	6	
32	454	42	9	330	13	
67	466	12	3	342	4	
34	473	7	1	349	2	
60	487	14	3	363	4	
37	535	48	9	411	12	
52	542	7	1	418	2	
44	551	9	2	427	2	
15	552	1	0	428	0	
10,47	565	13	2	441	3	
26	571	6	1	447	1	
31	582	11	2	458	2	
9	602	20	3	478	4	

Table 13. Nitrogen in Tree Biomass: Ranking and Class Groupings (continued)

Map Unit Number	N Mass	Differences				Class Groupings
		absolute		cumulative		range (interval)
	kg/ha	kg/ha	%	kg/ha	%	
9	602	20	3	478	4	592-790 kg/ha (198)
55	605	3	0	481	1	
5	626	21	3	502	4	
50	640	14	2	516	3	
20	684	44	6	560	8	
66	701	17	2	577	3	
59	746	45	6	622	7	
36,72	836	90	11	712	13	791-1119 kg/ha (328)
71	852	16	2	728	2	
21	893	41	5	769	5	
30	964	71	7	840	8	
49	1070	106	10	946	11	
25	1089	19	2	965	2	
4	1149	60	5	1025	6	1120-2669 kg/ha (1549)
29	1235	86	7	1111	8	
65	1338	103	8	1214	8	
58	1401	63	4	1277	5	
70	1571	170	11	1447	12	
63	1648	77	5	1524	5	
69	2452	804	33	2328	35	

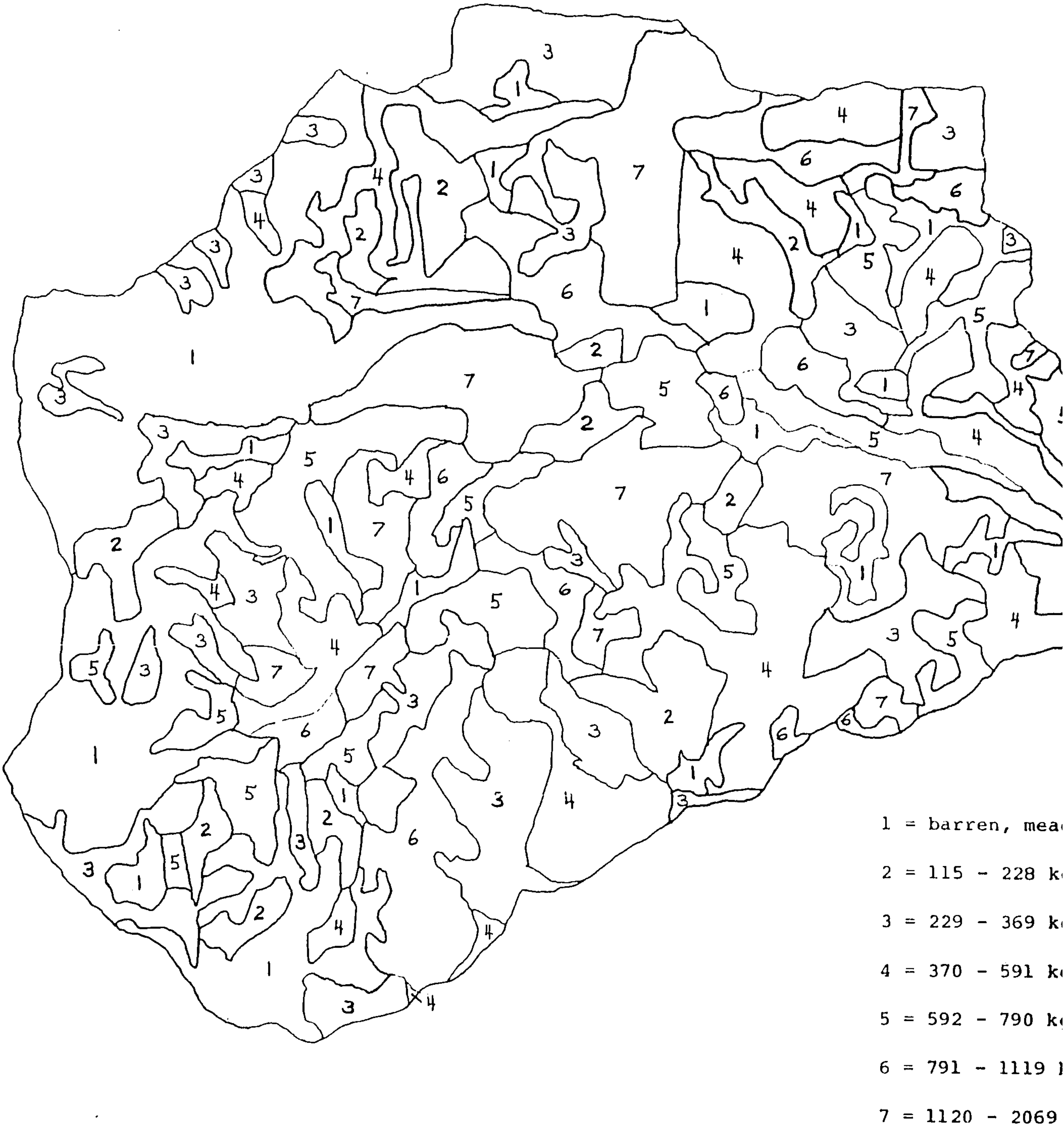
Table 14. Phosphorus in Tree Biomass: Ranking and Class Groupings

Map Unit Number	P Mass kg/ha	Differences				Class Groupings
		absolute kg/ha	%	cumulative kg/ha	%	range (interval)
3	11					
24,41	12	1	9	1	100	10-30 kg/ha (20)
57	13	1	8	2	50	
40	14	1	7	3	33	
7,8,19,43,68	15	1	7	4	25	
23,51	17	2	12	6	33	
18	18	1	6	7	14	
61,62	20	2	10	9	22	
45	21	1	5	10	10	
28	22	1	5	11	9	
2	23	1	4	12	8	
14,64	24	1	4	13	8	
11	25	1	4	14	7	
33,27	26	1	4	15	7	
28,56	28	2	7	17	12	
22,35,38,39,48	29	1	3	18	6	
46	32	3	9	21	14	31-47 kg/ha (16)
54	33	1	3	22	5	
32,42	35	2	6	24	8	
67	39	4	10	28	14	
13	40	1	3	29	3	
26	41	1	2	30	3	
60,20	42	1	2	31	3	
31	45	3	7	34	9	
12	46	1	2	35	3	
9,10	50	4	8	39	10	48-79 kg/ha (31)
55	51	1	2	40	3	
34,5	52	1	2	41	2	
37,47	54	2	4	43	5	
52	55	1	2	44	2	
72	58	3	5	47	6	
21,50,59	62	4	6	51	8	
44	64	2	3	53	4	
15	69	5	7	58	9	
71	70	1	1	59	2	
66	71	1	1	60	2	
25,30	72	1	1	61	2	
36	86	14	16	75	19	80-99 kg/ha (19)
4	95	9	9	84	11	
29	104	9	9	93	10	

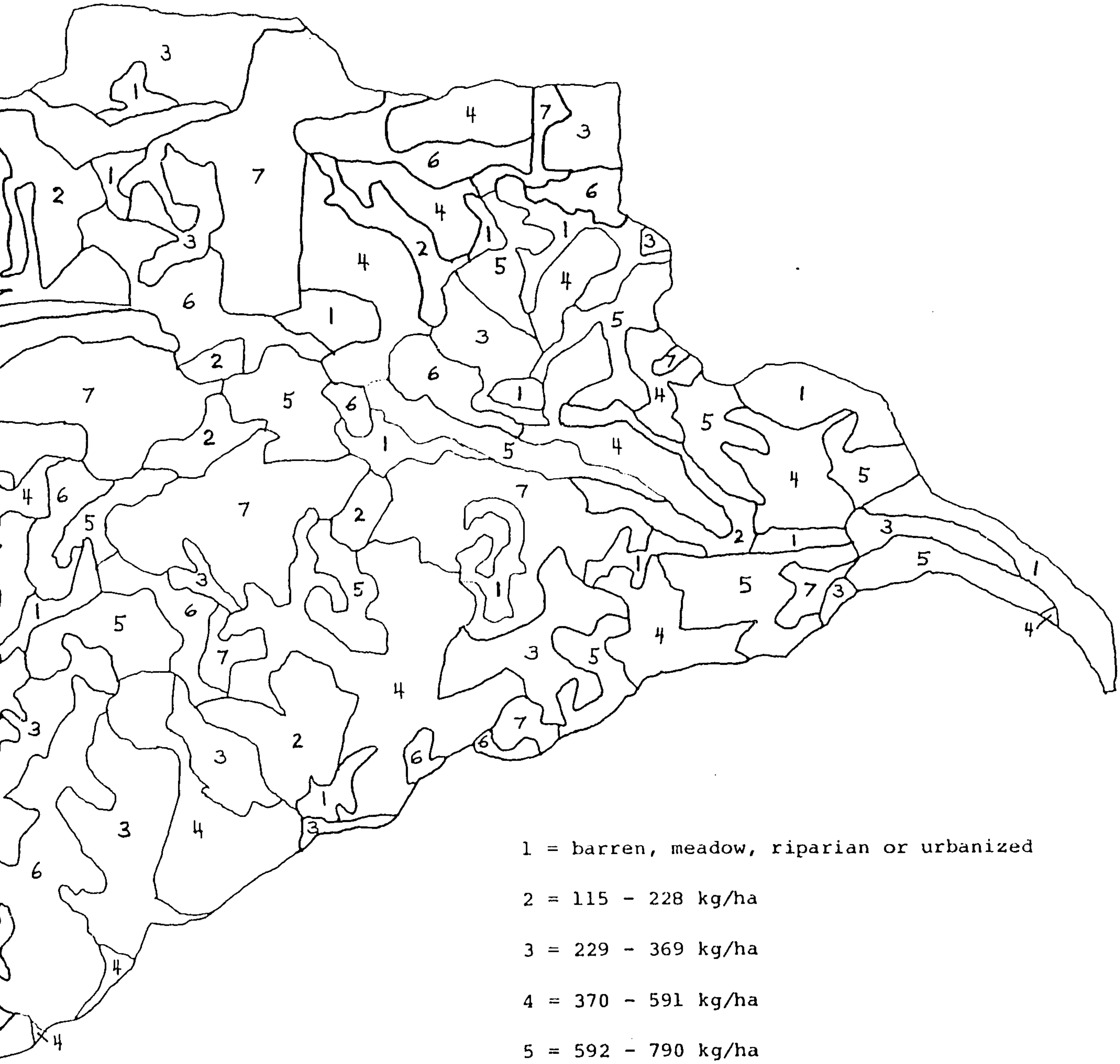
Table 14. Phosphorus in Tree Biomass: Ranking and Class Groupings (continued)

Map Unit Number	P Mass kg/ha	Differences				Class Groupings
		absolute kg/ha	%	cumulative kg/ha	%	range (interval)
29	104	9	9	93	10	100-123 kg/ha (23)
49	105	1	1	94	1	
65	109	4	4	98	4	
58	116	7	6	105	7	
70	130	14	11	119	12	124-240 kg/ha (116)
63	139	9	6	128	7	
69	204	65	32	193	34	

FIGURE 13. Tree Biomass Nitrogen Distribution in Ward Creek Watershed



en Distribution in Ward Creek Watershed



1 = barren, meadow, riparian or urbanized

2 = 115 - 228 kg/ha

3 = 229 - 369 kg/ha

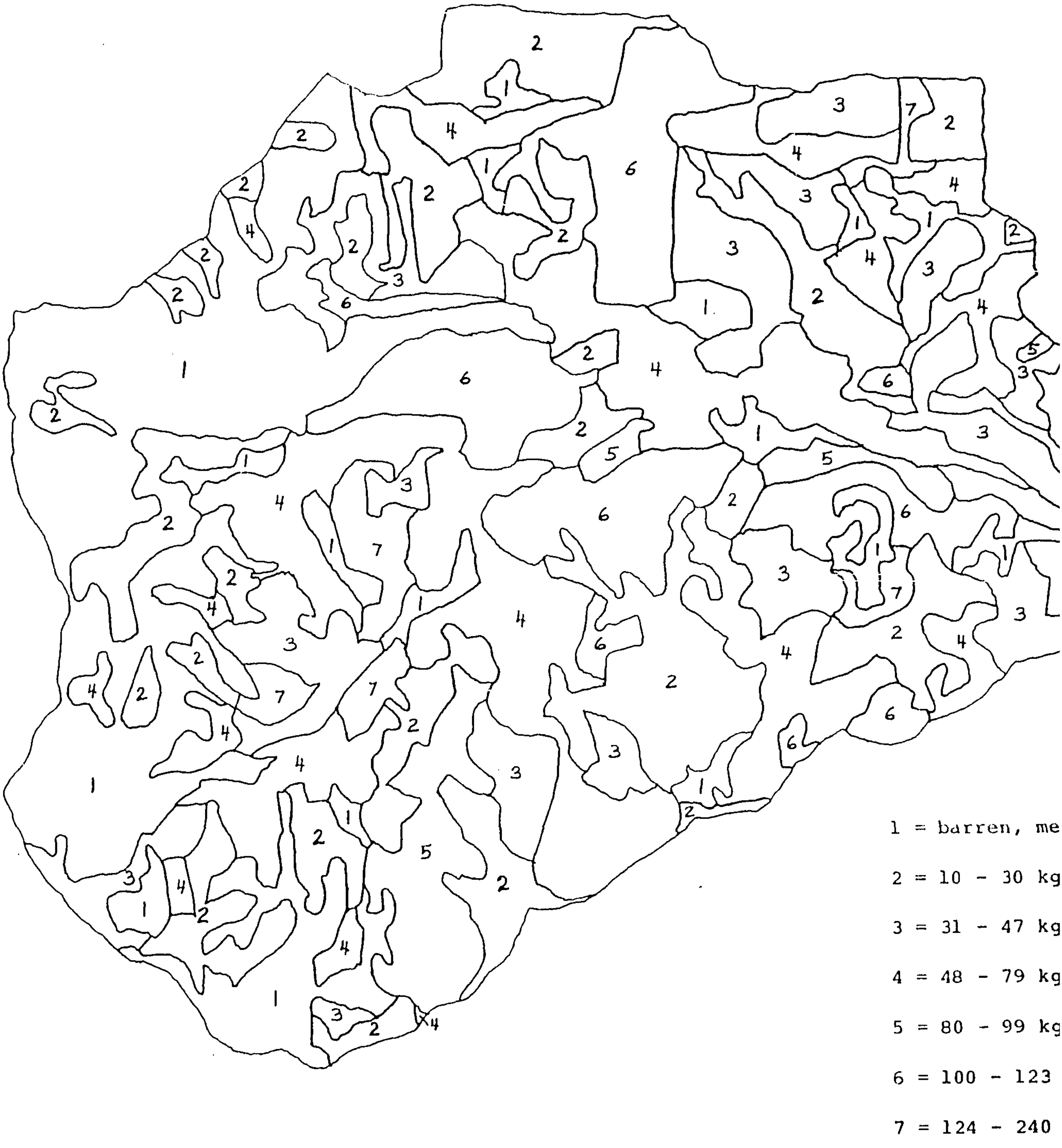
4 = 370 - 591 kg/ha

5 = 592 - 790 kg/ha

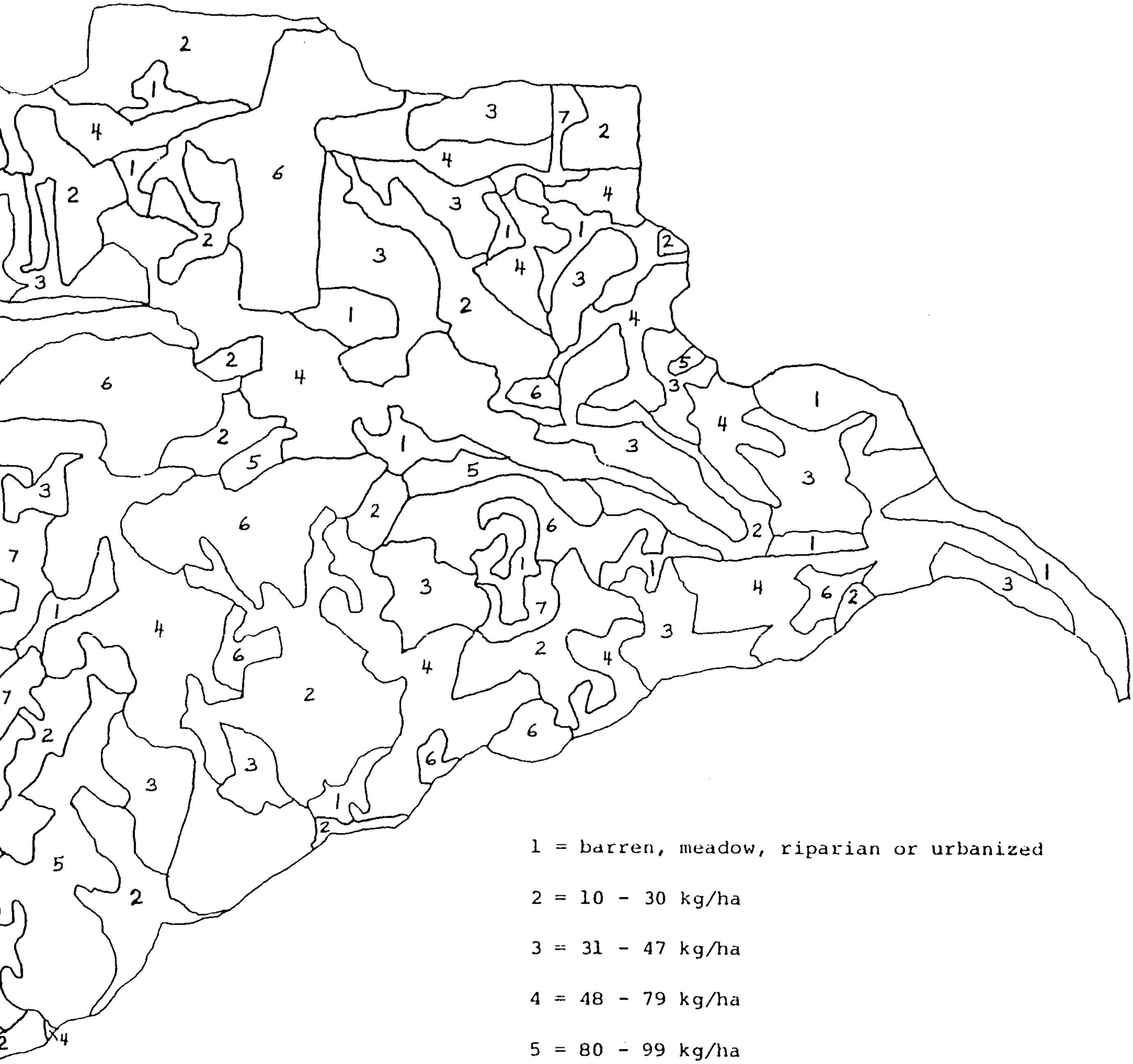
6 = 791 - 1119 kg/ha

7 = 1120 - 2069 kg/ha

FIGURE 14 Tree Biomass Phosporus Distribution in Ward Creek Watershed



orus Distribution in Ward Creek Watershed



1 = barren, meadow, riparian or urbanized

2 = 10 - 30 kg/ha

3 = 31 - 47 kg/ha

4 = 48 - 79 kg/ha

5 = 80 - 99 kg/ha

6 = 100 - 123 kg/ha

7 = 124 - 240 kg/ha

These values are ranked and divided into classes in Table 15. The classes for litter nitrogen mass are 0-212, 213-450, 451-761, 762-1325, and 1326-1924 kg/ha and for phosphorus, 0-21, 22-42, 43-72, 73-124 and 125-182 kg/ha.

Soil Nutrient Storage

The Tahoe Basin Area Soil Survey Report contains no information on phosphorus, but its Table 17 (Rogers 1974) gives nitrogen values for two (Tallac and Waca) of the three soil series in Ward Creek watershed. Zinke and Stagenberger (1974a) and Sierra Cooperative Pilot Project (1978) contain soil phosphorus information for Tallac and Waca soils.

Nitrogen Storage by Soil Map Units

The mapped units of soil phases and miscellaneous land types include small areas of different soils and land types. Therefore, I adjust the amount of nitrogen reported for samples of pure soil series to reflect the inclusions in map units. Information in the Soil Report descriptions of soil and land type map units gives the approximate amount of inclusions. The adjustment process generally consists of correcting values for pure soil and land types to compensate for differing amounts of particles greater than 2 mm in diameter and soil material depths as well as for the proportion of map unit areas occupied by inclusions. Soil map unit descriptions and my method for making specific adjustments are shown in more detail in Chapter 12.

The adjusted nitrogen storage values for each map unit are given in Table 16. They range in 13 levels from 605 kg/ha for rocklands (Ra) to

Table 15. Litter Nitrogen and Phosphorus Mass: Ranks and Classes

N Mass	Difference		Classes range (interval) kg/ha	Map Unit Number	P Mass	Diff.		Classes range (interval) kg/ha	Map Unit Number
kg/ha	kg/ha	%				kg/ha	%		
12				24	1			0-21 (21)	24
24	12	50	0-212 (212)	23,28	3	2	67		3,23,28
34	10	29		3	5	2	40		2,7,8,18,27
38	4	11		14					,19,32
48	10	21		18,27	8	3	38		57
49	1	2		19,32	9	1	11		14,26
66	17	26		2	10	1	10		6,11,22,31
67	1	1		8,7					,54
69	2	3		12	14	4	29		25,43
75	6	8		13	16	2	13		12
89	14	16		26,57	17	1	6		13,61,62,68
96	7	7		22,31	18	1	6		5,9,10,56
105	9	9		54					,64
132	27	20		6,11	19	1	5		21,30
138	6	4		25	25	6	24	22-42 (20)	33,40
139	1	1		15	28	3	11		4,45,51
147	8	5		43	29	1	3		20,29
176	29	16		56,64	31	2	6		55
177	1	1		21,30	32	1	3		15
181	4	2		61,62,68	34	2	6		60,67
244	63	26	213-450 (237)	5,9,10	49	15	31	43-72 (29)	38,39,48
265	21	8		40	52	3	6		35,42,46
272	7	3		33	58	6	10		71
277	5	2		20,29	62	4	6		59,66,72
300	23	8		45,51	81	19	23	73-124 (51)	34,41,44
325	25	8		55	90	9	10		37,47,50,52
356	31	9		60,67	97	7	7		58,65
380	24	6		4	108	11	10		63,70
521	141	27	451-761 (310)	38,39,48	141	33	23	125-182 (57)	36,49
554	33	6		35,42,46	168	27	16		69
619	65	11		71					
658	39	6		59,66,72					
864	206	24	762-1325 (563)	34,41,44					
962	98	10		37,47,50 52					
1026	64	6		58,65					
1149	123	11		63,70					
1501	352	23	1326-1924 (598)	36,49					
1783	282	16		69					

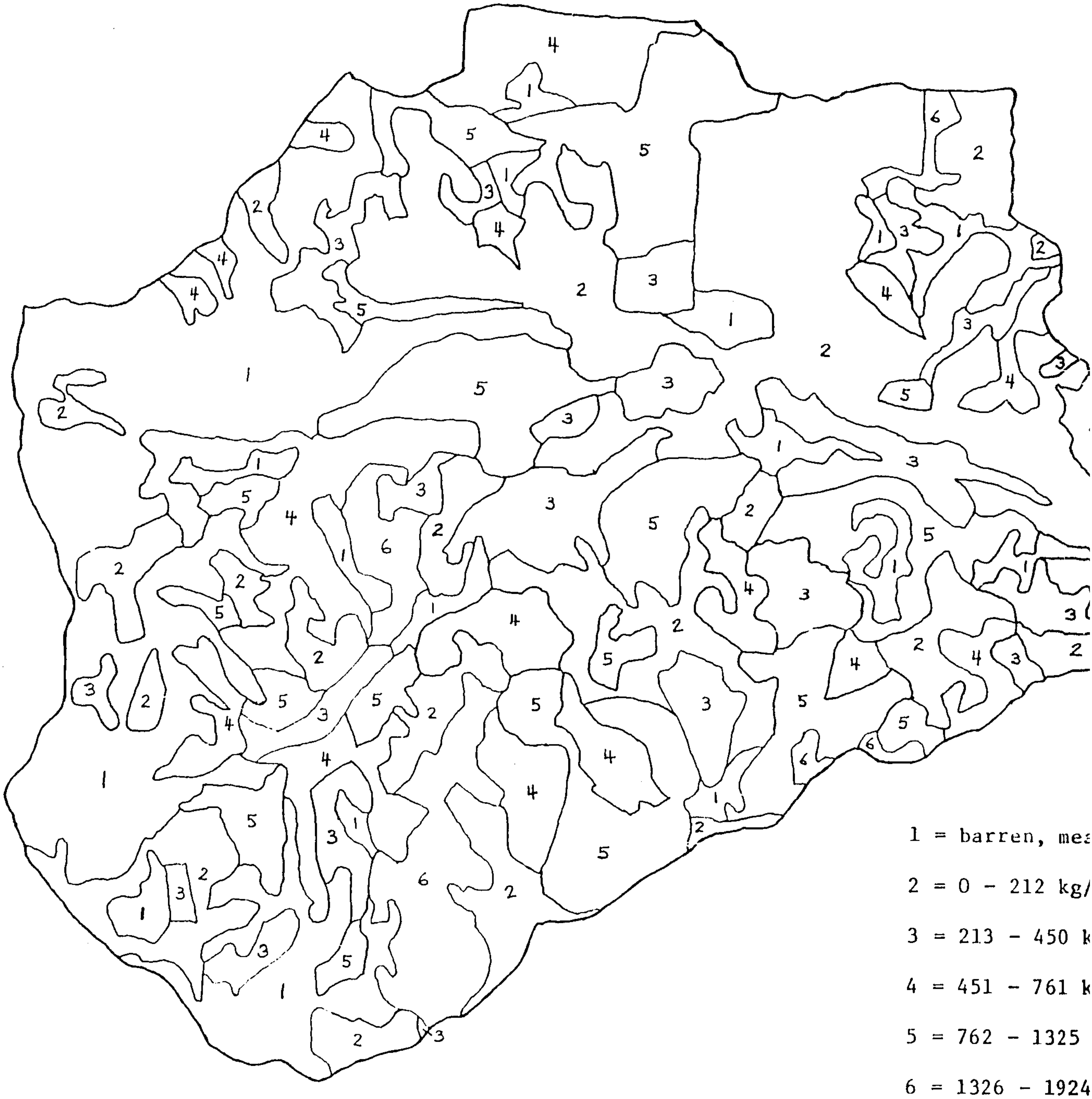
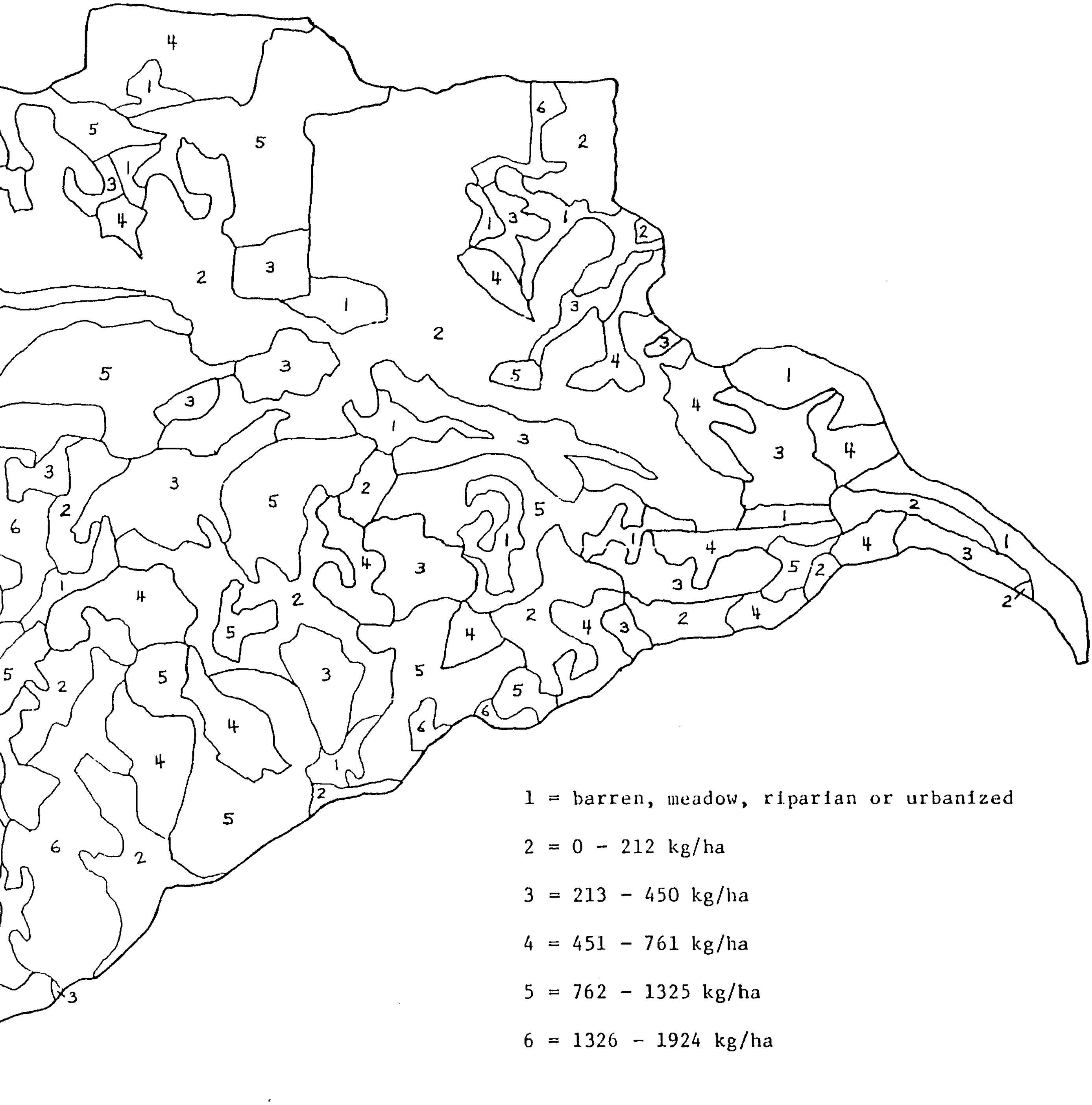


FIGURE 15. Litter Deposit Nitrogen Distribution in Ward Creek Watershed

trogen Distribution in Ward Creek Watershed



1 = barren, meadow, riparian or urbanized

2 = 0 - 212 kg/ha

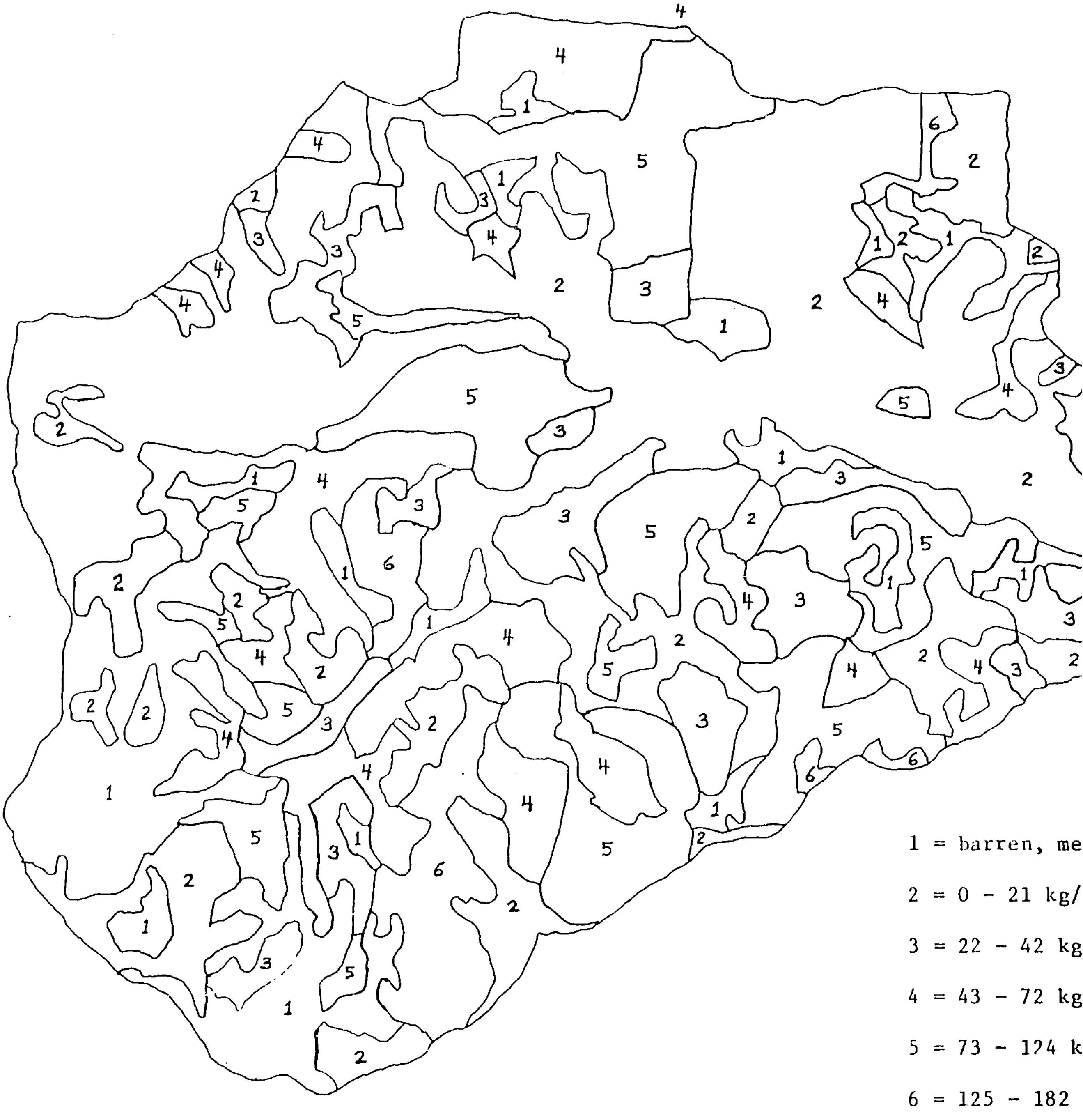
3 = 213 - 450 kg/ha

4 = 451 - 761 kg/ha

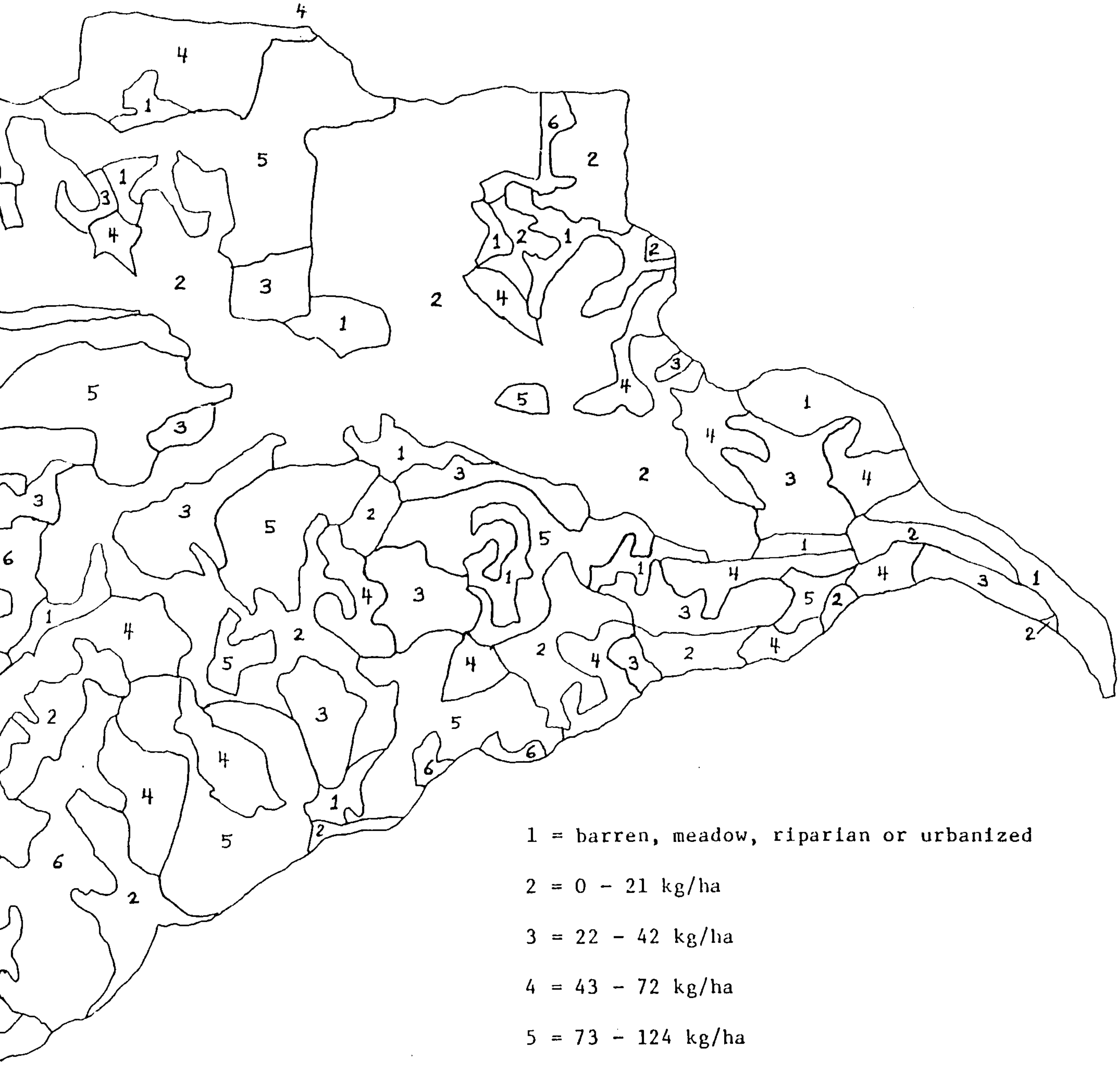
5 = 762 - 1325 kg/ha

6 = 1326 - 1924 kg/ha

FIGURE 16. Litter Deposit Phosphorus Distribution in Ward Creek Watershed



sphorus Distribution in Ward Creek Watershed



1 = barren, meadow, riparian or urbanized

2 = 0 - 21 kg/ha

3 = 22 - 42 kg/ha

4 = 43 - 72 kg/ha

5 = 73 - 124 kg/ha

6 = 125 - 182 kg/ha

12801 kg/ha for gravelly alluvial lands (Gr)--a 21-fold difference. Tallac and gravelly alluvial lands contain at least four times more nitrogen than any of the others. In Table 16, I group the values into five classes with ranges of 0-946, 947-1680, 1681-2534, 2535-3706 and 10706-13150 kg/ha. The miscellanous land types range from the highest to the lowest classes; not surprisingly, all the phases of a soil type readily fall into the same nitrogen mass class. The areal distribution of the soil total nitrogen classes is shown in Figure 17.

Total Nitrogen Storage

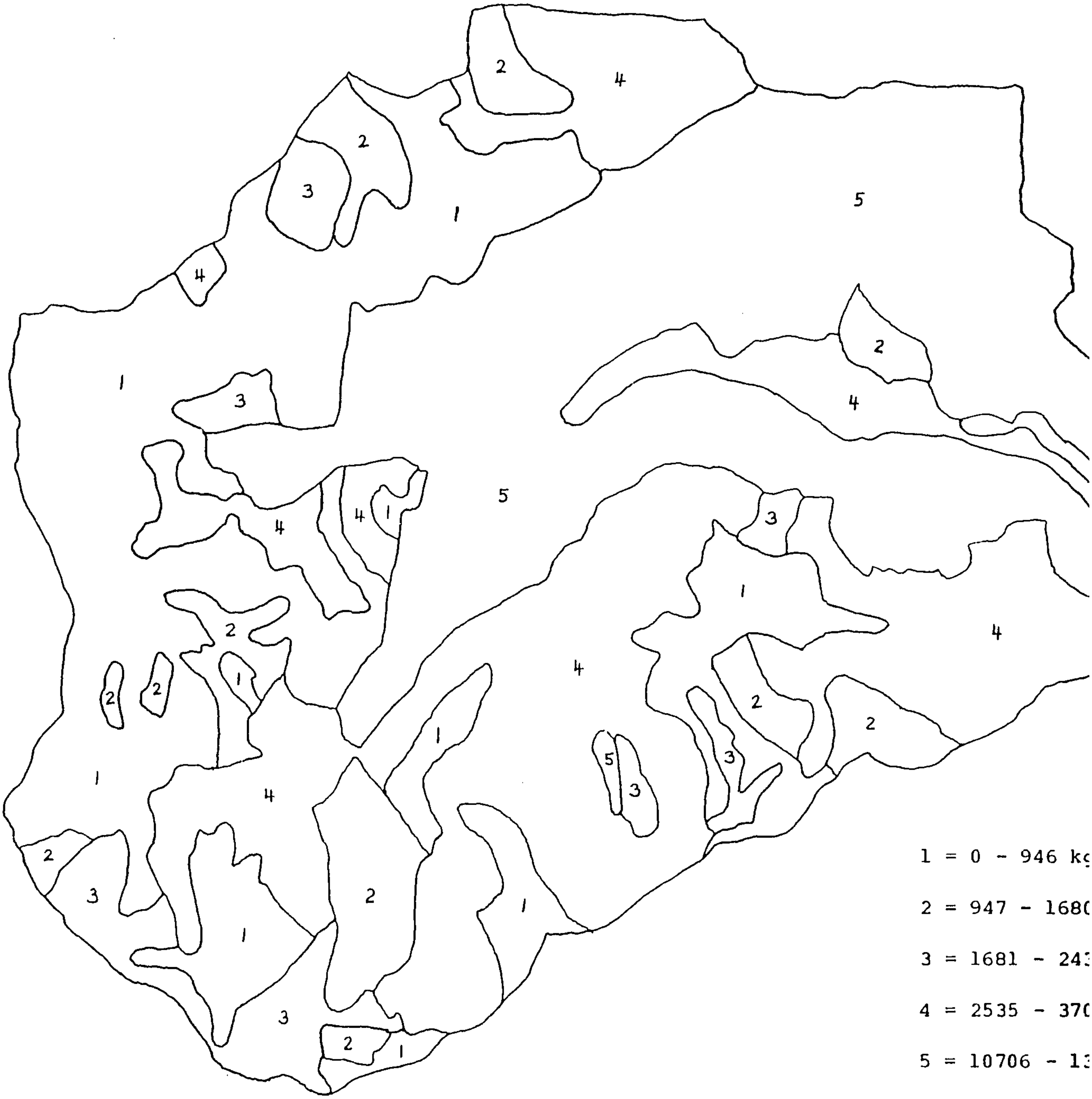
Superimposition of the maps of nitrogen in standing forest, litter deposits and soils yeilds a composite map of the distribution of total nitrogen stored in the watershed. Such a map is an initial input to the development of an overall LCC for watershed lands. I develop an analogous map of the distribution of suspended sediment-sized particles in the next chapter. These two maps are key pieces of information necessary for developing a LCC to protect lake water color and transparency.

As is typical in combining maps, nearly every nitrogen mass level of every variable occurs in combination with all others. Consequently a composite map of soil, tree and litter nitrogen shows high value combination totals of 13,152-17,743 kg/ha. Soil contains 81-74 percent of the total nitrogen and trees and litter, 9-15 and 10-11 percent, respectively. The much less common combination of high soil nitrogen values with low ones for trees and litter yield totals of 10,821-13,580 kg/ha with soil containing 97-99 percent of the nitrogen. The combination of the lowest soil nitrogen mass with low ones for trees

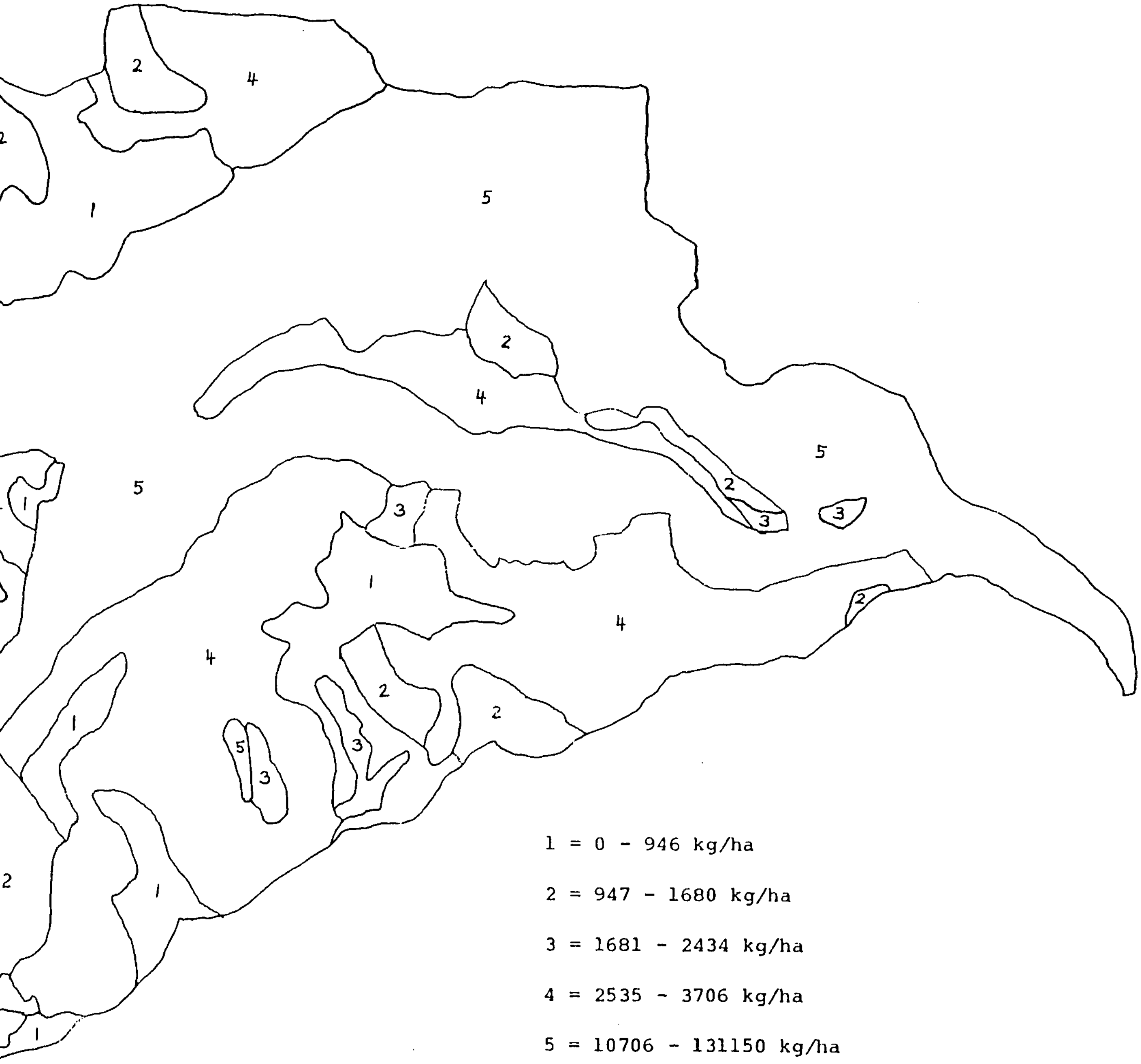
Table 16. Weight of Nitrogen in Mapped Soil and Land Types: Classes

Nitrogen Mass kg/ha	Difference		Class Range (interval) kg/ha	Map Unit
	kg/ha	%		
605			0-946	Ra
1288	683	53	947-1680 (733)	MxF
1439	151	10		MxE
1922	483	25	1681-2534 (853)	Rx
2207	285	13		Sm
2862	655	23	2535-3706 (844)	WcF
3145	283	9		WcE
11055	7910	72	10706-13150 (2444)	TeG
11071	16	0		TeE
11436	365	3		TdD
12274	838	7		TcC
12752	478	4		TkC
12801	49	0		Gr

FIGURE 17. Soil Nitrogen Storage Distribution in Ward Creek Watershed



torage Distribution in Ward Creek Watershed



1 = 0 - 946 kg/ha

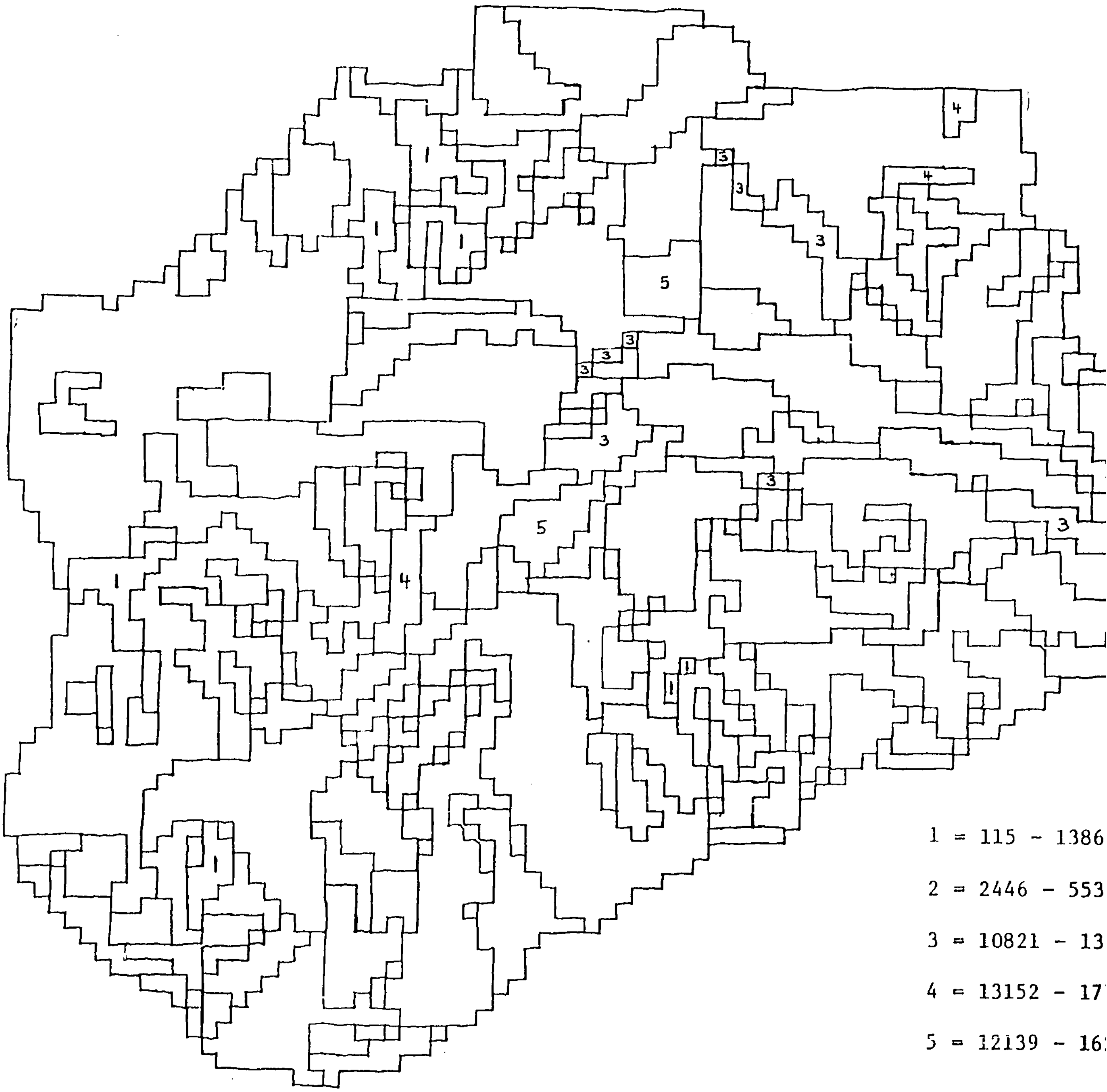
2 = 947 - 1680 kg/ha

3 = 1681 - 2434 kg/ha

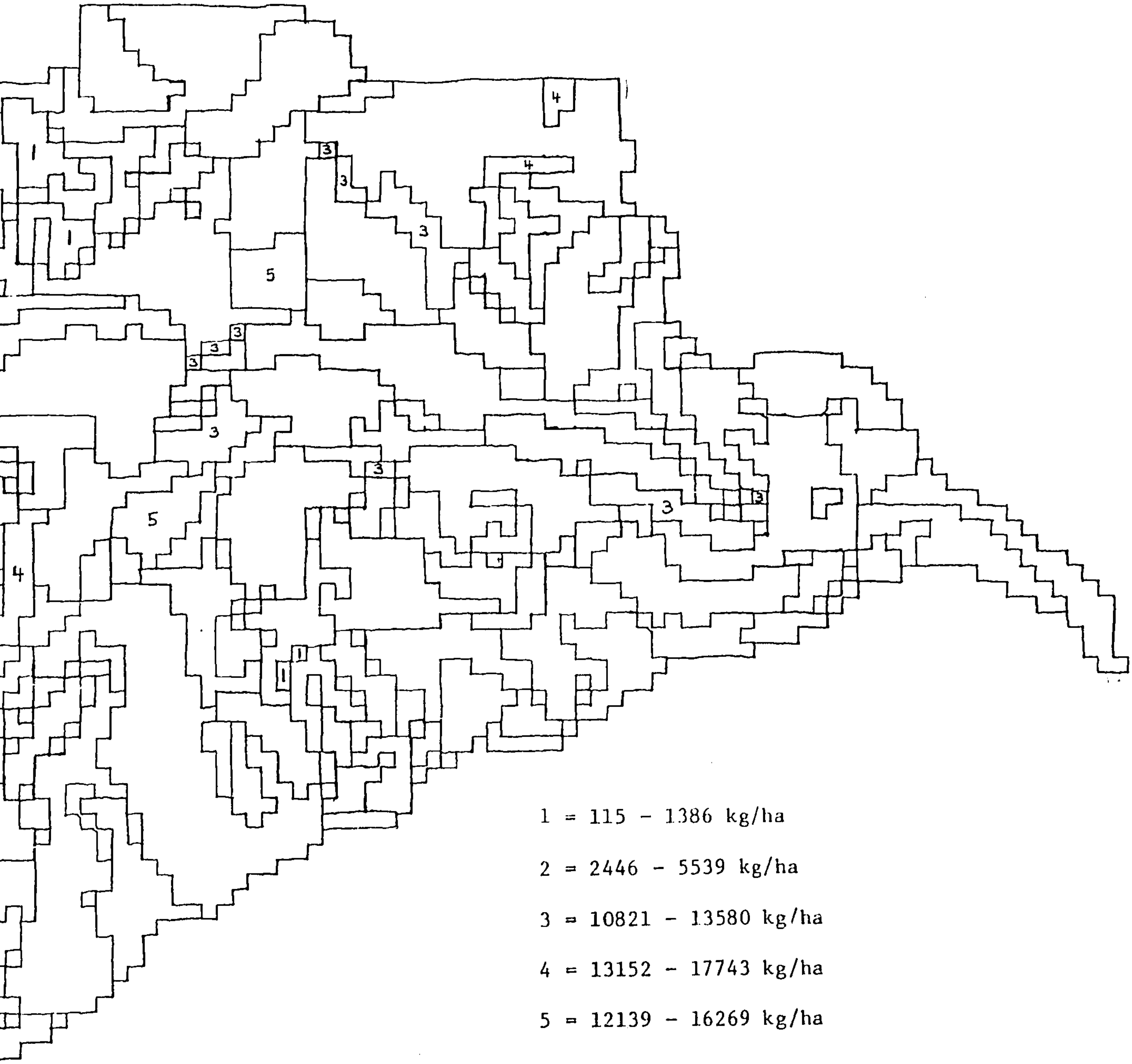
4 = 2535 - 3706 kg/ha

5 = 10706 - 131150 kg/ha

FIGURE 18. Combined Soil, Tree and Litter Nitrogen Masses



e and Litter Nitrogen Masses



and litter gives totals of 115-1,386 kg/ha with each respectively containing 0-68, 100-16 and 0-15 percent of the nitrogen. In the rare occasions when low soil nitrogen mass combine with high values for trees and litter, total nitrogen ranges from 2,446-5,539 kg/ha, with each respectively containing 0-17, 45-48 and 54-35 percent of the nitrogen.

Nutrient Management Implication

The objective of using stored amounts of nutrients and sediments as the basis for a LCC is to constrain their delivery to the lake, particularly as a consequence of land use activities in the watershed. Management of nutrient storage, in particular, can be approached from static or dynamic viewpoints or combinations thereof. Concentrating solely on the total amount of nutrients present in soil, trees and litter deposits, and using a LCC to minimize the disruption of their storage are both static approaches to nutrient management. My approach has conceptual weaknesses because it does not explicitly incorporate nutrient dynamics and nutrient availability considerations. Its limited emphasis does not suggest to planners that additional nutrient management strategies are available and are probably needed for long range protection of the lake.

Large portions of the total nutrients stored on watershed lands are in forms not directly available for use by terrestrial or aquatic plants. Low availability poses more of an evaluation problem for phosphorus compounds than for nitrogen because of the former commonly have low solubilities. Including nutrient availability as a factor in LCC is difficult because it has to be evaluated for both aquatic and terrestrial conditions and organisms. Forms of nutrients which might be unavailable to terrestrial plants may be (or readily become) available in an aquatic environment. Physical, chemical and/or biologic processes operating at microsite scales in soil, bottom sediments and on organisms surfaces are commonly capable of transforming unavailable to available nutrients. It is difficult to distinguish definitively between available and unavailable nutients in different environments, ambient conditions, time frames, etc. In contrast it is comparatively easy to quantify the total nutrients present on a site. Thus there are scientific and practical reasons for regarding all nutrients as having high enough potential availabilities to be included in evaluation schemes.

It is important to realize that protection of soil and plant cover only slows down the delivery of nutrients to the lake; it does not indefinitely prevent their release. The low natural rates of nutrient delivery that characterize Tahoe Basin streams cannot be maintained in perpetuity by protection of soils and plant cover.

New nutrients are continually being brought into the basin by precipitation, aerosols, dust, biologic nitrogen fixation, and the weathering of geologic materials continues to add nutrients from within the basin. Limits exist on the capacity of soils to store nutrients (Isik et al. 1974, Stark & Zuuring 1981); standing biomass reaches maximum in a few hundred years; deposits of plant litter increase only until a dynamic balance is attained between decay and soil incorporation rates and new litter fall. For example, Stangenberger's dynamic model (1979) indicates that white fir standing biomass is greatest at about 150 years (p. 175), and its litter deposits are greatest at 130 years (p. 127).

If watershed lands are protected from major disturbances for long periods, they reach a steady-state condition where as many nutrients are released by leaching from the soils, litter and vegetation as enter the ecosystem. Thus the terrestrial ecosystem has a finite capacity to delay the amount of nutrients delivered to the lake. Steady-state conditions do not occur suddenly once some threshold amount of biomass and litter has accumulated. In terms of the development of plant cover on watershed lands, the efficiency of nutrient uptake changes during succession and aging stages (Vitousek & Reimers 1975). The lowest nutrient stocks and uptake rates in the watershed are, of course, on the rocky barrens where precipitation-borne nutrients flow through without any biotic interruption. Nutrient uptake efficiency is initially low as vegetation becomes established, gradually increases as the soil becomes interlaced with roots and its surface covered by a canopy of foliage and litter deposits, reaches a maximum at intermediate stand age, and gradually declines as the rate of new biomass growth slows. Much of the timber forest cover in the Ward Creek watershed is over 100 years old (Leonard et al. 1979 p. 284); hence the red fir stands have another 80 years before their biomass reaches a maximum, but they are already passed the age (90 years) at which maxumum nutrient uptake occurs (Stangenberger 1979 p. 128).

As the mass of nutrients increases, so does the hazard of adverse consequences to lake water quality from their release by catastrophic natural events or accidental human actions.

Litter deposits are the major above-ground source of nitrogen introduction into soils (Swank & Wade 1980 p. 141, Powers 1981 p. 18).

A reason for not allowing litter masses to grow to their maximum is that their nutrients become increasingly incorportated in the soil--a location where there are few feasible options for nutrient removal. Because it is more beneficial to establish a plant cover to intercept and store incoming nutrients, nothing preventive can be done about the equally large or greater proportion of nutrients placed in soils stocks by the death, decay, sloughing and exudation of roots (Swank & Wade 1980 p. 143).

From the preceeding discussion it is obvious that, in the long run, preventing nutrients from reaching the lake is not just a matter of preventing soil erosion and maintaining intact the vegetation cover. It is also apparent that there are several distinct but related management objectives for controlling the amount of nutrients reaching the lake: 1) minimize release of nutrient accumulations by disruption of sites; 2) maximize nutrient uptake rates and detention periods in biomass, litter and soils; and 3) systematically remove some of the nutrient accumulation from watershed sites. LCC is for accomplishing the first objective by controlling the placement of land use activities with respect to the size of total nutrient stocks and conditions and processes controlling their release and transport. For both short- and long-term considerations and for other purposes, keeping the soil and vegetation cover in place must be a high priority environmental management objective. However in terms of maintaining low nutrient delivery to the lake, this delaying tactic cannot succeed forever and becomes increasingly ineffective and hazardous with time. Effective long range nutrient management requires that land planning and management agencies also take some action on the other two objectives.

Development of management strategies for the second objective--high nutrient uptake from precipitation, rock weathering inputs and fixation rates--requires management of the vegetation to keep the soil covered and to keep them growing rapidly and in their most productive growth stages--e.g., by quickly establishing new plant cover and not letting tree growth rates greatly slow down. It also includes controlling establishment of nitrogen fixing plant species such as mountain alder.

To accomplish the second objective, some action must be taken on the third. Management strategies must be developed for scheduling periodic removal of some of the accumulated nutrients. The obvious and probably only economical means of taking action on the third is carefully done logging with complete removal of the resulting foliage, branch and top slash but leaving litter deposits to protect the soil until a new vegetation cover is established. Once established the litter deposits should be removed.

Dynamic models such as those of Stangenberger (1979) are helpful for both rate oriented objectives. They indicate the age at which species specific biomass increase rates are highest (e.g., 120 years for RF, op. cit. p. 175) and when accumulations of different types of nutrient-bearing materials are at their maxima (150 years, loc. cit.). Litter deposits are most economically and readily removed by controlled burns volatilizing most of their nitrogen but leaving all their phosphorus. Controlled burns have the added advantage of reducing the flammable materials which become increasingly hazardous as standing biomass quantities increase in the aging vegetation cover. With careful scheduling, controlled burning can take place without exacerbating the sometimes serious air pollution conditions (WFRC 1979

p. 101-116) in the basin.

The amount of nutrients in soils is much greater than in litter deposits and trees--two to ten times greater for Ward Creek soils. Previous nutrient management research for forest lands has been directed toward obtaining and maintaining high nutrient levels on sites; hence there is little information on how to manage for a diametric objective, soil nutrient depletion. I know of no feasible management strategies for depleting the nitrogen and phosphorus in soils without those nutrients reaching the lake. Considerable evidence indicates it is difficult to deplete soil nutrient stocks by harvesting biomass and burning litter deposits. Those management techniques only slow down the rate of nitrogen accumulation in soils. Perhaps a strategy can be formulated for preventing long-term soil nitrogen increases or for reducing existing accumulations in locations where there are high concentrations (e.g., Tallac soils) that may be released by natural hazards or land use activities.

Nutrient Removal by Logging

The mere suggestion of logging will undoubtedly alarm those most concerned about environmental quality conditions in the basin. Their wariness and distrust is understandable because of the numerous instances where logging has been shown to stimulate sediment and nutrient releases from watershed lands and hence damage, rather than improve water quality (Utzig & Herring 1975, Bell et al. 1974, Sidhu & Case 1977, Anderson et al. 1976, JMMCE 1976). However, when compared to the feasibility of different nutrient management options, periodic harvesting and physical removal of the terrestrial biomass, primarily to remove their nutrient contents, is most viable. Stopping all further land development in the basin is probably not a politically acceptable option, but repairing damages which continue to bleed nutrients and sediments into the lake is a more realistic goal. However, diminishing state and federal funding for large scale environmental management activities probably obviates this option.

To preserve Lake Tahoe water color and transparency, some action must be taken to counteract the permanent damage to nutrient interception and storage processes that has occurred where high tree growth rate lands have been deforested and covered by urban development.* Action must also be taken to counteract the increased nutrient and sediment production coming from lands disturbed but not built upon by urbanization activities--e.g., cut and fill embankments, deforested areas and channels enlarged by increased stream flow volume.

If public fears of nutrient management by logging are too great, biomass nutrient harvesting and disposal could be done in the nonrenumerative manner the National Park Service uses in some places to return plant cover to earlier seral stages--i.e., cutting trees and burning them in place. This approach causes no ground surface disturbance by dragging logs; slopes are not disturbed by the construction of logging roads, and much of the nitrogen can be volatilized if the fires are hot.

---

* For perspective, the recommeded rate of fertilizer (16% nitrogen) application to lawns and golf courses adds 97.6 kg/ha/yr of nitrogen. Nearly all of this nitrogen is washed away as little above or below ground biomass storage occurs in grassland vegetation. The maximum mean annual uptake of nitrogen by red fir between the ages of 120 and 130 years is 7.41 kg/ha (Stangenberger 1979 p. 76), less than a thirteenth of the nitrogen application rate to grass.

The cut-and-burn-in-place approach may be rational in small isolated locations, but I believe it would be a profligate waste of valuable raw materials if used extensively. The "byproduct" of harvesting of nutrients stored in woody biomass can be jobs, building materials, energy and other societal benefits, thereby broadening public and private political support for environmental management activities in the basin. The cut-and-burn-in-place technique is such an obvious waste of resources that it would also offend the large segment of the public concerned about conservation of natural resources, rather than preservation per se.

Public funds for environmental management are becoming scarce because of increasing fiscal austerity by all levels of government. Thus a most important reason for removing large woody biomass rather than cutting and burning in place is the funds provided for careful nutrient and sediment management activities. The funds incidentally generated by the sale of logs could be used primarily to pay the cost of careful nutrient management activities via manipulation of woody plant biomass. Logging planned and done by agency personel primarily as a nutrient harvesting technique would avoid many of the difficulties with job performance quality that occur when revenue and profit generation are the primary behavioral motivators.

To remove timber without releasing other nutrients and sediments, and from on- and off-site stores, cutting and log removal must be done carefully using techniques not common in California. Helicopter, balloons and skyline yarding techniques (Studier and Binkley 1974, Dyrness 1972) are widely used in Oregon and Washington to remove cut timber without building haul roads and disturbing the soil by dragging logs to landings. Also seedlings must be replanted quickly and densely to rapidly cover the ground surface with their foliage and interlace the soil with their roots--to lose no time in reestablishing woody plant uptake and storage of precipitation-borne nutrients.

For logging to take place with the degree of control and safeguards needed to prevent release of nutrients and sediment and to gain public confidence that it can be done without causing those problems, some new formal relationships between government agencies must be developed. Particularly needed are cooperative arrangements between the Tahoe Regional Planning Agency (TRPA) and the U.S. Forest Service, which administer most of the lands on which biomass nutrient-timber harvesting would be done. TRPA is primarily responsible for environmental management of the basin, and hence is politically more able to ensure that harvesting is conducted solely for nutrient management objectives, rather than for economic returns to the U.S. treasury, local counties or logging firms.

Cutting and yarding have to be done with more care than I believe is consistently possible using contract loggers. Contract specifications cannot be written precisely enough to eliminate all legal "loopholes" and prevent the innovative deviousness that maximizes profits. Written job performance specifications cannot guarantee careful removal of the nutrients stored in tree biomass while not releasing nutrients and sediments stored in soils. Nor can job performance be inspected often enough, and with sufficient authority and thoroughness to attain biomass nutrient removal without causing other water quality problems. Probably the best means for quaranteeing consistently high quality job performance is for TRPA to employ its own specially trained and motivated team to do the cutting, yarding, replanting, controlled burning and other biomass manipulating nutrient management activities. Once yarded to roadside landings logs could be disposed of by sale to private firms using the traditional bidding approach.

Such an arrangement between TRPA and the U.S. Forest Service would be a unique procedure for timber harvesting on public lands. It would generate considerable political opposition from loggers fearing a precident for other environmentally sensitive public lands. However, I know of no watersheds where nutrient harvesting and removal should be a primary timber management objective. In some areas, sewage effluent is sprayed on forest lands (Foster et al. 1965), but trees are not harvested to remove nutrient accumulations. The timber harvesting options in environmentally and politically sensitive situations such as Tahoe are either no logging or very careful cutting, yarding and replanting. Standard quality logging is not truly an option since the quality of logging practices cannot be quaranteed by contract specifications, job inspection and supervision, enforcement, threat of litigation or blacklisting.

The financial arrangements between TRPA and the Forest Service must also be innovative and probably would require special legislative authorization. The two agencies would somehow share the receipts from the sale of the logs. Perhaps logging rights could be sold to the TRPA on a permanent basis, with the United States Treasury receiving the remainder of receipts from log sales once TRPA has deducted the costs of cutting, yarding, replanting, thinning and its other timber-nutrient management expenses. Or the Forest Service could handle sale of the logs via standard bidding procedures and reimburse TRPA for the cost of harvesting, replanting and managing cut areas. Whatever the form of the financial arrangement between the two agencies, it is highly plausible that timber could be harvested to remove its nutrient content while not causing other environmental problems.

CHAPTER 12

POTENTIAL SUSPENDED SEDIMENT QUANTITIES ON WATERSHED SITES

Chapter Scope

In this chapter I develop an estimate of the amount of potential suspended sediments in Ward Creek watershed--largely from data in the Soil Survey of the Tahoe Basin Area, California and Nevada (Rogers 1974).* I discuss the variability and reliability of my estimates and follow this with estimates of the potential effects of the quantities of fine particles in the soils on lake water color and transparency. Lastly I discuss the relative transportability of different size classes of soil particles.

Soil Type Particle Content

In Appendix Tables B4 through B10 I develop estimates of the amount of potential suspended sediments from the data given in the Soil Report for the soil types occurring in the Ward Creek watershed: Meiss, Tallac and Waca.

---

* Subsequently referred to as "Soil Report" or "Report" in this chapter.

FIGURE 19. Soil and Land Types of Ward Creek Watershed

of Ward Creek Watershed

Table 17. Soil and Miscellaneous Land Types of Ward Creek Watershed

Map Symbol	Area (ha)[a]	Names of Soils and Land Types
MxE a.	14.5	Meiss cobbly loam, 9-30% slopes
b.	3.3	
c.	3.7	
d.	25.3	
e.	45.3	
f.	6.7	
	98.8	
MxF a.	25.3	Meiss cobbly loam, 30-50% slopes
b.	19.3	
c.	13.4	
d.	5.9	
e.	5.6	
f.	15.2	
g.	17.1	
h.	1.9	
	103.7	
TcB a.	36.8	Tallac gravelly coarse sandy loam, seeped, 0-5% slopes
b.	1.1	
	37.9	
TcC a.	13.0	Tallac gravelly coarse sandy loam, seeped, 5-9% slopes
b.	10.4	
c.	11.9	
	35.3	
TdD a.	15.2	Tallac stony coarse sandy loam, 5-15% slopes
b.	201.8	
c.	1.9	
d.	81.8	
e.	4.5	
f.	80.6	
g.	8.2	
	394.0	
TeE a.	117.1	Tallac very stony coarse sandy loam, 15-30% slopes
b.	18.6	
c.	40.1	
d.	4.5	
	180.3	
TeG	12.3	Tallac very stony coarse sandy loam, 30-60% slopes
Tkc a.	38.6	Tallac very stony coarse sandy loam, seeped, 2-9% slopes
b.	84.4	
	123.0	
WcE a.	41.6	Waca cobbly coarse sandy loam-rock outcrop complex, 9-30% slopes
b.	34.9	
c.	12.3	
d.	42.0	
e.	41.2	
f.	1.1	
	173.1	

Table 17. Soils and Miscellaneous Land Types--continued

Map Symbol	Area (ha)	Names of Soils and Land Types
WcF a.	5.6	Waca cobbly coarse sandy loam-rock outcrop complex, 9-30% slopes
b.	45.3	
c.	67.3	
d.	33.8	
e.	262.0	
f.	115.2	
	592.2	
Gr a.	2.6	gravelly alluvial land
b.	1.9	
c.	42.7	
d.	44.2	
e.	4.1	
	95.5	
Px	1.9	sand and gravel pits

Map Symbol	Area (ha)	Names of Soils and Land Types
Ra a.	406.2	rockland
b.	5.6	
c.	3.7	
d.	43.8	
e.	18.6	
f.	37.5	
g.	73.9	
	589.3	
Rx a.	69.5	rock outcrop and rubble land
b.	12.3	
c.	3.3	
d.	3.0	
	88.1	
Sm a.	18.6	stony colluvial land
b.	11.1	
c.	7.1	
d.	8.5	
	45.3	

TOTALS (ha)

202.5	Meiss soil type (8.1%)
782.8	Tallac soil type (31.2%)
702.3	Waca soil type (28.0%)
1687.5	all soils (67.3%)
142.7	alluvial & colluvial lands (5.7%)
677.4	rock & rubble lands (27.0%)
820.1	all miscellaneous land types (32.7%)

15	soil & land types
70	map units

[a] Areas determined by polar planimeter on 1:24000 scale Tahoe Basin Area Soil Survey report maps. Measurement accuracy is 0.01 in.^{2} (±0.37 ha) for small units and never less than ±0.03 in. for large units.

The content of fine particles varies greatly between soil types (Table 18). Therefore, knowledge of the relative and absolute concentrations of fine particles in different soils is an important consideration in establishing comparative suspended sediment hazard ratings. In terms of potential environmental impacts, and hence of regulation design, it makes a great difference whether land use caused disturbances occur on Tallac or Meiss soils.

On an areal basis (i.e., kg/m^2), Tallac soils contain 3.9 and 8.3 times more total fine particles than Waca and Meiss soils, respectively. On a volume basis (i.e., kg/m^3) these ratios are 2.1 and 1.7. To a great extent the relative amount of total stored fine particles is directly proportional to a the depth of soil. However, Tallac soils are only twice as deep as Waca soils while containing four times as many particles. Thus relative depth is not the total reason for the large differences. Hence designers of regulations cannot assume that the amount of particles potentially released is merely a function of the depth of disturbance.

Particle Content Variations Within Soil Types

Most soil properties vary with depth. However, to facilitate discussion of particulate content variations in this chapter I generally talk only in terms of total content for full soil "material" depths. However, development activities usually do not imperil equally the release of particulates from all depths in soils. Particles closer to the surface (both on and off site) are more likely to be released by development disturbances. Deeper on-site particles are likely to be

Table 18. Summary of Particle Contents of Soils in Terms of Suspended Sediment Transport Categories

Tahoe Basin Soil Survey Report Table	Suspended Sediment Transportation Type									All Type Totals		
	Wash Load 0-0.35 mm			Empirical 0.35-1.0 mm			Impact Law 1.0-2.0 mm					
	Meiss	Tallac	Waca	Meiss	Tallac	Waca	Meiss	Tallac	Waca	Meiss	Tallac	Waca
Tab. 2 kg/m^3		521[a]	275		205	81		120	40		846	396
kg/m^2		885[a]	250		338	74		197	36		1420	360
Tab. 3 kg/m^3	400	370	224	32	73	24	48	116	32	480	558	280
kg/m^2	132	610	205	11	121	22	16	191	29	159	922	256
Tab.16 kg/m^3		632	293		254	91		102	67		988	450
kg/m^2		1043	268		419	83		169	61		1631	412
average kg/m^3	400	508	264	32	177	65	48	113	46	480	798	375
kg/m^2	132	846	241	11	293	60	16	186	42	159	1324	343

[a] Includes the 1% colloid particles.

released only by grading and other site excavation activities, and deeper, off-site, downslope particles by gully erosion and mass movements. Thus, both for evaluation of individual development proposals and LCC development, some consideration must be given to the relative release hazard of fine sediments located at different depths and the cumulative amounts that may be released by disturbances extending to different depths.

I can estimate the variation of fine particles with depth from the textural descriptions given for representative profiles of soils. However, for two soils the Report contains quantitative information on the variability of fine particle contents with depth--see Appendix Tables B8 and B10. The variability with depth information and relative concentration ratios are summarized in Table 19. The Tallac and Waca soils occupy nearly 60 percent of the watershed area. The highest weight variations per unit of depth are 2.84, 2.41 and 3.42 times greater than the lowest for Tallac's 0-0.35 mm, 0.35-1.0 mm, and 1-2 mm fractions, respectively. For Waca soils the ratios are 2.02, 2.09 and 2.39. These variations with depth are as great or greater than the differences between the average fine particle concentrations (kg/m^3) of the three soil types which are 1.28, 1.66, and 2.13.

The amount of fine particle variation at different depth intervals is even greater than the amount of difference between all map units--except for the rock, rock outcrop, rubble and colluvial land units. Information on concentration variation with depth obviously is important for evaluating potential impacts of proposed projects because detailed, site specific information is available on their areal extent,

Table 19. Variation of Fine Particle Concentrations with Depth

Soil Type	Depth Range	Depth Inter-val size	0-.35 mm Diameter			0.35-1.0 mm Diameter		
			Weight of Fine Particles		Larger: Smaller Ratio	Weight of Fine Particles		Larger: Smaller Ratio
	cm	cm	kg/m^3	kg/cm/m^2		kg/m^3	kg/cm/m^3	
Tallac	0-38	38	763	7.63		269	2.69	
TcC	38-53	15	539	5.39	1.42	188	1.88	1.43
	53-79	26	528	5.28	1.02	182	1.82	1.03
	79-107	28	405	4.05	1.30	242	2.42	1.33
	107-165	58	726	7.26	1.79	298	2.98	1.23
largest:smallest			1.88			1.64		
Waca								
WaF	0-23	23	314	3.14		97	0.97	
	23-36	13	257	2.57	1.22	76	0.76	1.28
	36-53	17	369	3.69	1.44	107	1.07	1.41
	53-79	26	261	2.61	1.41	84	0.84	1.27
	70-91	12	241	2.41	1.08	88	0.88	1.05
largest:smallest			1.53			1.41		

Table 19. Variation of Fine Particle with Depth (continued)

Soil Type	Depth Range cm	Depth Inter-val size cm	1.0-2.0 mm Diameter		
			Weight of Fine Particles		Larger: Smaller Ratio
			kg/m^3	kg/cm/m^2	
Tallac	0-38	38	130	1.30	
TcC	38-53	15	73	.73	1.78
	53-79	26	86	.86	1.18
	79-107	28	135	1.35	1.57
	107-165	58	83	.83	1.63
largest:smallest			1.85		
Waca	0-23	23	98	0.98	
WaF	23-36	13	57	0.57	1.72
	36-53	17	78	0.78	1.37
	53-79	26	50	0.50	1.56
	79-91	12	41	0.41	1.22
largest:smallest			2.39		

placement and depth of disturbances. Variability with depth is less valuable for LCC because it is not available for all soil and land types and because the mechanics of simultaneously handling depth and areal variations is difficult for LCC utilization of three-dimensional information. The numerous reversals of concentration with depth in both soils indicate that no simplifying working assumptions can be made about constant increases or decreases with depth.

Use of the aggregate statistic kg/m^2 of a soil land type best enables expression of the total potential fine sediment hazards for LCC purposes. Generally summary statistics are easier to use and hence more desirable for LCC development and for evaluations by land use planners. The accompanying reduction of evaluation flexibility and information detail is inevitable--a compromise that must be made for area-wide planning. The full information is still available for evaluation of proposed projects during the plan administration stage of regional environmental management.

Particle Content of Land Types

Undoubtedly the most serious data gap of the Soil Report is the absence of any quantitive information on the fine fraction contents of the miscellaneous land types covering a third of the watershed area. Analyses were not conducted on these areas because their soil materials are too variable to characterize (Rogers 1974 p. 44, 48, 50).

When the upper eight inches of depth contain 90 percent or more coarse fragments, areas are mapped as "miscellaneous land types" (Soil Survey Staff 1951 p. 215). The "Descriptions of the Soils" section of the Report provides some information on the miscellaneous land types useful for estimating their total fine particulate contents. The description of the texture of their soil materials also enables a rougher estimation of the particle size distribution in their fine fragments. In Appendix B I develop estimates of fine particles in the land types--primarily from information in the "Descriptions" section of the Report. The results are summarized in Table 20.

Particle Content of Soil Type Map Units

The particle content values calculated from the fine fraction analysis data in the three Soil Report tables (my Appendix Tables B1-B3) apply to pure soil types. The analyses were made for only one of the soil phases in the series--the one whose profile is described as "representative of the series." The values given in Report Table 3 are based on those in Report Table 2 on field examination and estimations based on experience with similar soils (Rogers 1974 p. 39) rather than independent measurements. Hence the value estimates of only 2 of the 14 soil and land types are based on actual analyses of samples. Typically included in soil and land type map units are some areas of the other types too small to map separately. In some cases, especially those involving evaluation of individual projects, it may be possible and important to delineate the smaller inclusions. In others, such as "complexes," they are inextricably intertwined. However, for area-wide LCC purposes it is more useful and practical to develop average value estimates for the particle contents of whole map units.

The amount and type of inclusions are usually stated in the Report description of each map unit. For each soil type, phase or land type in each map unit category I calculated estimates of the average fine particle content for the whole unit. My methods and assumptions for making these calculations are given and discussed in Appendix B. The resulting estimates are shown in Table 20. The amount of difference between fine particle contents in pure types and map units of types is nearly always less than 20 percent, though it is very large in some cases. Thus the correction can produce significantly different results.

Grouping Particle Content of Types

The 14 soil and land types are ordered in Table 21 with the amounts of estimated total fine particle content increasing toward the bottom. The average contents for the full depth of the soil materials range from 67 to 1350 kg/m^2 and from 74 to 813 kg/m^3. The individual map units should be kept separated for site-specific evaluation of individual project development proposals. However, for an area-wide LCC map it is always desirable to reduce the number of levels for individual classification variables. The number of possible and realized combinations of variables proliferates rapidly as they are superimposed, causing information management and new analysis problems if they become too abundant. Also the range of differences between some values of variables is probably not significant for capability evaluation distinctions. Frequently the values for variables exhibit an even, continous distribution--making their division into groups a completely arbitrary choice. Fortunately, particle content values for Ward Creek soil and land types show a stepped distribution, and hence are readily aggregated into four or five categories. If the percent difference between the particle content of soil and land types is used as the criterion for significant separations, four exist: 1) Ra, 2)

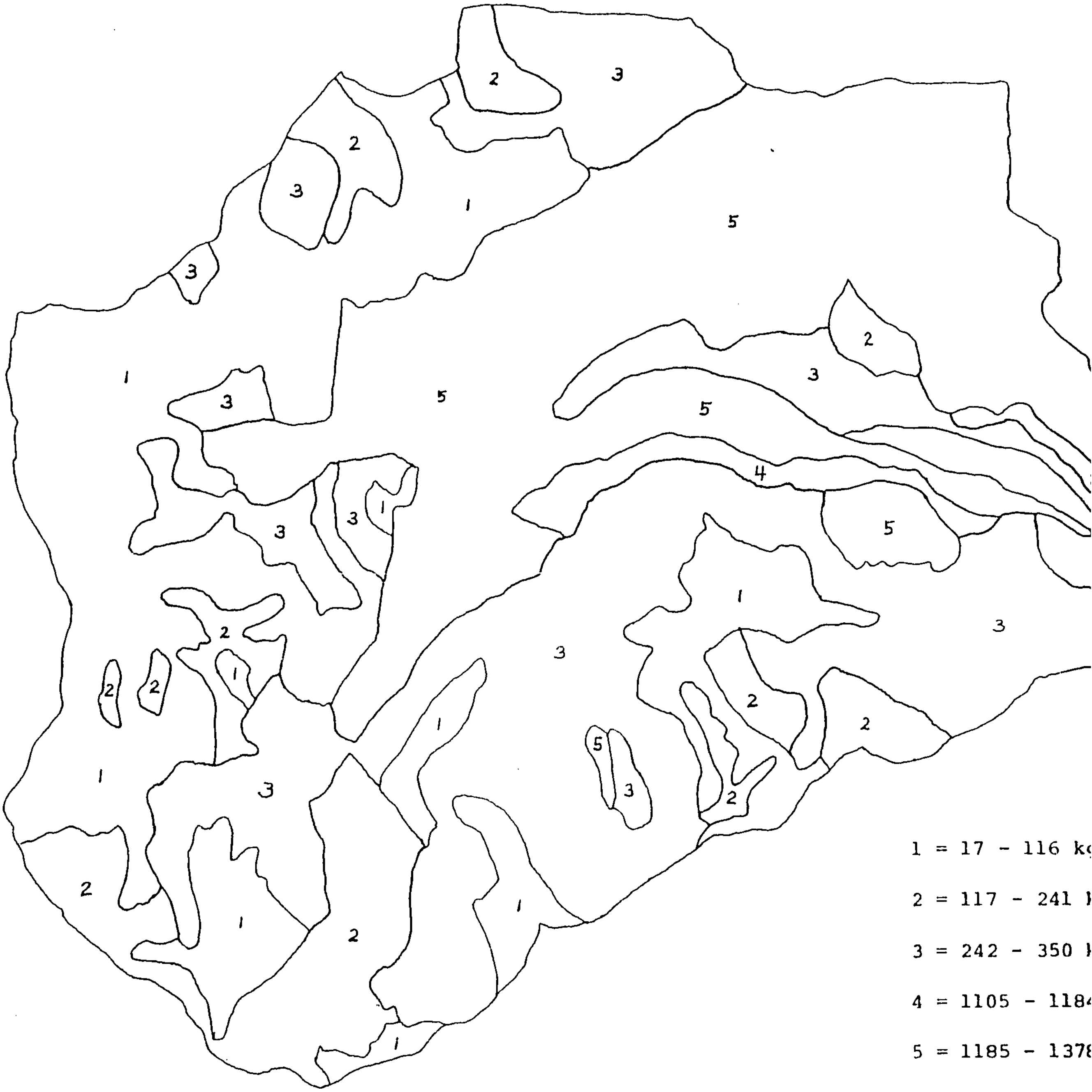
Table 20. Variations Between the Weight of Fine Particles In Pure and Mapped Types

Soil or Land Type	kg/m^2 in type		kg/m^3 in type	
	pure (% dif)	mapped	pure (% dif)	mapped
Meiss	160		480	
MxE	(+12.5)	180	(-4.8)	457
MxF	(+3.8)	166	(-6.6)	448
Tallac	1324		798	
TcB	(+2.0)	1350	(+1.9)	813
TcC	(+2.0)	1350	(+1.9)	813
TdD	(-3.3)	1280	(-3.3)	772
TeF	(-6.3)	1240	(-6.4)	747
TeG	(-15.6)	1117	(-15.5)	674
TkC	(-14.7)	1129	(-14.8)	680
Waca	343		375	
WcE	(-4.7)	327	(-1.6)	369
WcF	(-11.4)	304	(-4.8)	357
Ra	5		5	
	(+1240)	67	(+1380)	74
Sm	238		261	
	(+17.6)	280	(+17.6)	307
Rx	50		57	
	(+306)	203	(+198)	170

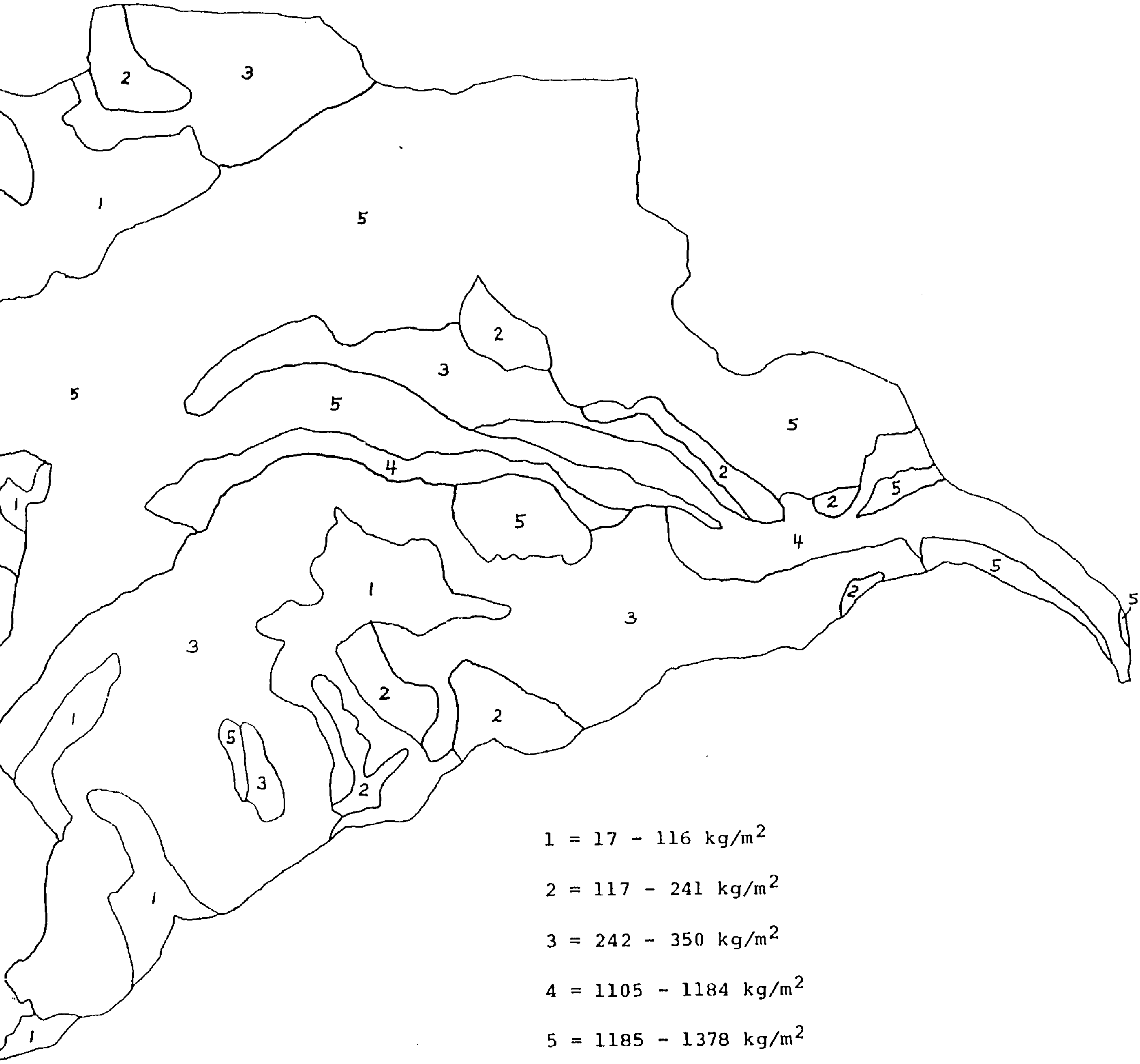
Table 21. Groupings of types Determined by the Size of Gaps Between Values

Soil or Land Type	Weight of Fines kg/m^2	Difference kg/m^2	%	Range of classes (interval) kg/m^2
Ra	67			17-116 (99)
MxF	166	99	60	117-241 (124)
MxE	180	14	8	
Rx	203	23	11	
Sm	280	77	28	242-350 (108)
WcF	304	24	8	
WcE	327	23	7	
TeG	1117	790	71	1105-1184 (79)
TkC	1129	12	1	
TeE	1240	111	9	1185-1378 (193)
TdD	1280	40	3	
Gr	1324	44	3	
TcB	1350	26	2	
TcC	1350	0	0	

FIGURE 20. Distribution of Fine Particle Abundance Classes



ine Particle Abundance Classes



1 = 17 - 116 kg/m^2

2 = 117 - 241 kg/m^2

3 = 242 - 350 kg/m^2

4 = 1105 - 1184 kg/m^2

5 = 1185 - 1378 kg/m^2

MxF, MxE and Rx, 3) Sm, WcF and WcE and 4) TeG, TkC, TeE, TdD, Gr, TcB and TcC. If the size of the difference between adjacent values for particle contents is used as the criterion for significant differences, five groups exist: 1)Ra, 2) MxF, MxE and Rx, 3) Sm, WcF and WcE, 4) TeG and TkC and 5) TeE, TdD, Gr, TcB and TcC. Both categorizations are defensible for different points of view. I prefer to use the latter five groups since the absolute amount of particles reaching the lake determines their effect on water color and transparency. A map showing the distribution of the five potential suspended sediment concentration categories is shown in Figure 20.

The five groups determined by gaps in the continuum of absolute values shows that 1) 677 ha (26%) have essentially no stored fine sediments, 2) 203 ha (8%) have low stores and low hazard potential, 3) 748 ha (30%) have enough stores to pose a moderate hazard, 4) 135 ha (5%) store large amounts posing high hazards, and 5) 708 ha (28%) store very highly hazardous quantities of suspended sediment sized particles.

Some Neglected Types of Fine Particles

The organic matter content in soils is often eliminated from sample before particle size analysis (Buckman and Brady 1969 p. 43, U.S. Soil Survey Staff 1951 p. 208). Therefore, the quantities of fine particles I calculated for the soil map land units is a conservative estimate. It probably does not include the considerable amount of fine organic particles existing in soils such as Waca, whose low bulk density is largely due to them. My calculation procedures for soil organic particules are given in Appendix B.

Nearly 20 percent, by weight, of the particles in some Ward Creek watershed soils may be organic. I have not increased the amounts calculated for soils from the particle analysis data in the Report because of uncertainty about whether organic particles were omitted by analysis procedures. Rather than possibly inflate the total count, I left out specific consideration of soil organic particles.

I also omitted the sometimes considerable weight of organic fine particles present in plant litter deposits on soils under forest cover. The Report describes Tallac soils as being typically covered with one to three inches of litter (Rogers 1974 p. 32) and Waca soils with two inches of fir litter and duff (op. cit. p. 37). These deposits contain a considerable weight of potential suspended sediments. Even their undecayed needles are readily broken down to fine size by physical and biologic forces during transport in streams. Those particulates in the fermentation and humus layers are already either broken down to fine sizes or decomposed suffícently to break up readily into small pieces early in fluvial transportation process.

Particle Size Relative Transportability Relationships

The behavior of different sized particles in motion varies so greatly that many different schemes have been devised to categorize sediments. Several general particle size classification schemes have been proposed in the illusory search for a "natural-behavior" determined classification system (Shea 1973) with universal validity--e.g., the Udden-Wentworth-Krumbein grade scale. However considerable evidence indicates that meaningful categories exist only within the context of their purpose (Shea 1973)--confirming the principle that all classification is purposive (Stamp 1961 p. 335 citing Hartshorne 1951). Consequently, little agreement exists between disciplines and applications on the placement of size category boundaries.

The analyses in the Soils Report provide categories of too many particle sizes for simple analyses and discussion. Therefore I regroup that information into three categories, thus enabling a discussion of particle size variability not possible using the aggregate statistics developed for LCC. My purpose is to divide particles into size categories reasonably (but not definitively) meaningful in terms of their relative transportability by flowing water and in terms of their effect on the color and transparency of the waters of the lake. The duration of their effect on water color and transparency is determined by the length of time they remain suspended in the visible portion of the water column (Appendix Table B11), by dilution of their initial concentration by lake waters (Chapter 15), by size-related selective light scattering and attenuation (Chapter 6), and by inflowing stream water mass placement in the lake (Chapter 15).

Biologic and electrostatic events cause even the smallest particles to settle gradually below Secchi depth--though theoretically colloids should be maintained in suspension by molecular turbulance as long as there is water. It is intuitively obvious that larger particles remain in the visible portion of the water column only until gravitational forces carry them deeper (Appendix Table B11).

Fortunately for simultaneous expression of the two purposes of my regrouping--relative transportability and ability to settle--the former is largely determined by the latter. Horizontal movement of particles first requires their suspension; those moving by rolling and bouncing have no effect on water color and transparency as they are too heavy to remain suspended for significant periods (Einstein 1964 p. 17 - 54 citing Kalinske). The amount of forward movement and the tendency to be transported horizontally is largely determined by the time in suspension rather than by the velocity of moving waters.

Suspension is related to flow velocity by fluid lift forces (Friedman & Sanders 1978 p. 97 - 99) analagous to the airfoil principle. However, these are relatively unimportant in sustaining suspension (Einstein 1964 p. 17 - 40), and saltation, while dramatic, plays only a minor role even in the suspension of larger particles (op. cit. p. 17 - 54 citing Kalinske 1942).

During calculation of the summary statistics used for the watershed sediment storage map (Appendix Tables B5, B6 & B8), I regrouped the particle size categories in the Report (Rogers 1°74) into three size ranges (0-.35, .35-1 and 1-2 mm) of general significance to discussing them in terms of their relative ability to be transported and to settle slowly or rapidly. The starting point for my establishment of those categories was the four category scheme of Krumbein and Sloss (1963 p. 196-198): 0-.001, .001-1, .1-1 and greater than 1 mm. I discuss the basis of their scheme and my adjustments of it in Appendix B.

The 0-.35 mm particles are the wash load which, once entrained in channel flows, is rapidly and completely transported to the lake where they take not less than 16.5 minutes (Appendix Table B11) in the calmest waters to settle below maximum Secchi depth. These particles are of most concern because of their high transportability and the relatively long duration of their effects on water color and transparency. The 0.35-1.0 mm particles move part of the time as suspended load and partly as bedload. Upon entering the lake they drop below maximum Secchi depth in less than six minutes in still waters. Particles in the 1-2 mm category move as suspended load in only the most turbulent water and settle to the bottom within a few minutes of entering the lake (e.g., Welch 1971 p. 114). The latter two size categories are primarily of interest because of their ability to be suspended by wave turbulence in the shallow, near shore zones of the lake where they are initially deposited.

Variations of Particle Size Categories Between Soils

Table 22 shows the ratios between soil particle contents of the three size categories discussed in the preceeding section. Note that there can be large differences between the relative abundances of size categories both in a soil and in different soils. For example, Meiss soils contain 12 times more 0-0.35 mm particles than 0.35-1.0 mm and 8.25 times more than 1-2mm, while the proportions of Tallac are more nearly balanced, having ratios of 3.3 and 3.9 respectively. Meiss soils contain only a fifth of the potential wash load sediments as Tallac soils and little more than half as many as Waca. Similarly, Meiss soils have only a twentieth as many 0.35-1.0 mm particles as Tallac and a quarter as many as Waca.

This information on the relative content of different-sized fine particles in soils can be used to more finely adjust the weighting of

Table 22. Ratios[a] Between the Contents of Particle Size Categories in Soil Types

Soil Type	Particle		Soil Types								
	abundance	size range	Meiss			Tallac			Waca		
	kg/m^2	mm	.35	.35-1	1-2	.35	.35-1	1-2	.35	.35-1	1-2
Meiss	132	.35	1.0	12.0	8.25	.18	.57	.68	.58	2.75	4.00
	11	.35-1	1.0	1.0	.68	.01	.05	.06	.05	.23	.33
	16	1-2			1.00	.02	.07	.08	.07	.33	.48
Tallac	748 18%[b]	.35				1.00	3.25	3.85	3.28	15.6	22.7
	230 47%	.35-1					1.00	1.19	1.01	4.79	6.97
	194 2%	1-2						1.00	.85	4.04	5.89
Waca	228 10%	.35							1.00	4.75	6.91
	48 54%	.35-1								1.00	1.45
	33 9%	1-2									1.00

[a] Ratio of those in left-side column to those in columns to right.

[b] Average and percent variation from 2 values given in Tables 17, 18 and 21 (Rogers 1974) for these soils.

suspended sediment hazards I establish using the total quantities of fines in soils. Such adjustments might be appropriate considering the greatly differing effect different size categories have on water color and transparency. However for these three soils, examination of the effect of relative abundance of the most important size category (0-.35 mm) on hazardness ratings reveals no reversals or even, I believe, important changes of the relative abundance. Total (0-2.00 mm) weight (kg/m^2) relationships show Tallac contains 8.25 times more than Meiss, and 3.9 times more than Waca and Waca 2.1 times more than Meiss. On the basis of the weight of only 0-0.35 mm particles, Tallac contains 5.7 times more than Meiss and 3.3 times more than Waca, and Waca 1.7 times more than Meiss. Adding on the next most important particle size category (0.35-1.0 mm) only increases the resemblance between the ratios.

Potential Sediment Effects on Water Transparency

The relationship between quantities of suspended sediment particles in soils and their potential effects on water color and transparency is of considerable interest because it provides perspective. In the case of suspended sediments, it is possible to estimate their direct effects on water transparency. In contrast, estimation of the impacts of increased nutrient additions on water color and transparency is difficult because many intermediate steps and synergistic and antagonistic conditions affect the occurrence, magnitude and duration of such water quality changes (Chapters 7, 13, 14 & 15). Introduced nutrients are, of course, invisible and affect those qualities only by stimulation of phytoplankton population growth--provided the other physical conditions necessary for growth are present. Most stream suspended sediments also carry nutrients into the lake (Cal SWRBC 1980 p. 23), and while in suspension the finer particles provide surfaces from which bacteria rapidly recycle nutrients in lake waters (Paerl & Goldman 1972, Jannasch & Pritchard 1972) However, the presence of suspended sediments directly causes water color and transparency changes.

The effect of a given amount of suspended sediment-sized particles on the transparency of lake waters can be estimated if some broad assumptions and questionable (but necessary) omissions are acceptable. What is the effect of all the fine particles in a cubic meter of soil being delivered to the lake? The initial necessary assumption is that delivery of particles from the site be simultaneous and complete. I must also assume that the sediment-laden stream water mass is placed in the top waters of the lake, above Secchi depth. I assume, for ease of calculation, that the particles are all the same size and are evenly distributed throughout the affected water mass (i.e., there are no higher or lower concentration patches). I must also assume that the particles are all minerals having a specific gravity of 2.65 gm/cc, and are cohesionless--i.e., do not form into agglomerations.

The estimation of water transparency effects is determined by calculating the particle volume (.35 mm diameter = .0000428 ml), number of particles per ml (23,364), number per gram (5770), per kilogram (8,816,787) and per the kilograms of particles in a cubic meter of soil (Meiss = 3.53×10^9, Tallac = 4.52×10^9, Waca = 2.33×10^9). The awareness that there are billions of 0-.35 mm particles in a cubic meter of any Tahoe soil is an impressive indication of the suspended sediment hazards soil materials represent. However, we should realize that the true amount is many magnitudes more, because that number is the consequence of using the largest member (.35 mm) of the size class in my calculations.

The relationship between suspended particle concentrations and light transmission and attenuation coefficients or Secchi disk visibility has been established by Gibbs (1974 p. 8), Scherz et al. (1973) and Jones & Wills (1956). I use the graph in the latter (op. cit. p. 440) of particle concentration (mg/l) versus Secchi depth to estimate the amount of lake water that can be degraded by the presence of certain concentrations of suspended particles. Converting the weight of the particles in a cubic meter of soil to milligrams, I calculate the volume of water needed to dilute that amount to 10 and 5 mg/l. The results show that, when diluted to a concentration of 10 mg/l, the 0-.35 mm particles in a cubic meter of Meiss, Tallac and Waca can reduce Secchi visibility to 1.8 m (5.9 ft) in 40,000, 51,300 and 26,400 m^3 of lake water, respectively. If I assume that their dispersal is confined to above that 1.8 m Secchi depth, the affected water volumes will discolor 2.2 ha (5.4 ac), 2.9 ha (7.2 ac) and 1.5 ha (3.7 ac) respectively. If diluted to 5 mg/l by intermixing lake water, the Secchi depth would be lowered to 3.3 m (10.8 ft) in 80,000; 102,000 and 52,800 m^3 respectively and affect areas above Secchi depth of 2.4 ha (5.9 ac), 3.1 ha (7.7 ac) and 1.6 ha (4.0 ac). The concentration of suspended sediment in surface runoff from general undeveloped forest lands in the basin, cut and fill banks, denuded areas, construction sites and unpaved parking lots is 66, 440, 990, 8700 and 17,000 mg/l respectively (Cal SWRCB 1980 p. 76).

The effect of particles on water transparency is not only a function of particle concentration (i.e., mg/l) but also is greatly affected by particle size. The smaller the particle diameter, the more particles reduce transparency for the same concentration (Edmondson 1980, Patrick 1962 p. 1510).* Hence as the 0-0.35 mm fraction contains many more particles smaller than its upper size limit, its effect on transparency would be greater than indicated--if the graph of Jones and Willis was based on data for only 0.35 mm particles. However, their graph was developed from data for a mixture of particles (mineral, detrital and living phytoplankton) with most considerably smaller than 0.35 mm. Therefore, in the example I used, the net effect of suspended sediments on water transparency is probably not as great as indicated.

From these idealized results it is apparent that relatively small amounts of soil can discolor and greatly decrease the transparency of large volumes and areas of lake water. Hence the problem of controlling the amount of soil materials reaching the lake from watershed sites is important if those qualities of water are to be protected. The persistence of "discolored" water masses depends upon particle settling rates and their dilution by mixing with lake waters. Still, the specter created by the scenario of what can happen under certain conditions provides a perspective on the magnitude of the hazard.

The amount of lake waters "discolored" annually by suspended sediments delivered by streams must be phenomenal--given the large

---

* Refer to Chapter 6 discussion of the relative light attenuation effects of different particle sizes.

volume of water that can be "colored" by the suspended sediments in only a cubic meter of soil. For example, Ward Creek delivered 0.914, 2.119 and 1.043 trillion grams of suspended sediment to the lake in water years (i.e., October to October) 1973, 1974 and 1975, respectively (Leonard et al. 1979 p. 287). The adjacent Blackwood Creek delivered 2.184 trillion grams of suspended sediments to the lake in 1975, twice as much as Ward Creek (loc. cit.), because Blackwood Creek watershed lands have been disturbed more recently . Both these watersheds produce ten times as much suspended sediment (per unit of land surface area and streamflow volume) as does the undisturbed watershed of Meeks Creek (op. cit. citing Kroll 1976). Glancy (1973) measured an annual average of 2.2 trillion grams of clay and silt particles (i.e., $\leq$.05 mm) delivered to the lake by Incline area streams. The current annual rates of total sediment introduction into the lake from all watershed lands are estimated to be 60-65 million kg (WFRC 1979 p. 126). The State Water Quality Control Board (1980 p. 64) estimates that, under natural conditions 3.1 million kg of suspended sediments would be introduced per year.

On a unit area basis, the rate of sediment production from undisturbed forest lands in the basin is estimated to be 38 kg/ha/yr (Cal. SWRCB 1980 p. 63). The rates Leonard et al. (1979 p. 287) measure for the Ward Creek watershed were 364, 844 and 416 kg/ha for 1973, 1974 and 1975, respectively, and 753 kg/ha for the Blackwood Creek watershed in 1975.

The cumulative effect of continued high suspended sediment inputs to Lake Tahoe, the nutrients they carry and the numerous bacterial nutient recycling surfaces they provide, are seriously affecting water transparency even in the mid-lake watermass. At the February 1982 Cal-Neva Wildlife Meeting,* Professor C. R. Goldman reported that for the past few years measurements in this formerly pristine quality water mass have shown an average Secchi transparency decrease of 0.8 m/yr. He attributes this change primarily to continued, unnaturally high rates of suspended sediment introduction from disturbed lands.

---

* The Transactions containing papers presented at the meeting will be published in late 1982.

CHAPTER 13

LAKE NITROGEN CYCLING

Chapter Scope

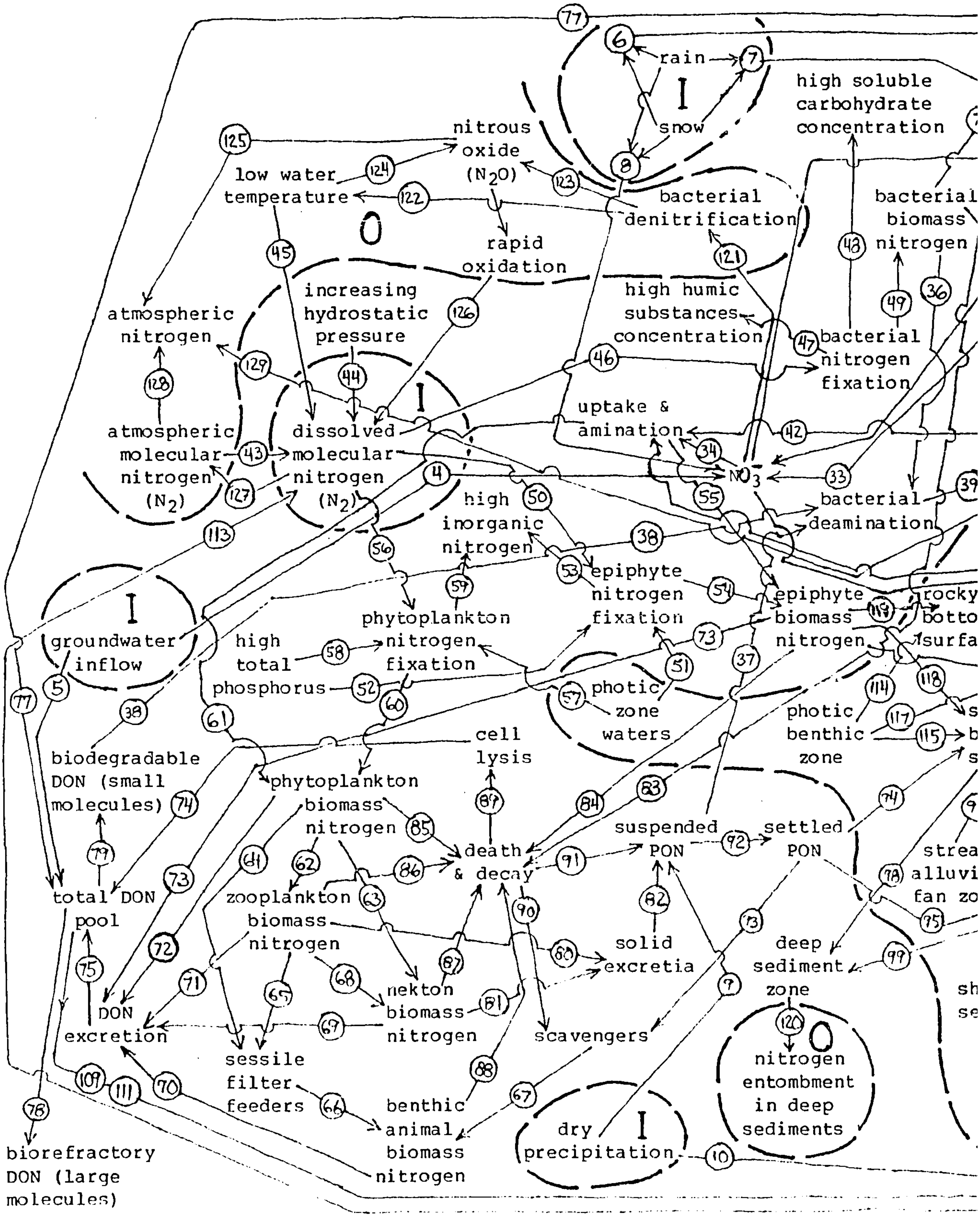
Nitrogen is generally considered to be the nutrient limiting the size of phytoplankton biomass in Lake Tahoe (Goldman, 1971, Leonard et al., 1979). Therefore, an understanding of the dynamics of nitrogen cycling within the lake and its watershed is particularly important for appreciating the potential effects of land use on the phytoplankton biomass of the lake, and consequently, on the color of its waters.

In this chapter I first give a brief overview of my conceptual model of the Lake Tahoe nitrogen cycle, then a diagramatic representation of the model followed by an explanation of it. Lastly I discuss the implications of the model with respect to potential land use activity-caused increases of nitrogen inputs to the lake.

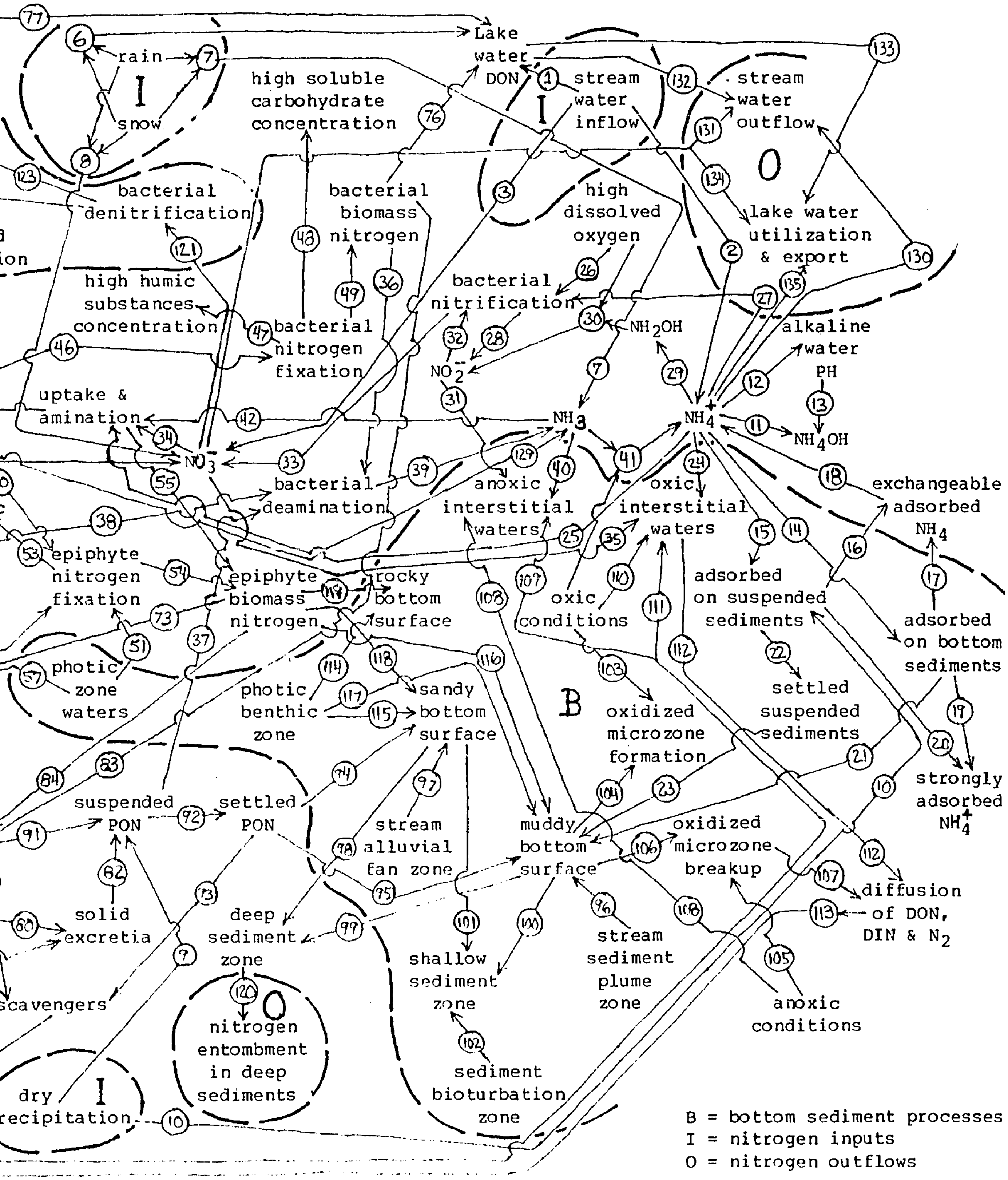
Model Overview

The model's 135 relationships are roughly divisible into four sections: 1) input sources, 2) chemical and biologic transformations and transfers, 3) lake bottom sediment processes, and 4) loss processes. The input sources are atmospheric liquid and solid precipitation, dissolving gasses, and above and below ground runoff from watershed lands. The transformations and transfers section contains oxidation and reduction transformations of inorganic nitrogen compounds with differing biologic activities, environmental conditions affecting those transformations, biochemical conversions of nitrogen to and from its organic forms, food chain transfers of nitrogenous substances and organisms' excreation of others. Nitrogen is a biologically very diverse and necessary nutrient; one which is reused 10 to 40 times each year by lake organisms (Golterman 1975 p. 117). As the phytoplankton biomass affecting water color presently is limited by the availability of nitrogen, this section of the model is particularly important for assessing the land use impacts on water color. Lake bottom nitrogen storage and conversion processes are important because typically most of the nitrogen in a lake is held in such deposits (Wetzel 1975 p. 212). Nitrogen losses occur via waters flowing out of the lake or by other means being permanently removed from it, via the return of gaseous nitrogen forms to the atmosphere, and via permanent burial deep in lake sediments. Some (Cal. State Water Resources Control board 1980 p. 33) consider the latter two removal processes as quantitatively more important than the former.

Figure 21. Conceptual Model of Nitrogen Cycling Within Lake



ng Within Lake



B = bottom sediment processes
I = nitrogen inputs
O = nitrogen outflows

Table 23. Legend for Lake Nitrogen Cycling Model

Number	Description
	Influx Sources
1.	Stream water-borne dissolved organic nitrogen (DON).
2.	Stream water-borne ammonium ion nitrogen (NH_4^+-N).
3.	Stream water-borne nitrate ion nitrogen (NO_3^--N).
4.	Groundwater-borne NO_3^--N.
5.	Groundwater-borne DON.
6.	Rain- and snow-borne DON.
7.	Rain- and snow-borne ammonia nitrogen (NH_3-N).
8.	Rain- and snow-borne NO_3^--N.
9.	Dry precipitation-borne particulate organic nitrogen (PON).
10.	Dry precipitation-borne adsorbed NH_4^+-N.
	Chemical & Biologic Transformations & Transfers
11.	Formation of ammonium hydroxide (NH_4OH) from lake NH_4^+.
12.	NH_4^+: NH_4OH ratio is determined by water's pH.
13.	Amount of NH_4OH formation is directly proportional to pH.
14.	NH_4^+ electrostatically adsorbed on bottom sediment particles.
15.	NH_4^+ adsorbed on suspended sediment particles.
16.	Easily displacable NH_4^+ adsorbed on suspended sediments.
17.	Easily displacable NH_4^+ adsorbed on bottom sediments.
18.	Displacable adsorbed NH_4^+ returned to lake waters.
19.	NH_4^+ strongly adsorbed on bottom sediment particles.
20.	Strongly adsorbed NH_4^+ locked in muddy bottom sediments.
21.	NH_4^+ adsorbed on muddy bottom surface sediments.
22.	Settling of sediments with strongly adsorbed NH_4^+ .
23.	Strongly adsorbed NH_4^+ deposited on muddy bottom surfaces.
24.	NH_4^+ in oxic interstitial waters within sediment deposits.
25.	Uptake of NH_4^+ by lake flora & conversion to biomass nitrogen.
26.	High dissolved oxygen concentrations needed for nitrification.
27.	Bacterial nitrification of NH_4^+.
28.	Conversion of NH_4^+ to nitrite ion (NO_2^-) by nitrification.
29.	Transformation of NH_4^+ to hydroxyl amine (NH_2OH).
30.	Rapid oxidation of NH_2OH to NO_2^-.

31. Formation & accumulation on NO_2^- in anoxic interstitial waters.
32. Bacterial nitrification of NO_2^- .
33. Formation of NO_3^- by bacterial nitrification.
34. Uptake of NO_3^- by lake flora & conversion to biomass nitrogen.
35. NO_3^- in oxic interstitial waters.
36. Bacterial deamination of organic matter.
37. Deamination of suspended PON.
38. Deamination of biodegradable DON.
39. Formation of NH_3 by deamination.
40. Formation & accumulation of NH_3 in anoxic interstitial waters.
41. Transformation of NH_3 to NH_4^+ under oxic conditions.
42. Uptake of NH_3 by lake flora & conversion to biomass nitrogen.
43. Atmosheric molecular nitrogen (N_2) dissolved in lake water.
44. Dissolved N_2 concentration increases with water depth.
45. Dissolved N_2 increases with decreasing water temperature.
46. Bacterial conversion of N_2 to combined N.
47. Dissolved humic substances retard bacterial conversion of N_2.
48. Dissolved carbohydrates retard bacterial conversion of N_2 .
49. Bacterial conversion of N_2 to biomass N.
50. Blue-green (B-G) algal epiphyte conversion of N_2 to combined N.
51. Algal N_2 fixation is a light-dependent photosynthetic reaction.
52. N_2 fixation does not occur if phosphorus supply is limiting.
53. N_2 fixation does not occur when inorganic N supply is abundant.
54. Epiphyte conversion of N_2 to biomass N.
55. B-G algal epiphyte conversion of combined N to biomass N.
56. B-G algal phytoplankton conversion of N_2 to combined N.
57. Algal N_2 fixation is a light-dependent photosynthetic reaction.
58. N_2 fixation does not occur if phosphorus supply is limiting.
59. N_2 fixation does not occur when inorganic N supply is abundant.
60. B-G algae conversion of combined N to phytoplankton biomass N.
61. Conversion of combined N to biomass N by all phytoplankton.
62. Conversion of phytoplankton biomass N to zooplankton biomass N.
63. Conversion of phytoplakton biomass by sessile filter feeders.
64. Consumption of phytoplakton biomass by sessile filter feeders.
65. Consumption of zooplankton biomass by sessile filter feeders

66. Conversion of plankton biomass N to filter feeder biomass N.
67. Conversion of zooplankton biomass N to nekton biomass N.
68. Conversion of inanimate organic N to scavenger biomass N.
69. Excretion of DON by nekton.
70. Excretion of DON by benthic animals.
71. Excretion of DON by zooplankton.
72. Excretion of DON by phytoplankton.
73. Excretion of DON by epiphytes.
74. Lake water DON originating from cell lysis.
75. Lake water DON originating from aquatic organism excretions.
76. Excretion of DON by bacteria.
77. Lake DON originating from stream & bulk precipitation inputs.
78. Lake DON decomposed very slowly by bacteria.
79. Lake DON readily available to bacteria.
80. Zooplankton fecal pellet nitrogen.
81. Nekton fecal nitrogen.
82. Solid excretia added to suspended PON.
83. Dead bacteria.
84. Dead epiphytes.
85. Dead phytoplankton.
86. Dead zooplankton.
87. Dead nekton.
88. Dead benthic animals.
89. Release of carcass N by abiotic decomposition processes.
90. Conversion of carcass N to scavenger biomass N.
91. Dead & decomposing carcass additions to lake water PON.
92. Settling of PON to lake bottom surfaces.
93. Conversion of settled PON to scavenger biomass N.

Bottom Sediment Processes

94. PON settled onto sandy bottom deposits.
95. PON settled onto muddy bottom deposits.
96. Deposition of more fine particles by stream sediment plume.
97. Deposition of more sand on stream alluvial fan.
98. Deep burial of settled PON by deposited sand.

99. Deep burial of settled PON by deposited fine particles.
100. Shallow burial of PON by fine sediment particles.
101. Shallow burial of PON by sand particles.
102. Release of bottom sediment N by bioturbation.
103. Formation of oxidized microzone by oxic water conditions.
104. All N forms locked in muddy sediments by microzone seal.
105. Breakup of oxidized microzone by anoxic water conditions.
106. Release of nitrogenous substances locked in by microzone seal.
107. Diffusion of DON & DIN from bottom sediments into Lake waters.
108. Formation of NO_2^- & NH_3 in anoxic interstitial waters.
109. DON in anoxic interstitial waters.
110. Formation of NO_3^- & NH_4^+ in oxic interstitial water.
111. DON in oxic interstitial waters.
112. Diffusion of DON & DIN from oxic interstitial waters.
113. Diffusion of N_2 from sediments into overlying waters.
114. Photic zone rocky lake bottom.
115. Photic zone sandy lake bottom.
116. Photic zone muddy lake bottom.
117. Epiphyte biomass N on muddy photic zone lake bottom deposits.
118. Epiphyte biomass N on sandy photic zone lake bottom deposits.
119. Epiphyte biomass N on rocky photic zone lake bottom deposits.

Loss Processes

120. Permanent entombment of deeply buried N in sediments.
121. Bacterial denitrification of NO_3^-.
122. Bacterial denitrification inhibition by low water temperature.
123. Formation of N_2O by denitrification of NO_3^-.
124. Low temperature favors denitrificaton of NO_3^- to N_2O.
125. Diffusion of N_2O from lake waters into the atmosphere.
126. Rapid oxidation of dissolved N_2O to N_2.
127. Diffusion of N_2 from lake waters into the atmosphere.
128. N_2 returned to atmospheric N pool by in-lake dentrification.
129. Diffusion of NH_3 from lake waters into the atmosphere.
130. NH_4^+ leaving in lake outlet water flow.
131. NO_3^- leaving in lake outlet water flow.
132. DON leaving in lake outlet water flow.

133. DON leaving via lake water utilization & exported waste waters.

134. NO_3^- leaving via lake water utilization & exported waste waters.

135. NH_4^+ leaving via lake water utilization & exported waste waters.

Explanation of Lake Nitrogen Cycling Model

Influx -Sources

Nitrogen is carried into the lake by stream waters in several forms; dissolved organic (DON) (1), ammonium ion (NH_4^+) (2) and nitrate ion (NO_3^-) (3). Ground waters entering the lake bring in nitrogen in NO_3^- (4) and DON (5) forms. Rain an snow deposit DON (6), NH_4^+ (7) and NO_3^- (8) in the lake. Dry precipitation (dust) deposits particulate organic nitrogen (PON) (9) and NH_4^+ adsorbed to other particles (10) in the lake.

Chemical & Biologic Transformations & Transfers

Some of the NH_4^+ in lake waters forms ammonium hydroxide (NH_4OH) (11), and the relative abundance of NH_4^+ compared to NH_4OH is directly proportional to the acidity or alkalinity of--i.e., water pH (12)(13). Some lake water NH_4^+ is electrostatically adsorbed to suspended (15) and bottom sediments (14). Some of the adsorbed NH_4^+ is easily displaced (16)(17) (particularly that recently adsorbed) and readily returned to lake waters (18). With time, adsorbed NH_4^+ becomes strongly fixed to particles in surficial (21) and deeper (20) bottom sediments (19). Some settling suspended sediments containing strongly adsorbed NH_4^+ (22) also are deposited on lake bottom surfaces (23).

In the interstitial waters within lake sediment deposits, the NH_4^+ and NO_3^- forms exist in significant quantities only if oxic conditions (free molecular oxygen) are present (24)(35). Under the typical anoxic conditions (little or no free, molecular oxygen) in interstitial waters, chemical equilibria convert NH_4^+ to ammonia (NH_3) which accumulates in lake bottom sediments (40). The reverse chemical transformation occurs under oxic conditions (41). When high concentrations of dissolved oxygen (DO) are present (26), certain species of bacteria convert NH_4^+ to nitrite ion (NO_2^-) by a biochemical process termed nitrification (27) (28). Under high DO concentrations, some NH_4^+ is also converted to hydroxylamine (NH_2OH) (29), which rapidly oxidizes to form nitrite ion (NO_2^-) (30). Some NO_2^- also forms and accumulates in anoxic interstitial waters (31). Certain bacteria convert NO_2^- to NO_3^- by the process of nitrification (32)(33). Rooted plants growing on bottom deposits rapidly take up NH_4^+ (25), NH_3 (42) and NO_3^- (34) from interstitial waters and adsorbed on particle surfaces and convert it to organic forms in their biomass (25).

Certain types of bacteria also break down (deaminate) amines (NH_2^-), (the principal form of nitrogen in organic matter (36)) in sediments, suspended PON (37) or biodegradeable DON (38)) to form NH_3 (39).

Considerable quantities of nitrogen gas (N_2) from atmospheric sources are dissolved in lake waters (43), and the concentration increases with water depth (44) (due to increasing hydrostatic pressure) and with decreasing water temperature (45). Some dissolved N_2 is converted to chemically combined organic and inorganic forms of nitrogen (46), especially bacterial biomass nitrogen (49), but this process is inhibited by dissolved humic substances (47) and carbohydrates (48). Epiphytic and planktonic blue-green algae also$_2$ convert dissolved N (50)(56) to chemically combined forms of nitrogen stored in their biomass (55)(60), by light-dependent photosynthetic reactions (51)(57) inhibited by low concentrations of dissolved phosporus (58) and high dissolved inorganic nitrogen (DIN) concentrations (53)(59).

All other types of lake phytoplankton also convert DIN to organic forms in their biomass (61), and their consumption by zooplankton and sessile filter feeders (64) converts much of their biomass nitrogen to predator biomass nitrogen (62)(63). Some zooplankton are also consumed by sessile filter feeders (65), nekton (large swimming organisms) and larger zooplankton, and much of their biomass N is converted to the biomass of those predators (66)(67). Dead PON is also consumed by scavengers and converted to their biomass (68).

In addition to the exogenously produced DON added to lake waters by stream and bulk (wet, dry and frozen) precipitation (77), all lake organisms add DON to lake waters (75) by active or passive means. Nekton, benthic animals and zooplankton add DON in the unassimilated wastes from their digestive and absorption processes (69)(70)(71); zooplankton, phytoplankton, epiphytes and bacteria by leakage through their cell walls (71)(72)(73)(76). Some lake water DON is also produced by the lysis (spontaneous breakdown) of dead cells (74). A portion of lake DON is biorefractory and hence can be broken down only slowly by bacteria (78) and other processes.

All lake organisms, some while alive, all in death, add PON to lake waters and sediments. Zooplankton and nekton add PON via fecal excretions (80)(81)(82); bacteria, epiphytes, phytoplankton, zooplankton, nekton and benthic animals via their carcasses (83)(84)(85)(86)(87)(88). Some of the PON in these carcasses is converted to DON and DIN by abiotic decomposition processes (89) and some is converted to biomass nitrogen (90) of floating or swimming scavengers. Some decomposing carcasses are broken up into finer particles as they settle through the water column (91). That portion of carcass PON not dissolved nor consumed during its fall through the water column settles to the lake bottom (92) onto sandy (94) or muddy bottom deposits (95), where it is almost entirely converted by scavengers to their biomass nitrogen (93).

Bottom Sediment Processes

PON deposited on lake bottom sediments and not consumed by scavengers nor dissolved by biotic and abiotic decomposition processes is buried as more sand (97) and fine particles (96) are deposited on the submerged portions of alluvial fans at stream mouths and farther out by plumes of stream sediment. Eventually some PON is buried so deeply by deposited sand and fine particles (98)(99) that it becomes permanently entombed (120). While buried at only shallow depths beneath deposits of sand and fine particles (100)(101), some of the PON is released incidental to bioturbation of bottom sediments (102).

When lake bottom waters have high DO concentrations, as they do at Lake Tahoe, a thin, chemically cemented, impermeable crust forms (103) termed the oxidized microzone sealing in all forms of nitrogen (104) in muddy sediments. Some of the NO_2^-, NH_3 and DON in the anoxic interstital water below the crusts (107)(108) diffuses (107) through the oxidized microzone crust where it is penetrated by benthic animal burrows, broken by bioturbation or when the oxidized microzone crust is dissolved by anoxic conditions in overlying waters (105)(106). Where an oxidized microzone crust does not exist for some reason, the NO_3^-, NH_4^+, DON and N_2 in the thin oxic surface zone of sediments (110)(111) (113) also diffuse into overlying waters (112).

On some areas of lake bottom materials (rocky, sandy or muddy)

(114)(115)(116) in the photic zone, some DIN in bottom sediment deposits and interstitial waters is also converted to epiphyte, and less commonly, macrophyte biomass nitrogen (117)(118)(119).

Loss Processes

In addition to all forms of nitrogen in sediments essentially lost by being sealed off from exchange with lake waters by deep burial (120), the pool of biologically available nitrogen is reduced by the conversion of some forms under certain circumstances to gases which can escape back into the atmosphere (125)(127)(128)(129). Some NO_3^- is converted to nitrous oxide gas (N_2O) (123) by certain types of bacteria (121)--a denitrification process favored by low water temperatures (124). The resulting dissolved N_2O is rapidly oxidized to N_2 gas (126). Some of the ammonia gas (NH_3) formed and existing under anoxic conditions also diffuses into overlying waters and escapes into the atmosphere (129).

Some of the total supply of NH_4^+, NO_3^- and DON in lake waters leaves with waters flowing out of the outlet (130)(131)(132). Some lake water DON, NO_3^- and NH_4^+ also leaves with waters pumped for drinking and other uses and then exported from the basin (133)(134)(135).

CHAPTER 14

LAKE PHOSPHORUS CYCLING

Chapter Scope

Phosphorus is generally considered the nutrient limiting the size of phytoplankton biomass in most lakes (Schindler 1976, Slater & Borg 1978, Wetzel 1975 p. 243). It is not considered to currently constrain the amount of phytoplankton growth in Lake Tahoe (Leonard et al. 1979). However, control of the rate of phosphorus additions to lakes is much more feasible than control of nitrogen additions (Wetzel 1975 p. 244). If stream phosphorus concentrations could be lowered by careful watershed management practices and appropriate land use regulations, theoretically the impact of nitrogen additions on lake algal biomass could be lessened. It is at least conceivable that phosphorus could be made the limiting nutrient in Lake Tahoe. For these reasons it is important to understand the dynamics of phosphorus cycling within the lake, the effect of cycling on the phytoplankton biomass of the lake, and consequently, on the color of its waters.

In this chapter I first give a brief overview of the organization of my conceptual model of the lake phosphorus cycle, followed by a diagrammatic representation and explanation of the model.

Model Overview

The model's 127 relationships are divided into four sections: modes of phosphorus influx; chemical and biologic transformations and transfers of phosphorus in the water column between particulate (living and dead) and dissolved organic and inorganic forms; similar transformations and transfers occurring in the bottom sediments; and processes by which phosphorus leaves the lake or is lost from biologically active zones.

Description of Lake Phosphorus Cycling CEM

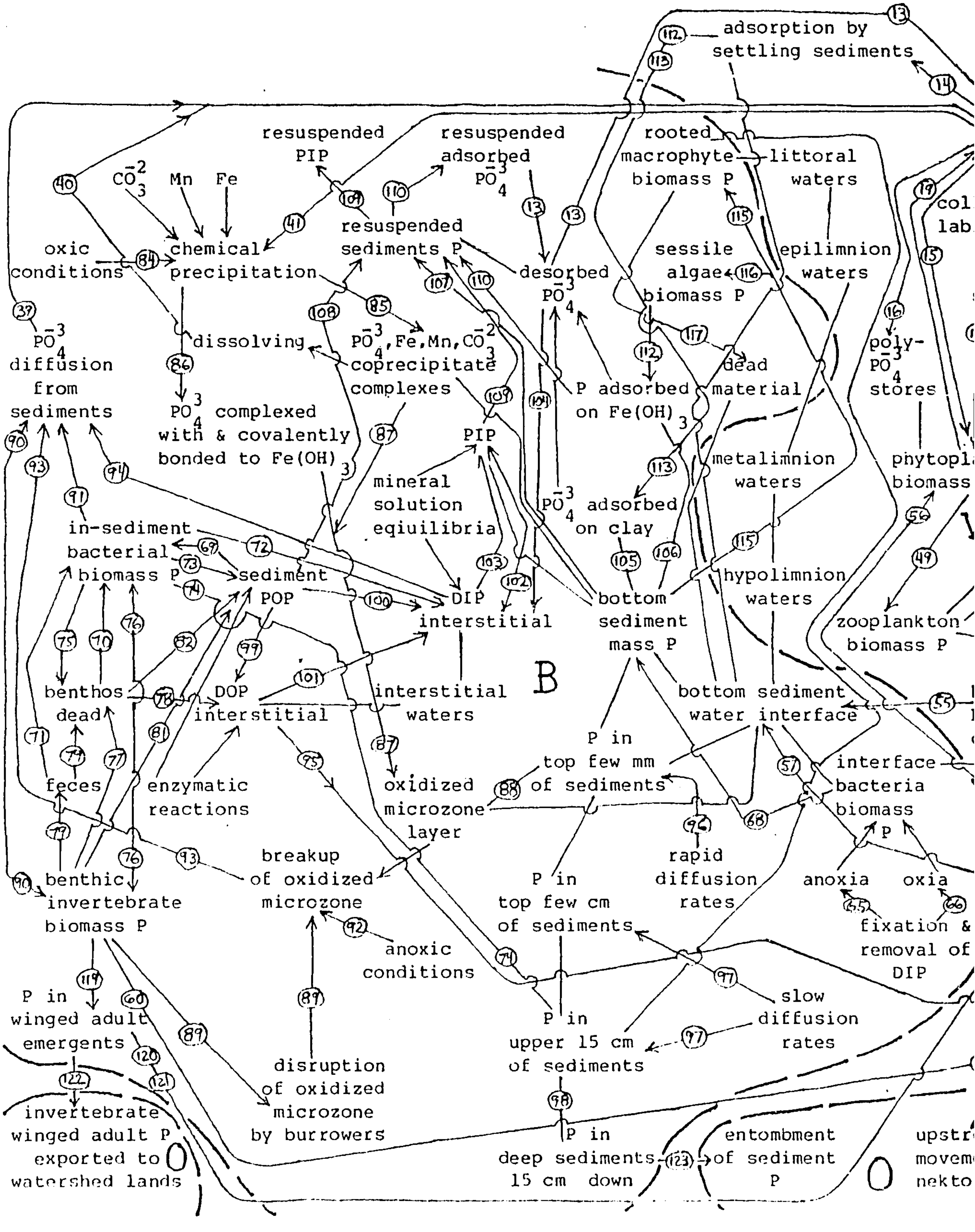
Influx Sources

Lake waters bring phosphorus into the lake in the form of living and dead particulate organic (POP)(1) and inorganic phosphorus (PIP)(2), and dissolved inorganic (DIP)(3) and organic phosphorus (DOP). Most stream PIP is in inorganic sediments which rapidly settle to the lake bottom (57) (Leonard et al. 1979). Groundwaters, rain and snow bring in more DOP (5)(8) and DIP (6)(7), and dry precipitation, more POP (9) and PIP (10).

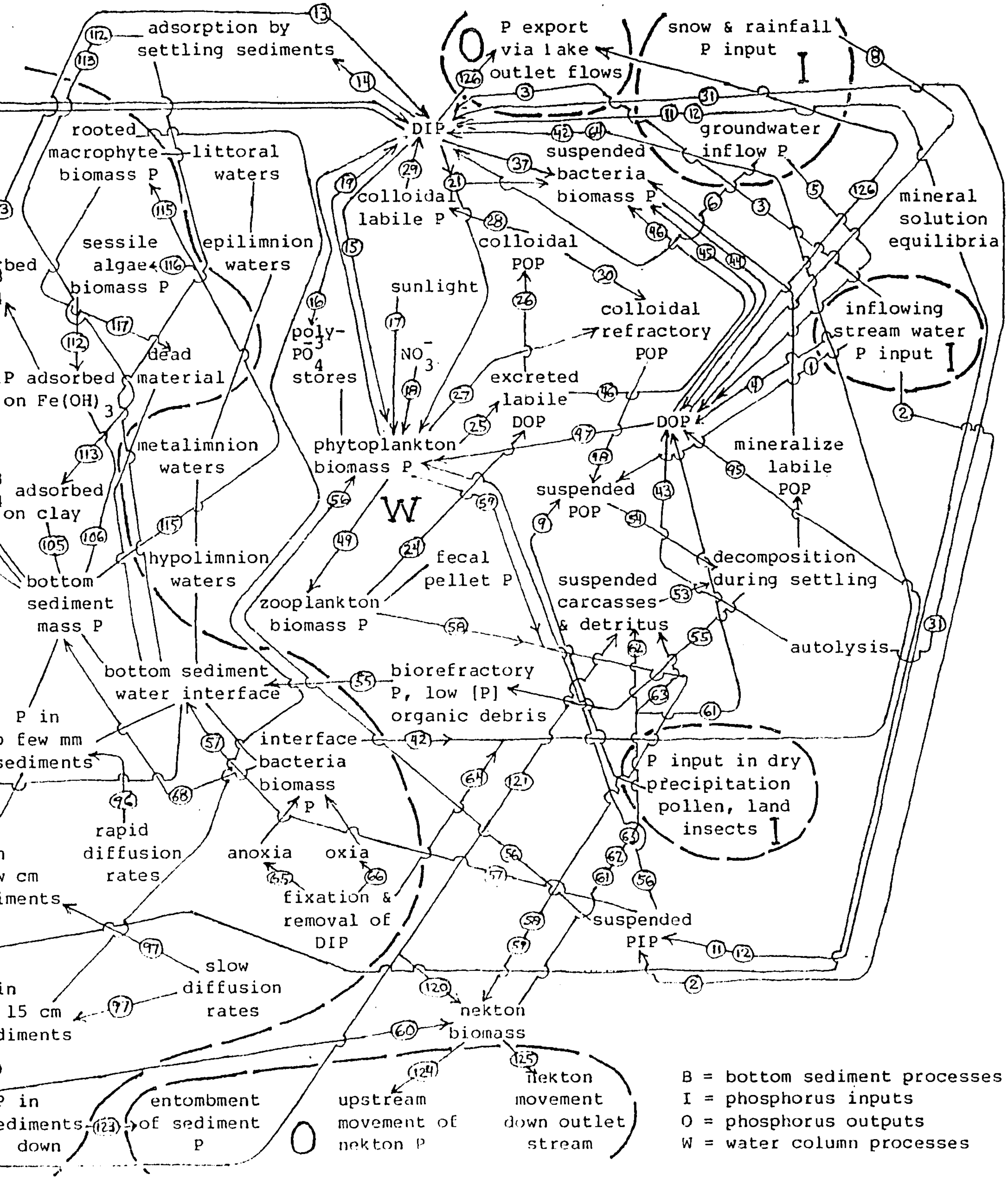
Chemical & Biologic Transformations & Transfers

Within lake waters some DIP originates from the solution of PIP of primary or precipitate origins (11)(40), and some DIP is converted to PIP by the dynamic equilibrium maintained by phosphate mineral solubility processes (12)(41). Other DIP is added to lake waters by diffusion from bottom sediments (39) and some by desorbtion from the surface of suspended organic and inorganic particles (13).

Figure 22. Conceptual Model of Phosphorus Cycling Within Lake



Within Lake



B = bottom sediment processes
I = phosphorus inputs
O = phosphorus outputs
W = water column processes

Table 24. Legend for Lake Phosphorus Cycling Model

Number	Description
	Influx Sources
1.	Stream water-borne particulate organic phosphorus (POP).
2.	Stream water-borne particulate inorganic phosphorus (PIP).
3.	Stream water-borne dissolved inorganic phosphorus (DIP).
4.	Stream water-borne dissolved organic phosphorus (DOP).
5.	Groundwater-borne DOP.
6.	Groundwater-borne DIP.
7.	Rain- and snow-borne DIP.
8.	Rain- and snow-borne DOP.
9.	Dry precipitation-borne POP.
10.	Dry precipitation-borne PIP.
	Chemical & Biologic Transformations & Transfers
11.	DIP originating from dissolving PIP.
12.	DIP converted to PIP by mineral solubility equilibria balances.
13.	DIP (orthophosphate, PO_4^{-3}) desorbed from suspended particles.
14.	DIP adsorbed onto suspended particles.
15.	Phytoplankton uptake of DIP & conversion to biomass P.
16.	Phytoplankton conversion of DIP to polyphosphate stores.
17.	Sunlight intensity needed for phytoplankton utilization of P.
18.	NO_3^{-1} concentration needed for phytoplankton utilization of P.
19.	Phytoplankton excretion of DIP.
20.	Phytoplankton/particle sorption capacity competition for DIP.
21.	Phytoplankton/bacteria competition for DIP.
22.	Zooplankton DIP uptake and conversion to biomass P.
23.	Zooplankton excretion of DIP.
24.	Zooplankton excretion of labile DOP.
25.	Phytoplankton excretion of labile DOP.
26.	Formation of colloidal POP by polycondensation of excreted DOP.
27.	Phytoplankton excretion of colloidal POP.
28.	Labile P fraction of colloidal P.
29.	Colloidal labile P hydrolized to DIP.

30. Refractory P fraction of colloidal P.
31. DIP coming from autolysis of dead phyto- & zooplankton cells.
32. Rooted macrophyte uptake of DIP & conversion to biomass P.
33. Rooted macrophyte excretion of DIP.
34. Sessile algae uptake of DIP & conversion to biomass P.
35. Sessile algae excretion of DIP.
36. DIP coming from dead & decaying sessile algae & macrophytes.
37. Suspended bacteria uptake of DIP & conversion to biomass P.
38. Suspended bacteria excretion of DIP.
39. DIP diffusing from bottom sediments.
40. DIP originating from dissolving of chemical precipitates.
41. Chemical precipitation of DIP.
42. Sediment/water interface (SWI) bacteria excretion of DIP.
43. DOP coming from autolysis of dead phyto- & zooplankton cells.
44. DOP excreted by suspended bacteria (SB).
45. SB uptake & conversion of DOP to biomass P.
46. SB uptake & conversion of excreted labile DOP to biomass P.
47. Phytoplankton uptake & conversion of DOP to biomass P.
48. Suspended POP consisting of colloidal refractory POP.
49. Conversion of Phytoplankton biomass P to zooplankton biomass P.
50. Zooplankton fecal pellet POP.
51. Phytoplankton carcass POP.
52. Zooplankton carcass POP.
53. Rapid loss of labile P during settling of plankter carcasses.
54. Decompostion of other detritus POP during settling.
55. Settling of P-impoverished organic debris to bottom sediments.
56. Phytoplankton biomass P formed from suspended stream PIP.
57. Settling of suspended stream PIP onto bottom sediments.
58. Conversion of zooplankton biomass P to nekton biomass P.
59. Conversion of phytoplankton biomass P to nekton biomass P.
60. Conversion of benthic invertebrate P to nekton biomass P.
61. Nekton excretion of DOP.
62. Nekton fecal POP.
63. Nekton carcass POP.

Bottom Sediment Processes

64. SWI bacteria conversion of DIP to biomass P.
65. Minor DIP removal by SWI bacteria under anoxic conditions.
66. Significant DIP removal by SWI bacteria under oxic conditions.
67. Conversion of bottom detritus P to SWI bacteria biomass P.
68. Incorporation of SWI bacteria biomass P into bottom sediments.
69. Conversion of sediment POP to in-sediment bacteria biomass P.
70. Conversion of benthos carcass P to sediment bacteria biomass P.
71. Converson of benthos fecal P to sediment bacteria biomass P.
72. Sediment bacteria excretion of DIP.
73. Sediment bacteria biomass P fraction of sediment POP mass.
74. Sediment bacteria biomass P concentrated in top 15 cm of sediment.
75. Dead sediment bacteria.
76. Conversion of bacteria to burrowing invertebrate P.
77. Conversion of in-sediment detritus P to burrowing invertebrate P.
78. Burrowing invertebrate excretion of DOP.
79. Burrowing invertebrate excretion of POP.
80. Dead burrowing invertebrates.
81. Burrowing invertebrate biomass P fraction of sediment POP mass.
82. Dead particulate organic matter fraction of sediment POP mass.
83. Oxic conditions in top few mm of bottom sediments.
84. Chemical precipitation of DIP by oxic conditions.
85. PO_4^{-3} bound to insoluble Mn & CO_3^{-2} coprecipitate complexes.
86. PO_4^{-3} bound to insoluble $Fe(OH)_3$ chemical complex.
87. Formation of an oxidized crust by insoluble compounds.
88. Impermeable oxidized crust in top few mm of sediments.
89. Disruption of oxidized crust seal by burrowing invertebrates.
90. Burrowing invertebrates release DIP & DOP from below crust.
91. Release of DIP from below crust by sediment bacteria.
92. Dissolving of oxidized crust seal by anoxic conditions.
93. Release of PO_4^{-3} formerly in oxidized crust insoluble compounds.
94. Diffusion of interstitial DIP from sediments.
95. Diffusion of interstitial DOP from sediments.
96. Rapid diffusion of P from top few mm of sediments.

97. Slow diffusion of P from deeper sediments.

98. No diffusion of P from sediments more than 15 cm down.

99. Enzymatic conversion of sediment POP to interstitial DOP.

100. Enzymatic conversion of sediment POP to interstitial DIP.

101. Conversion of interstitial DOP to interstitial DIP.

102. Interstitial DIP originating from dissolving sediment PIP.

103. Interstitial DIP converted to sediment PIP by solution equilibria.

104. Interstitial DIP coming from desorbed PO_4^{-3}.

105. PO_4^{-3} adsorbed on clay particles in bottom sediments.

106. PO_4^{-3} adsorbed on $Fe(OH)_3$ particles in bottom sediments.

107. Resuspension of bottom sediment by water turbulence.

108. Resuspension of bottom sediment POP particles.

109. Resuspension of bottom sediment PIP particles.

110. Resuspension of bottom sediment particles with adsorbed PO_4^{-3}.

111. Suspended bacteria conversion of sorbed PO_4^{-3} to biomass P.

112. PO_4^{-3} resorbed by $Fe(OH)_3$ particles settling to bottom sediments.

113. PO_4^{-3} resorbed by clay particles settling to bottom sediments.

114. Phytoplankton conversion of resuspended PIP to biomass P.

115. Rooted macrophyte conversion of bottom sediment P to biomass P.

116. Sessile algae conversion of bottom sediment P to biomass P.

117. Dead rooted macrophyte P at sediment/water interface.

118. Dead sessile algae P at sediment/water interface.

119. Bottom sediment P exported by winged adult invertebrates.

120. Invertebrate winged adult P converted to nekton biomass P.

121. Dead invertebrate winged adult carcasses added to suspended POP.

Loss Processes

122. P exported to lake watershed lands by invertebrate winged adults.

123. P permanently entombed deep in sediments.

124. P returned to watershed by upstream movement of nekton.

125. P exported by nekton movement down lake outlet stream.

126. DIP & DOP exported in lake outlet flows.

127. Lake biomass P lost via outlet flows.

Some lake water DIP is lost by absorbtion to particles (14). A portion of lake water DIP is also taken up by phytoplankton and transformed to their biomass phosphorus (15). When DIP is present in amounts in excess of their immediate needs, phytoplankton take up an excess (luxury consumption) and store it as polyphosphate grains in their cells (16). The ability of phytoplankton to utilize DIP in lake water is also dependent upon sufficient light intensity (17) and nitrate concentrations (18). They must also compete for readily available DIP with the sorption capabilities of suspended inanimate particles (20) and bacteria (21).

Some zooplankton can directly take up DIP from lake waters and convert it to organic forms in their biomass (22). All the phosphorus in zooplankton and phytoplankton not consumed by other organisms is returned to lake waters by the autolysis (spontaneous, abiotic breakup) of their cells upon their deaths (31)(43)(51). Both zooplankton and phytoplankton, while living, return some DIP and DOP to lake waters; the latter passively via the extracellular fluids which seep through their cell walls (19)(25); the former to some extent by that same process, but (24) most via urine and fecal pellets (23). Some of the excreted DOP coalesces by the process of polycondensation to form colliodal POP (26), and phytoplankton excretion adds more of this form of phosphorus to lake waters (27). Some colloidal phosphorus, especially when freshly excreted, is labile (28) and readily transformed by hydrolization to DIP (29). However, the remainder is biorefractory (30)(48) (Lean 1973).

Rooted macrophytes, sessile algae and suspended bacteria also take up DIP from lake waters and transform it to organic forms in their respective biomasses (32)(34)(37). While living, they return some DIP to lake waters via excretion through their cell walls (33)(35)(38) and all of it, not consumed by other organisms, by decay and mineralization upon their deaths (36). Phytoplankton and suspended bacteria also remove DIP from lake waters and transform it to their biomass phosphorus (47)(45)(46), and both add DOP to lake waters (44) by leakage through their cell walls. Some phytoplankton biomass phosphorus also comes from their direct utilization of very fine suspended PIP introduced by stream waters (56).

Biomass phosphorus is transferred between aquatic organisms by predation. Thus some phytoplankton biomass phosphorus becomes zooplankton phosphorus (49) and both and benthic invertebrates may become nekton biomass phosphorus (58)(59)(60). The predators return DOP and POP to lake waters in excretions while alive (50)(61)(62), and by the portions of their carcasses not consumed by others on their death and decay (52)(63). During the fall of uneaten plankter carcasses to the lake bottom, labile phosphorus is rapidly removed by bacteria (53), and by similar processes, much phosphorus is lost from other settling POP detritus (54). Consequently much of the rain of organic debris falling onto lake sediments has little remaining phosphorus (55).

Bottom Sediment Processes

Bacteria are most active in recycling and significant in the amount of uptake and conversion of lake water phosphorus. Their population and conversion activity is greatest at the interface where they take up and convert DIP to their biomass when conditions are oxic (64)(66), but only minor amounts are converted under anoxic conditions (65). They also convert any readily biodegradeable phosphorus remaining in bottom detritus to their biomass (67). That portion of the latter not excreted as DIP (42) which does not decompose and return directly to the waters or is not eaten by others is incorporated into bottom sediments (68). Bacteria residing within lake sediments are concentrated in the top 15 cm (74) and comprise a significant fraction of the POP mass in sediments (73). They also convert buried POP, burrowing benthos carcasses (70) and feces (71) into their biomass (69), and return some excreted DIP (72) to lake waters via the seepage of interstitial waters through the walls of burrows and other sediment-water interfaces. All their phosphorus is returned to interstitial waters upon their death and decay (75).

Many benthic invertebrates feed by burrowing in sediments, ingesting them in mass but only digesting detritus and bacteria (the latter is typically a large portion of sediment POP mass (82)) as the sources of phosphorus for their new biomass (77)(76). Burrowers also constitute one fraction of sediment POP mass, excrete both DOP and POP byproducts (78)(79) while alive, and in their death (80) most of their phosphorus is converted to bacterial biomass (70).

Much of the bottom sediments of Lake Tahoe must be surfaced with an oxidized microzone seal because of the high dissolved oxygen concentrations in bottom waters. These oxic conditions extend into at least the top few mm of all sediments (83). As a consequence of the oxic conditions of waters, DIP coprecipitates with manganese and carbonate ions (84)(85) and is bound into insoluble complexes with precipitated iron compounds (ferric hydroxide, $Fe(OH)_3$) (86), forming a crust a few mm thick on the surface of bottom sediments (87)(88). This crust is an effective seal against the exchange of phosphorus between sediments and overlying waters, except where it is breached by burrows and burrowing (89), which release some of the DIP and DOP from sediments below the crust (90)--e.g. the DIP excreted by in-sediment bacteria (91).

The oxidized microzone crust is only dissolved--with the concomitant release of its phosphorus contents (93) and free diffusion of interstitial DIP and DOP into overlying waters (94)(95)--by anoxic conditions in waters (92), a state which must be rare and only occurs in microsites in Lake Tahoe. When lake bottom sediments are not sealed, DOP and DIP rapidly diffuse from the top few mm of sediments (96), more slowly from increasing depths (97), and essentially not at all from deeper than 15 cm in bottom sediments (98). Some POP buried in sediments is converted to interstitial DOP and DIP by enzymatic processes (99)(100), and other processes convert some interstitial DOP to DIP (101). Interstitial DOP also originates from the solution of PIP (102) and phosphate desorbed from sediment particle surfaces (104). However, phosphorus mineral solution equilibria keep the amount of DIP low by converting it to PIP (103).

Some orthophosphate is adsorbed on the surface of clay and iron oxide particles in bottom sediment deposits (105)(106). When these POP and PIP particles are resuspended (110)(108)(109) by turbulent waters (107), some of the orthophosphate is desorbed, some removed by suspended bacteria to form more biomass (111), and some of the very fine PIP is taken up by phytoplankton and converted to their biomass (114). As they resettle, the iron oxide and clay particles may sorb phosphate from lake waters (112)(113).

DIP and sorbed phosphorus in bottom sediments also may be taken up by rooted macrophytes and sessile algae and converted to organic phosphorus compounds in their biomass (115)(116). Upon their death, their POP is deposited as organic detritus on the bottom at the sediment-water interface (117)(118) where most of the phosphorus is removed by intense bacterial decomposition activity at that surface. Some of the total phosphorus mass in bottom sediments is removed in the biomass of the winged adult stages of certain invertebrates (119). Some of their biomass is captured by nekton and transformed to the biomass of the latter (120), and some falls on land surfaces (122). Those falling on the lake and not consumed by nekton are added to the suspended POP mass of the lake (121).

Loss Processes

Much of the phosphorus initially introduced to lake waters is lost via permanent entombment deep in sediments (123); e.g., most PIP entering the lake is rapidly deposited and buried offshore of stream mouths (Leonard et al. 1979). A relatively small amount of lake phosphorus is returned to streams by the upstream movement of nekton (124), and they similarly remove some by moving downstream at the outlet to the lake (125). Some of the lake water DIP, DOP and phosphorus in plankton organisms are lost in the waters flowing out its outlet (126)(127).

CHAPTER 15

THE STREAM-LAKE WATER MASS INTEGRATION SUBSYSTEM

Chapter Scope

In this chapter I describe and discuss lake processes controlling the spatial movement of and eventual integration of stream water masses. I first discuss my reasons for including a discussion on lake distribution and mixing, even though that information is not directly a factor in a land capability classification map--a primary objective of this study. Nor can those lake processes feasibly be manipulated to minimize the effects of stream-borne watershed nutrients and sediments on water color and transparency. Next I give a brief overview of my conceptual model of the lake-stream water mass mixing and distribution, and then a diagramatic representation of it, followed by an explanation. Lastly I discuss some general seasonal relationships between stream water density and lake density stratifications which largely determine where stream water masses and their sediment and nutrient loads are likely to travel.

Justification

Stream nutrient additions to the lake are not uniformly distributed throughout its waters until long after their initial introduction--a time lag of at least a year in monomictic Lake Tahoe. Lake phytoplankton are able to utilize rapidly nutrient additions by streams. Their population size begins to increase within hours after streams add waters containing concentrations of nutrients greater than those in the lake. Consequently, the biostimulant effects of stream nutrient additions observably affect water color on the short-term basis when they are most concentrated.

Stream suspended sediment additions to the lake never become uniformly distributed. Even in the case of colloidal washload particles, which theoretically should remain suspended forever because of water molecule turbulence, some agglomerative processes result in their disappearance from visible waters before they become uniformly distributed. Larger suspended sediment particles rapidly drop out of the visible portions of the water column and settle to the bottom along the path of dissipating stream water masses.

Because the quantitative effects of additions of both of these substances do not uniformly alter water color and transparency throughout the lake, it is necessary to be aware of the processes controlling the spatial and temporal existence of these substances in the visible water column.

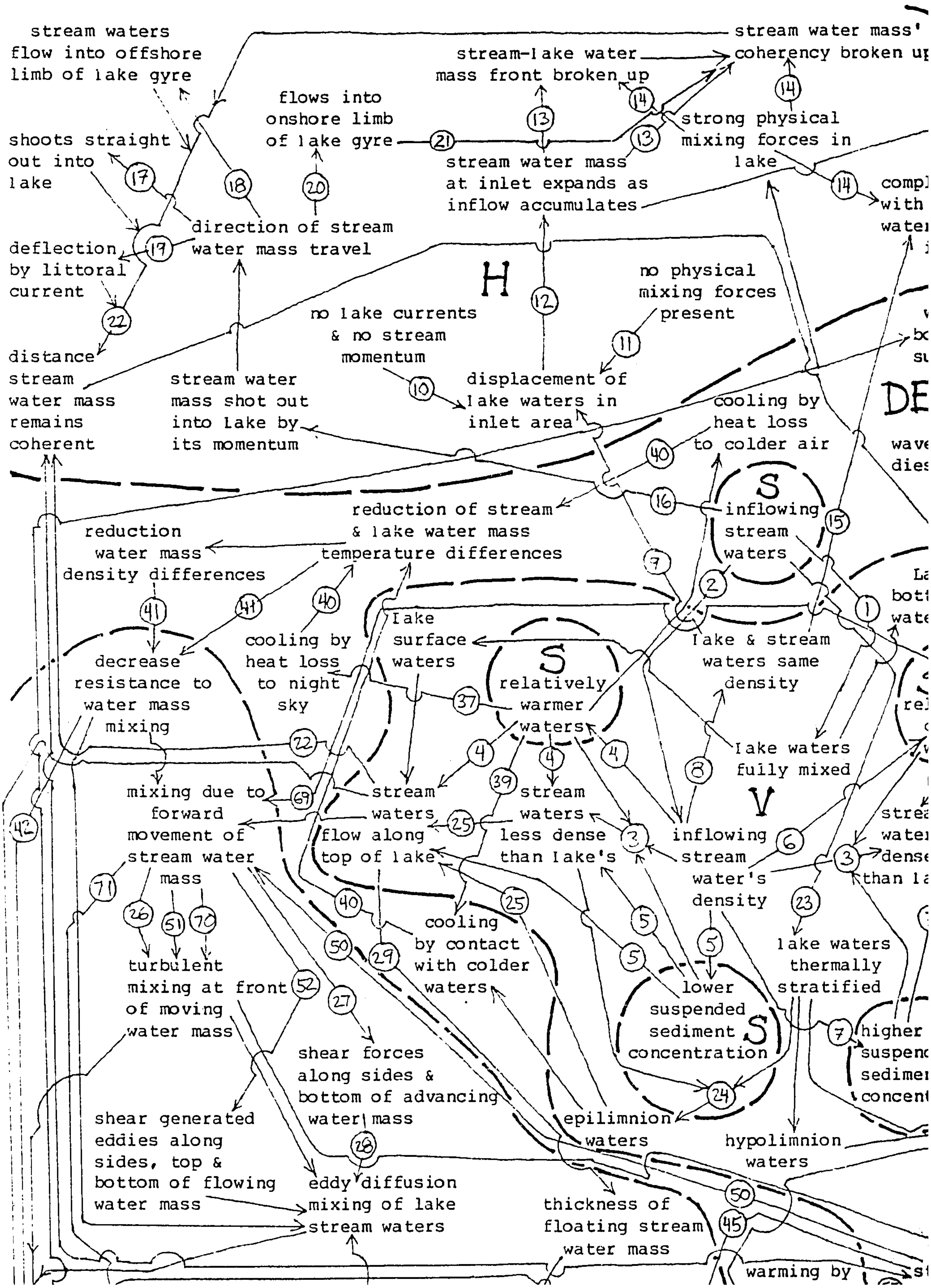
The stream-lake water mass mixing processes cannot be manipulated. However, Chapters 15 and 16 can be regarded as closing the loop of subsystem processes controlling the production of nutrients and sediments by the ecosystem and their effects on water color and transparency.

To be able to make intelligent use of the information in all preceding chapters, public agency decisionmakers must understand there is not a simple linear relationship between the cumulative amount of nutrients and sediments added to the lake and water color and transparency changes. The relationships are complex, and with respect to introduced suspended sediments, their relationships are ephemeral rather than cumulative in any meaningful sense of that word. The very logical and understandable reasons for the inability of science to predict with certainty that the additions of x amount of sediments will result in y amounts of water color change must be understood. In this chapter there is a rapid breakdown of the ability of science to mechanistically predict effects, because of the great concentration of stochastic variables controlling the outcome of events. The substance of these last two conceptual model chapters is not needed for the development of a land capability classification map. However, without the information contained in Chapters 15 and 16, we would have omitted the final steps in completing our understanding of how watershed nutrient and sediment loads finally affect lake water color.

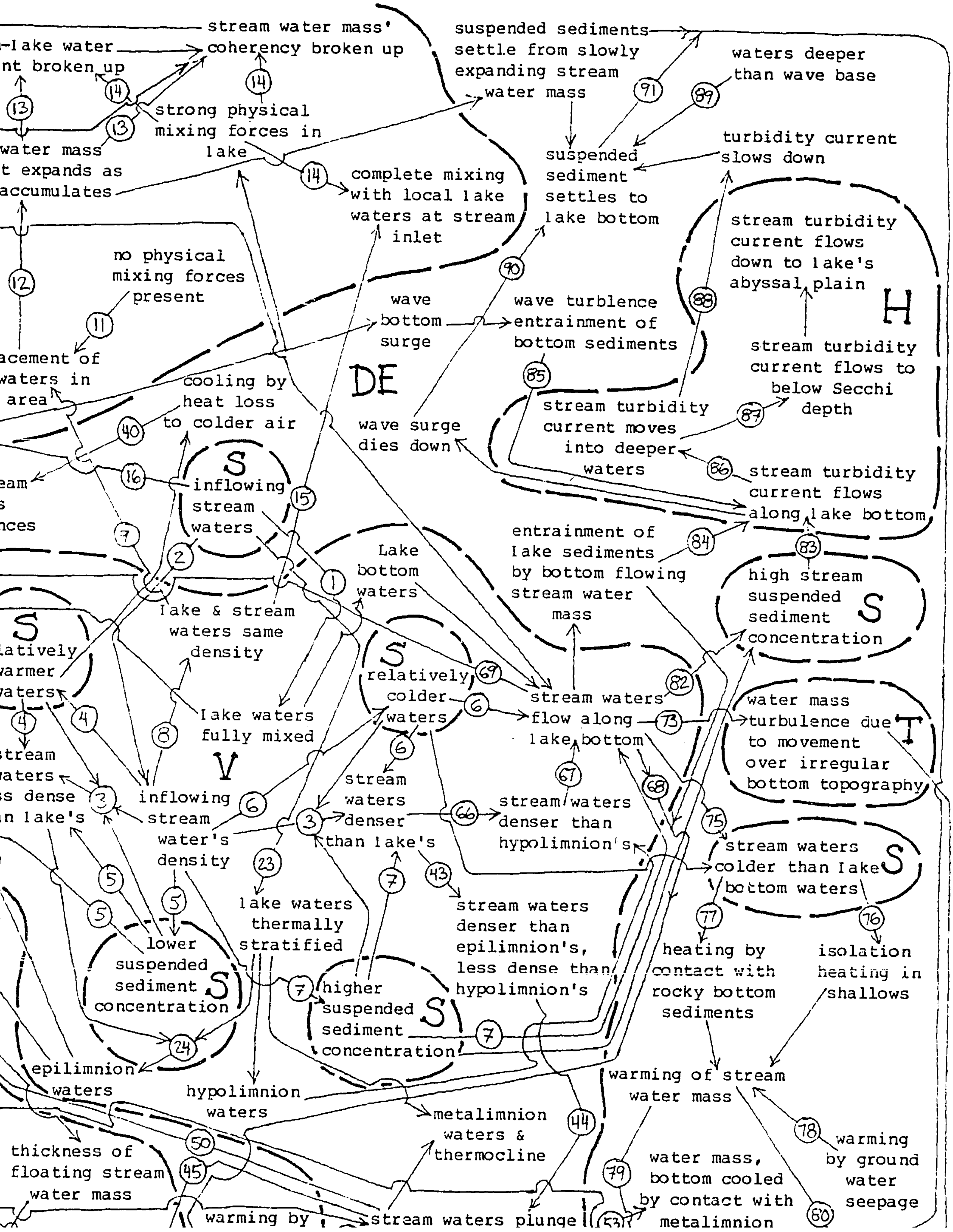
Model Overview

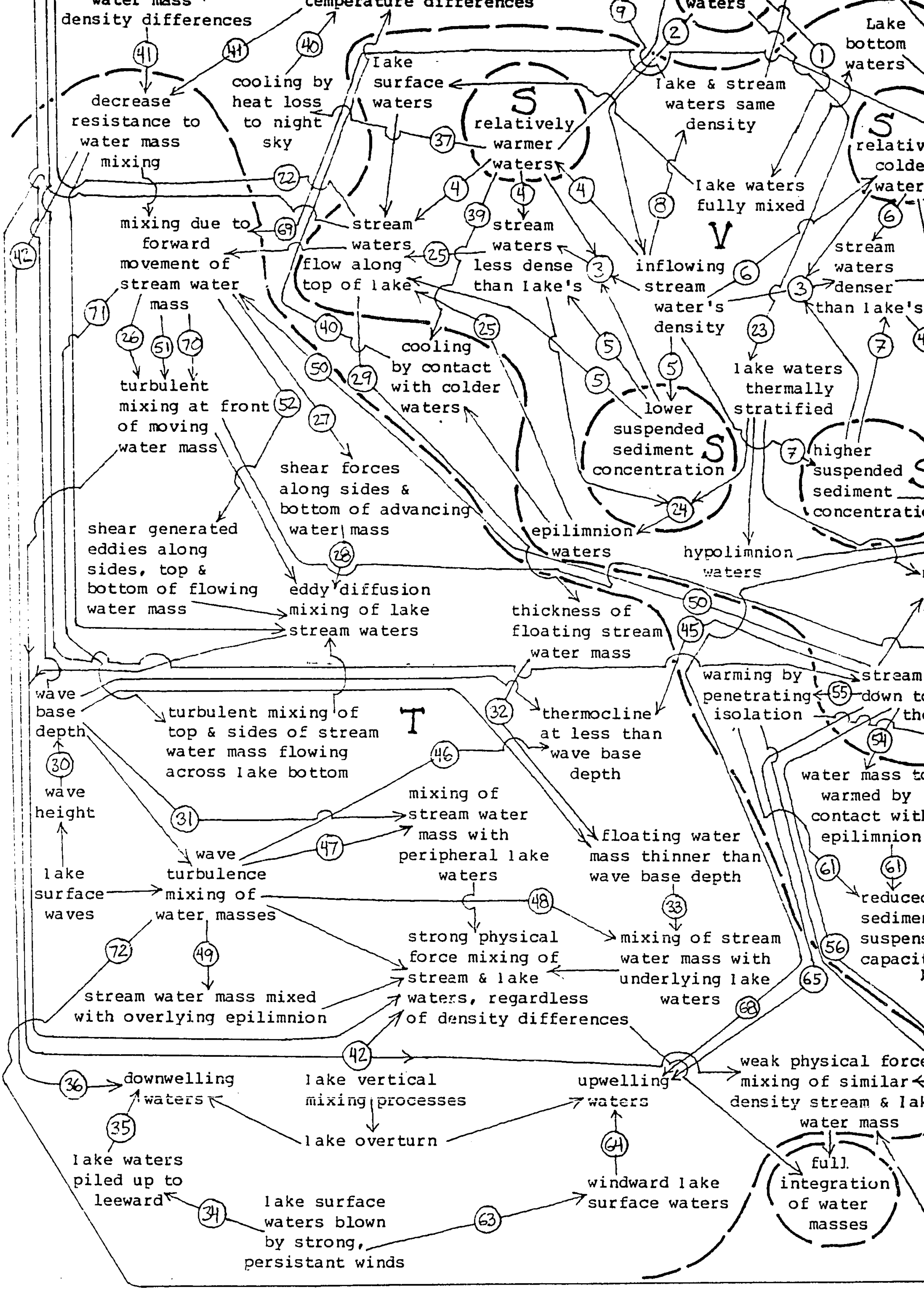
The 91 variables and relationships shown in the conceptual model can be grouped into five general categories: 1) conditions determining the density of inflowing stream waters; 2) conditions controlling the vertical emplacement of stream water masses flowing in the lake, and/or 3) their horizontal movements; 4) turbulent forces mixing stream and lake water masses; and 5) processes equalizing stream and lake water mass densities by cooling, warming and sediment settling removing those water mass differences retarding ready intermingling. The boundaries of these general groups of relationships are outlined in red on the diagram of the conceptual model.

Figure 23. Lake-Stream Water Mass Integration Conceptual Model



onceptual Model




water mass density differences
temperature differences
waters
Lake bottom waters
(9)
(2)
(1)
(41)
(41)
(40)
lake surface waters
cooling by heat loss to night sky
decrease resistance to water mass mixing
S
relatively warmer waters
lake & stream waters same density
S
relativ
colde
water
(37)
lake waters fully mixed
(22)
(4)
(4)
(4)
(8)
(6)
mixing due to forward movement of stream water mass
stream waters flow along top of lake
(39)
stream waters less dense than lake's
V
inflowing stream water's density
stream waters denser than lake's
(42)
(69)
(25)
(3)
(6)
(3)
(71)
(26)
(51)
(70)
(40)
(25)
(5)
(5)
(5)
(23)
(7)
(4)
cooling by contact with colder waters
turbulent mixing at front of moving water mass
(50)
(29)
(52)
(27)
lower suspended sediment concentration
S
lake waters thermally stratified
(7)
higher suspended sediment concentratio
S
shear forces along sides & bottom of advancing water mass
(24)
shear generated eddies along sides, top & bottom of flowing water mass
(28)
epilimnion waters
hypolimnion waters
eddy diffusion mixing of lake stream waters
thickness of floating stream water mass
(50)
(45)
wave base depth
turbulent mixing of top & sides of stream water mass flowing across lake bottom
T
(32)
thermocline at less than wave base depth
warming by penetrating isolation
(55)
stream down to the
(54)
(30)
wave height
(46)
water mass to warmed by contact with epilimnion
mixing of stream water mass with peripheral lake waters
(31)
floating water mass thinner than wave base depth
(47)
lake surface waters
wave turbulence mixing of water masses
(48)
(61)
(61)
reduced sedimen suspens capacit
(72)
(49)
(33)
strong physical force mixing of stream & lake waters, regardless of density differences
mixing of stream water mass with underlying lake waters
(56)
(65)
(68)
stream water mass mixed with overlying epilimnion
(42)
weak physical force mixing of similar density stream & lak water mass
(36)
downwelling waters
lake vertical mixing processes
upwelling waters
(35)
lake overturn
(64)
lake waters piled up to leeward
full integration of water masses
windward lake surface waters
(34)
lake surface waters blown by strong, persistant winds
(63)

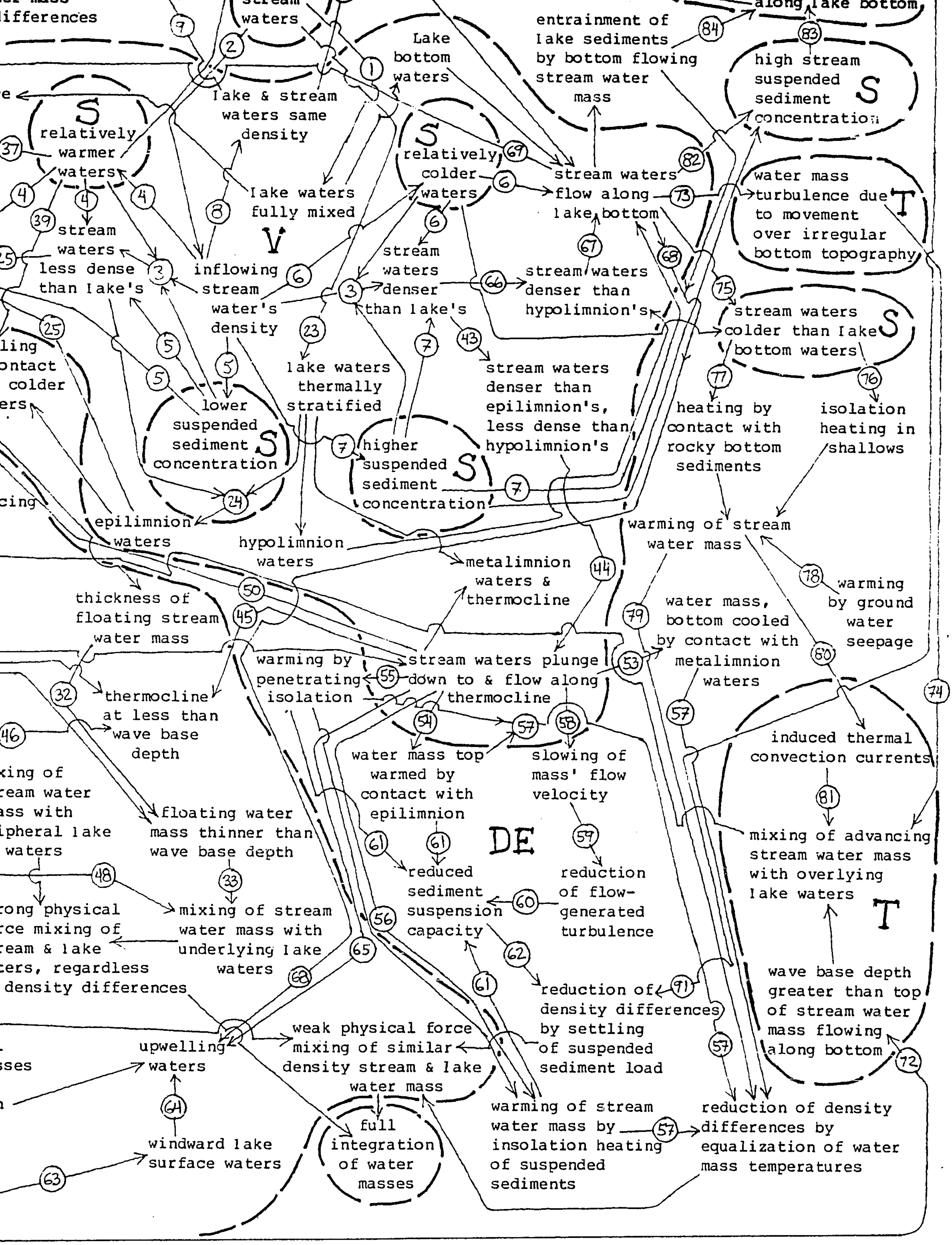

differences
stream waters
Lake bottom waters
entrainment of lake sediments by bottom flowing stream water mass
along lake bottom
high stream suspended sediment concentration
S
lake & stream waters same density
S
relatively warmer waters
S
relatively colder waters
stream waters flow along lake bottom
water mass turbulence due to movement over irregular bottom topography
T
lake waters fully mixed
V
stream waters less dense than lake's
inflowing stream water's density
stream waters denser than lake's
stream waters denser than hypolimnion's
stream waters colder than lake bottom waters
S
lake waters thermally stratified
stream waters denser than epilimnion's, less dense than hypolimnion's
heating by contact with rocky bottom sediments
isolation heating in shallows
lower suspended sediment concentration
S
higher suspended sediment concentration
S
epilimnion waters
hypolimnion waters
metalimnion waters & thermocline
warming of stream water mass
warming by ground water seepage
thickness of floating stream water mass
water mass, bottom cooled by contact with metalimnion waters
warming by penetrating isolation
stream waters plunge down to & flow along thermocline
thermocline at less than wave base depth
induced thermal convection currents
water mass top warmed by contact with epilimnion
slowing of mass' flow velocity
floating water mass thinner than wave base depth
mixing of advancing stream water mass with overlying lake waters
T
DE
reduced sediment suspension capacity
reduction of flow-generated turbulence
mixing of stream water mass with underlying lake waters
strong physical force mixing of stream & lake waters, regardless of density differences
mixing of stream water mass with peripheral lake waters
wave base depth greater than top of stream water mass flowing along bottom
reduction of density differences by settling of suspended sediment load
weak physical force mixing of similar density stream & lake water mass
upwelling waters
full integration of water masses
warming of stream water mass by insolation heating of suspended sediments
reduction of density differences by equalization of water mass temperatures
windward lake surface waters
1
2
3
4
5
6
7
8
23
24
25
32
33
37
39
43
44
45
46
48
50
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
72
73
74
75
76
77
78
79
80
81
82
83
84
91

Table 25. Legend for Lake-Stream Water Mass Integration Model

Number	Description
1.	Waters flow into lake waters of vertically uniform density.
2.	Relative density determines depth of stream water mass emplacement.
3.	Temperature & sediment concentration determine relative density.
4.	Warmer, less dense stream waters displace lake surface waters.
5.	Lower sediment concentration stream waters displace surface waters.
6.	Colder, denser stream waters displace lake bottom waters.
7.	Higher sediment concentration stream waters displace bottom waters.
8.	Lake & stream waters same density.
9.	Equal density stream waters displace lake waters in inlet area.
10.	No physical mixing forces operant to cause mixing at inlet.
11.	No lake currents operant to move stream waters from inlet area.
12.	Coherent stream water mass expands as flow accumulates.
13.	Gradual dissipation of stream mass by weak lake mixing forces.
14.	Strong physical mixing forces operant in inlet area.
15.	Equal density waters mix completely at stream inlet.
16.	Stream water mass shot out into lake by its momentum.
17.	Distance undeflected momentum carries stream mass into lake.
18.	Stream water mass carried offshore by lake gyre.
19.	Mass flows along shore, deflected by littoral current or gyre.
20.	Mass offshore movement abated by onshore limb of lake gyre.
21.	Mass dissipated by collision with onshore gyre limb.
22.	Distance stream water mass remains coherent in lake.
23.	Stream waters flow into density-stratified lake waters.
24.	Lower density stream waters flow on top of epilimnion waters.
25.	Stream waters flow out over top of lake.
26.	Turbulent mixing of stream & lake surface waters at sides & bottom.
27.	Eddies form along sides & bottom of advancing stream mass.
28.	Eddy mixing of stream & lake surface waters at sides & bottom.
29.	Thickness of stream water mass on top of lake.
30.	Depth to which wave turbulence occurs depends upon wave heighth.
31.	Wave turbulence mixes lake with stream waters at edges of mass.
32.	Floating stream mass thinner than depth of wave turbulence.
33.	Deeper turbulence mixes lake & stream waters at bottom of mass.
34.	Winds pile up epilimnion waters on leeward side of lake.
35.	Downwelling occurs on extreme leeward side of piled up waters.
36.	Epilimnetic stream water mass submerged by downwelling waters.
37.	Warmer stream mass on surface cooled by night heat loss.
38.	Warmer stream mass on surface cooled by contact with cold air.

39. Stream water mass on surface cooled by underlying waters.
40. Cooling reduces stream & lake water mass density differences.
41. Reduced density difference decreases resistance to mixing.
42. Forced mixing of low density difference water masses.
43. Stream waters denser than epilimnion's, less than hypolimnion's.
44. Stream waters sink to and flow along thermocline.
45. Thermocline in wave turbulence zone.
46. Wave turbulence mixing of stream water mass with lake waters.
47. Wave turbulence mixing of stream mass edges with lake waters.
48. Wave turbulence mixing of stream with metalimnion waters.
49. Wave turbulence mixing of stream with epilimnion waters.
50. Mixing due to forward motion of stream mass on themocline.
51. Turbulent mixing of stream & lake waters at advancing front.
52. Eddy mixing along sides, top & bottom of advancing front.
53. Bottom waters of stream mass cooled by metalimnion contact.
54. Top waters of stream mass heated by contact with epilimnion.
55. Stream mass heated by insolation penetrating to thermocline.
56. Mass warmed by insolation heating of entrained particles.
57. Warming & cooling reduces density differences of water masses.
58. Slowing of forward motion of stream masses along thermocline.
59. Slowing reduces flow-generated turbulence in stream water mass.
60. Less turbulence reduces ability of stream mass to hold sediment.
61. Warming lessens viscosity, reducing sediment carrying capacity.
62. Reduction of density differences by sediment settling.
63. Epilimnion waters blown away from windward side of lake.
64. Upwelling waters on windward side of lake.
65. Stream mass on thermocline mixed with lake waters by upwelling.
66. Stream waters denser than hypolimnion waters.
67. Stream water mass sinks to & flows along lake bottom.
68. Stream mass on bottom mixed with lake waters by upwelling.
69. Mixing with lake bottom waters due to forward movement of mass.
70. Turbulent mixing of stream & lake bottom waters at front of mass.
71. Eddy mixing of stream & lake bottom waters at top & sides of mass.
72. Wave surge mixing of stream & lake bottom waters in shallows.
73. Turbulence generated by flow of stream mass over rough bottom.
74. Mixing of stream & lake bottom waters due to turbulent flow.
75. Stream mass waters colder than lake bottom waters.
76. Stream water mass heated by insolation penetrating to bottom.
77. Rocky bottom warming of stream mass waters on lake bottom.
78. Ground water seepage warming of stream waters on lake bottom.
79. Warming reduces density differences retarding mixing.
80. Thermal convection currents induced by warming of stream mass.
81. Mixing of stream & lake bottom waters by convection currents.
82. Greater density of stream waters due to high suspended sediments.

83. Stream water mass flows as turbidity current on lake bottom.
84. Bottom sediments entrained by flowing stream water mass.
85. Wave surge entrainment of bottom sediment into flowing mass.
86. Stream mass turbidity current flows into deeper waters.
87. Turbidity current flows in waters deeper than Secchi depth.
88. Stream mass turbidity current slows & sediment settles.
89. Current flows deeper than wave base & sediment settles.
90. Wave surge dies down & suspended sediments settle.
91. Sediment settling reduces density differences retarding mixing.

Explanation of Water Mass Integration Model

How rapidly and where vertically and horizontally in the lake inflowing stream waters mix with lake waters depends primarily upon their relative densities and by the inertia of inflowing waters. Relative density determines the depth at which stream waters move out into the lake and (2) hence whether they will influence water transparency and upwelling water color. Relative density is determined by comparative water temperature and by suspended sediment concentrations (3). Whether lake waters are layered by density or not (1), if stream waters are warmer than or have lower suspended sediment concentrations than lake surface waters, they displace the latter (4)(5). If they are colder or contain higher suspended sediment concentrations than lake waters they rapidly sink to the bottom, displacing bottom waters (6)(7).

Sometimes lake and stream waters are the same density, and turbulent forces, such as waves (10) and lake currents (11), are insignificant mixing and transport forces in the inlet area. Under these conditions, the stream water mass remains largely coherent, expands as inflow accumulates (12), displaces lake waters from the inlet (9) and is gradually dissipated by weak, small-scale lake mixing forces operating about its margins (13). The suspended sediments and nutrients in stream water masses remaining in the inlet area occupy a relatively small portion of the lake surface area because they are concentrated rather than thinned and spread out.

Alternatively, when strong physical mixing forces are operant in the inlet area (14), the equal density stream and lake waters rapidly mix (15). Depending upon their depth, the merged water may form a mass of nutrient enriched and possible muddy waters throughout the water column, affecting water transparency and color over a larger area than in the previous case.

Depending upon how the channel joins the lake and the flow volume, sometimes the stream water mass is carried out into the lake by its momentum (16) for a distance determined by the latter (17). A stream water mass may also be carried out into the lake by flowing into the offshore-moving limb of a lake gyre (18). Alternatively, if a stream water mass encounters the limb of a gyre moving along the shoreline (or a littoral current) the inflowing waters are carried in that direction (19). If inflowing stream waters encounter the shoreward moving limb of a lake gyre, their subsequent movement out into the lake is abruptly truncated, and their waters are rapidly mixed (21) with lake waters. The distance the stream water mass retains coherence in the lake (22) depends upon its inertia and volume relative to the strength of mixing forces in the lake.

If inflowing stream waters are less dense than the surface waters of a density-stratified lake they flow on top of or displace surface (epilimnion) layer waters (23)(24)(25). Because they are in the shore zone and dispersed over the top of the lake, such low density stream waters potentially affect the upwelling water color and transparency of a relatively large, high visibility area. A surface layer of stream waters quickly mixes with lake waters along its sides and bottom if considerable turbulence is present (26) and slowly if turbulence is weak or absent. Stream waters on the surface are also integrated with lake waters via the formation and breaking off of eddies along their moving interfaces (27)(28).

The suspended sediment concentration in surface floating stream waters must be very low to account for their low density. Their nutrient concentrations conceivably could be high, but this is unlikely during the comparatively warm stream flow periods when lake waters stratify. Hence, when the combination of conditions occurs resulting in steam waters staying on the lake surface, the scant quantity of materials brought in by stream waters is not likely to affect water color or transparency.

The relative importance of water turbulence in the integration of a stream water mass on the surface of the lake depends upon the thickness of the mass (29) relative to the depth of wave turbulence (30). Regardless of this depth relationship, wave turbulence mixes the two waters along the periphery of their interface (31). When the floating stream water mass is thinner than the depth of wave turbulence (32), the latter also mixes the two masses at their horizontal interface (33). When the floating stream water mass is thicker, surface wave turbulence has no such affect.

When the lake is stratified, strong, directionally persistent winds pile up epilmnion waters on the leeward side of the lake (Powell et al. 1976) (34). To compensate for this tilting of the lake surface and return it to a gravitationally stable horizontal position, surface waters are carried downward on the high side of the lake (35). Hence, if stream waters are on the surface when downwelling occurs, they are submerged and mixed with lake waters (36).

Integration of a floating stream water mass with lake waters may also occur by radiative cooling. Because they are less dense, they must contain essentially no suspended sediments and be warmer than lake waters. The relatively warmer surface floating stream water mass is cooled by heat loss to the night sky (37) or by contact with colder air (38). It is also cooled by contact with the colder underlying lake water mass (39). Cooling of a floating stream water mass reduces or eliminates density differences between the two masses (40), reducing or eliminating resistance to their integration (41). Consequently they are readily intermingled by even the weakest of mixing forces (42).

Stream waters flowing into a density stratified lake may be denser than its epilimnion waters but less dense than cold bottom (hypolimnion) waters (43). If they are of such an intermediate density, the inflowing stream water mass sinks to and flows along the sharp density gradient (thermocline) separating epilmnion from deeper lake waters (44).

Under certain circumstances, water turbulence generated by waves forcibly mixes lake waters and all or portions of a stream water mass on the thermocline (46). When the top of the stream water mass on the thermocline is in the wave turbulence zone, that portion of its waters are mixed with epilimnion waters (49). Rarely is the thermocline shallow enough to be in the wave turbulence zone, because it would rapidly mix and erase the distinction between the two water layers or at least truncate and lower the thermocline. However, when this situation occurs, wave turbulence mixes the stream and lake waters all about the stream water mass edges (47), and at both its top interface with epilmnion waters (49) and at its bottom interface with metalimnion waters (48) (waters in the zone of rapid lake water density transition).

Stream waters on the thermocline also are mixed with lake waters by the turbulence caused by forward motion (50) along their advancing front (51) and by eddies forming along the sides, top and bottom of the advancing stream water mass (52).

Their density differences from surrounding waters are reduced by their bottom waters being cooled by heat loss across the interface with metalimnion waters (53), their top waters by heat gain across the interface with epilmnion waters (54) or by insolation penetrating to the thermocline (55) and heating particles suspended in the stream water mass (56). These warming and cooling processes reduce or eliminate stream and lake water mass density differences (57), and they are subsequently intermingled by even the weakest of mixing forces.

The density of a stream water mass emplaced on top of the thermocline may also be reduced by two processes which reduce any suspended sediments in it. As the forward motion of the stream waters on the thermocline slows (58), turbulence within the water mass decreases (59), reducing its ability to continue suspending sediments (60). Warming of the stream water mass on the hypolimnion, as by insolation (55), also reduces its capacity to suspend sediments (61).

Stream waters on the thermocline are also forcibly mixed with lake waters by upwelling and downwelling when strong, directionally persistent winds blow epilimnion waters away from the windward side of the lake (63), piling them up on the opposite side. To restore the resulting tilted lake surface to a gravitationally stable horizontal position, surface waters move downward on the leeward side, mixing stream waters on the thermocline with underlying lake water, and deep waters move upward to the surface on the windward side (64), mixing stream waters on the thermocline with overlying lake waters (65).

If stream waters flowing into a density-stratified lake are even denser than hypolimnion waters (66), they sink to and flow along the lake bottom (67). Some of the stream waters flowing along the lake bottom are forcibly mixed with overlying lake waters by upwelling (68), some by turbulent mixing along the front of the moving water mass (70) and some by eddy diffusion along its top and sides (71). In shallow waters, wave surge mixes stream waters on the bottom with overlying and peripheral lake waters (72). The internal turbulence generated when they flow over rough bottom surfaces (73) also may be intense enough to mix stream with lake waters (74).

When the greater density of the stream waters is due to their relative coldness (75), the differences may be reduced or eliminated in shallow lake waters by several processes: heating by sunlight penetrating to the bottom (76), warming by heat re-radiated from storage in bottom rocks (77) and by relatively warm ground waters seeping through the lake bottom (78). Warming of relatively dense influent stream waters on the lake bottom reduces their resistence to intermingling with lake waters (79) and may also create thermal convection currents in the stream mass (80)--further facilitating mixing of stream and lake bottom waters (81).

When the greater density of the stream waters residing on the lake bottom is due to relatively high suspended sediment concentrations (82), they flow as a turbidity current down submarine depressions and slopes (83). Passing turbidity currents may entrain still more sediments from lake bottom deposits (84), and wave surge may pick up and add still more to turbidity currents (85) flowing through shallow waters. Stream water mass-initiated turbidity currents sooner or later flow downslope from the stream mouth area into increasingly deeper waters (86), and when deeper than Secchi depth (87), they no longer can significantly affect apparent water transparency and upwelling water color. Eventually their forward motion slows and their load of suspended sediments settles to the bottom (88)--typically in the abyssal plain at Lake Tahoe.

Winds and the lake surface eventually calm down; so does the bottom surge created by waves in shallow waters, and no more suspended sediments are added (90) to passing turbidity current waters from this process. Wave surge also ceases to aid maintenance of sediments suspended in turbidity currents as soon as they flow into waters deeper than the wave base (89). The settlement of the load of sediments in a stream water mass to the lake bottom reduces or eliminates the water density differences retarding the intermingling of the two waters (91). They are then subject to mixing by the weakest of mixing forces.

Seasonal Patterns of Stream-Lake Water Mixing

The number of possible combinations of stream and lake water conditions affecting the movement of the former in the lake and the miscibility of both are not as numerous as all the cells in a matrix of stream times lake water variables. The likelihood of combinations of different sets of water mass mixing variables has a strong seasonal component.

Concerning volume, most Tahoe Basin streamflow occurs in the spring as the snowpack melts. During the snowmelt period, stream water temperatures are only slightly warmer than freezing (e.g., 0-2°C , Leonard et al. 1979 p. 288). Hence surface erosion almost never occurs as the snowpack melts, since melt waters are released slowly enough for them to infiltrate into the soil mantle and percolate laterally until they emerge from the banks of channels. While not acquiring sediment from surface soils, snowmelt streamflows transport the bulk of the total annual stream sediment load. They acquire this sediment load by reworking stream bed deposits. The maximum concentration of suspended sediments in snowmelt-fed stream flows is less than one-fifth that of rainstorm flows (Leonard et al. 1979 p. 289-90).

During the snowmelt streamflow period, the waters of the lake are not thermal-density stratified, and its surface waters are cold--though seldom colder than 4.0°C (McGauhey et al. 1963 p. 62). The sediment laden, near freezing snowmelt streamflow waters are denser than the surface waters of the lake and tend to rapidly sink and to flow as turbidity currents along the bottom. While flowing across the coastal shelf bottom, their sediment load, consisting almost entirely of silt and sand (Leonard et al. 1979), settles.

During the summer the lake is strongly stratified. Rainstorms produce stream discharges which are colder, and if the rainfall is intense as frequently is the case for thunderstorms, more sediment-laden than the surface waters of the lake. These denser stream discharges sink to the thermocline or bottom soon after flowing into the lake. As winds are typically weak and erratic during the summer, lake gyres and littoral currents are also weak or absent. However, the short-lived but strong winds of summer thunderstorms are frequently strong enough to whip up waves large enough to be significant mixing forces.

Nearly all of the phytoplankton biomass is also below the thermocline (Holm-Hansen et al. 1978), and large amounts of nutrients and sediments emplanted at that depth by storm runoff can be expected to stimulate subsequent growth of that population. However, because that biomass is far below Secchi depth, its growth has no immediate effect on lake water color. Only on a long-term cumulative basis will the biostimulatory consequences of such additions begin to alter lake water color and transparency, after their nutrient contents are fully mixed throughout the water column of the lake.

A third stream flow density regime occurs during the late spring and summer months when most waters originate from groundwater seepage into channels. During this period, stream water temperatures rise rapidly as the snow pack disappears, reaching a maximum of 15-20°C in August (Leonard et al. 1979 p. 288). No suspended sediment of natural origins is present in summer base flow stream waters.

During this same period, the lake waters are warming. A warmer water epilimnion layer begins to form in the surface waters in midspring (McGauhey et al. 1963 p. 64) and continues to deepen through the summer, reaching a maximum thickness of 30 m by late September (Powell & Richersen 1978). The maximum temperature of the surface waters reaches 14-17°C, depending upon whether cooler water upwelling is occurring (op. cit.; Dillon, Powell & Myrup 1975). Lake suspended sediment concentrations are unmeasurably low except occasionally when winds stir up bottom sediments in shallow waters.

In terms of stream-lake water mass mixing, the relative water densities are somewhat ambiguous. Only water temperature controls the relative density during this period, and the temperature differences are not large. Thus at times lake waters are slightly denser, and stream waters have a tendency to flow out on top of the epilimnion. Sometimes lake waters are less dense, and stream waters have a slight tendency to sink to the thermocline. However, as the great volume of lake water heats up more slowly than stream waters, most of the time the latter are lighter and tend to float on top of the epilimnion. The volume of water issuing from most streams during the summer base flow period is small, as are their sediment and nutrient concentrations (e.g., NO_3N 4-15 ppb), and the extreme intensity of summer sunlight inhibits photosynthesis in the uppermost 15 m (Tilzer at al. 1975) discouraging occupation of surface waters by phytoplankton. Consequently stream waters remaining on the surface pose no immediate threat to lake water color and transparency. They remain on the surface until equalization of their slight temperature differences or surface waves totally mix the stream and lake epilimnion waters.

A fourth stream flow density regime occurs during rainstorms before snowpacks cover the ground (i.e., before December). As no snowpack is present to absorb much of the rain and prevent raindrop erosion, high streamflows laden with relatively high suspended sediment concentrations are common. Those concentrations can be five to ten times greater than during the snowmelt streamflow period (Leonard 1979 p. 289). They come largely from the scouring of channels by high flows.

Stream water temperature during this time may be either colder or warmer than the surface waters of the lake, depending upon whether the storms come from the Gulf of Alaska or from the direction of the Hawaiian Islands. The warmer streamflows produced by the latter are less common, and their higher temperatures probably do not offset the affect of high suspended sediment concentration on water density.

Even-density stream waters are produced by the more common cold rains.

By October, epilimnion waters begin to cool, and the strong winds typically accompanying fall rainstorms break up the lake thermal-density stratification late in the fall. Cooling of surface waters and the downward migration of the thermocline result in lake surface water temperatures of about 8°C by December 20th (McGauhey et al. 1963 fig. 11-7). Lake surface waters continue to cool, reaching a minimum of 4.5-7.0°C in February (op. cit. p. 62).

In terms of stream-lake water mass mixing, the net consequence is that fall rainstorm flows are denser than lake surface waters and hence have a tendency to sink, especially when carrying high sediment loads. As the lake surface and internal waters frequently are agitated by the winds accompanying rainstorms, those denser streamflows are integrated rapidly with the turbulent lake waters. These are times of cooling lake waters and decreasing insolation. Consequently the phytoplankton population is unable to bloom quickly into water discoloring abundances, even though the concentration of nutrients in these stream water masses are high (Leonard et al. 1979 p. 293).

Another streamflow density type occurs when winter and spring rains fall on snowpack-covered watersheds. Snowpacks can absorb large amounts of rainfall. In some winters when the snow pack is deep (e.g., February 1982), a particularly intense, long duration, warm rainstorm drops enough water to melt the pack entirely, and such events produce very heavy runoff throughout the basin (Leonard et al. 1979 p. 283). However, usually most streams are entirely covered by ice and snow from December to April, and rains falling on snowpack-covered watersheds seldom affect streamflows significantly. When these rains affect stream water characteristics, the resulting flows contain little or no suspended sediments because the ground surface is protected from raindrop erosion by the snowpack, and channels from bank erosion by an icy sheath. Stream water temperatures will be about the same as the now destratified lake. As the waters of the stream and lake are of similar density, and the surface waters of the lake are likely to be whipped up by the winds accompanying the rainstorm, the two water masses rapidly intermingle.

Winter base flow streamwaters are essentially of the same quality as the previous case--i.e., about the same temperature and containing no suspended sediments. Thus they are readily miscible with lake waters. Their only significant distinction with respect to stream-lake water mass integration lies in their small flow volumes and in not necessarily flowing into lake waters still turbulently mixing because of the winds accompanying rainstorms. The surface waters of the lake are calm much of the time they are receiving winter base flow from streams, and if there is any significant water temperature difference, the two may not immediately intermingle.

The relationships discussed in the preceding paragraphs between different streamflow water temperature and suspended sediment regimes and lake water density and stratification conditions are summarized in Table 26.

Table 26. General Stream-Lake Water Mass Density Relationships

		stream water density compared to lake				
		more dense		less dense	same density	
		stream water conditions relative to lake surface waters in the shore zone				
		suspended sediment concentration				
lake water vertical homogeneity	streamflow period	higher	water temperature			same
			cooler	warmer	same	
unlayered	spring snowmelt flows	X	X			
waters in thermal & density layers	summer thunderstorm flows	X	X			
	summer base flow			X	X	X
	fall rainstorm flows (before snowpack forms)	X	X	X		
unlayered water	winter & spring rainstorm flows (snowpack covers ground)				X	X
	winter base flow				X	X

CHAPTER 16

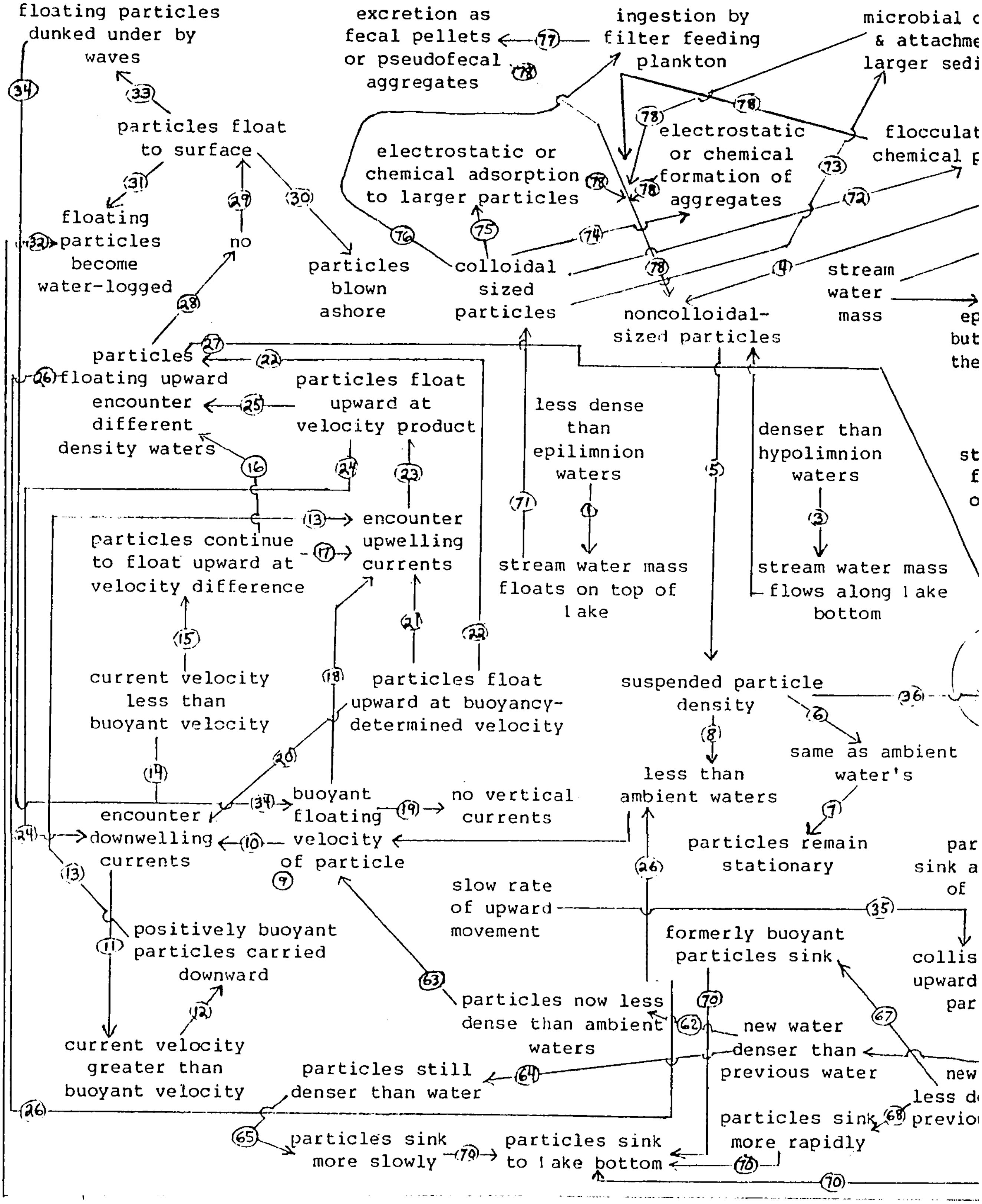
LAKE SUSPENDED PARTICLES AND LAKE BOTTOM SEDIMENTS SUBSYSTEMS

Chapter Scope

In this chapter I discuss the factors affecting the disposition of suspended sediment in the lake water column: what variables determine how, when, whether, or where they eventually settle to the lake bottom sediments. I also discuss the factors affecting how long they stay on or in the bottom sediments, factors causing their resuspension and the modes which ultimately and permanently seal them in or on the sediments or carry them to a depth where they will never again affect the optical properties of the lake surface waters.

Separately for the lake water column and the bottom sediments, I first discuss my reasons for including models and of these two subsystems even though there is no practical means available to protect water color and transparency directly by intervening in such lake processes. I then give introductions to the two models, diagrams representing my conceptual models of the two subsystems and explain them.

Figure 24. Suspended Particles Sinking Subsystem Conceptual Model



stem Conceptual Model

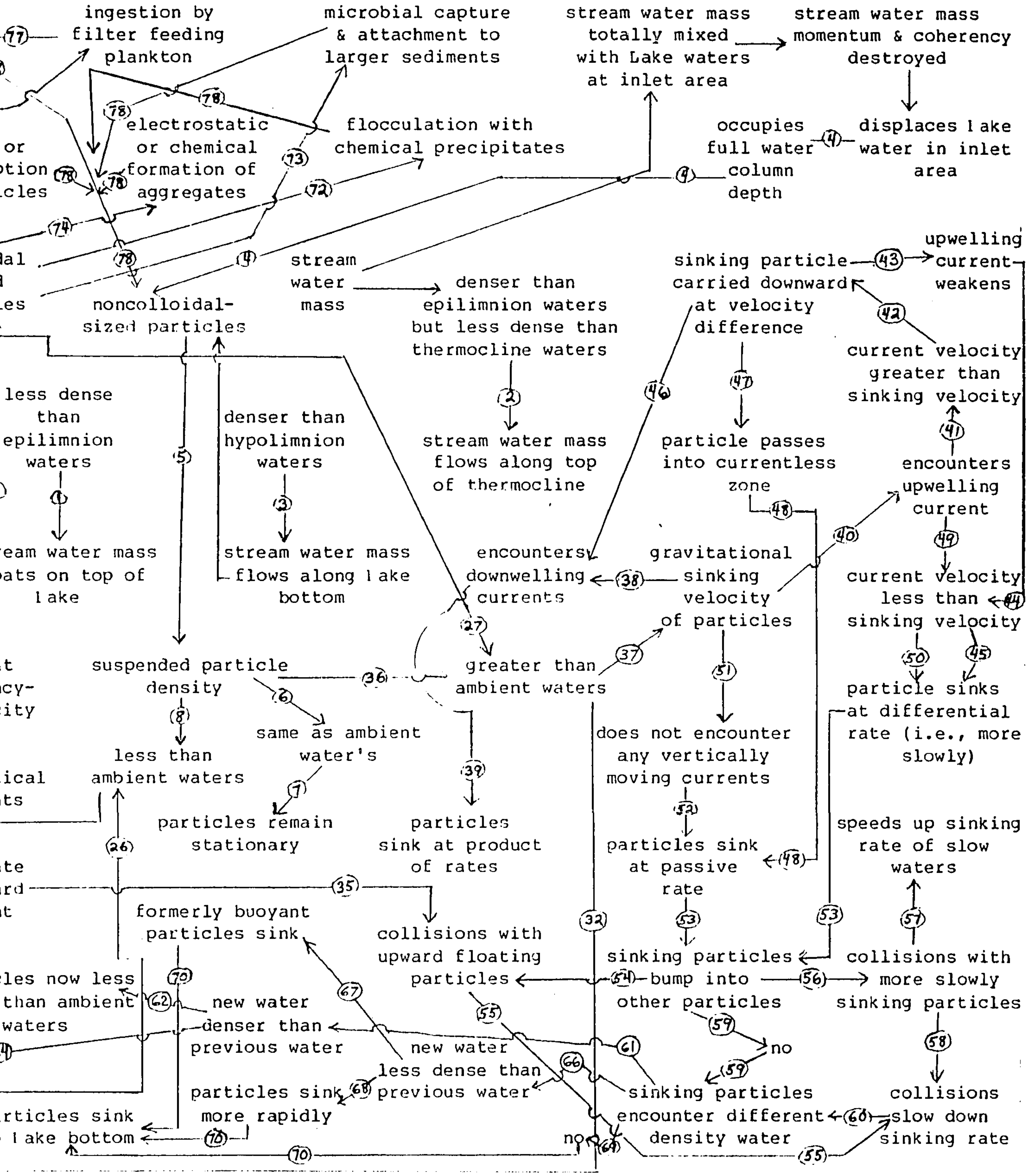


Table 27. Legend for the Sinking Suspended Particles Model

Number	Description
1.	Particles carried onto epilimnion by stream water mass.
2.	Particles carried to thermocline by sinking stream water mass.
3.	Particles carried to lake bottom by sinking stream water mass.
4.	Particles in stream mass occupying full inlet area water depth.
5.	Larger than colloidal particles in stream water mass.
6.	Suspended particles of densities similar to ambient waters.
7.	Particles of same density rise or sink with ambient water mass.
8.	Suspended particles less dense than ambient waters.
9.	Rising velocity of buoyant suspended particles.
10.	Buoyant particles encountering downwelling currents.
11.	Downwelling rate greater than rising rate of buoyant particles.
12.	Buoyant particles carried downward by downwelling currents.
13.	Buoyant particles being carried downward encounter upwellings.
14.	Buoyant particles encounter downwellings of lesser velocity.
15.	Weaker downwelling currents slow rising rate of buoyant particles.
16.	Rising buoyant particles encounter different density waters.
17.	Rising, buoyant particles encounter upwelling currents.
18.	Buoyant particles rise at additive velocities in upwellings.
19.	Rising, buoyant particles encounter no vertical currents.
20.	Buoyant particles float upward at normal hydrodynamic rate.
21.	Normally rising buoyant particles encounter upwelling currents.
22.	Normally buoyant particles encounter other density waters.
23.	Buoyant particles in upwellings rise at additive velocities.
24.	Buoyant particles in upwellings encounter downwelling currents.
25.	Buoyant particles in upwellings encounter other density waters.
26.	Buoyant particles in upwellings encounter less dense waters.
27.	Buoyant particles in upwellings encounter denser waters.
28.	Buoyant particles in upwellings encounter no density differences.
29.	Buoyant particles float to lake surface.
30.	Buoyant particles floating on lake surface are blown ashore.
31.	Buoyant particles floating on lake surface become waterlogged.
32.	Density of waterlogged particles greater than ambient waters.
33.	Buoyant particles floating on surface forced under by waves.
34.	Buoyant particles submerged by waves begin rising again.
35.	Buoyant rising slowed by collisions with sinking particles.
36.	Suspended sediment particles denser than ambient waters.
37.	Normal hydrodynamic sinking velocity of denser particles.
38.	Sinking, denser particles encounter a downwelling current.
39.	Denser particles in downwelling sink at sum of velocities.
40.	Sinking, denser particles encounter an upwelling current.
41.	Speed of upwelling current exceeds normal sinking rate.
42.	Denser particles are carried upward at velocity differential.
43.	Upwelling current slackens speed.
44.	Speed of upwelling reduced to less than particle sinking rate.
45.	Denser particles sink at velocity differential.

46. Denser particles rising in upwelling encounter a downwelling.
47. Denser particles rising in upwelling pass into still waters.
48. Dense particles passing into still waters sink at normal rate.
49. Denser particles sinking in weaker upwelling currents.
50. Dense particles not encountering vertical currents.
51. Sinking, denser particles not encountering vertical currents.
52. Denser particles sinking at normal hydrodynamic rate.
53. Sinking, denser particles bump into other suspended particles.
54. Denser sinking particles collide with rising, buoyant particles.
55. Denser-lighter particle collisions slow sinking rate of former.
56. Denser particles bump into more slowly sinking particles.
57. Collision momentarily speeds up sinking rate of slower sinkers.
58. Collision momentarily slows down sinking rate of faster sinkers.
59. Sinking, denser particles not colliding with other particles.
60. Sinking, denser particles encounter different density waters.
61. Sinking particles encounter denser waters.
62. Particles now less dense than encountered denser waters.
63. Formerly sinking particles begin rising in denser waters.
64. Particles still denser than encountered denser waters.
65. Particles continue sinking more slowly in denser waters.
66. Sinking particles encounter less dense waters.
67. Formerly buoyant particles begin sinking in less dense waters.
68. Denser particles sink more rapidly in less dense waters.
69. Sinking particles encounter no water density differences.
70. Denser particles sink to lake bottom sediments.
71. Colloidal size suspended particles carried in by stream masses.
72. Colloidal particles flocculated by chemical precipitates.
73. Bacterial capture of colloids & attachment to larger sediments.
74. Electrostatic or chemical formation of aggregates from colloids.
75. Electrostatic or chemical adsorption of colloids.
76. Ingestion of colloids by filter feeding plankton.
77. Excretion of colloids as fecal pellets or pseudofeces.
78. Physical, chemical or biologic conversion of colloids to larger particles

Explanation of Sinking Suspended Particles Model

In addition to suspended particles already in lake water, inflowing stream water masses bring in other, largely inorganic sediments. When the lake is stratified, inflowing waters place suspended sediments on epilimnion or thermocline waters or the bottom of the lake (1)(2)(3) --depending respectively on whether stream waters are less dense than epilimnion or metalimnion waters or denser than hypolimnion waters. When lake waters are not stratified, suspended particles in stream water masses are placed on the top, bottom or throughout the depth of the water column in the inlet area (4), depending on whether they are less, more or the same density as lake waters.

The subsequent pathways leading to the eventual settling of all particles to the lake bottom depend upon particle size and density relative to lake waters. Particles of larger than colloidal sizes (5), and with densities similar to ambient waters (6), rise or sink with their surrounding waters (7).

Suspended particles less dense than ambient waters (8) have a tendency to rise at a velocity determined firstly by their buoyancy (9) and secondarily as modified by their surface area and cross section and by the viscosity of waters through which they move. Buoyant particles may also encounter downwelling currents (10) which carry them downward (12) if the current velocity is greater than the rising rate of buoyant particles (11). If the encountered downwelling currents have lesser velocities (14), the rising rate of buoyant particles is merely slowed (15). Rising buoyant particles (or those being carried downward) may also encounter upwelling currents (17)(21)(13) and subsequently rise at velocities higher than attainable by buoyancy alone (18)(23). Similarly the rise of buoyant particles in upwelling currents may be slowed or reversed by encounters with downwelling currents (24). Most rising, buoyant particles in upwellings encounter no water density differences (28), but some may (25)--their rising rate being sped up if the waters are less dense (26) and slowed or stopped if the waters are of greater density (27). Particles not encountering vertical currents (19) and rising solely by their natural buoyancy (20) may also encounter different density waters (16)(22) and be affected in the same way. The rising rate of buoyant particles may also be slowed by collisions with sinking particles (35).

Some buoyant particles eventually float to the surface of the lake (29) where some are windrowed and blown ashore (30), and some are forced under again by breaking waves (33) and resume rising (34)--though from a shallower starting depth. Some floating particles also become waterlogged (31) and sink if their density is greater than ambient waters (30).

Most suspended sediment particles are denser than ambient lake waters (36) and normally encounter no vertical currents (50)(51). Hence they sink at a velocity determined by their hydrodynamic shape as well as by their density (37)(52). These normally sinking particles may encounter downwelling currents (38) and subsequently sink at a rate about equal to the sum of the two velocities (39). Relatively dense particles may also encounter upwelling currents (40) and sink more slowly if the currents are weak (49) or may be carried upward at the velocity differential (42) if the current is strong enough (41). The speed of strong upwelling currents eventually slackens (43), and relatively dense particles begin sinking again (44) at the velocity differential rate (45). Relatively dense particles being carried by upwelling currents may also encounter downwelling currents (46) or still waters (47) and resume sinking at normal (48) or more rapid rates.

A few sinking denser particles do not collide with other suspended particles (59), but most bump into others (53). The sinking rate of relatively dense particles is slowed by collisions (58) with rising, buoyant particles (54), slower sinking lighter particles (56)(55) and stationary particles. Such collisions also momentarily speed up the sinking rate of slower sinking lighter particles (57).

Particles sinking when the lake is completely mixed encounter no water density differences (69). During other times, sinking, relatively dense particles may encounter denser ambient waters (61), which if denser than the particles (62), stop further sinking and may even cause some particles to begin rising (63). More usually, sinking particles will still be denser than such waters (64) and consequently continue downward at a somewhat slower rate (65).

Rarely will sinking particles encounter less dense waters, because such waters are always found near the surface of the lake. However, (66) if they do, formerly buoyant particles may stabilize or begin to sink (67), and relatively dense particles will begin to sink more rapidly (68). Eventually all relatively dense suspended particles larger than colloids sink to the lake bottom sediments (70).

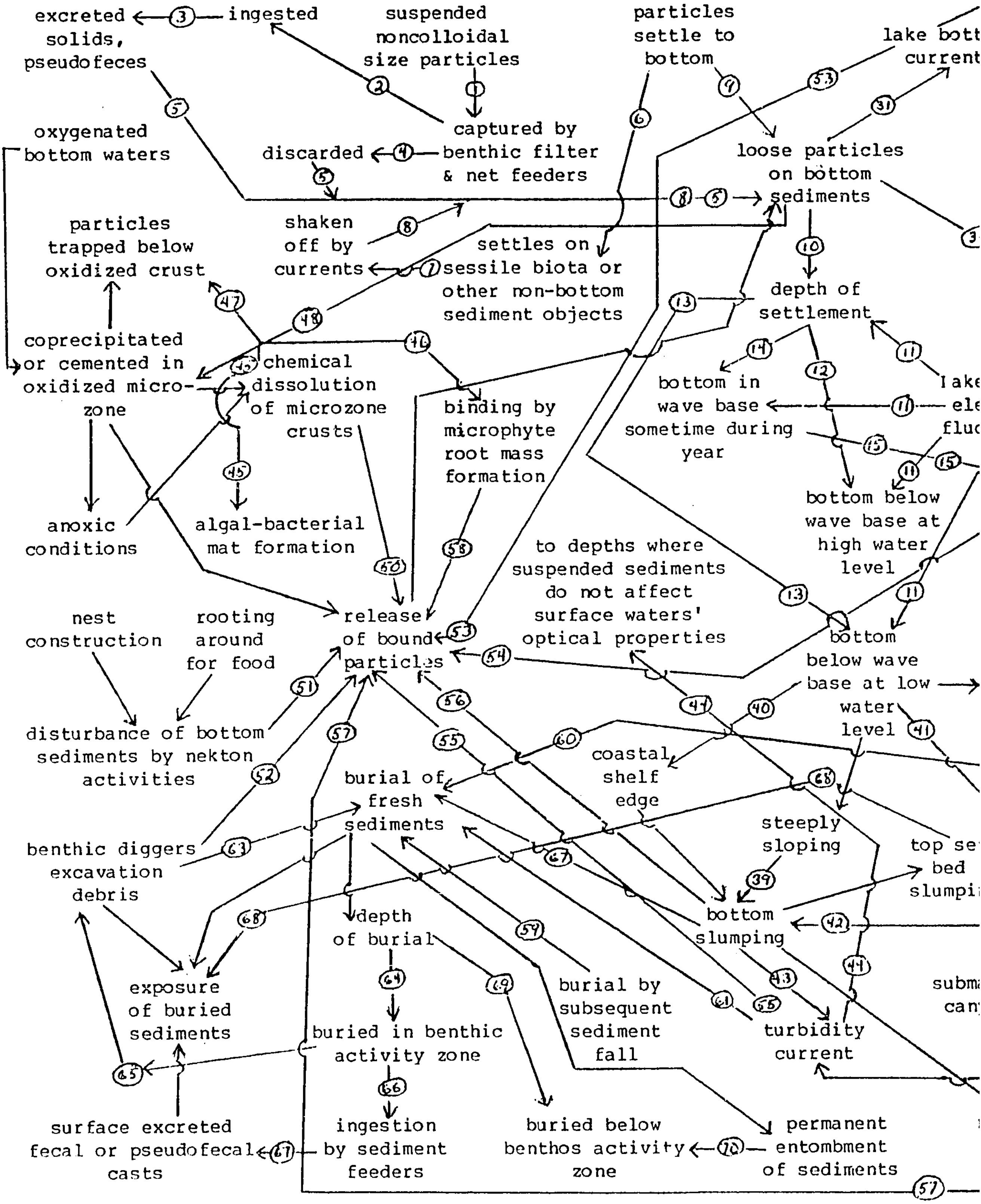
In addition to the colloidal-sized suspended particles produced within the lake, stream water masses carry in others of terrestrial or fluvial origins (71). Potentially, colloidal particles virtually never settle. In fact they are flocculated by certain chemicals (72) and aggregated by or absorbed on larger particles by electrostatic or chemical processes (74)(75). They are also captured by bacteria that attach them to larger suspended sediments (73), and they are ingested by filter feeding plankton (76) and excreted as fecal pellets or pseudofeces (77). Hence physical, chemical and biologic conversion processes convert colloids to larger particles (78), and even they eventually settle to the lake bottom.

Lake Bottom Sediments Subsystem

Particles settled to the lake bottom do not necessarily remain there and have no further affect on lake water color and transparency. In addition to any optical effects they might have by altering bottom sediment color and/or reflectivity (e.g., Welch 1971 p. 106 & 116), many physical processes exist which may resuspend the settled sediments. Thus settlement, at least in its initial stages, does not allow us to dismiss further consideration of the possible effects those sediments may have on the optical properties of the visible portion of the water column.

Many variables control the probability that particles will be resuspended: their depth of settlement, proximity to shoreline processes, steepness of bottom slope, amount of benthic burrowing, proximity to submarine canyons, shoreline shelf edge, bottom currrent pathways, etc. Physical resuspension processes are particularly important at bottom depths still in the visible water column zone. Since suspended sediments of larger than colloidal sizes rapidly settle to the bottom once stream waters enter the comparatively still waters of the lake, most of them are deposited initially in shallow water depths close to the shore, where the optical effects of their resuspension will be most apparent. Eventually these shallow water sediments are reworked by physical hydrodynamic forces; they are resuspended, again affecting water color and transparency and shifted until they are ultimately deposited at sufficient depths that further resuspension and movement has absolutely no effect on visible water optical properties. Settled sediments may be sequestered in the bottom, even in relatively shallow waters, by other sedimentary processes: oxidized microcrust or algal-bacterial mat formation, burial by subsequent sediments, etc. No reasonable lake-watershed management option can alter what naturally occurs at this stage in the overall sediment cycle process. However, because initially settled particles in many instances will again affect lake water color and transparency, it is useful to know the different processes and relationships which resuspend particles and determine their ultimate fate--i.e., removal from the possibility of affecting water optical properties visible to surface observers. This final subsystem description and discussion, as in the case of the previous two (Figures 23 and 24), is another necessary link for understanding how watershed substances affect the water color and transparency of the lake.

Figure 25. Lake Bottom Particles Subsystem Conceptual Model



onceptual Model

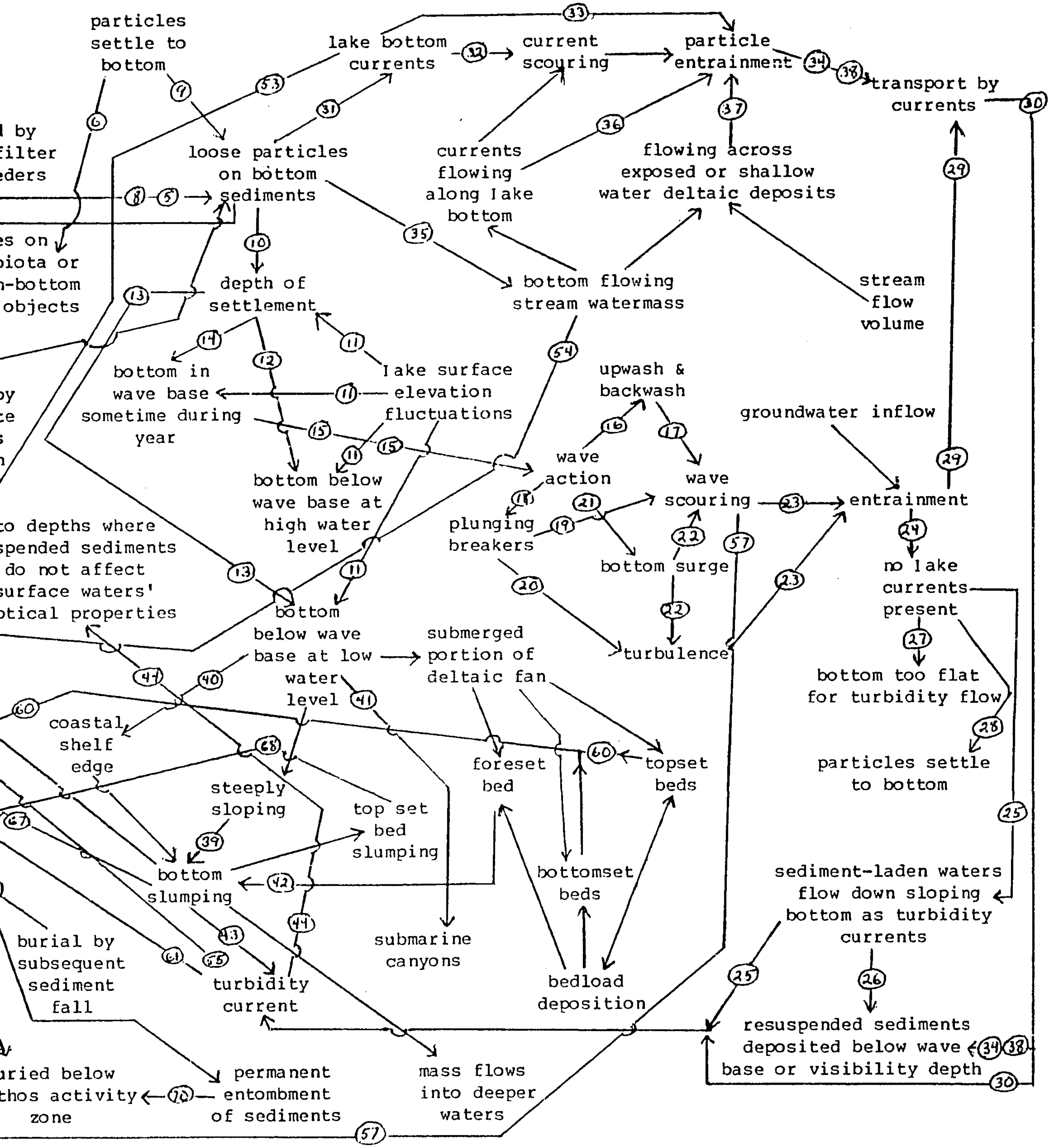


Table 28. Legend for Model of the Disposition of Particles on the Bottom of the Lake

Number	Description
1.	Suspended particles captured by sessile filter feeders.
2.	Captured particles ingested by sessile filter feeders.
3.	Ingested particles excreted in feces or pseudofeces.
4.	Discarded particles captured by sessile filter feeders.
5.	Ingested & discarded particles deposited on bottom sediments.
6.	Sediments initially settling on sessile, benthic biota.
7.	Sediments on sessile benthos are shaken or fall off.
8.	Sediments initially settling on sessile benthos fall to bottom.
9.	Suspended particles settling directly on lake bottom sediments.
10.	Immediate fate of settled particles depends upon bottom depth.
11.	Annual lake surface fluctuations affect bottom exposure to waves.
12.	Loose particles on bottoms below high water wave base depth.
13.	Loose particles on bottoms below low water wave base depth.
14.	Loose particles on bottoms annually above wave base depth.
15.	Loose particles on bottoms at depths subject to wave actions.
16.	Sediments initially deposited in up- & backwash shore zone.
17.	Sediment winnowed into deeper waters by wave backwash scouring.
18.	Sediments initially deposited on bottom in surf zone.
19.	Sediments moved into deeper waters by waves plunging & scouring.
20.	Sediments moved into deeper waters by breaker turbulence.
21.	Sediments initially deposited at depths subject to bottom surge.
22.	Sediments entrained & moved into deeper waters by bottom surge.
23.	Sediments entrained by wave turbulence & scouring.
24.	Sediments resuspended where no transporting lake currents exist.
25.	Waters laden with resuspended sediment flow down bottom slopes.
26.	Sediments redeposited below wave base or visibility depth.
27.	Sediments resuspended where bottom too flat for turbidity flows.
28.	Resuspended sediments again sink to bottom once waves die down.
29.	Sediments resuspended where lake currents exist.
30.	Resuspended sediments carried into deeper waters by currents.
31.	Particles deposited in areas periodically subject to lake currents.
32.	Deposited particles scoured loose by lake bottom currents.
33.	Particles resuspended by lake bottom currents.
34.	Resuspended particles carried into deeper water by lake currents.
35.	Particles deposited in areas subject to stream water mass flows.
36.	Particles resuspended by stream mass flowing along lake bottom.
37.	Resuspension by stream mass exposed or shallow water deposits.
38.	Resuspended particles carried into deeper water by stream mass.

39. Particle deposits on sloping bottoms slump into deeper water.
40. Deposits near coastal shelf edge slump into deeper water.
41. Deposits near edge of submarine canyons slump into deep waters.
42. Foreset bed deltaic deposits slump into deeper waters.
43. Slumping particle deposits becoming turbidity currents.
44. Slumping generated turbidity currents flow into abyssal depths.
45. Binding of settled particles by formation of algal-bacterial mats.
46. Particles bound to bottom by macrophyte root masses.
47. Particles trapped beneath formation of oxidized microzone crust.
48. Particles bound in the oxidized microzone crust.
50. Release of particles locked in crust by chemical dissolution .
51. Release by nekton feeding & breeding bottom disturbances.
52. Release by benthic digger excavation activities.
53. Release by lake current erosion of crusts & mats.
54. Release by stream water mass erosion of crusts & mats.
55. Release by turbidity current erosion of crusts & mats.
56. Release by bottom slumping disruption of crusts & mats.
57. Release by wave erosion of crusts, mats & root masses.
58. Release by seasonal death & decay of macrophyte root masses.
59. Burial of settled particles beneath subsequent falling sediments.
60. Burial beneath bedload particles deposited on inlet alluvial fans.
61. Burial of settled particles by turbidity currents.
62. Burial of settled particles by bottom slumps.
63. Burial of settled particles by benthos digging activities.
64. Settled particles buried no deeper than zone of benthos activity.
65. Buried particles reexposed by benthos digging.
66. Buried particles ingested by sediment feeding benthos.
67. Buried particles reexposed by fecal casts excreted on surface.
68. Buried particles reexposed by bottom slumps.
69. Settled particles buried deeper than benthic activity zone.
70. Settled particles permanently entombed deep in sediments.

Explanation of Lake Bottom Particles Model

On the bottom of the lake some suspended particles are captured by sessile filter feeders (1) and ingested (2), and some are excreted in feces or pseudofeces (3). Some of the discarded bottom particles are picked up by other sessile filter feeders (4), but most become part of bottom sediment deposits (5).

Some suspended sediments initially settle on sessile and other benthic organisms (6) and are shaken or fall off (7) into the bottom deposits (8). Most particles settle directly onto other lake bottom sediments (9) where their immediate and final fate depends upon the depth of that bottom below the lake surface (10). This depth, and hence the vulnerability, of settled sediments to resuspension varies somewhat through the year because the surface elevation of the lake fluctuates. These fluctuations affect the amount and location of lake bottom sediments exposed to erosion and resuspension by waves (11). Loose particles settled on lake bottom areas below the depth at which wave turbulence has any effect on them (wave base depth) are not disturbed even when waters are low (13). However, particles on lake bottom areas above this depth and its high (12) water equivalent are, sometime during the year, in wave base depth (14) and subject to resuspension by wave turbulence (15).

Sediments initially deposited on near-shore areas subject to wave upwash and backwash (16) are subsequently picked up and carried into deeper waters by the scouring of waves (17). Stream-borne sediments initially deposited on bottom areas in the surf zone (18) at some times of the year are subsequently resuspended and moved into deeper waters by plunging and scouring wave action (19). Stream-borne particles deposited a little farther out are resuspended and moved into deeper water by breaker-genereated turbulence (20). Stream-borne suspended particles deposited on bottoms at depths sometimes subject to wave surge (21) are subsequently entrained and moved into deeper waters by that turbulent process (22).

Some stream-borne sediments initially deposited in lake bottom areas where lake water mass currents do not exist are resuspended (24) by wave turbulence and scouring (23) or passing turbidity currents. When the lake bottom topography is favorable, these resuspended terrigenous sediments form into or join passing turbidity currents and flow downslope (25). When the lake bottom is too flat to promote turbidity flows (27), the resuspended terrigenous sediments settle to the bottom once again as surface waves calm down (28). If they are redeposited at bottom depths below wave base or Secchi depth (26), they are not likely to subsequently affect lake water color and transparency.

When stream-borne sediments are deposited on bottom areas subject to lake water mass currents (31), they may be scoured loose (32) and entrained by them (33). When resuspended by wave turbulence (29), they may be carried by passing bottom currents out into usually deeper waters (30)(34) where they are unlikely to again affect lake water color and transparency.

Terrigenous particles deposited in lake bottom areas subject to stream water masses flowing along the bottom (35) may be resuspended by them (36). Some lake bottom particles are also certain to be resuspended from shoreline or shallow water deposits by the scouring of passing stream water masses (37), be carried into deeper waters by them

(38), and be redeposited where they will not influence lake water color and transparency again.

Some stream-borne particles are deposited on steeply sloping portions of the lake bottom, which may slump into deeper areas of the lake (39). This lake bottom sediment transport process is most likely to occur on portions of the bottom near the edge of coastal shelf deposits (40), and submarine canyons (41) and on foreset bed portions of submarine delta deposits (42). Lake bottom particles in slumping sediment deposits move either in mass into deep waters or are resuspended upon being stirred up and subsequently flow as turbidity currents (43) into the abyssal depths of the lake (44).

Once on the lake bottom, settled particles may become bound to it by the formation of algal-bacterial mats (45), macrophyte root masses (46)(49) or incorporation in or trapped beneath the oxidized microzone crust (47)(48). Settled particles bound to the lake bottom by such forces are again freed by dissolving of the microzone crust (50), the excavation activities of nekton and benthic diggers (51)(52), lake current, stream water mass turbidity current or wave erosion of bottom crusts, mats and root masses (53)(54)(55)(57), disruptions caused by slumping (56) and death and decay of macrophyte root masses (58). Stream-borne and autochthonous lake particles settled on the bottom are buried beneath other particles, subsequently falling to the bottom (59). This burial process proceeds particularly rapidly around the edges of submarine alluvial fans (60). Some settled bottom particles are also buried by turbidity current materials (61), beneath slump deposits (62) and some by the digging activities of benthic organisms (63).

The final stages in the fate of settled and subsequently buried particles depends upon how deeply they are in lake bottom sediment deposits. If buried no deeper than the zone affected by benthic digger activities (64), they may be reexposed by those excavations (65). Less directly, they may be reexposed by ingestion by sediment feeding benthos (66) and then reexposed by excretion of fecal casts on the surface (67). If buried deeper than the zone of possible benthic activity (69), some particles may be subsequently reexposed by slumping (68), but most are permanently entombed in the lake bottom sediments (70).

CHAPTER 17

LAND CAPABILITY CLASSIFICATION TO PROTECT WATER COLOR AND TRANSPARENCY

Introduction and Scope

In this chapter I use the understanding gained in developing the CEMs in the preceding chapters (Chapters 6-10, 12-16) to select watershed variables which can be mapped and which best express the potential for sediment and nutrient storage, release, transport and delivery from watershed lands and streams. I give my general strategy for expressing LCC, examples of a procedure for selection of mapping variables, and discuss the mechanics of producing maps of chosen variables and a composite LCC map.

Land Capability Classification Scheme

Gravitational forces drive all the fluvial processes responsible for release and transport of nutrients and sediments from watershed sites to the lake. Hence, the sequence of variable conditions affecting the transmission of these materials occurs along the fall line of waters flowing over land surfaces, in channels and seeping underground. Overland fall lines are perpendicular to land surface contours and extend from ridge top divides to intersections with channels down slope, and thence, by the fall lines of a sequence of enlarging channels to the lake. Generally the down slope movement of underground waters also follows the fall lines of land surface contours. Lateral movement of interflow on slopes and of groundwaters in aquifers and alluvial deposits occurs only when impermeable materials block their normal gravitational pathways. However, I assume that the amount of water moving in such deviant pathways is relatively insignificant compared to the quantities flowing down-slope in mountainous terrain, such as is characteristic of the Ward Creek watershed.

Fall lines are the dominant pathway of hydrologic transport; therefore I organize my land capability classification scheme for potential nutrient and sediment delivery according to a sequence of downhill linkages and pathways. I consider the sediment and nutrient delivery capability classification for watershed sites to be some function of: (1) the total amount of those substances on sites and conditions on sites favoring their retention or loss, (2) upslope processes and conditions affecting site retention and loss processes, (3) downslope processes and conditions controlling transmission of substances moving from sites, and (4) channel processes and conditions controlling the conduction of substances received from sites to the lake.

The number of different watershed classification sites is largely determined by how they are defined. Their number may be determined by the minimum or average size of privately owned parcels or of individual land development proposals. One common approach used by many environmental planners establishes the number of classification sites as the units of different natural factor combinations obtained by overlaying maps of vegetation, soil, geology and other types of physical and conceptual information. The number and size of watershed classification sites produced by this approach is determined by the number of map overlays used and the detail of information on each map. Frequently the rote use of this approach produces an unmanageable abundance of units, some of them impractically small.

Another commonly used approach for combining mapped data is to divide watersheds into a regular network of standard-sized squares. Consequently, a set maximum number of watershed classification sites classification are established and their minimum size and total number are explicit choices determined by manageability and the amount of spatial detail needed. These site-cells regroup into a lesser number of map units as some cells possess the same combination of classification variables. I favor this grid cell approach and the use of one hectare cells in the grid network superimposed over a watershed map.

In Appendix C I give a more detailed comparison of the two basic approaches for combining mapped data. I favor hectare-size cells because of the trend toward metrification, because much quantitative ecologic data useful for comparative and supportive purposes is given in units/ha, and because when clustered in groups of four they form cells approximately the size of the ten-acre grid cells used for developing earlier planning agency LCC studies of the basin.

My classification scheme gives each site-cell 16 separate ratings describing its potential to supply nutrients and suspended sediments to the lake and to affect their delivery from other cells in the same fall line pathway. Three ratings are needed for the total amount of (1) phosphorus, (2) nitrogen and (3) potential suspended sediment particles in each hectare cell. Three ratings are needed for the conditions in cells affecting the release of each of those substances--(4) nutrients by leaching and interflow, (5) nutrient- containing and inert particles by surface erosion and (6) by mass movement. Two ratings are needed for cells as upslope areas whose conditions and hydrologic products affect the tendency of adjacent, downslope cells to retain or release nutrients or suspended sediment particles to (7) interflow and (8) overland flow. Two similar ratings of cells indicate their efficiency as downslope conduits for (9) interflow and (10) overland flow transport of the nutrients and sediments released from adjacent, upslope cells.

Two ratings are needed for the (11) suspended sediment and (12) nutrient delivery conditions in channels from the base of the slope fall line to the lake.

It is unlikely that the upslope and downslope cells along a fall line sequence will have all synergistic or all antagonistic values for variables affecting release and transmission. Hence each cell also needs ratings of the aggregate effect of all cells along its hydrologic fall line upslope on release of site (13) nutrients and (14) sediments and for all the downslope cells on transmission of released site (15) nutrients and (16) sediments to the stream. These summary ratings are obtained by recording the individual ratings of cell effects on adjacent, up slope and down slope cells for all cells along the fall line. For example, consider only aggregate downslope effects, and a case where there are eight 1 ha cells between a site and the stream channel. The variables used to indicate conductive quality are slope length, slope steepness, soil infiltration and percolation rates and the quality of litter cover. My summary rating would consist of downslope length = 8, 6 slope steepness cells retarding and 2 favoring transmission; 3 cells with infiltration rates respectively retarding and 5 favoring transmission, etc. The result is a composite relative efficiency rating for downslope conduction for each cell-site.

The individual and composite ratings produced by my scheme are indicators of the relative amounts of transmission and delivery of nutrients and suspended sediment escaping from a watershed site. I do not attempt to quantify the amount of nutrients and sediments delivered to the lake from each watershed cell. Detailed, site-specific investigations and fluvial studies of transport rates by tagging are needed to give reliable quantitative estimates for mountainous wildland terrain.

Sixteen separate ratings may seem like excessive work, but each should be fairly simple and only use four or five variables. The total set of variables is limited with frequenty only different combinations of the same few variables being used from a different perspective. Consequently the total rating process does not involve evaluation of combinations of sixty or more completely different independent variables. The simplicity of the ratings facilitates computerization of the entire process--an ideal combination with grid-cell spatial compositing capabilities.

Conceptual and Mechanical Aspects of Classification

In this section I discuss the selection and organization of variables used in the classification scheme and some practical decisions needed for application of the scheme. I begin by pointing out some of the actual complications which may affect the validity of simplification of nutrient and sediment transport processes by my scheme .

Modes of Sediment and Nutrient Transport

Definitions and Distinctions

Four modes of transport must be accounted for by ratings of the tendency for nutrients or suspended sediments to move from a watershed site to the lake: 1) overland flow, 2) interflow, 3) channel flow, and 4) mass movement. Overland flow (synonym; surface runoff, Chorley 1978) refers to draining waters that move in sheets or discontinuous rivulets across the top of the ground surface. Interflow refers to subsurface waters draining vertically and horizontally through the regolith and returning to the surface without reaching the water table (Chorely 1978). Channel flow refers to waters draining in permanent linear depressions--most continuing downward and merging with others until they reach the lake. However, some channels are discontinuous: e.g., those whose waters sink into porous deposits of coarse colluvium at the base of steep slopes, or those whose linear depressions disappear into flat marshy areas.

I use mass movement to refer to all other nonfluvial processes which move nutrients and sediments. Thus, for example, I consider rockfalls, landslides, mudflows, and snow avalanches all to be mass movement transport processes. My usage is broader than the orthodox definition of "mass movement," (Sharpe 1938, Varnes 1978) which emphasizes the sudden to gradual movement of entire blocks of earth (American Geological Institute 1962). The orthodox definition excludes snow avalanches, because they transport only small, if any, amounts of soil or rock. Certainly snow avalanches are not major nutrient and sediment transport processes because they typically slide along over deeper snow rather than in direct contact with the soil surface (U.S. Department of Agriculture 1968 p. 17) and seldom flow directly into stream channels. However pure snow contains nitrogen; thus avalanches move snow-borne nitrogen closer to channels reducing the chance of its storage or delay by uptake processes along the fall line. Snow avalanches frequently occur in chutes carved by some mass movement process, possibly other avalanches, demonstrating the ability of some downslope transport process to scour out nutrients and sediment-containing materials carried in from lateral sources. Thus my more general interpretation of "mass movement" provides a useful category for all fall line transport processes not driven by moving waters.

Relationships Between Modes

Some mass movements in the Tahoe Basin are watery mudflows which move into, flow down, and scour out stream channels much like high water flows (e.g., Glancy 1969). Technically, the distinction between mudflows and muddy waters occurs when particles become so abundant that the fluid turbulence, responsible for sediment suspension in flowing water, begins to abate. This occurs when suspended sediments exceed half the weight of the emulsion (Friedman and Sanders 1978 p. 10). Such fine categorical distinctions between transport modes are unimportant for my purposes.

Nutrients and suspended sediments are not transported equally well by all four processes. Dissolved and soluble nutrients are transported by the three fluvial modes, but interflow does not transport suspended sediments and particulate nutrients because they are filtered out and remain on the surface when draining waters seep into the ground (Statham 1977 p. 64-68). The soils in the basin have low clay contents; hence soil piping should not occur (Heede 1971). Fossorial animal tunnels and root channels do not interconnect and run continuously down the length of slopes. Hence no significant amount of runoff is able to move continuously underground in macropores (Aubertin 1971), nor are they large enough to allow below-ground sediment transport.

Only flow in channels transports significant amounts of suspended sediment to the lake. On a watershed basis, the amount of overland flow directly into the lake is insignificant. Channel flows are also the most significant mode of nutrient transport to the lake, though interflow and overland flow have a larger but still insignificant role in nutrient transport than they do in the transport of sediment. Throughflow and seepage from channel flow carry nutrients into the comparatively slow-moving ground water deposits. In the Ward study area, nutrient concentrations are high in ground waters (Loeb and Goldman 1979), and most of these in the lower portion of the watershed drain directly into the lake (Leonard, et al. 1979 p. 283), delivering many more nutrients than overland flow and interflow but seldom originating farther than 2.5 km from the lake.

Temporal Discontinuities

Transportation is not usually a continuous process, nor does it necessarily occur by a set sequence of modes; interchange of modes may occur several times along the fall line pathway of draining waters. For example, draining waters switch back and forth between modes upon encountering changes of soil infiltration and percolation rates, soil water saturation conditions or changes in slope steepness. Where draining waters seep in, their sediment load is deposited on the surface. The dissolved nutrient load of draining waters is sometimes enhanced by flushing of the soil solution and leaching (Statham 1977 p. 125) when infiltrating waters exceed the water holding capacity of soils and the transpiration capacity of plants (Brown 1973 p. 9-13). However, when there is a well developed forest cover, bacteria, soil exchange sites, mycorrhizae, or roots, dissolved nutrients are often taken up from infiltrating overland flow waters, resulting in decreased concentrations (Coates 1975).

Depending upon their forcefulness, surface materials and conditions, waters seeping from the ground or into stream beds (Clayton et al. 1966) may release suspended sediments. Draining waters may move both into and out of channels via leakage and overland flow, though the latter rare event occurs only when channels overflow their banks or disappear as their waters are spread out on gently sloping meadows, marshes or undissected flats. Waters overflowing channels drop their suspended sediments as they lose velocity and turbulence. Deposition on overflow lands is transitory for they are eventually picked up and transported by subsequent high stream flows. Loss of flow by seepage from channels also reduces the amount of supended sediment which channels can transport and transfers the nutrient contents of those waters into more slowly moving ground waters.

Deposition of sediments and nutrients by evaporation and transpiration occurs when channel, overland flow, and interflow waters dry up between rainstorms or after snowpacks melt. The sediment load of overland flows may be deposited on the surface by being trapped in the interstices of plant litter deposits, by stranding when overland flow infiltrates or evaporates, or by settling from still waters of puddles. Where the quantities of fine sediments deposited on the surface are large, they may plug the ground pores, preventing further infiltration and increasing surface runoff. This problem is particularly common downslope of areas heavily disturbed by earth moving activities.

Some types of mass movement are active only during the wet seasons or during particularly wet years. For example, most soil creep movement occurs when the ground is wet. The deposits at the bases of initially very rapid mass movements may be reactivated and continue moving, though at slower rates, when saturated during particularly wet years, resulting in, for example, the continued movement of landslide deposits into stream channels.

Spatial Distribution of Modes

It is usually obvious where drainage channels are present on sites, though whether gentle swales function as significant transport channels can be difficult to determine. The presence, absence or magnitude of activity of the other transport modes is usually not so readily apparent. In some places or circumstances they are present and important, while in others they are totally absent. Their presence, absence and strength in a given location can also change rapidly as a consequence of human use activities.

Interflow and Overland Flow

Overland and interflow are transport processes not found everywhere in a watershed. Low surface permeability, whether due to, for example, large areas of exposed bedrock, inherent soil properties, or sealing by deposited fines, makes interflow insignificant in some areas, and hence transport is dominated entirely by overland flow. Temporally variable conditions, such as frozen and saturated soil, have the same consequences. Conversely, overland flow rarely occurs on undisturbed areas covered by plant litter. Snowmelt waters also seep into the soils directly below the pack and hence move entirely as interflow, except in those rare instances when they melt more rapidly than percolation and interflow can transmit water or when the soil surface is frozen. As the Ward Creek watershed is largely forest-covered (79%) and most of its precipitation is snowfall (Leonard et al. 1979 p. 286), most waters draining from its surface must move as interflow.

Overland Flow and Channel Flow

Distinguishing between the relative dominance of overland flow and channel flow is desirable because of their widely differing transportation capabilities. Waters drain off more rapidly when flowing in channels than when flowing overland. As a consequence of their faster movement and greater depth, waters flowing in channels have a much greater erosional capability than overland flowing waters. In both channel and overland flow, particles are rolled along the surface. In channels particles are also moved by saltation and suspension. As a consequence of their greater drainage efficiency and erosional strength, channels have a strong tendency to enlarge and extend themselves upslope as far as runoff is sufficient to initiate channel flow. Hence where runoff volume and surface conditions permit, draining waters move as channel flow. Consequently, on barren, friable surfaces we frequently find a network of tiny channels (rills) beginning close to the source of sheet flow waters. Usually channel flow is able to begin within a few meters of where overland flow begins (Statham 1977 p. 135,161). Thus, when trying to make sound operational distinctions between the relative spatial dominance of the two processes, we quickly encounter difficulties.

When attempting to distinguish between areas largely drained by sheet flow and those where channel flow dominates, no existing resource inventory record is sufficiently detailed to allow such fine spatial distinctions. Contour maps are the only widely available descriptive information useful for determining channel distribution. On them the probable existence of a stream channel can be inferred from a string of undulations bending into the slope on consecutive contour lines.

A string of adjacent contour line indentations may indicate excavation processes other than flowing water, such as landslide, rockfall, or snow avalanche locations. The desirability of separating the two channel transport processes, as for separating overland from channel flows, lies in the significantly differing nature of the materials moving down them and the likelihood that those materials will be wholely and rapidly carried to the lake. Dry transport process chutes have characteristic features which make them readily distinguishable from fluvial channels on aerial photos and, to a limited extent, even on contour maps. Channels caused by those "dry" excavation and transport processes are typically: 1) straight lines running directly down the slope fall line on steep slopes (c.f. Leaf and Martinelli 1977 p. 20-41), 2) barren and not bordered by riparian vegetation (White 1981), 3) terminated by hummocky deposits, 4) not connected to fluvial channels, nor continued far out over flatter terrain. These and other distinguishing physical characteristics make it possible to separate most undulations caused by dry transport processes from those caused by wet processes.

The distinction between wet and dry transport process channels is probably unimportant in the Ward Creek watershed. Dry movement chutes are common only on very steep slopes--30 to 60 degrees for snow avalanches (U.S. Department of Agriculture 1968 p. 29) and greater than 25 degrees for landslides (Johnson 1979 p. 98). Presence of the continuous dense forest cover over 80 percent of the watershed also indicates the general stability of that landscape. Consequently, fluvial chutes are much more frequent and significant transportation routes than dry chutes. Even dry chutes intercept and channelize overland flow from adjacent land surfaces and wet transport channels some of the time--as during summer cloudbursts. Most of the nutrients and sediments moving from them into fluvial transport channels occur during such wet flow times.

Only if the dry transported materials moving down chutes are deposited directly in stream channels will mass movement down these cavities be major sources of the sediment load of a stream. Even then, most of the mass movement deposits from chutes are poor sources of nutrients, and frequently, of suspended sediments. They consist largely of rock and subsoil materials from areas where soil and vegetation cover are not sufficiently developed to have concentrated stores of nutrients and where weathering has not proceeded long enough to produce the clay and silt and fine sand particles that become suspended sediments.

The major deficiency of relying solely on existing contour maps to delineate the extent and density of the drainage channel network is that their countour intervals are so widely spaced, and the maps are of such a large scale that the spatial extent of the smaller (shallow and/or narrow) channels is not shown by contour undulations. The depth of the smallest channels shown by contour lines is also directly proportional to slope steepness. Consequently, on gentler slopes undulations are more sensitive indicators of the presence of shallow channels than they are on steeper slopes. The density and height of vegetation cover also affects the ability to distinguish small channels on aerial photos. Consequently, contour maps of densely forested areas do not accurately indicate the presence of small channels. For example, the contour interval on the 7.5 minute (1:24,000 scale) U.S. Geological Survey quadrangle maps is 12.2 m (40 ft). The shallowest channels that can be discerned from undulations on the portion of the Tahoe City map covering Ward Creek watershed are respectively 4 m (13 ft) deep on 120 percent* slopes and 0.4 m (1.4 ft) on 4 percent

---

*Based on a calculation for an undulation in the 7360 ft elevation contour line on the southeast quadrant of section 21.

slopes.*

As channel flow begins in rills only fractions of and inch deep, obviously the drainage network extends much further, and channels are much more frequent than can be inferred from 1:24,000 scale, 40 ft contour interval maps. Indicative of how much more extensive the smaller drainage channels are, Leopold, Wolman and Miller (1964 p. 138-141), studying arid watersheds showed that the total length of such channels was nearly thirteen times greater** than the smallest ones that could be detected on 1:24,000 scale, 40 ft contour interval maps. However, only 16.5 percent of the Ward Creek watershed is equally barren (NB type in Table 12), enabling such an assessment to be made using aerial photos.

A channel 4 m deep is very large, and even one 0.4 m is much deeper than the fine network of rills in which channel flow begins to occur. Thus topography maps with such dimensional characteristics are insensitive indicators of the spatial extent of the drainage channel network. Such a high level of insensitivity renders them unsuitable for detailed site studies, but they are probably acceptable for entire watershed planning studies and certainly for region-wide studies. The regional planning agency could obtain more information on the extent

---

*Based on a calculation for an undulation in the 6960 ft elevation contour line in the northeast quadrant of section 15.

**Calculated by dividing the total length of Strahler stream order numbers 1 through 4 by the length of 5th order channels--the first class detectable by interpretation of contour lines on 1:24,000 scale maps. The total lengths are derived from the graphs of Fig. 54 A and B (Leopold et al. 1964 p 140) showing the number of streams of each order and their average length.

of small drainage channels by requiring developers to submit more detailed maps showing, for example, channels of 0.1 m (4 in.) depth or greater along the fall lines on which their site drains and receives drainage. The planning agency might also estimate the full extent of channels by developing correction factors based on slope steepness, soil type, vegetation cover and other such correlates. Leopold et al. (1964 p. 140) suggest estimating the additional smaller streams by extrapolations from a graph of the number of streams in each Strahler stream order.

What are the consequences of assuming that fall line drainage becomes channel flow only when it encounters one of the 0.4 m to 4 m deep channels determined from 7.5 minute USGS contour maps? Potentially they are an underestimation of the amount, rapidity and thoroughness of nutrient and sediment transport from sites. The true zone of channel flow and transport must extend much farther than indicated on steep slopes than on gentle slopes; hence the underestimation caused by the assumption is much greater on the former.

Several common drainage phenomena lessen the significance of discrepancies which might result from my channel delineation and fall line intersection assumptions. The foremost mitigating phenomenon is the rarity of overland flow in undisturbed densely forested areas (Anderson, et al. 1976 p. 11-12), such as cover almost 80 percent of the Ward Creek watershed. Overland flow is usually a necessary precedent to the initiation of channel flow (Statham 1977 p. 161). The many trunks and branches in forest litter deposits (c.f. Maxwell and Ward 1979) inhibit the development of small channels by providing the nucleus for formation of organic debris dams whenever surface flow occurs. Under normal rainfall, snow melt, and natural ground surface conditions, nearly all runoff waters seep in and drain as throughflow. Only channels large enough not to be permanently dammed by fallen trees and limbs are likely to exist, and they are fed by subsurface flow through the streambed, or during extreme rain fall or snow melt events, by throughflow upwelling through the ground surface on areas adjacent to channels (Ragan 1968).

Thus accurate representation of the areas dominated by either transport process is unimportant for undisturbed forests as neither overland flow nor flow in small channels is likely to be significant on most of the watershed. However, it is necessary to retain explicit consideration of these transport modes for all areas covered by my capability classification scheme, because they are the nutrient and sediment movement processes most likely to be increased by land use alterations of sites.

The amount of underestimation of smaller channels in the drainage network is not as great as it would appear to be. My underestimation of small channel transport may be significant only for the 20 percent of the watershed not densely vegetated. Most low cover density vegetation occurs on high elevation, rocky, barren areas. As large portions of such areas are covered by bedrock, rock armor and skeletal soils, my underestimation of suspended sediment production by these small channels is unlikely to produce a serious distortion. However, Leonard et al. (1979 p. 290) report that splash and rill erosion in high elevation barren areas is the second most important source of sediments moving in Ward Creek. Thus, as most sediment movement to the Creek is initially via the small channels not detectable on contour maps, that network must be extensive in some of the barren areas. The general magnitude of underestimation resulting from my assumptions can only be determined quantitatively by individual detailed site studies.

In the absence of fire, human disturbance, or mass movement, the amount of suspended sediments coming from undisturbed forest areas is small. Even transport of dissolved nutrients via interflow is impaired by biologic uptake in such areas.

Mass Movement Distribution

Mass movement activity is far more sporadic in time and space than are the other transport modes. When such incidents occur, they are prominent and are a significant sediment transport mechanism. When earth masses move into channels they frequently become the dominant source of suspended sediments (Anderson 1971) until washed away. Mass movement is highly unlikely to occur where slopes are gentle and is most infrequent where a continuous cover of older trees exists. Conversely they are likely to occur, but still infrequently, where slopes are very steep and where topographic chutes having characteristics described earlier are prominent. Steep slopes provide the necessary gravitational driving force for land and snow slides, and long extant vegetation cover is merely an indicator that slides have not occurred recently. However, many other factors, particularly geologic conditions, affect their incidence (c.f. Johnson 1979). Thus slope steepness and plant cover alone are not adequate predictors of mass movement potentials.

Past movement occurrences are frequently discernable from physical clues. However, recognition of old movement deposits has equivocal implications for assessing whether they will become active again or whether the past release of stresses produced a relatively stable area.

Channel erosion, particularly bank erosion and collapse, is a major source of stream suspended sediments (Leonard, et al., p. 290; Anderson et al. 1976 p. 26) not explicitly included in my storage and transport scheme. The magnitude of channel erosion processes is usually controlled by natural flow regimes. However, channel erosion processes are magnified by the peak flow increases caused by land development and consequently sediment is released by adjustment of channel geometry to accommodate the larger flow volume (Leopold 1968). Seldom do overland flow and throughflow drainage significantly increase the magnitude of channel erosion processes. Because channel process sources of sediment are known to be important, and because the potential effects of land uses on their magnitude are understood at a semi-quantitative level (Leopold 1968), planning agencies should attempt to quantify sediment production by channel geometry changes for use in their allocation decisions. I chose not to develop that suspended sediment source factor in this study because of time limitations.

Channel Transport Rating Variables

Moving water is the medium transporting essentially all materials in channels. For transport to occur in dry channels, they must be steeper than the angle of repose. In wet areas such as Ward Creek, the amount of materials moving in dry channels on steep slopes is insignificant compared to wet transport. Dry sediments never move far on steep ephemeral channels because of their plunge-pool profiles. Intermittent flow channel profiles are usually too flat for dry sediment movement to occur--and frequently also having plunge-pool or riffle-pool profiles

Two aspects of water movement in channels are responsible for the transport of suspended and dissolved substances: downstream motion of water and the turbulent motion occurring in moving waters. Therefore, these two must be the central considerations in the design of any channel transport rating scheme. These fundamental fluvial mechanisms control delivery of nutrients and sediments to the lake. Hence when developing a rating scheme, the primary task is to decide which parameters to use in developing ratings; i.e., which feasibly mappable watershed and channel parameters or proxy variables control flow volume and turbulence.

The transport of both dissolved substances and colloidial particles depends only upon the downstream flow of water. Only during the slow, low flows of late spring through fall is the transport of either hindered by other conditions in channels. During those times and conditions, stream flora and fauna capture and/or absorb many of the dissolved nutrients and colloidal particles from flowing waters--retaining many of them until scouring and flushing by the first high stream flows of late or early winter. However, during the most important transport periods, so long as waters flow, dissolved nutrients and colloids are delivered to the lake. The amount delivered is controlled by the volume of flowing water and its concentration of those substances.

Channel transport of larger than colloid-sized particles requires both downstream flow for their lakeward movement and turbulent flow for their suspension in those moving waters. Turbulence is generally defined as the random motion of water; only its upward motion components are capable of counteracting the constant sinking motion caused by gravitational attraction.

Where and when interflow and groundwater seepage into stream beds are vigorous, they also greatly increase channel sediment transport by initiating levitation of bottom sediments (Clayton et al. 1966). The prevalence of such events is not well known and hence is particularly difficult to estimate. I assume here that seepage into channels is generally unimportant as a particle suspension force when compared to turbulence.

Flow volume and turbulence are not independent variables. As flow volume increases, so does flow velocity--an important variable controlling the amount of turbulence (Friedman and Sanders 1978 p. 100). However, the amount of turbulence is seldom great enough to constrain flow volume in channels.

Flow Turbulence Variable

In addition to its flow volume-velocity relationship, turbulence is largely a function of channel roughness and water depth in channels. The deeper the waters are, the greater is the proportion of their cross sectional area not in contact with, and therefore not influenced, by channel bed and bank irregularities.

Channel longitudinal and cross sectional irregularities also induce water motions aiding the suspension, and therefore transport of sediments. The horizontal and vertical spirals and eddys they induce aid suspension primarily by their upward gyres retarding sediment sinking, by carrying upward near bottom waters where suspended sediment concentrations are greatest (Allen 1970), and to a lesser extent, by raising sediments from bottom deposits. However, the fluid motions induced by channel shape irregularities only become significant sediment suspending factors in larger, deeper flows and /or in channel reaches with compact cross sections. Such conditions and reaches are rare in the small mountain streams of the Tahoe Basin. When the ratio of the "wetted" perimeter of a channel section to its cross sectional area is large (e.g., shallow waters in a broad, flat channel), the magnitude of suspended sediment transport is totally determined by the turbulence generated by bed and bank surface roughness.

Many channel variables could be used as estimators of the differing amount of turbulence in channel reaches--e.g., the hardness of geologic material being traversed. Many potentially useful estimators cannot be determined from available maps or even from aerial photos. Hence their distribution would require field examination of the many tens of miles of channels in the Ward Creek watershed. However, channel bed steepness can be determined readily from topographic maps and is a relatively good estimator of the probable distribution of bed and bank roughness and flow velocity largely responsible for turbulence. Hence it is one of the variables I recommend for estimating channel transport conditons.

Flow Volume Variables

The ability of a channel to deliver dissolved nutrients or suspended sediments is solely and most directly a function of the total amount of water moving down a channel. This ability to transport larger suspended sediments is additionally affected by flow velocity, fluctuations of flow volumes, and to a lesser degree, by the duration of the flow. These latter flow variables have no affect on the ability of channels to transport dissolved nutrients and colloidal particles. They do, however, have some effect on the ability of stream biotic processes to pick up and delay the passage of dissolved nutrients and colloids when flows continue into the stream biomass growth period of late spring through early fall.

Flow velocity is an important variable because of its strong relationship to the induction and magnitude of turbulence (Friedman and Sanders 1978 p. 100). However, the channel steepness variable already included for turbulence estimation is also an estimator of flow velocity conditions. Hence, an additional variable for flow velocity estimation should not be needed.

Flow duration is potentially important because transport of suspended sediments is more likely to occur if land disturbance activities take place when streams are flowing. Transport of most suspended sediments occurs as stream flow volume increases; suspended sediment concentration peaks before flow reaches maximum values. I do not consider flow duration an important enough characteristic to separately estimate by including specific variables in a LCC rating scheme. In the absence of channel disturbance by use activities, nearly all suspended sediment transport occurs during high flows, not during the remainder of the flow duration period. Also, flow durations are inherently included in an estimation of total flow volume as the two variables are autocorrelated in all but flash flow channels. Hence watershed and/or channel variables seemingly providing a good estimate of either flow volume or flow durations are reciprocally useful proxy variables. If deemed especially desirable, flow duration estimation can be improved by including in the estimation parameters such mapped information as snow pack depth zones, soil depth to bedrock or impermeable layers, sideslope steepness or the height of ridge tops above channels.

The amount of larger suspended sediments delivered has both minimum and maximum flow condition thresholds. During low flows, the presence and transport of even colloidal particles occurs only if human distubances are occurring in the channel. The magnitude of suspended sediment transport during maximum flow events fluctuates with the volume and origin of peak flow waters. Maximum transport by channel runoff from rain storms occurs before peak streamflow and declines more rapidly than streamflow. In contrast, snowmelt causes high streamflows that persist for relatively long periods and do not fluctuate greatly on a daily basis. Hence they deliver a constant load of nutrients and suspended sediments.

The U.S. Geological Survey designates intermittent and perennial flow reaches of channels on its quadrangle series maps. Some regulatory agencies use their designations as the basis for application of differing use procedure requirements--c.f. California Forest Practices Act (17 Cal. Adm. Code 14 p. 60.6). The basis for the designations of the Geological Survey is perhaps based on water seen in the channels on the aerial photos used to make the map. However, channel reach flow duration designations must be largely arbitrary. They are not based on long-term steamflow records, as gauging stations are not abundant enough to provide such information for any but experimental watersheds. Hence I consider the Geological Survey flow duration designations too arbitrary for most LCC purposes.

A more dependable pair of flow volume estimators is the total annual precipitation falling above a channel location minus the water holding capacity of soils in each of those upstream and/or upslope cells. The resulting figure is a simply obtained estimator of the surplus precipitation input, most of which eventually drains into channels.

The true size of the surplus is not as large as indicated by such a simple calculation. Some precipitation waters are lost to evaporation and sublimation before entering the soil mantle.

The satiation of soil water holding capacity is not a single yearly event. Moisture stored in soils is partially consumed by vegetation transpiration between rainfall or snowmelt events with the resulting deficit partially or totally made up by subsequent precipitation events. This sequence of events is particularly significant during summer and fall rains when soil moisture has been greatly depleted by transpirational activity. However, nearly all Ward Creek precipitation falls as snow. Transpirational consumption of soil moisture is minimal during the cold times when there is a snow pack and the water holding capacity is being filled by cold snowmelt waters. Summer rains are too erratic to predict, and their amounts are typically too small to justify a correction factor.

It is also possible for some of the precipitation in excess of soil water holding capacity to fail to run off as channel flow because of ground water storage recharge and/or leakage from a watershed. The amount of precipitation water possibly lost or detained in such manners is difficult to assess; Leonard et al. (1979 p. 228) estimate about 6 percentage goes to ground water storage. I do not expect that such losses are significant in all but the lowest 2.5 km of the Ward Creek watershed, considering its geologic materials and conditions. I expect that in other than postdrought years, any precipitational excess diverted to ground water supply recharge (or its equivalent displaced volume) will drain into channels again somewhere downstream in the same year in which it was diverted. Certainly the observation of Leonard et al. (1979 p. 283) that only the main channels and the lower 4 km of the south branch of the creek have perennial water flow indicates that ground water is not an important factor controlling streamflow.

The potential significance of ground water flow and storage cannot be dismissed so readily on the lower 2.5 km of the watershed. Beyond that point of geologic constraint of ground water flow (Leonard et al. 1979 p. 283), the bedrocks begin to be buried under increasingly thick alluvial deposits. However, the amount of interchange between those large ground water deposits and the main stream channel in that lower portion of the watershed is unknown. There is no reason to expect that the extensive and nutrient rich ground water deposits in that area are solely or even largely fed by leakage from the main channel. The existence of many other channel notches in the extensive watershed zone near the lake included in the Ward Creek watershed by Leonard et al. (1979 p. 283), the Tahoe Regional Planning Agency (1971c p. 24) and McGauhey et al. (1963 Figure 3-8) indicates that much of the water drains from that area without even becoming a part of the main creek's flow. The main channel-groundwater supply interchange probably extends little more than half way between Ward Creek and the next channel on either side of it--i.e., 90 to 150 m (300 to 500 ft). The maximum depth of incision of all basin channels is constrained by the elevation of the lake--though, of course, Ward Creek's channel is cut somewhat deeper than immediately adjacent ones because of its much greater flow volume.

To summarize the preceding decisions, I recommend channel bed steepness and annual streamflow volume (as estimated by subtracting soil water holding capacity from total precipitation) as the best, simple set of channel and watershed variables for estimating the relative ability of different channels (and portions of them) to transport nutrient and suspended sediments to the lake. I would also include distance via channels to the lake because this variable so obviously affects the rapidity and completeness of delivery of those substances to the lake, and also the presence of any intervening lakes or reservoirs because they typically remove all suspended sediments and alter delivery of dissolved nutrients.

CHAPTER 18

AN ASSESSMENT OF CONCEPTUAL ECOLOGIC MODELS FOR ANALYSIS OF REGIONAL ENVIRONMENTAL MANAGEMENT MEASURES

Chapter Scope

In the opening two chapters I pointed out some potential advantages of using scientific information and analysis techniques, ecologic modeling in particular, and expressed my concern that planners are not making enough use of these evaluation resources. In this final chapter I assess some practical difficulties and benefits of CEM that became apparent as I developed them, and used them to select the variables of a LCC. I also discuss some general characteristics of science, scientific information and scientific analysis techniques (jargon, information and analytic complexity) which may disuade planners from increasing their use of scientific information resources, whatever their value.

Some Practical Difficulties

Revision and Flexibility

Where information is abundant, easily obtained and/or already preorganized, I had a strong tendency to try to include all of it rather than to summarize or extract key parts from it. I believe others developing CEM will have similar tendencies. When information was sparse, difficult to obtain, widely scattered or difficult to understand, I tended to underdevelop that portion of a CEM. Consequently, my CEMs are under- and over-detailed in some places, in terms of the relative importance of different variables and interactions. A basic principle of systems analysis is never to add more detail than is needed. However, when working alone, adherence to that principle requires great insight, foresight, perspective and self discipline. Following that rule probably would be easier in CEMs developed by teams directed by efficiency-minded professional planners.

My cognizance of the existence of such unevenness usually came when I was far along in their development, writing the narrative explaining them or working on subsequent models. If the CEM is to be used for explaining potential consequences to decisionmakers and the public (Gilliland 1982, Gilliland & Clark 1981) or to decide whether to proceed with development of an ESM, the planning team and/or special consultants need to revise the initial CEM to adjust the level of detail--retaining or adding to it for particularly important portions of the CEM and thinning it out in less important portions. If the CEM was developed just to display, synthesize and organize ideas and information and for the hueristic values of the development processes it is probably not worthwhile to invest the additional time needed to make such adjustments.

While writing the narrative explanation of the CEMs I often realized that a slightly different numeric ordering of sequences on the CEM diagram would make it flow more evenly and make it easier to explain relationships in a linear sequence. However, I did not revise most of my CEMs because of the time it requires. Revision of CEMs is tedious because of the in-series display of cause-effect relations shown in the diagram, accompaning legend and narrative explanation. Thus, if a variable or linkage is changed and it is near the beginning, all subsequent numbers must be adjusted, and mistakes are easily made during the process. Consequently, after the experience of making changes in the first few models, in the interest of time I decided not to change them once the diagram was drawn and the legend written. Thus, because of time pressures and behavioral tendencies, once CEMs are assembled they may be fairly inflexible analysis tools--like complex computer programs. Using an ecologic principle metaphor, like the ecosystem functions they represent, everything is linked to everything else in CEMs; hence they gain stability because their developers are reluctant to invest the often considerable additonal effort needed to change them.

Team Task

While attempting to develop single-handedly a number of CEMs, I became acutely aware that ecologic modeling, even during its conceptual stage, is a task which should be undertaken only by a team--especially one containing members with or ready access to scientific expertise on the particular topic of the model. No individual can possibly possess the extensive, in-depth multidisciplinary training needed to develop the system of CEMs I present in Chapters 6-10 and 13-15. When I initially chose the problem of water color-transparency as the topic of my case study, I mistakenly believed the subject was so specific and so well understood that I would have little difficulty assembling the necessary information into a series of CEMs. For example, while there is abundant literature on the topic of water color and transparency (more specific information than on any other CEM), as cited in Chapter 4, it is scattered throughout many different scientific fields (psychology, physics, limnology, oceanography, remote sensing, optics, optical engineering and sanitary engineering. Nowhere is all this information summarized in an understandable manner; nor is it anywhere even pulled together in a manner showing the full modern scientific understanding of water color and transparency. Each discipline studies light-water interactions for different reasons, and hence emphasizes different aspects.

In a way, development of the CEMs by individuals not having in-depth knowledge has the potential advantage that their limited knowledge makes it less likely that the model will become overly detailed in its inclusion of variables and interactions. But there is (or should be) a sense of insecurity concerning the validity of the results if the developers are not sufficiently knowledgeable to be certain they have chosen the right variables to include and emphasize in their simplification of reality. This problem could be overcome by having the initial CEM checked for reasonableness by experts on the subjects. Another option is to include experts in the CEM development group. However, experts may be aware of so many possible variables and complications as to experience difficulty making the generalizations needed to reduce them to a reasonable number in a CEM. Consequently the model may become excessively complex and detailed for the degree of understanding planners need. Of course this is the kind of planning process problem which professional planners are trained to manage: keeping analysis efforts on track and including only enough effort and information to produce the results needed for formulating and assessing alternatives.

The subject matter included in most of the CEMs exceeds the breadth of any single expert's in-depth knowledge. Presumably several might be involved either directly in development or indirectly as technical consultants called upon to assess the work of the planning team and its special consultants and advisors.

Interdisciplinary Tasks vs. Disciplinary Jargon

The scattering of scientific information throughout many different disciplines creates a more serious problem than the absence of a central repository from which I can readily extract what is needed for any of the models. The additional problem it creates is the expression of that information in the specialized terminology, symbolic logic and measurement unit jargon of each discipline, thus seriously hampering recognition, extraction and synthesis of it by individuals. For example, the current state of scientific knowledge on water color and transparency may be summarized in Priesendorfer's seven volume treatise on hydrologic optics. However, the information in that set of references is largely unavailable to me because of the jargon problem. I could spend the considerable time needed to recognize and master the needed material in those 1840 pages, but in terms of the overall objective of my study, it is not worthwhile. The water color and transparency subsystem is central to my study, but is only one of the twelve CEMs I develop. Also the other CEMs are not as topically discrete as the former; hence they typically need knowledge from a greater diversity of scientific disciplines. Thus the equivalent scientific background acquisition time would be considerably longer. The jargon problem is epitomized in the hypersubdivision existing for color terminology and measurement. Four roughly parallel sets of jargon exist; optical physics, psychophysics, sensory psychology and perceptual psychology (c.f., Optical Society of America 1968 p. 67 for a tabular comparison.)

Terminology Changes

An additional problem is that the jargon of single scientific disciplines has significantly changed through time. For example, the terminology and units of measurement used by optical physicists investigating water color in the 1920's is very different than that used by present-day physicists. The early developmental literature on water-light interactions is particularly important as its accounts and explanations are more understandable than recent studies because the jargon was not so well developed. Also current investigations concentrate on increasingly small, specialized aspects of the overall water color-transparancy topic.

While jargon is a convenient shorthand for expressing often complicated concepts, facts and measurements, its prevalence is the single greatest impediment to interdisciplinary communication and multidisciplinary understanding and synthesis of information, and it is becoming worse as scientific specialization increases.

Public Participation: a Problem

In the last ten years the amount of activity directed toward public involvement in the process of land use planning has increased greatly. Certainly it is desirable to involve those affected by decisions in the process of formulating and evaluating alternative possible plans. When they are substantive (i.e., consisting of more than personal preferences) and particularly when accompanied by supporting documentation or data, the comments and constructive criticisms of the public can improve the scientific content, objectivity and comprehensiveness of alternatives and assessments. However this increasing emphasis on public involvement may retard increased utilization of scientific knowledge and analysis techniques by planners.

The goal of rational-comprehensive analysis has long dominated the thinking of many planners (Althshuler 1966). That goal is to be dispassionately objective in evaluation and making choices and to use all possible information in the analysis of planning problems and for developing recommended best plans. Continual striving to attain rational-comprehensive plans eventually would increase the use of natural science information and analysis techniques by planners. However, pragmatically comprehensive plans are unattainable because of the limited resources available for developing and analyzing alternative plans.

Other divergent philosophies have now developed in the planning profession. Some planners now advocate developing plans by direct negotiations between competing interest groups (Suskin 1968)--a process termed "environmental mediation" when the issues are primarily environmental ones. Some technologically oriented individuals suggest that planning decisions should be made via public referenda. Some planners assume the nonobjective role of advocating special consideration for certain disadvantaged socioeconomic or ethnic groups. These relatively new approaches for conducting planning are contrary to the objectives of rational-comprehensive planning. A shift to popular public preferences as the primary basis for formulating, evaluating and choosing from alternative plans would be ironic in a time when there is greater emphasis by the scientific community on application of science to analysis of societal problems and when communication technology and computerization have greatly increased the ability of planners to produce increasingly comprehensive analyses of land use options and their consequences.

Increasing public involvement and use of scientific information and analysis techniques are not necessarily incompatible goals. Generally however, I fear the evolving redirection of the efforts of planners and planning resources into public participation activities may discourage planners from making increased use of scientific knowledge and seemingly complex analysis techniques, such as ESM. I believe the increasing emphasis on public participation poses four potentially serious impediments to an increased role for science in the process of land use planning: 1) shortened analysis phases, 2) reduced funds for analysis, 3) decreased planner time available to participate in analysis and 4) perceived communication difficulties with the public and decisionmakers. All of these concerns are included (but not elaborated on) in the Selection Guidelines for Simulation Modeling of Planning Problems in Chapter 3.

With increased devotion of time to public involvement activities, legal requirements for public hearings, comment periods on draft and final EISs, etc., there has been no lengthening of the time span commonly alloted (about 2 years) for the development of land use plans. Constraining the time in which plans must be completed is generally a desirable objective because property values, use options and land development are typically curtailed, accelerated or in turmoil during such periods, and analysis of the complicated problems could go on almost indefinitely before decisions are made. Thus, to provide time for public comments and participation activities, land use planning agencies have to greatly shorten the amount of time available to conduct formal, in-depth analysis of specific and general problems.

Some public land management agencies try to complete all analysis of problems and issues and finish the formulation of alternative plans in the first year, reserving half of the total planning period for accomplishing legally mandated public involvement periods and activities and adjustments of the initial proposals. Analysis of specific problems is just one step in the formulaton of alternative plans; therefore much less than a year, probably seldom more than six months, is available for analysis. This is an impossibly short interval in which to develop an ESM for most problems and is a short time in which to research, construct and interpret some CEMs for their implications for management decisions. CEMs can be developed and provide useful guidance much more rapidly than ESMs, but planners may still be reluctant to use any time-consuming analysis technique which cannot guarantee useful results.

As for the planning period, the budgets for planning efforts have not been increased to fund increased public participation. Rosenbaum (1978) estimates that the direct and indirect costs of providing for public participation in development of the state plan for the California coastal zone was 75 percent of the total cost. This is an unusually high proportion (one whose exact value is disputed by J. Bodovitz, the executive director of that planning activity [Healy 1978 p. 223]) because of the great amount of activity aimed at generating public support for the plan. However it does demonstrate that a large proportion of the funds for planning can be spent on public participation activities.

As funding has not been increased to pay for the new emphasis, the total funding available for data collection and analysis is proportionally much less than ten years ago. Thus planning funds are not likely to be available to increase the intensity of analysis activities to compensate for shortened analysis periods nor to pay the costs of expensive analysis techniques. To some extent certain types of substantive public comments and participation can be used (or even encouraged) to increase the scientific caliber of alternatives and their assessments. However, as this type of activity is voluntary it probably cannot be used to produce the equivalent of what can be accomplished by using paid, well managed direct, scientific assistance.

ESM may be costly but the CEM phase of it usually is not. However, the need to carefully manage a small analysis budget may cause planners to make such conservative decisions on the allocation of those funds that consideration of even CEM will be adversely affected.

Planners must now spend a considerably greater proportion of their efforts working on public participation related matters. Consequently they are able to devote less time actively participating in specific problem analysis efforts. While planners do not have the scientific expertise to develop a CEM by themselves, it is highly desirable for them to be active participants in CEM development. Their direct participation is needed both to steer that activity continually and efficiently toward only the objective of that particular analysis and because the full analytic benefits of the model are obtained only by active participants in CEM development. A CEM is probably most useful as a hueristic tool. Hence those who have worked on developing the CEM can best use its information to understand problems, to rationally or intuitively develop alternatives and evaluate them, to recommend decisions and to explain the basis for recommendations to decisionmakers and the public.

CEM is an analysis technique yielding a depth of understanding from which technically sound options can be formulated and evaluated. Because planners must now devote so much of their attentions to managing public participation, they may favor techniques yielding discrete answers to specific problems rather than in-depth understanding of complicated ones, and may reject techniques requiring their extensive personal involvement.

As a general principle, decisionmakers and the general public should be able to understand the reasons specific choices are recommended by planners. Scientific information and analysis techniques are generally perceived as being especially difficult to understand because of their unfamiliar terminology, concepts, technical nature and often complicated appearing mathematical and symbolic logic expressions and data display formats. Many planners assume that most of the public are unable to comprehend scientific and other technical information. Thus, I am also concerned that the effect of increased emphasis on public participation may portend a tendency to use less rather than more scientific knowledge and analysis techniques. EMs particularly can be expected to raise such concerns among planners about their communicability, because at first exposure to those unfamiliar with their nature and purpose, or to those not participating in their development, they appear to be terribly complicated and difficult to understand.

Scientific information, analysis techniques and logic are more difficult to explain to decisionmakers and the general public than reasons understandable through common knowledge and experience. Thus planners have some justifiable concerns about the appropriateness of using them as bases for comparative assessments of alternative solutions and recommending decisions. But certainly scientific information and analysis techniques are no more difficult to follow and accept than the tangle of many economic, sociologic, philosophic and other reasons planners use for developing alternative plans and recommending choices to decisionmakers. The overall use allocations which planners must analyze and develop recommendations solutions for are typically complex. Therefore I think it is reasonable to expect that sometimes the analyses and recommendations must be based on complicated information and logic and that planners should explain and defend them on such bases.

Nobody should assume the public is incapable of understanding scientific information or complex trains of scientific logic. I believe it is not beyond the ability of most of the general public (and certainly all decisionmakers) to understand most scientific information and logic. The public is highly varied in terms of their intelligence and educational backgrounds. Their comprehension of science is more a matter of sufficient commitment and interest on their part and the use of good educational procedures by planners (and good communication by scientists) than of planners innate abilities to understand.

I assume that decisionmakers and the general public are no more fluent than planners in the breadth of science that may be necessary to analyze issues and problems, develop and assess alternative solutions and recommend decisions. However the solution to the dilemma of increasing scientific content while encouraging public involvement is to use better communication techniques and communicators. There are many good examples of science communication and communicators in the mass media (e.g., Carl Sagan's "Cosmos"). A number of universities now train specifically for these capabilities (e.g., U.C. Santa Cruz's Science Communication Program), and most major newspapers have columns by science correspondents. All of these examples of how science can be explained to nonscientists can be used as models for communicating its meaning in land use planning contexts. Planners should use the techniques science communicators use to make scientific information and analysis approaches understandable and meaningful, or they should hire professional science communicators to write explanations or make presentations to decisionmakers and the public.

Education must be an integral part of any public involvement process if the public is expected to understand and support intelligent, informed decisions. Because receptivity of decisionmakers and the public to scientific arguements and evidence may be greatly inhibited by the development of mental blocks if they are exposed to too much at once or without proper preparation, care must be taken in the manner of presentation to those audiences. I discuss this particular problem more in the next section and point out some ways to avoid it.

EM has an important communication advantage over most other analysis techniques. The initial stage in the development of an EM is the assembly of a graphic CEM, which may be refined subsequently and updated as analysis proceeds. This graphic representation of the problem and the analysis approach and its use as a central coordinating and explanatory device greatly facilitates communication, serving as a pictoral representation that provides a focus for attention, a perceptual holistic summation of the problem and a by-the-numbers device useful for explaining complexity in a logical, orderly sequence. I discuss other advantanges of the graphic mode in more detail in the next section.

Graphic Complexity: A Communication Problem

When first encountered, CEM diagrams can be intellectually intimidating because of their apparent complexity. Therefore they appear to be too complex to be useful for quiding planners' evaluation of the consequences of alternative decisions, too complex to help decisionmakers understand those consequences and the reasons for the choices planners recommend and certainly too complex to impart that same understanding to the general public. Nevertheless planners should not automatically dismiss an analysis tool which directly shows the complexity of problems, as there are few endeavors that must deal with more complexity than land use planning. Planners may be apprehensive about using CEM models because it appears that their use greatly increases the amount and variety of the information they must consider. However, the complex of potential cause and effect relationships shown in a CEM diagram is a true indication of the number of variables that can affect results. Even a complicated-appearing CEM is usually a considerable understatement of the true number of variables.

As a general principle, I believe the more realistic the planning analysis the more technically defensible are recommendations of planners to decisionmakers. Thus I believe explicitly recognizing and dealing with necessary amounts of functional complexity is a proper objective and expenditure of effort in analysis. Regulating the depth of analysis by determining how close to full functional reality analysis must come involves good team and project management skills--tasks for which planners are well trained.

Several graphic approaches can make CEM diagrams more comprehensible and less intimidating. The amount of detail shown can be added in progressive stages. I use this approach in Chapter 5 where I show the simple conceptual framework of the flow of matter and its affects on water quality (p. 4), expand this into a schematic model of the full nutrient-sediment-water color-transparency system (Figure 2), subdivide the system into a series of functional subsystems (Figure 3), and then expand on the amount of detail in each in Chapters 6-10 and 13-16. I also explain most of the subsystem CEMs by introducing them in terms of a group of more specific subsystems. After developing a full CEM, to aid communication with decisionmakers and the public, the number of factors and relationships shown in the model can be reduced to only those determined to be most important. The approach of adding detail in steps has communication advantages similar to those of composite mapping processes. One reason many land use planners find the latter a particularly appealing analysis approach is that it can show in isolation each of the factors that shape the final analysis result--the composite map. Thus, even though the final product looks complicated, the decisionmakers and the public can readily understand its origins.

Another approach useful for increasing the communicability of CEM diagrams is to make the widths of lines representing interactions between variables proportional to magnitudes, frequency, probability or other measures of relative significance. Similar graphic devices can be used to show the relative significance of different variables. Sets of symbols, such as the energy circuit language of Odum (1970 p. 38-39) can also be used to reduce the complex appearance of CEM diagrams by simplifying many different variables into repeated occurrences of a few graphic representations. Initially I tried to use the energy circuit language in the first few CEMs and found it unacceptable to me to force all variables into those terms. Others using the approach for planning-oriented CEMs have had similar problems (Lyle & von Wodtke 1974) but believe the value of graphically reducing complexity is not diminished by the need to compromise symbol definitions and the exact nature of variables. These and other graphic devices are used by ecologists and systems analysts to explain their models; similarly they enable planners to overcome much of the potential communication difficulty caused by the graphic complexity of CEMs.

The most valuable benefits of CEM probably accrue only to those directly participating in their development, for the mental activity of working them out imparts a degree of familiarity with the problem, its component parts and complexity that will enable planners to use that information at the intuitive as well as the conscious, intellectual level of problem solving. The first-hand use of graphic techniques, such as development of CEM diagram relationships between factors is a powerful learning technique.

CEM: Some Strengths and Weaknesses

In the opening chapters I extolled the potential virtues of using EM and scientific information for land use planning. In this section I comment on the veracity of some of those virtues from the perspective gained when developing and using CEMs. My assessment of the value and limitations of CEM and scientific information is, of course, not definitive as this is but a single experience and its thoroughness has been limited by other constraints--working alone, restricted possession of and access to necessary scientific information, time and finances. My general objective in this case study has been to examine the value of CEM for analyzing problems and for increasing planners' use of the scientific information relevant to their problems. In the accomplishment criteria in the Preface, I stated six more specific objectives for judging the values of CEM to be revealed by my case study. In this section I comment briefly on each of them--though readers should make their own assessment of the degree to which each was accomplished.

Does CEM help identify the scientific knowledge relevant to a particular problem and its organization to analyze that problem? Examination of the CEMs I developed and the large, though not comprehensive number of variables clearly show that the process of constructing a model demonstrates that much scientific knowledge is relevant to problems. The process of constructing a CEM stimulates developers to build initially a nearly comprehensive list of variables and interactions, resulting in near maximum recognition of the types of information that may affect the outcome of the problem. Recognizing so many potential affecting variables can create a management problem, but it also provides alternative pathways for analysis should data on some variables be unobtainable.

The number of variables I include is certainly not exhaustive but is probably in excess of the minimum amount needed for an adequate level of understanding and analysis. Good management of CEM by a professional planner would limit the number of CEM variables.

Does using CEM as an analysis technique encourage planners to make more and better use of the scientific knowledge relevant to some of their problems? This question cannot be answered in the affirmative as strongly as the initial one because no explicit evidence is generated. CEM will certainly expose planners to much more scientific knowledge than they are used to, and if that experience is favorable (i.e., it significantly aids the analyses of planners by showing them what is available, relevant, needed and relatively important information), they will be inclined to make repeated use of it. This does not mean that suddenly planners so exposed and experienced will greatly increase their use of scientific knowledge in the planning process. Their professional training and experience makes them take a pragmatic attitude toward any type of information. Thus they will and should withhold blanket judgments and only use scientific knowledge when it is appropriate for a particular problem. Also once exposed, ideally they will realize that its specialized jargon is no worse than that of economics, sociology and other disciplines and disciples they work with. Once exposed and used to scientific knowledge, planners should be less reticent to seek the specialized help needed to use scientific knowledge more frequently.

Is CEM useful for analyzing and solving certain types of planning problems? I have indicated why it should prove useful in the opening chapters. This question must be altered to emphasize the important role of CEMs in understanding and studying certain planning problems--particularly with respect to the general problem of identifying the potential effects of land use decisions on water color and transparency.

Seldom does CEM solve problems directly. It is more useful to view CEM as a hueristic, organization and analysis process rather than as a technique which produces a discrete solution. Viewed thus the primary value coming from use of CEM is to inform those participating in the process of its development rather than being a product with other uses. As a hueristic device, the primary value in developing a CEM is that it can help planners, decisionmakers and the public understand the potential system-wide ramifications of disturbances that may be caused by land uses and by implication, what can be done to reduce the disturbances. I believe CEM is better as a huerist tool, for studying land use--ecosystem interactions than any other analysis technique.

Thus the "answer" CEM provides to planners is a new depth of understanding of a particular problem, a depth of perception that should enable them to construct and propose a set of reasonable, well founded alternative land use allocations--in this case study alternatives that will provide different degrees of protection of water color-transparency. The use of CEM also should impart to planners the important realization that the relationship between land use types and their ecosystem consequences are not linear and deterministic but rather are more likely to depend upon many stochastic variables whose significance changes with time, location, situations, and events. Hence, in general, CEM is a good analysis technique for helping professional planners gain a more realistic understanding of planning problems and for helping an interdisciplinary team to synthesize information needed to understand and respond to problems and to develop alternatives.

Is CEM useful for establishing the relative importance of different types of information and hence for helping planners and analysts allocate analysis efforts and funds? CEM provides a graphic checklist of the variables that should be considered, and additional graphic techniques are available for displaying the relative importance of variables and interactions. A CEM diagram is also of value as a mnemonic aid for what has been learned and decided. Thus it provides a good device for establishing relative import, because all relevant information types are displayed simultaneously, making it easy for an expert on part of the model to indicate the relative importance of variables under different conditions. As a checklist, it also provides planners with a means for seeing that most variables have been considered, ranked and/or rated, and a basis for questioning others on the relative signicance of different types of information.

However, the relative import of variables is not just a function of the number of interactions linking one variable to others. Thus there is nothing inherently produced by constructing a CEM diagram which establishes the relative import of its variables. That has to be a separate step and an additional developmental consideration and refinement of the initial CEM. Thus CEM is not particularly nor inherently good for establishing the relative import of variables. Efforts are initially concentrated much more on identifying variables and showing relations. Establishing their relative importance requires much more information and effort to accomplish, though developers with a technical background ought to be able to categorize initially many variables and interactions on the basis of their strength, frequency, magnitude, etc., and subsequently confirm these upon quick consultation with experts. Establishing the relative import of variables is more important for developing a CEM into an ESM. It is certainly a necessary step in the reduction of variables into a number that can be handled by an ESM. CEM is most useful for planning purposes if kept simple by concentrating efforts on showing initially all variables and interactions.

Is CEM a systematic method for choosing best variables for a LCC system? Is it a good analysis technique for improving the rationality of such choices, for increasing their scientific sophistication, for documenting and showing the reasons for choice of variables, for making the choice process more of a deliberate prodecure and a carefully studied task rather than an opportunistic decision? The transfer of understanding developed in the CEM to the selection of LCC variables is not a straighforward procedure. There are so many variables to choose from, yet only one or two to represent each subsystem affecting nutrient and/or sediment delivery to the lake can be chosen for use in the LCC. Otherwise the LCC gets too complicated to delineate and may start in effect double-counting some functional variable if it appears important in more than one CEM.

I do not know if going through the CEM process truly helped me choose the variables I suggest for a LCC to protect water color-transparency or what role that experience had in my choice of the variables. It is difficult for me to separate what I gained from developing the CEM from the knowledge I already possessed from my other educational and experiential backgrounds. Certainly one thing CEM did was to aid my structuring of the many different facts I have acquired over the years to address that one problem.

For those totally unfamiliar with such information, e.g., most professionally trained land use planners, the CEM process would introduce them to that information (and only that information) in its reference problem context. Thus the process of CEM and the diagram product provides a vehicle which can be used to transmit to planners, in a highly structured and problem oriented manner, background information on what is likely to cause what, to what extent and why. With this understanding, it ought to be much easier for them to understand and support the choice of LCC variables. Thus in this sense, the relationship of CEMs to the selection of LCC variables would be clearer. Perhaps the transfer would be more obvious if I had gone farther into establishing the relative import of variables, particularly in key CEMs such as sediment transport. But it takes considerably more time and effort to establish the relative import of variables and interactions than it does to identify them in an initial CEM.

One reason the relationship between the CEM variables and selection of the LCC variables is not a straightforward transfer process is that an additional set of assessments must be taken into account when selecting land classification variables. The apparently most important ones in the CEM may be difficult to express in map form and/or spatial distribution information may not be available. To some extent spatial specifications can be built into CEMs as I have done in the sediment tranport CEM, where I use types of spatial areas of particular significance to sediment deposition and transport as variables--e.g., flood plains, inside channel bends, outside channel bends. This initial inclusion of mappable spatial types as variables probably should be developed even further in each CEM of the terrestrial-stream portions of the watershed ecosystem. It is almost common knowledge that certain types of locations are likely to favor or impede nutrient and sediment release and/or transport. Their explicit inclusion helps make the relationship between the variables in the CEM and the choice of variables for the LCC clearer.

One realization produced by the cause-effect linkages emphasized in the CEM was the obvious need to consider more than onsite characteristics in the LCC. The traditional approach to LCC is to consider just the characteristics of the site and what may happen only on the site. This conservative approach to LCC is strange since we know that offsite conditions both above and below can greatly affect the consequences of onsite activities. After recording these sequential relationships on paper, it became obvious that a LCC to enable protection of water color-transparency must somehow account for all that may happen along the fall line pathway of nutrients and sediments. I only became acutely aware of this need when viewing the problem in the context of substance transport continuity. Consequently, the LCC system I propose is different than others I am aware of.

Is CEM a good way of demonstrating the scientific basis of a LCC? Since it is seldom obvious how the variables for a LCC are derivative of the related CEM, it is a bit tenuous to even consider CEM as a good technique for showing the scientific basis for a LCC. However, in another sense, the CEM diagram may serve as a convenient if not convincing way to illustrate how a LCC variable relates to all the other factors controlling nutrient and sediment impacts on water color-transparency. The CEM diagram certainly provides a good graphic aid to do this, as it can be drawn over to show where chosen variables fit in the overall picture of system-wide reactions. As each variable and interaction is documented or readily documentable, in this sense CEM is also a good way of showing the scientific basis for selected LCC variables. But in a strict sense, it proves nothing.

Recommendations

In this section I make recommendations for the future conduct of regional planning and environmental management. Some recommendations concern the general planning process; some are for geographic areas with specific environmental management problems like the Tahoe Basin. My recommendations are based largely on the understanding I gained from developing the CEMs and the LCC scheme. However, some are derived from the findings of others I encountered or consulted in this study. Apparently planners and decisionmakers have not recognized the implications of such findings for environmental management of the Tahoe Basin. These latter findings result in recommendations not explicitly based on evidence presented or developed in earlier chapters. They are included here because they are relevant as part of the recommendations regional planners ought to consider when developing plans and policies for environmental management of the problems I focus on in this dissertation.

Some of my recommendations are undoubtedly not new, and some may already be incorporated in existing land use regulations for the Basin. I did not attempt the major task of comparing them to the many rules and regulations promulgated by numerous governmental agencies.

My recommendations for regional planners and planning agencies are of three kinds; (1) the type of information needed for analysis and decisionmaking, (2) plan preparation procedures for spatial use allocation decisions, and (3) policy formulation and plan administration procedures. Some recommendations appear in more than one of the three categories, though in somewhat different forms. Thus, for example, the need for a particular type of data need may also be incorporated in a recommended policy requiring development proposers to provide or pay for the collection of such data for their site and downslope areas. This redundancy is merely a suggestion of an adminstrative means for acquiring needed data.

Data and Research Needs

Four types of data are most needed for the capability rating scheme I develop in the preceding chapter: (1) more detailed contour maps, and better characterization of soil (2) nitrogen, (3) phosphorus, and (4) fine particle contents. Of lesser importance for my rating scheme is the need for data enabling a more accurate characterization of the comparative nutrient and suspended sediment transport capabilities of channels. Preventing or retarding the movement of those substances into channels is of paramount importance. The options for controlling delivery once they are in channels are fewer, more drastic and less effective.

The accuracy of soil infiltration and throughflow characterizations is also important for my scheme. The spatial variability of values given for those variables in the soils report (Rogers, 1974) is unknown. However, nearly all of the Ward Creek watershed is either forested or barren. Anderson et al. (1976) report that infiltration rates are so great for most forested areas where patches with low rates exist, adjacent areas are readily able to absorb any surface runoff from them. Similarly they and Harr (1974) note that the throughflow capacity of forest soils on slopes is nearly always great enough to transmit most naturally occurring amounts of water.

The various types of barren lands mapped in the Basin probably have infiltration and throughflow capabilities either equivalent to or totally opposite those of forest lands--depending upon whether they are loose rock deposits or bedrock. Little information on the properties of barren land categories in the Basin is provided by any published reports. These abundant types of lands are major sources of nutrient-laden runoff (Carballeira 1972) and sediments (Leonard et al. 1979). Hence much more should be known about their properties and characteristics. However, the need for that information is of lower priority because barren lands are largely in high elevation areas, and hence unlikely to be used for activities causing much ground disturbance, except for ski runs. Also, there is probably little that can be done subtly enough to alter the nutrient and sediment yield characteristics of barren land areas to not cause aesthetic problems on many highly visible locations.

We do not necessarily need exotic new data to improve the scientific quality of Tahoe Basin environmental management decisions. The greater need is for better quality data of some of the types already available. For example, better delineation of the extent of small channels in the drainage network is needed to improve our ability to assess the comparative hazard of nutrient and sediment transport and delivery to the Lake. The most expedient means for obtaining more detailed drainage channel delineations is to obtain topographic maps with small contour intervals and with contours drawn without having to estimate the land surface beneath dense forest canopies. Side scanning radar is capable of providing aerial imagery for overcoming the latter problem. Maps with smaller contour intervals also make it possible to distinguish more finely between slope steepness and shape categories--both important information for assessing erosion hazard and sediment transport.

Plan Preparation Procedures

Regional land use planners should use CEMs to facilitate assessment of the potential ecologic impacts of alternative plans, both as a guide for the overall procedure and for determining the specific topics of evaluation. Planners should encourage or require those conducting technical analyses to use CEM as a diagrammatic display and conceptual analysis technique for showing relationships, aiding comprehension, communication, organization of tasks and establishing priorities. However, planners should not development a CEM into an ESM unless the problem is extremely decisive and can be analytically described by a few variables--especially one which can be used as a basis for land use regulations.

Planners should generally require consultants conducting special technical studies to develop first a CEM of the problem and analysis approach so that planners can better follow the progress of analysis and steer the content and direction of the study. Technical studies to aid the formulation and evaluation of alternative plans must be conducted so that planners are able to understand thoroughly their basis and limitations as well as the conclusions, because planners are responsible for communicating with and educating the public and decisionmakers. At least one member of the planning staff should have sufficient training in the natural sciences to work with scientific information specialists and on interpreting such information for the needs and purposes of planners.

Planners should sponsor development of general CEMs of the ecosystems of planning areas to determine which environmental parameters should be studied for environmental management of the region. Also, CEMs should be used to make and assign priorities to recommendations for regional planning research needs--e.g., on what specific on- and off-site variables should development proposers supply information to enable effective project review.

Policy Formulation and Plan Administration

In this category of recommendations I include consideration both of impact statement procedures for proposed development projects and monitoring the real consequences of regional plans and individual development projects. Both actions occur after a regional plan is developed, and hence can be considered plan administration activities. CEMs can be used to outline and establish the specific topics and unifying concepts in EISs for proposed development projects. For example, their use for the topic I studied and formulation of the LCC I propose indicates that review of development project proposals should be expanded to examine the whole spatial sequence of processes and conditions occurring along the hydrologic transmission routes on which projects are located. Only when evaluated in that manner will project reviewers be able to assess adequately the potential suspended sediment and nutrient release consequences of proposed land use activities. Consequently, to assess site capability classification and the magnitude and acceptability of project consequences, project impact reviewers need to examine considerably more than conditions on and immediately adjacent to sites where development is proposed. As a policy, plan regulations could require developers to submit a complete fall-line profile above and below the project area showing the distribution of the processes and variables indicated in Chapter 17.

Planners also can use CEM to help decide what impact mitigation measures to require for developments necessary for transportation, housing, etc., those not causing enough damage to justify denial, or those which cannot be prevented. For example, one possible mitigation procedure when forest area is permanently cleared for a project is to transfer the high nutrient content top soil and litter to currently low nutrient holding capacity sites where forest cover is sparse or absent.

Planners can also use CEM to determine which variables should be measured to monitor the effects of newly built projects or old ones in environmentally sensitive locations. For example, the planning agency might routinely monitor such characteristics as changes of channel geometry, downslope tree growth rates or ground surface infiltration rates for indications of arising environmental problem.

REFERENCES

Aller, R.C.
1979. Relationships of tube-dwelling benthos with sediment and overlying water chemistry. *In Marine benthic dynamics*. K.R. Tenore and B.C. Coull (editors). Belle W. Baruch Library in Marine Science 11. University of South Carolina Press, Columbia. p. 285-308.

Altshuler, A.
1965. The goals of comprehensive planning. *Journal of the American Institute of Planners* 31:186-195.

American Geological Institute
1962. *Dictionary of Geological Terms*. Dolphin Books, New York. 545p.

American Water Works Association
1951. *Water quality and treatment*. 2nd edition. New York. 451p.

Amick, D.J.
1973. Scientific elitism and the information system of science. *Journal of the American Society of Information Science* 24(5)317-329.

Anderson, H.W.
1971. Relative contributions of sediment from source areas, and transport processes. *In Proceedings symposium on forestland uses and stream environment*. Oregon State University, School of Forestry, Corvallis, Oregon. p.55-63. (October, 1970)

Anderson, H.W., Hoover, M.D. and Reinhart, K.G.
1976. *Forests and water: effects of forest management on floods, sedimentation, and water supply*. USDA Forest Service General Technical Report PSW-18. Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 115p.

Applegate, R.
1978. The multiple use planning process: descent into the maelstrom? *Environmental Law* 8(2):427-460.

Aubertin, G.M.
1971. *Nature and extent of macropores in forest soils and their influence on subsurface water movement*. USDA, Forest Service Research Paper NE-192. Northeastern Forest Experiment Station, Upper Darby Pennsylvania. 33p.

AWWA
See American Water Works Association

Axler, R.P., Redfield, G.W. and Goldman, C.R.
1981. The importance of regenerated nitrogen to phytoplankton productivity in a subalpine lake. *Ecology* 62:345-354.

Baker, J.
1969. *Soil properties and nutritional status of western-hemlock tissue from over-stocked stands.* Information Report BC-X-38. Canada Forestry Service, Victoria. 8p.

Banwart, W.L., Hassett, J.J., Wood, S.G. and Means, J.C.
1982. Sorption of nitrogen-heterocyclic compounds by soils and sediments. *Soil Science* 133(1):42-47.

Baskerville, G.L.
1965. Estimation of dry weight of tree components and total standing crop in conifer stands. *Ecology* 46(6):867-869.

Batty, M.
1979. Progress, success, and failure in urban modelling. *Environment and Planning A* 11:863-878.

Beaton, J.D., Moss, A., MacRae, I., Konkin, J.W., McGhee, W.P.T. and Kosick, R.
1965. Observations of foliage nutrient content of several coniferous tree species in British Columbia. *Forestry Chronicle* 41 (2):222-236.

Behan, R.W.
1971. Bureaucracy, democracy and "parapolitics": an analytical and speculative essay *In Wilderness decisions in Region I, United States Forest Service: a case study of professional bureau policymaking.* Ph.D. Thesis, University of California at Berkeley. p. 278-302. (unpublished manuscript)

Bell, M.A.M., Beckett, J.M. and Hubbard, W.F.
1974. *Impact of harvesting on forest environments and resources: a review of literature and evaluation of research needs.* Pacific Forest Research Centre, Victoria, British Columbia. 141 p.

Bilby, R.E.
1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology* 62(5):1234-1243.

Birman, J.H.
1964. *Glacial geology across the crest of the Sierra Nevada, California.* Geological Society of America Special Paper 75. 80p.

Black, A.P. and Christman, R.F.
1963. Characteristics of colored surface waters. *Journal of the American Water Works Association* 55(6):753-770.

Bollen, W.B.

1969. Properties of tree barks in relation to their agricultural utilization. USDA Forest Service Research Paper PNW-77. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 36p.

Bonnor, G.M.

1964. The influence of stand density on the correlation of stem diameter with crown width and height for lodgepole pine. Forestry Chronicle 40(3):347-349.

Borgo, J.

1979. Journal of Legal Studies 8:419-455.

Bottoms, K.E. and Bartlett, E.T.

1975. Resource allocation through goal programming. Journal of Range Management 28(6):442-447.

Bowie, G. and Schwarz, C.

1978. Hydrologic modeling bibliography. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 450p. (unpublished manuscript)

Boynton, W., Hawkins, D.E. and Gray, C.

1977. A modeling approach to regional planning in Franklin County and Apalachicola Bay, Florida. In Ecosystem modeling in theory and practice: An introduction with case histories, C.A.S. Hall and J.W. Day (editors), John Wiley and Sons, New York. p. 477-506.

Brady, N.C.

1974. The nature and properties of soils. 8th edition. Macmillan Publishing. New York. 639p.

Brezonik, P.L.

1973. Nitrogen sources and cycling in natural waters. Ecological Research Series EPA-660/3-73-002. U.S. Environmental Protection Agency, Washington, D.C. 167p.

Brickell, J.E.

1970. Test of an equation for predicting bark thickness of western Montana species. USDA Forest Service Research Note INT-107. Intermountain Forest and Range Experiment Station, Ogden, Utah. 7p.

Bronstein

1980. Love canal and legal precedent. Science 209:1470.

Brown, G.W.

1973. The Impact of timber harvest on soil and water resources. Oregon State University. Extension Service. Extension Bulletin 827. Corvallis, Oregon. 16p.

Brown, J.K.
1978. *Weight and density of crowns of Rocky Mountain conifers.* USDA Forest Service Research Paper INT-197. Intermountain Forest and Range Experiment Station, Ogden, Utah. 56p.

Brown, J.K. and See, T.E.
1981. *Downed dead woody fuel and biomass in the northern Rocky Mountains.* USDA Forest Service General Technical Report INT-117. Intermountain Forest and Range Experiment Station, Ogden, Utah. 48p.

Bryant, F.D., Seiber, B.A. and Latimer, P.
1969. Absolute optical cross sections of cells and chloroplasts. *Archives of Biochemistry and Biophysics* 135:79-108.

Bryant, N.A. and Zobrist, A.L.
1976. Integration of socioeconomic data and remotely sensed imagery for land use applications *In Proceedings Annual Pecora Symposium, 2nd.* American Society of Photogrammetry, Falls Church, Virginia. p. 120-130 (15-25 Oct. 1976).

Buckman, H.O. and Brady, N.C.
1969. *The Nature and Properties of Soils.* 7th edition. Macmillan, New York. 653p.

Burt, W.V.
1956. A light scattering diagram. *Journal of Marine Research* 15(1):76-80.

Butler, E., Reid, J.K. and Berwick, V.K.
1966. *Magnitude and frequency of Floods in the U.S., Part 10, the Great Basin.* U.S. Geological Survey. Water Supply Paper 1684. Washington, D.C. 265p.

California Coastal Zone Conservation Commission
1973-5. *Technical Background Reports.* San Francisco. (unpublished manuscripts)

California Polytechnic Laboratory for Experimental Design
1972. *A planning system for the coastal plain of San Diego County: phase 1, northern sector.* California State Polytechnic University, Pomona. 392p.

California, State of
1978. California Administrative Code. Title 14. natural resources. Office of Administrative Hearings, Sacramento.

California State Water Resources Control Board
1980. *Draft water quality plan: Lake Tahoe Basin.* Sacramento. 306p.

Cal. SWRCB
(See California State Water Resources Control Board.)

Carballeira, Z.J.
1972. Lake Tahoe Basin: land-water nutrients relationships. M.S. thesis. Environmental Health Science, University of California, Berkeley. 50p. (unpublished manuscript)

Carlson, R.E.
1977. A trophic state index for lakes. Limnology and Oceanography 22(2):361-368.

Carmack, E.C., Gray, C.B., Pharo, C.H. and Daley, R.J.
1979. Importance of lake-river interaction on seasonal patterns in the general circulation of Kamloops Lake, British Columbia. Limnology and Oceanography 24:634-644.

Chorley, R.J.
1978. Glossary of terms. In Hillslope hydrology. M.J. Kirby (editor). John Wiley and Sons, New York. p. 365-375.

Clark, J.
1974. Rookery Bay: ecological constraints on coastal development. Conservation Foundation, Washington, D.C. 91p.

Clark, J.R.
1978. Natural science and coastal planning: the California experience. In Protecting the golden shore: lessons from the California Coastal Commissions. R.G. Healy (editor). Conservation Foundation, Washington, D.C. p.177-206.

Clayton, J.L. and Kennedy, D.A.
1980. A comparison of the nutrient content of Rocky Mountain douglas-fir and ponderosa pine trees. USDA Forest Service Research Note INT-281. Intermountain Forest and Range Experiment Station, Ogden, Utah. 13p.

Clayton, L., Tuthill, S.J. and Bickley, W.B.
1966. Effects of groundwater seepage on the regimen of an Alaskan stream. American Geophysical Union. Transactions 47(1):83

Cline, M.G.
1949. Basic principles of soil classification. Soil Science 67:81-92.

Coats, R.N.
1975. Nitrogen flux through a forested watershed near Lake Tahoe, California. Ph.D. Thesis, University of California. 191p.

Cole, G.A.
1975. Textbook of limnology. C.V. Mosby, Saint Louis. 283p.

Crippen, J.B. and Pavelka, B.R.
1970. Lake Tahoe Basin, California-Nevada. U.S. Geological Survey. Water Supply Paper 1972. Washington, D.C. 56p.

Cummins, K.W., Klud, J.J., Wetzel, R.G., Petersen, R.C., Suberkropp, K.F., Manny, B.A., Wuycheck, J.C. and Howard, F.O.
1972. Organic enrichment with leaf leachate in experimental lotic ecosystems. Bioscience 12(12):719-722.

Daubenmire, R.F.
1963. Nutrient content of leaf litter of trees. Ecology 34:786-793.

DeByle, N.V.
1980. Harvesting and site treatment influences on the nutrient status of lodgepole pine forests in western Wyoming. In Environmental consequences of timber harvesting in Rocky Mountain coniferous forests, symposium proceedings. USDA Forest Service General Technical Report INT-90. Intermountain Forest and Range Experiment Station, Ogden, Utah. p. 137-155. (September, 1979, Missoula, Montana).

Dice, S.F.
1970. The biomass and nutrient flux in a second growth douglas-fir ecosystem (a study in quantitative ecology). Ph.D. Thesis University of Washington, Seattle. 165p.

Dickey, J.W. and Watts, T.M.
1978. Analytical techniques in urban and regional planning: with applications in public administration and affairs. McGraw-Hill Books, New York. 542p.

Dunne, T. and Leopold, L.B.
1978. Water in environmental planning. W. H. Freeman, San Francisco. 818p.

Dyrness, C.T.
1972. Soil surface conditions following balloon logging. USDA Forest Service Research Note PNW-182. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. 7 p.

Edmondson, W.T.
1980. Secchi disk and chlorophyll. Limnology and Oceanography 25 (2):378-9.

Edmondson, W.T.
1972. Nutrients and phytoplankton in Lake Washington. In Nutrients and eutrophication: the limiting-nutrient controversy. G.E. Likens (editor). American Society of Limnology and Oceanography. Special Symposia 1. p.172-188.

Einstein, H.A.
1964. River sedimentation In Handbook of applied hydrology. V.T. Chow (editor). McGraw-Hill, New York. p. 17-35 - 17-67.

Einstein, H.A., Anderson, A. and Johnson, J.W.
1940. A distinction between bed load and suspended load in natural streams. Transactions of the American Geophysical Union. 21:628-633.

Elder, J.F., Osborn, K.E. and Goldman, C.R.
1976. Iron transport in a Lake Tahoe tributary and its potential influence upon phytoplankton growth. Water Research 10:783-787.

Fabos, J.G. and Caswell, S.J.
1977. Composite landscape assessment: assessment procedures for special resources, hazards and development suitability; part II of the Metropolitan Landscape Planning Model (METLAND). Research Bulletin 637. Massachusetts Agricultural Experiment Station, Amherst. 323p.

Faurot, J.L.
1977. Estimating merchantable volume and stem residue in four timber species: ponderosa pine, lodgepole pine, western larch, douglas-fir. USDA Forest Service Research paper INT-196. Intermountain Forest and Range Experiment Station, Ogden, Utah. 55p.

Fleming, G. and Leytham, K.M.
1976. The hydrologic and sediment processes in natural watershed areas p.1-232 to 1-246. In Proceedings of the Federal Interagency Sedimentation Conference (3rd). U.S. Water Resources Council, Washington, D.C., p.1-232 - 1-246. (Denver, March, 1976)

Flemming, R.S.
1976. Ecosystem and resource capability models. In Regional environmental systems: assessment of RANN projects. University of Washington, Department of Civil Engineering, Seattle. p.144-165.

Fogg, G.E.
1965. Algal cultures and phytoplankton ecology. University of Wisconsin Press, Madison. 126p.

Foster, H.B., Ward, P.C. and Prucha, A.A.
1965. Nutrient removal by effluent spraying. American Society of Civil Engineers. Journal of the Sanitary Engineering Division SA6:1-11.

Foth, H.D.
1978. Fundamentals of soil science. 6th edition. John Wiley and Sons, N.Y. 436p.

Fowells, H.A.
1965. Silvics of forest trees of the United States. Agriculture Handbook 271. USDA Forest Service, Washington, D.C. 762p.

Frantz, T.C. and Cordone, A.J.
1967. Observation on deepwater plants in Lake Tahoe, California and Nevada. Ecology 48(5):709-714.

Frenkiel, F.N. and Goodall, D.W. (editors)
1978. Simulation modeling of environmental problems. Scientific Committee on Problems of the Environment. SCOPE 9. John Wiley and Sons, New York. 112p.

Friedman, G.M. and Sanders, J.E.
1978. Principles of sedimentology. John Wiley and Sons, New York. 791p.

Friedmann, J.
1966. A response to Altshuler: comprehensive planning as a process. Journal of the American Institute of Planners 31:195-197.

Friedmann, J.
1963. Regional planning as a field of study. Journal of the American Institute of Planners 29(3):168-175.

Fujimori, T., Kawamabe, S., Saito, H., Grier, C.C. and Shidei, T.
1976. Biomass and primary production in forests of three major vegetation zones of the northwestern United States. Japanese Forestry Society Journal. 58(10):360-373.

Gholz, H.L., Grier, C.C., Campbell, A.G. and Brown, A.T.
1979. Equations for estimating biomass and leaf area of plants in the Pacific Northwest. Oregon State University. Forest Research Laboratory. Research Paper 41. Corvallis. 39p.

Gibbs, R.J.
1974. Principles of studying suspended materials in water. In Suspended solids in water. R.J. Gibbs (editor). Marine Science volume 4. Plenum Press, New York. p.3-15.

Gibor, A. and Meehan, W.R.
1961. Diurnal variations in chlorophyll a content of some freshwater algae. Ecology 42(1):156-157.

Gilliland, M.W.
1982. [Rebuttal to Suter (1981) Ecosystem theory and NEPA assessment]. Bulletin of the Ecological Society of America 63(1):2-3.

Gilliland, M.W. and Clark, B.D.
1981. The Lake Tahoe Basin: a systems analysis of its characteristics and human carrying capacity. Environmental Management 5:397-407.

Gilliland, M.W. and Risser, P.G.
1977. The use of systems diagrams for environmental impact assessment: procedures and application. Ecological Modelling 3:183-209.

Glancy, P.A.
1969. A mudflow in the Second Creek drainage Lake Tahoe Basin and its relation to sedimentation and urbanization. In U.S. Geological Survey Professional Paper 650-C. Washington, D.C. p.195-200.

Glancy, P.A.
1973. A reconnaissance of streamflow and fluvial sediment transport, Incline Village area, Lake Tahoe, Nevada. Water Resources Information Series Report 19. Nevada Division of Water Resources, Carson City. 37 p.

Goldman, C.P., Moshiri, G.A. and de Amezaga, E.
1970. Synoptic study of accelerated eutrophication in Lake Tahoe - a subalpine lake. In Water pollution control in cold climates. R.S. Murphy and D. Nyquist (editors). U.S. Government Printing Office, Washington, D. C. p.1-21. (University of Alaska, July, 1970).

Grant, D.P.
1974. The problem of weighting. DMG-DRS Journal: Design Research and Methods 8(3):136-141.

Gray, D.H. and Megaham, W.F.
1981. Forest vegetation, removal and slope stability in the Idaho batholith. USDA Forest Service Research Paper INT-271. Intermountain Forest and Range Experiment Station, Ogden, Utah. 23 p.

Gupta, M.K., Agnew, R.W. and Kobriger, N.P.
1981. Constituents of highway runoff. Volume 1: state-of-the-art report. U.S. Federal Highway Administration, Environmental Sciences Division, Washington, D.C. 121p.

Hairston, N.G.
1980. The vertical distribution of diaptomid copepods in relation to body pigmentation. In Evolution and ecology of zooplankton communities. W. C. Kerfoot (editor). American Society of Limnology and Oceanography. Special Symposium 3. University Press of New England, Hanover, New Hampshire. p.98-110.

Hall, C.A.S. and Day, J.W.
1977. Ecosystem modeling in theory and practice: an introduction with case histories. John Wiley and Sons, New York. 684p.

Harder, W.
1968. Reactions of phytoplankton organisms to water stratification. Limnology and Oceanography 13(1):156-168.

Hazen, A.
1904. On sedimentation. American Society of Civil Engineers. ASCE Transactions 53:45-

Healy, R.G., editor.
1978. Protecting the golden shore: lessons from the California coastal commissions. Conservation Foundation, Washington, D.C. 257 p.

Heede, B.H.
1971. Characteristics and processes of soil piping in gullies. USDA Forest Service Research Paper RM-68. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 15p.

Hellebust, J.A. and Lewin, J.
1977. Heterotrophic nutrition. In The biology of diatoms. D. Werner (editor). University of California Press. Botanical Monograph 13. Berkeley. p.169-197.

Henderson, F.M.
1980. Effects of interpretation techniques on land-use mapping accuracy. Photogrammetric Engineering and Remote Sensing 46(3):339-367.

Hilborn, R.
1979. Some failures and successes in applying systems analysis to ecological systems. Journal of Applied Systems Analysis 6:25-31.

Hills, G.A.
1961. The ecological basis for land-use planning. Research Report 46. Ontario Department of Lands and Forests, Toronto. 210p.

Holcomb Research Institute
1976. Environmental modeling and decision making, the U.S. experience. Praeger Publishers, New York. 152p.

Holling, C.S. (editor)
1978. Adaptive environmental assessment and management. IIASA International Series on Applied Systems Analysis 3. John Wiley and Sons, New York. 377p.

Hopkins, L.D.
1977. Methods for generating land suitability maps: a comparative evaluation. Journal of the American Institute of Planners 43(4):386-400.

House, P.W. and McLeod, J.
1977. Large-scale models for policy evaluation. John Wiley and Sons, New York. 326p.

Hovis, W.A. Clark, D.K., Anderson, F., Austin, R.W., Wilson, W.H., Baker, E.T., Ball, D., Gordon, H.R., Mueller, J.L., El-Sayed, S.Z., Strum, B., Wrigley, R.C. and Yentsch, C.S.
1980. Nimbus-7 coastal zone color scanner: system description and initial imagery. Science 210:60-66.

Howard, A.D. and Remson, I.
1978. Geology in environmental planning. McGraw-Hill, New York. 478 p.

Hulburt, E.O.
1934. The polarization of light at sea. Journal of the Optical Society of America 24:35-42.

Hutchinson, G.E.
1957. A treatise on limnology: volume I. geography, physics, and chemistry. John Wiley and Sons, New York. 1015p.

Hyne, N.J., Court, J.E. and Goldman, C.R.
1973. Mounds in Lake Tahoe, California-Nevada: a model for landslide topography in the subaqueous environment. The Journal of Geology 81(2):176-188.

Inman, D.I.
1949. Sorting of sediments in the light of fluid mechanics. Journal of Sedimentary Petrology 19:51-70.

Isard, W, Choguill, C.L. Kissin, J., Seyfarth, R.H. and Tatlock, R.
1972. Ecologic-economic analysis for regional development. Free Press, New York. 269p.

Isik, K.
1974. Site, height, and foliar nutrient content relations of white fir (Abies concolor) populations: an environmental and genetic analysis. Ph.D. Thesis, University of California, Berkeley. 276p. (unpublished manuscript)

James M. Montgomery Consulting Engineers
1976. Forest harvest, residue treatment, reforestation and protection of water quality. EPA 910/9-76-020. US Environmental Protection Agency, Seattle, Washington. 273 p.

Jannasch, H.W. and Pritchard, P.H.
1972. The role of inert particulate matter in the activity of aquatic microorganisms. In Detritus and its role in aquatic ecosystems. U. Melchiorri-Santolini and J.W. Hopton (editors) Memorie dell' instituto italiano di idrobiologia 29 (supplement) :289-308.

Jasanoff, S. and Nelkim, D.
1981. Science, technology, and the limits of judicial competence. Science 214:1211-1215.

Jeffrey, S.W., Sielick, M. and Haxo, F.T.
1975. Chloroplast pigment patterns in dinoflagellates. Journal of Phycology 11:374-381.

Jerlov, N.G.
1976. *Marine Optics*. Elsevier Oceanography Series 14. Elsevier Scientific Publishing, Amsterdam. 231p.

Jerlov, N.G.
1968. *Optical oceanography*. Elsevier Oceanography Series 5. Elsevier Publishing, Amsterdam. 194p.

JMMCE
1976. see James M. Montgomery Consulting Engineers.

Johnson, R.B.
1979. *Factors that influence the stability of slopes--a literature review*. U.S. Federal Highway Administration, Washington, D.C. 123p.

Johnstone, W.D.
1970. *Component dry weights of 100-year-old lodgepole pine trees*. Canadian Forestry Service. Forest Research Laboratory Information Report A-X-31. Calgary, Alberta. 14p.

Jones, D. and Wills, M.S.
1956. The attenuation of light in sea and estuarine waters in relation to the concentration of suspended solid matter. *Journal of the Marine Biological Association of the United Kingdom* 35(2):431-444.

Jones, J.R.
1976. *Inventory of research activities in the Lake Tahoe area: a bibliography 1845-1976*. Lake Tahoe Area Research Coordination Board, South Lake Tahoe. 219p.

Juday, C.
1906. Notes on Lake Tahoe; its trout and trout fishing. *Bulletin of the Bureau of Fisheries* 26:133-146.

Judd, D.B., Wyszecki, G.
1975. *Color in business science and industry*. Third edition. John Wiley and Sons, New York. 565p.

Kalinske, A.A.
1942. Criteria for determining sand-transport by surface creep and saltation. *Transactions of the American Geophysical Union* 23:639-643.

Kalle, K.
1938. Zur problem des meereswasserfarbe. [On the problem of sea water color.] *Annalen der Hydrographie und Maritimen Meteorologie* (Berlin) 66:1-13.

Kalle, K.
1939. Die farbe des meeres. [The color of the sea.] *Rapports et Proces - Verbaux des Reunions, Conseil Permanent International pour l'Exploration de la Mer* 109:98-105.

Keeney, D.R.
1972. *The fate of nitrogen in aquatic ecosystems.* Eutrophication Information Program. Literature Review 3. University of Wisconsin Water Resources Center, Madison. 59p.

Kelsey, H.M.
1975. Slope classification map: Van Duzen River Basin: Humboldt and Trinity Counties, California. *In Van Duzen River Basin environmental atlas.* California Department of Water Resources, Sacramento. Plate 9.

Kelsey, H.M.
1977. *Landsliding, channel changes, sediment yield and land use in the Van Duzen River Basin, North Coastal California, 1941-1975.* Earth Resources Monograph 3. USDA Forest Service, Region 5, San Francisco, California. 370p.

Kerker, M.
1974. Movement of small particles by light. *American Scientist* 62(1):92-98.

Kiefer, D.A. and Austin, R.W.
1974. The effect of varying phytoplankton concentration on submarine light transmission in the Gulf of California. *Limnology and Oceanology* 19:(1):55-65.

Kiefer, D.A., Holm-Hansen, O, Goldman, C.R. and Richards, R.
1972. Plankton in Lake Tahoe; deep living populations. *Limnology and Oceanography* 17:418-422

Kimmins, J.P.
1973. Nutrient removal associated with whole-tree logging on two different sites in the Prince George Forest District. Report submitted to British Columbia Forestry Service Productivity Committee. 100p. (unpublished manuscript)

Kirk, J.T.O.
1980. Spectral absorption properties of natural waters: contribution of the soluble and particulate fractions to light absorption in some inland waters of south-eastern Australia. *Australian Journal of Marine and Freshwater Research* 31:287-296.

Kittredge, J.
1948. *Forest influences: the effects of woody vegetation on climate, water and soil, with applications to the conservation of water and the control of floods and erosion.* Dover Publications, New York, New York. 394p.

Kittredge, J.
1955. Some characteristics of forest floors from a variety of forest types in California. *Journal of Forestry* 53(9):645-647.

Kochel, R.C. and Baker, V.R.
1982. Paleoflood hydrology. *Science* 215:353-361.

Kornerup, A. and Wanscher, J.H.
1967. *Methuen handbook of color*. Second edition. Methuen, London. 248 p.

Korwek, E.L.
1980. Science and the courts. *Science* 210:376.

Kracht, J.B.
1971. *The application of models to the planning process with special emphasis on land use*. Council of Planning Librarians Exchange Bibliography 194. Monticello, Illinois. 17p.

Kramer, B.M. and Fox, D.G.
1980. Air quality modeling: judicial, legislative and administrative reactions. *In* *Proceedings second joint conference on applications of air pollution meteorology and on industrial meteorology*. American Meteorological Society, Boston. p. 683-686. (New Orleans, 1980)

Kroll, C.G.
1976. *Sediment discharge from highway cut-slopes in the Lake Tahoe Basin, California, 1972-74*. Water-Resources Investigations Report Number 76-19. U.S. Geological Survey, Washington, DC.

Krumbein, W.C. and Sloss, L.L.
1963. *Stratigraphy and sedimentation*. 2nd edition. W.H. Freeman, San Francisco. 660p.

Krumlik, J.G.
1974. *Biomass and nutrient distribution in two old-growth forest ecosystems in south central British Columbia*. M.S. Thesis, University of British Columbia, Vancover. 87p.

Lacate, D.S.
1969. *Guidelines for bio-physical land classification: for classification of forest lands and associated wildlands*. Canada Forestry Service Publication 1264. Ottawa. 61 p.

Lane, E.W.
1938. Notes on the formation of sand. *Transactions of the American Geophysical Union*. 19:505-508.

Lang, R.
1979. Environmental information in a planning/management context. *In* *Applications of ecological (biophysical) land classification in Canada*. C.D.A. Rubec (editor). Proceedings of the second meeting Canada Committee on Ecological (Biophysical) Land Classification. Ecological Land Classification Series 7. Lands Directorate, Environment Canada, Quebec. p. 285-294. (Victoria, British Columbia, April 1978)

Lange, R.W.
1971. Bark thickness, k, factors for four Montana coniferous tree species. Montana Forest and Conservation Experiment Station Research Note 9. University of Montana, Missoula. 2p.

Latimer, P., Moore, D.M. and Bryant, F.D.
1968. Changes in total light scattering and absorption causes by changes in particle conformation. Journal of Theoretical Biology 21(3):348-367.

Leaf, C.F. and Martinelli, M.
1977. Avalanche dynamics: engineering applications for land use planning. USDA Forest Service Research Paper RM-183. Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. 51p.

Lean, D.R.S.
1973. Phosphorus dynamics in lake water. Science 179:678-680.

Le Conte, J.
1883 and 1884. Physical studies of Lake Tahoe. Overland Monthly 2:506-516, 2:595-612, 3:41-46.

Lee, D.B.
1973. Requiem for large-scale models. Journal of the American Institute of Planners 39(3):163-178.

Leiser, A.T., Nussbaum, J.J., Kay, B., Paul, J. and Thornhill, W.
1974. Revegetation of disturbed soils in the Tahoe Basin California Department of Transportation, Sacramento. 72p.

Lenhard, S.C. and Witter, J.A.
1977. Insects as biological indicators of environmental change. In Entomological Society of America Bulletin 23(3):191-193.

Leonard, R.L., Kaplan, L.A., Elder, J.F., Coats, R.N. and Goldman, C.R.
1979. Nutrient transport in surface runoff from a subalpine watershed, Lake Tahoe Basin, California. Ecological Monographs 49(3):281-310.

Leopold, L.B.
1969. Quantitative comparison of some aesthetic factors among rivers. U.S. Geological Survey Circular 620. Washington, D.C. 16p.

Leopold, L.B., Wolman, M.G. and Miller, J.P.
1964. Fluvial processes in geomorphology. W.H. Freeman, San Francisco. 535p.

Leopold, L.B.
1968. Hydrology for urban land palnning - a guidebook on the hydrologic effects of urban land use. U.S. Geological Survey Circular 554. 18p.

Lewis, P.H.
1961. Recreation and open space in Illinois. University of Illinois, Department of Landscape Architecture and Bureau of Community Planning, Urbana. 128p.

Likens, G.E. (editor).
1972. Nutrients and eutrophication: the limiting-nutrient controversy. Special Symposia 1. American Society of Limnology and Oceanography, Lawrence, Kansas. 328p. (Hickory Corners, Michigan, February 1971.)

Lorenzen, C.J.
1972. Extinction of light in the ocean by phytoplankton. International Council for the Exploration of the Sea. Journal du Conseil 34(2):262-267

Loucks, O.L.
1974. Systems methods in environmental court actions. In Systems Analysis and Simulation in Ecology. B.C. Patten (editor). Academic Press, New York. p. 419-473.

Lull, N.W. and Sopper, W.E.
1969. Hydrologic effects from urbanization of forested watersheds in the Northeast. USDA Forest Service Research Paper NE-146. Northeastern Forest Experiment Station, Upper Darby, Pennsylavania. 31p.

Lyle, J. and von Wodtke, M.
1974. An information system for environmental planning. Journal of the American Institute of Planners 40(6):394-413.

Lynch, D.L. and Broome, S.R.
1973. Mountain land planning. Colorado State Forest Service, Fort Collins. 38p.

MacAdam, D.L.
1971. Geodesic chromaticity diagram based on variances of color matching by 14 normal observers. Applied Optics 10(1):1-8.

Mackett, R.L.
1977. Models and the urban planning crisis. Town Planning Review 48:287-298.

Mackett, R.L.
1978. A response to Stephen Chait's comment. Town Planning Review 49:229-231.

Mar, B.W.
1974. Problems encountered in multidisciplinary resources and environmental simulation models development. Journal of Environmental Management 2(1):83-100.

Matthes, F.E.
1942. Glaciers. In Hydrology. O.E. Meinzer (editor). Dover Publications, New York. p.149-219.

McCloskey, M.C.
1971. Planning and regional planning: what are they? an annotated bibliography of definitions. Council of Planning Librarians Exchange Bibliography 174. Monticello, Illinois. 62p.

McEvoy, J.
1972. Multi- and interdisciplinary research--problems of initiation, integration and reward. Policy Sciences 3:201-208.

McHarg, I.L.
1963. Regional landscape planning. In Resources, the Metropolis and the land-grant university, proceedings of a conference. A.W.J. Scheffey (editor). University of Massachusetts, Cooperative Agriculture Extension Service, Amherst. p. 31-35.

McHarg, I.L.
1969. Design with nature. Natural History Press, Garden City, New Jersey. 197p.

Meals, D.W. and Cassell, E.A.
1978. Phosphorus interactions in the aquatic environment: a survey of the literature. U.S. National Technical Information Service, Springfield, Virginia. 104p.

Mellanby, H.
1963. Animal life in freshwater: a guide to freshwater invertebrates. Methuen, London. 308p.

Meshenberg, M.J.
1976. Environmental planning: a guide to information resources. Man and the Environment Information Guide Series 3. Gale Research, Detroit. 492p.

Meyers, C.R.
1973. Regional modeling abstracts: a bibliography of regional analysis: volume V. Oak Ridge National Laboratory, Tennessee. 378p.

Mitchell, B.G. and Kiefer, D.A.
1980. Ocean color analysis: an investigation of bacterioplankton. (Paper presented at American Society of Limnology and Oceanography Winter Meeting, 3rd, Seattle, December 1980.)

Moeur, M.
1981. *Crown width and foliage weight of northern Rocky Mountain conifers.* USDA Forest Service Research Paper INT-283. Intermountain Forest and Range Experiment Station, Ogden, Utah. 14p.

Moir, W.H. and Grier, H.
1969. Weight and nitrogen, phosphorus, potassium and calcium content of forest floor humus of lodgepole pine stands in Colorado. *Soil Science Society of America Proceedings* 33(1):137-140.

Moore, D.G. and Norris, L.A.
1974. Soil processes and introduced chemicals. *In Environmental effects of forest residues management in the Pacific Northwest, a state-of-knowledge compendium.* O.P. Cramer (editor). USDA Forest Service General Technical Report PNW-24. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon. p.C-1 - C-33.

Mortimer, C.H.
1941. The exchange of dissolved substances between mud and water in lakes. *Journal of Ecology* 29(2):280-329.

Nakao, D.I., Hatano, M.M., Howell, R.B. and Shirley, E.C.
1976. *Revegetation of disturbed soils in the Tahoe Region: final evaluation.* California Department of Transportation, Sacramento. 122p.
National Academy of Sciences
1968. *Eutrophication: causes, consequences, correctives.* Washington, D.C. 661p. (Madison, Wisconsin, June 1967.)

Neivelt, D. and Schwarz, C.
1978. *Environmental planning bibliography.* USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley. 394p. (unpublished manuscript)

Nelkin, D.
1979. Scientific knowledge, public policy and democracy. *Knowledge: Creation, Diffusion, Utilization* 1(1):106-122.

Nixon, S.W., Kelley, J.R., Furnas, B.N., Oviatt, C.A. and Hale, S.S.
1979. Phosphorus regeneration and the metabolism of coastal marine bottom communities. *In Marine benthic dynamics.* K.R. Tenore and B.C. Coull (editors). Bell W. Baruch Library in Marine Science 11. University of South Carolina Press, Columbia. p 219-242.

Norton, S. and Young, H.E.
1976. Forest biomass utilization and nutrient budgets. *In Oslo Biomass Studies.* H.E. Young (editor). University of Maine Press, Orono.

Odum, E.P.
1971. Fundamentals of ecology:3rd edition. W. B. Saunders, Philadelphia. 574p.

Odum, H.T.
1971. Environment, power, and society. John Wiley and Sons, New York. 331p.

Optical Society of America Committee on Colorimetry
1966. The science of color. Sixth edition. Washington, D.C. 373p.

Orme, A.R.
1971. The Shore-zone system for Lake Tahoe. A Guide for Planning Series. Tahoe Regional Planning Agency, South Lake Tahoe, California. 30p.

Ovington, J.D.
1957. The volatile matter, organic carbon and nitrogen contents of tree species grown in close stands. New Phytologist 56:1-11.

Paerl, H.W.
1975. Microbial attachment to particles in marine and freshwater ecosystems. Microbial Ecology 2(1):73-83.

Paerl, H.W. and Goldman, R.C.
1972. Simulation of heterotrophic and autotrophic activities of a planktonic microbial community by siltation of Lake Tahoe, California. In Detritus and its role in aquatic ecosystems. U. Melchiorri-Santolini and J. W. Hopton (editors). Memorie dell' instituto italiano di idrobiologia 29 (supplement):129-147.

Paerl, H.W., Richards, R.C., Leonard, R.L. and Goldman, C.R.
1975. Seasonal nitrate cycling as evidence for complete vertical mixing in Lake Tahoe, California-Nevada. Limnology and Oceanography 2(1):1-8.

Patric, J.H.
1981. Soil-water relation of shallow forested soils during flash floods in West Virginia. USDA Forest Service Research Paper NE-469. Northeastern Forest Experiment Station, Broomall, Pennsylvania. 20p.

Patrick, R.
1962. Discussion of paper by Charles E. Renn, "Ecology and fine-grained sediments." Journal of Geophysical Research 67(4):1509-1511.

Pennak, R.W.
1955. Comparative limnology of eight Colorado mountain lakes. University of Colorado Studies. Series in Biology 2. University of Colorado Press, Boulder. 75p.

Pfennigstorf, W.
1979. Environment, damages and compensation. American Bar Foundation Research Journal 1979:347-448.

Phillips, R.L.
1974. Computer graphics in urban and environmental systems. Proceedings. Institute of Electrical and Electronics Engineers 62 (4):437-452.

Pimental, D.
1966. Complexity of ecological systems and problems in their study and management. In Systems analysis in ecology. K.E.F. Watt (editor). Academic Press, New York. p.15-35

Powell, T. and Jassby, A.
1974. The estimation of vertical eddy diffusivities below the thermocline in lakes. Water Resources Research 10(2):191-198.

Powell, T.M., Richerson, P.J., Dillon, T.M., Agee, B.A., Dozier, B.J., Godden, D.A. and Myrup, L.O.
1975. Spatial scales of current speed and phytoplankton biomass in Lake Tahoe. Science 189:1088-1090.

Powers, R.F.
1981. Nutritional ecology of ponderosa pine (Pinus ponderosa Laws.) and associated species. Ph.D. Thesis, University of California, Berkekey. 234p. (umpublished manuscript)

Powers, R.F., Isik, K. and Zinke, P.J.
1975. Adding phosphorus to forest soils: storage capacity and possible risks. Bulletin of Environmental Contamination and Toxicology. 14(3):257-264.

Preisendorfer, R.W.
1976a. Hydrologic optics: volume I. introduction. U.S. National Oceanic and Atmospheric Administration, Honolulu. 253p.

Preisendorfer, R.W.
1976b. Hydrologic optics: volume II. foundations. U.S. National Oceanic and Atmospheric Administration, Honolulu. 411p.

Preisendorfer, R.W.
1976c. Hydrologic optics: volume III. solutions. U.S. Oceanic and Atmospheric Administration, Honolulu. 255p.

Preisendorfer, R.W.
1976d. Hydrologic optics: volume IV. imbeddings. U.S. Oceanic and Atmospheric Administration, Honolulu 216p.

Preisendorfer, R.W.
1976e. Hydrologic optics: volume V. properties. U.S. Oceanic and Atmospheric Administration, Honolulu. 304p.

Preisendorfer, R.W.
1976f. Hydrologic optics: volume VI. surfaces. U.S. Oceanic and Atmospheric Administration, Honolulu. 404p.

Preston, T., Stewart. W.D.P. and Reynolds, C.S.
1980. Bloom-forming cyanobacterium Microcystis aeruginosa overwinters on sediment surface. Nature 288:365-367.

Public Law 96-551/94
1980. (approved 12/19/80)
An Act to grant the consent of the Congress to the Tahoe Regional Planning compact and to authorize the Secretary of Agriculture and others to cooperate with the planning agency thereby created (96th Cong. 2nd session, Bill no. H.R. 8235)

Ragan, R.M.
1968. An experimental investigation of partial area contributions. International Association of Scientific Hydrology Publication 76:241-249.

Rainwater, C.
1971. Light and color. Golden Science Guide series. Golden Press, New York. 160p.

Raman, C.V.
1922. On the molecular scattering of light in water and the colour of the sea. Proceedings of the Royal Society (London) Series A, 101:64-79.

Reed, L.A.
1978. Effectiveness of sediment-control techniques used during highway construction in central Pennsylvania. U.S. Geological Survey Water Supply Paper 2054. Washington, D.C. 57p.

Reid, C.P., Odegard, P.J., Hokenstrom, J.C., McConnel, W.J. and Frayer, W.E.
1974. Effects of clearcutting on nutrient cycling in lodgepole pine forests. College of Forestry and Natural Resources, Colorado State University, Fort Collins. 321 p. (unpublished manuscript)

Reid, G.K.
1961. Ecology of inland waters and estuaries. Reinhold Publishing, New York. 375p.

Reid, G.K. and Wood. R.D.
1976. Ecology of inland waters and estuaries. Second edition. Van Nostrand, New York. 485p.

Reynolds, J.F. and Knight, D.H.
1973. The magnitude of snowmelt and rainfall interception by litter in lodgepole pine and spruce-fir forests in Wyoming. Northwest Science 47(1):50-60.

Richerson, P.J., Lopez, M.M. and Coon, T.
1978. The deep chlorophyll maximum layer of Lake Tahoe. *International Association for Theoretical and Applied Limnology. Transactions* 20(part 1):426-433.

Richerson, P.J., Powell, T.M., Leigh-Abbott, M.R. and Coil, J.A.
1978. Spatial heterogeneity in closed basins. *In Spatial pattern in plankton communities.* J.H. Steele (editor). NATO Conference Series: IV, Marine Sciences 3. Plenum Press, New York. p.239-276. (Erice, Italy, 1977.)

Rickert, D.A., Beach, G.L., Jackson, J.E., Anderson, D.M., Hazen, H.H. and Suwijn, E.
1978. *Oregon's procedure for assessing the impacts of land management activities on erosion related nonpoint source problems.* Oregon Department of Environmental Quality, Water Quality Program, Portland. 219p.

Ringelberg, J.
1980. Aspects of red pigmentation in zooplankton, especially copepods. *In Evolution and ecology of zooplankton communities.* W.C. Kerfoot (editor). American Society of Limnology and Oceanography. Special Symposium 3. University Press of New England, Hanover, New Hampshire. p.91--97.

Rittel, H.W.J. and Weber, M.M.
1973. Dilemmas in a general theory of planning. *Policy Sciences* 4:155-169.

Rogers, J.H.
1974. *Soil survey Tahoe Basin area California and Nevada.* U.S. Soil Conservation Service, Washington, D. C. 84p.

Rosenbaum, N.M.
1978. *Citizens and land use policy* Urban Institute, Washington, DC.

Rowe, J.S.
1979. Revised working paper on methodology/philosophy of ecological land classification in Canada. *In Applications of ecological (biophysical) land classification in Canada.* C.D.A. Rubec (editor). Ecological Land Classification Series 7. Lands Directorate, Environment Canada, Quebec. p. 23-30.

Rubec, C.D.A. (editor)
1979. *Applications of ecological (biophysical) land classification in Canada.* Proceedings of the second meeting Canada Committee on Ecological (Biophysical) Land Classification. Ecological Land Classification Series 7. Lands Directorate, Environment Canada, Quebec. 396 p. (Victoria, British Columbia, April 1978)

Rubey, W.W.
1933. Settling velocities of gravel, sand and silt particles. American Journal of Science 25(148):325-338.

Ryan, D.F. and Bormann, F.H.
1982. Nutrient resorption in northern hardwood forests. Bioscience 32(1):29-32.

Russell, C.S. (editor)
1975. Ecological modeling in a resource management framework. Resources for the Future, Washington, D.C. 394p.

Ruttner, F.
1963. Fundamentals of limnology. Third edition. University of Toronto Press. 295p.

Ryther, J.H. and Kramer, D.D.
1961. Relative iron requirements of some coastal and offshore plankton algae. Ecology 42(2):444-446.

San Francisco Bay Conservation and Development Commission
1966-8. Technical Background Reports. San Francisco. (unpublished manuscripts)

Satoo, T.
1974. Primary production relations in a young plantation of Abies sachalinensis in Hokkaido: materials for the studies of growth in forest stands--II. Tokyo Dafgaku. Nogakubu. Bulletin of the Tokyo University Forests. 66:127-127.

Sayer, R.A.
1976. A critique of urban modelling: from regional science to urban and regional political economy. Progress in Planning 6(3)187-254.

Scherz, J.P., Sydor, M. and Van Domelen, J.F.
1974. Aircraft and satellite monitoring of water quality in Lake Superior near Duluth. In Third earth resources technology satellite symposium. Volume I: technical presentations section B. S.K. Freden, E.P. Mercant and M.A. Becker (editors). NASA, Washington, D.C. p.1619-1636.

Schindler, D.W.
1974. Eutrophication and recovery in experimental lakes: implications for lake management. Science 184:897-899.

Schreuder, G.F.
1977. Forest land-use allocation and environmental systems evaluation: the SVEN research program. In Regional environmental systems: assessment of RANN projects. University of Washington, Department of Civil Engineering, Seattle. p. 353-363.

Schwarz, C.
1974. Bibliography on resource capability based land use planning. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. 57p. (unpublished manuscript)

Seidel, A.D.
1978. Research utilization by architects and planners. Vance Bibliographies, Monticello, Illinois. 35p.

Sharpe, C.F.S.
1938. Landslides and related phenomena: a study of mass movements of soil and rock. Columbia University Press, New York. 137p.

Shea, J.H.
1973. Proposal for a particle-size grade scale based on 10. Geology 1(1):3-8.

Shoulejkin, W.
1924. Scattering of light by very big colloidal particles. The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science, Series 6, 48(284):307-320.

Shugart, H.H., Klopatek, J.M. and Emanuel, W.R.
1981. Ecosystems analysis and land-use planning. In Handbook of Contemporary Developments in World Ecology. E.J. Kormondy and J.F. McCormick (editors). Greenwood Press, Westport, Connecticut. p.665-699.

Sidhu, S.S. and Case, A.B.
1977. A bibliography on the environmental impact of forest resource roads: a list. Information Report N-X-149. Newfoundland Forest Research Centre, St. Johns. 28 p.

Sierra Cooperative Pilot Project
1978. Soil nutrients. In The Sierra ecolgy project. volume 1. Engineering and Research Center, U.S. Bureau of Reclamation, Denver. p. III-40 - III-47.

Skopil, O.R.
1977. Siuslaw decision, opinion of Judge Otto R. Skopil in the Unites States District Court for the District of Oregon. Citizens Against Toxic Sprays, Inc., plaintiffs vs. Bob Berglund, Secretary, U.S. Department of Agriculture . . . Defendants Industrial Forestry Assoc., Defendant - Intervenda. Portland, Oregon. 60p.

Smayda, T.J.
1970. The suspension and sinking of phytoplankton in the sea. In Oceanography and marine biology: an annual review. H. Barnes (editor). 8:353-414.

Smith, G., Van Gorkan, K., Dyer, A.A. et al.
1973. Colorado environmental data systems. final report. College of Forestry and Natural Resources, Colorado State University, Fort Collins.

Smith, J.H.G., Walters, J. and Kozak, A.
1968. Influences of fertilizer on cone production and growth of young douglas fir, western hemlock and western red cedar on the U.B.C. Research Forest. University of British Columbia Faculty of Forestry Bulletin 5. p. 1-57.

Smith, N.D.
1978. Sedimention processes and patterns in a glacier-fed lake with low sediment input. Canadian Journal of Earth Sciences 15:741-756.

Smith, N.D.
1981. The effects of changing sediment supply on sedimentation in a glacier-fed lake. Artic and Alpine Research 13(1):75-82.

Smith, R.A.
1980. The theoretical basis for estimating phytoplankton production and specific growth rate from chlorophyll, light and temperature data. Ecological Modelling 10:243-264.

Smith, R.C., Tyler, J.E. and Goldman, C.R.
1973. Optical properties and color of Lake Tahoe and Crater Lake. Limnology and Oceanography 18(2):189-199.

Smith, R.F. and Ludwig, H.F.
1968a. Eutrophication mechanisms at Lake Tahoe-I. Source of an exogenous Spirogyra bloom on the South Shore, January 1967. Water Research 2:615-624.

Smith, R.F. and Ludwig, H.F.
1968b. Eutrophication mechanisms at Lake Tahoe-II. Source of an endogenous Ulothrix bloom on the South Shore, July 1969. Water Research 2:625-630.

Stamp, L.D.
1961. A glossary of geographical terms. John Wiley and Sons, New York. 539p.

Stangenberger, A.G.
1979. a simulation of nutrient cycling in red fir (Abies magnifica A. Murr.) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) forests. Ph.D. Thesis in Wildland Resource Science, University of California, Berkeley. 192p.

Stark, N.
1973. Nutrient cycling in a jeffrey pine ecosystem. Institute for microbiology, Univeristy of Montana, Missoula. 89p.

Stark, N. and Zuuring, H.
1981. Predicting the nutrient retention capacities of soils. Soil Science. 131(1):9-19.

Statham, I.
1977. Earth surface sediment transport. Clarendon Press, Oxford. 184p.

Steele, J.H.
1962. Environmental control of photosynthesis in the sea. Limnology and Oceanography 7:137-150.25Steinitz, C., Parker, P. and Jordan, L.
1976. Hand-drawn overlays: their history and prospective uses. Landscape Architecture 66(5):444-455.

Steward, K.M. and Rholich, G.A.
1967. Eutrophication: a review. California Water Quality Control Board, Sacramento. 188p.

Stiell, W.M.
1966. Red pine crown development in relation to spacing. Canada, Department of Forestry and Rural Development. Departmental Publication 1156. Ottawa. 44p.

Strand, R.F. and Rottink, B.A.
1976. Western hemlock foliage analyses of Crown Zellerbach fertilizer trials (personal communication cited by van den Driessche).

Strandberg, C.H.
1968. The sensation of color. In Manual of Color Aerial Photography First Edition. J.T. Smith (editor). American Society of Photogrammetry, Falls Church, Virginia. p. 3-11.

Studier, D.D. and Binkley, V.W.
1974. Cable logging systems. USDA Forest Service Pacific Northwest Region, Portland, Oregon. 205 p.

Sundborg, A.
1956. The river Klaralven: a study of fluvial processes. Geografiska Annaler 38:127-316.

Suter, G.W.
1981. Ecosystem theory and NEPA Assessment. Bulletin of the Ecological Society of America. 62(3):186-192.

Swank, W.T. and Wade, J.B.
1980. Interpretation of nutrient cycling research in a management context: evaluating potential effects of alternative management strategies on site productivity. In Forests: fresh perspectives from ecosystem analysis. Proceedings of the 40th Annual Biology Colloquium. R.H. Waring (editor). Oregon State University Press, Corvallis. p.137-157.

Swartzman, G.L.
1979. Comparison of plankton simulation-models emphasizing their applicability to impact assessment. Journal of Environmental Management 9(2):145-163.

Tahoe Regional Planning Agency
1971. Guidelines for planning series. South Lake Tahoe, California.

Tahoe Regional Planning Agency
1971a. Limnology and water quality of the Lake Tahoe Region. A Guide for Planning Series. South Lake Tahoe, California. 13p.

Tahoe Regional Planning Agency
1971b. Climate and air quality of the Lake Tahoe Region. Guide for Planning series. South Lake Tahoe, California. 31p.

Tahoe Regional Planning Agency
1971c. Hydrology and water resources of the Lake Tahoe Region. A Guide for Planning Series. South Lake Tahoe, California. 24p.

Tahoe Research Group
1975. Tahoe's troubled waters. Natural History 84(1):60-67.

Tarrant, R.F., Isaac, L.A. and Chandler, R.F.
1951. Observations on litter fall and foliage nutrient content of some Pacific Northwest tree species. Journal of Forestry 49:914-915.

Thie, J. and Ironside, G. (editors)
1976. Ecological (Biophysical) Land Classification in Canada. Proceedings of the first meeting Canada Committee on Ecological (Biophysical) Land Classification. Ecological Land Classification Series 1. Lands Directorate, Environment Canada, Quebec. 269 p. (Petawawa, Ontario, May 1976)

Thomas, J.M. and Eberhardt, L.L.
1975. Ecological impact assessment. Report number CONF-750706-9. Bastelle Pacific Northwest Laboratory, Richland, Washington. 17p.

Thomson, K.P.B. and Jerome, J.
1975. In situ colour measurements on the Great Lakes. International Association of Theoretical and Applied Limnology. Transactions 19(part 1):158-167.

Thomson, K.P.B. and Jerome, J.
1975. In situ colour measurements on the Great Lakes. Scientific Series 51. Environment Canada, Ottawa. 11p.

Thomson, K.P.B., Jerome, J. and McNeil, W.R.
1975. Optical properties of the Great Lakes. In Proceedings, seventeenth conference on Great Lakes research. part 2. International Association for Great Lakes Research. p.811-822. (Hamilton, Ontario, August 1974.)

Thurow, L.C.
1979. Zero-sum society: distribution and the possibility of economic change. Basic Books, New York.

Tilzer, M.M., Goldman, C.R. and de Amezaga, E.
1975. The efficiency of photosynthetic light energy utilization by lake phytoplankton. International Association of Theoretical and Applied Limnology. Transactions 19(part 2):800-807.

Tilzer, M.M., Goldman, C.R. and Richards, R.C.
1976. Influence of sediment inflow on phytoplankton primary productivity in Lake Tahoe (California-Nevada) Internationale Revue de Gesamten Hydrobiologie 61(2):169-181.

Tilzer, M.M. and Horne, A.J.
1979. Diel patterns of phytoplankton productivity and extracellular release in ultra-oligotrophic Lake Tahoe. Internationale Revue de Gesamten Hydrobiologie 64(2):157-176.

Todd, K.T. (editor)
1970. The water encyclopedia. Water Information Center, Port Washington, New York. 559p.

Triska, F.J. and Cromack, K.
1979. The role of wood debris in forests and streams. In Forests; fresh perspectives from ecosystem analysis. Proceedings of the 40th Annual Biology Colloquium. R.H. Waring (editor). Oregon State University Press, Corvallis. p.171-190.

Tyler, J.
1968. The Secchi Disk. Limnology and Oceanography 13(1):1-6.

U.S. Department of Agriculture
1968. Snow avalanches. A handbook for forecasting and control measures. Agriculture Handbook 194. Washington, D.C. 68p.

U.S. Department of Interior Geological Survey and US Department of Housing and Urban Development
1971. San Francisco Bay Region environment and resources planning study. Washington, D.C. 123p.

U.S. Department of Interior
1973. Lake Tahoe--a special place. Washington, D.C. 28p.

U.S. Environmental Protection Agency
1974. The Lake Tahoe study . . . as requested by the 92nd Congress in section 14 of the Federal Water Pollution Control Act Amendments of 1972. Washington, D.C. 141p.

U.S. Federal Water Pollution Control Administration
1966. A guide to the common diatoms of water pollution surveillance system stations. Cincinnati, Ohio. 101p.

U.S. Forest Service California Region
1978. Lake Tahoe Basin Management Unit land management plan--part 1. San Francisco, California. 91p.

U.S. Forest Service Region 5
See U.S. Forest Service California Region

U.S. Forest Service
1966. Handbook on soils. FSH/2559.2. USDA Forest Service, Washinton, D.C. 372p.

U.S. Soil Conservation Service
1970. Lake Tahoe Basin snowload zones map. Portland, Oregon. (folded map with text).

U.S. Soil Survey Staff
1951. Soil survey manual. U.S. Department of Agriculture Handbook 18. USGPO, Washington, D.C. 503p.

University of California Agricultural Extension Service.
1967. Climate of Placer County: agriculture-climate soil, water production. Berkeley. 107p.

University of Washington, Department of Civil Engineering
1977. Regional environmental systems: assessment of RANN projects. Seattle. 408p.

Utzig, G. and Herring, L.
1975. Forest harvesting impacts at high elevations five case studies. Research Note 72. British Columbia Forest Service, Victoria. 85 p.

Vallentyne, J.R., Johnson, W.E. and Harris, A.J.
1970. A visual demonstration of the beneficial effects of sewage treatment for phosphorus removal on particulate matter production in waters.1

van den Driessche, R.
1976. Mineral nutrition of western hemlock. In Proceedings Western Hemlock Management conference. W.A. Atkinson and R.J. Zasoski (editors). Institute of Forest Products Contribution 34. University of Washington, Seattle. p.56-70.

Van Dyne, G.M. and Abramsky, Z.
1975. Agricultural systems models and modelling: an overview. *In Study of agricultural systems*. G.E. Dalton (editor). Applied Science Publishers, London. p.23-106.

Van Wagner, C.E.
1965. The effect of the earth's curvature in visibility mapping. *Fire Control Notes* 26(4):10-11.

Varnes, D.J.
1978. Slope movement and types and processes. *In Landslides: analysis and control*. Transportation Research Board Special Report 176. National Academy of Sciences, Washington, D.C. p. 11-33.

Vitousek, P.M., Gosz, J.R., Grier, C.C., Melillo, J.M., Reiners, W.A., and Todd, R.L.
1979. Nitrate losses from disturbed ecosystems. *Science* 204:469-474.

Vitousek, P.M. and Melillo, J.M.
1979. Nitrate losses from disturbed forests: patterns and mechanisms. *Forest Science* 25(4):605-619.

Vitousek, P.M. and Reiners, W.A.
1975. Ecosystem succession and nutrient retention: a hypothesis. *Bioscience* 25(6):376-381.

Wallace-McHarg Associates
1963. *A plan for the valleys*. Green Spring and Worthington Valley Planning Council, Towson, Maryland. 63p.

Wallace, McHarg, Roberts and Todd
1972. *Amelia Island, Florida: a report on the master planning process for a new recreational community*. Sea Pines Plantation, Hilton Head Island, South Carolina. 56p.

Waring, R.H., Emmingham, W.H., Gholz, H.L., and Grier, C.C.
1978. Variation in maximum leaf area of coniferous forests in Oregon and its ecological significance. *Forest Science* 24:131-140.

Wehde, M.E.
1979. *Impact of cell size on inventory and mapping errors in a cellular geographic information system*. Interim Technical Report SDSU-RSI-79-03. Remote Sensing Institute, South Dakota State University, Brookings. 87p.

Welch, P.S.
1952. *Limnology*. McGraw-Hill Books, New York. 538p.

Welch, R.I.
1971. Lake Tahoe study In The use of multiband aerial photography in water resource management. Ph.D. Dissertation, University of California, Berkeley. p.104-120.

Western Federal Regional Council
1979. Lake Tahoe environmental assessment. Washington, D.C. 240p.

Wetzel, R.G.
1975. Limnology. W.B. Saunders, Philadelphia. 743p.

WFRC
see Western Federal Regional Council.

White, S.E.
1981. Alpine mass movement forms (noncatastrophic): classification, description and significance. Arctic and Alpine Research 13(2):127-137.

Wilen, B.O.
1975. Application of research on organic coloring matter. Watershed Management Symposium Proceedings. American Society of Civil Engineers, New York, NY. p 111-123. (Logan, Utah, August 1975.)

Wilson, A.G.
1974. Urban and regional models in geography and planning. John Wiley and Sons, New York. 418p.

Woodmansee, R.G.
1974. Glossary of systems ecology terms. International Biological Program. Grassland Biome (U.S.) Technical Report 256. Colorado State University, Natural Resource Ecology Laboratory, Fort Collins. 32p.

Yeilding, L. and Schwarz, C.
1978. Ecologic modeling bibliography. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley. 350p. (unpublished manuscript)

Yura, H.T.
1971. Small-angle scattering of light by ocean water. Applied Optics 10:114-118.

Zinke, P.J.
1963. Tree analysis to determine nutrient status. In Proceedings, Fourth California Forest Soil Fertility Conference. p. 30-44.

Zinke, P.J.
1981. Probability distributions of elemental quantities in hemlock foliage. (unpublished paper presented at Western Hemlock Workshop, Pack Forest, La Grande, Washington, October 16, 1981.)

Zinke, P.J. and Stangenberger, A.
1974a. Lake Tahoe soils. California Agricultural Experiment Station Projects 1762, 2595, 2937. Environmental microfiche data base catalog numbers 9.1-9.5 (1 microfiche, 232 frames)

Zinke, P.J. and Stangenberger, A.
1974b. Lake Tahoe Soil Conservation Service soil data. California Agricultural Experiment Station Projects 1762, 2595, 2937. Environmental microfiche data base catalog number 9.7 (1 microfiche, 247 frames)

Zinke, P.J. and Stangenberger, A.
1975. Lake Tahoe vegetation. California Agricultural Experiment Station Projects 1762, 2595, 2937. Environmental microfiche data base catalog number 9.8 (1 microfiche, 104 frames)

Zinke, P.J. and Stangenberger, A.
1979. Ponderosa pine and douglas-fir foliage analyses arrayed in probability distributions. In Proceedings Forest Fertilization Conference. College of Forest Resources, University of Washington, Seattle. p. 221-225 (Union, Washington, September 1979).

Zinke, P.J., Stangenberger, A. and Colwell, W.
1979. The fertility of the forest. In California Agriculture 33:11

APPENDIX A

SUPPLEMENTARY INFORMATION FOR CHAPTER 11

NUTRIENT QUANTITIES ON WATERSHED SITES

Forest Biomass Estimation

Biomass Per Tree

To calculate the biomass per tree of each species I use the U.S. Forest Service timber inventory rule-of-thumb that crown diameter (feet) is approximately equal to stem diameter (inches) at breast height (DBH).* The validity of this assumption is important because I chose biomass estimation equations with DBH as the independent variable. Other independent variables commonly used in biomass regression equations are tree height and tree canopy length, but information on those variables is more difficult to estimate from the vegetation cover data. Many factors may effect DBH-crown diameter relationships. Stand density affects the crown diameter of some species (red fir, Stiell 1966), but not others (lodgepole pine (LP), Bonnor 1964). Tree height is a better predictor variable of crown diameter than DBH for conifers smaller than 8.9 cm DBH (Moeur 1981 p. 3). However, only one of the 68 forest cover types (Number 54) is of this small size. For larger trees, Moeur's results (1981 p. 4-5) show that DBH is a much stronger predictor of the crown diameter (and

---

* Philip Aune, Tahoe National Forest Timber Management Officer (personal communication) and Frank Dufor, Stanislaus National Forest.

Table A1. Legend for Tree Species, Size and Density Map

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
1. a. b. c. d.	6.1 5.3 17.8 3.6 32.8	GL	predominantly grass; tree canopy cover less than 10% of area	not applicable	not applicable
2. a. b.	6.4 6.9 13.3	LP2P	predominantly lodgepole pine (*P. contorta var. murrayana*); no other tree species comprises 10% of crown area	1.8 - 3.8m	20 - 39%
3.	22.3	LP2S	same	same	less than 20%
4. a. b. c.	6.0 14.2 1.2 21.4	LP3G	same	3.8 - 7.5m	greater than 70%
5. a. b. c. d. e. f.	8.5 8.5 22.3 10.5 4.9 4.0 58.7	LP3N	same	same	40 - 69%
6. a. b. c. d. e. f. g. h.	2.4 10.1 5.7 3.2 22.7 4.0 7.3 1.5 56.9	LP3P	same	same	20 - 39%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
7. a. b.	5.3 12.5 17.8	LP3S	same	same	less than 20%
8. a. b.	16.2 12.5 28.7	LP3S /SR	predominantly lodgepole pine; no other tree species comprises 10% of crown cover; riparian	same	less than 20%
9.	15.0	LPPP3N	predominantly lodgepole pine; jeffrey pine comprises at least 10% of the tree crown area	same	40 - 69%
10.	1.2	LPRF3N	predominantly lodgepole pine; red fir (Abies magnifica) comprises at least 10% of tree crown area	same	same
11.	2.4	LPRF3P	same	same	20 - 39%
12. a. b.	17.4 3.6 21.0	MH2N	predominantly mountain hemlock (Tsuga mertensiana); no other tree species comprises 10% of crown area	1.8 - 3.8m	40 - 69%
13.	6.1	MH3P	same	3.8 - 7.5m	20 - 39%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
14.	15.4	MHLP2P	predominantly mountain hemlock; lodgepole pine comprises at least 10% of crown area	1.8 - 3.8m	same
15.	3.6	MHLP3N	same	3.8 - 7.5m	40 - 69%
16. a.	188.6	NB	barren areas; less than 10% of area covered by plants	not applicable	not applicable
b.	6.9				
c.	8.1				
d.	120.2				
e.	5.7				
f.	8.9				
g.	65.6				
	404.0				
17. a.	11.3	ND	urban development area	not applicable	not applicable
b.	26.3				
c.	19.8				
d.	17.4				
	74.8				
18.	21.4	PP3P	predominantly jeffrey pine (P. jeffreyi); no other species comprises 10% of canopy cover	3.8 - 7.5m	20 - 39%
19.	4.9	PP4S /SR	same; riparian	7.5 - 12.2m	less than 20%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
20.	13.4	PP6G	predominantly jeffrey pine; no other species makes up 10% of tree canopy cover	two-storied canopy overstory 7.5 - 12.2m understory 1.8 - 3.8m	overstory comprises 10 - 20% cf crown area total Cover density of understory at least 70%
21.	4.9	PPLP4N	predominantly jeffrey pine; lodgepole pine is at least 10% of tree crowns	7.5 - 12.2m	40 - 69%
22. a. b.	34.4 2.8 37.2	PPRF4P	predominantly jeffrey pine; red fir comprises at least 10% of tree crown area	same	20 - 39%
23.	9.3	PPWF2P	predominantly ponderosa pine; white fir (Abies concolor) comprises at least 10% of tree canopy cover	1.8 - 3.8m	same
24.	10.5	PPWF2S /NG a	same; grass, herbaceous plant groundcover	same	less than 20%
25. a. b.	32.4 15.8 48.2	PPWF3G	predominantly ponderosa pine; white fir comprises at least 10% of tree canopy cover	3.8 - 7.5m	greater than 70%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
26. a	19.0	PPWF3N	same	same	40 - 69%
b.	17.8				
c.	38.9				
d.	13.6				
e.	12.1				
f.	10.1				
g.	11.7				
h.	20.8				
	144.0				
27. a.	4.0	PPWF3P	same	same	20 - 39%
b.	12.1				
c.	26.3				
	42.4				
28.	7.3	PPWF3Sa	same	same	less than 20%
29. a.	14.2	PPWF4G	same	7.5 - 12.2m	greater than 70%
b.	4.9				
c.	21.0				
	40.1				
30. a.	23.9	PPWF4N	same	same	40 - 69%
b.	8.5				
c.	16.2				
d.	16.2				
	64.8				
31. a.	10.9	PPWF4P	same	same	20 - 39%
b.	1.2				
d.	4.5				
	16.6				

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
32.	13.0	PPWF4S	same	same	less than 20%
33.	4.9	RF2N	predominantly red fir; lodgepole pine comprises at least 10% of the tree crown area	1.8 - 3.8m	40-69%
34. a. b. c. d.	6.1 4.6 6.5 4.5 21.7	RF3G	same	3.8 - 7.5m	greater than 70%
35. a. b. c. d. e. f. g. h.	1.6 4.0 2.8 4.0 17.8 6.1 7.3 7.3 50.9	RF3N	same	same	40 - 69%
36.	67.2	RF4G	same	7.5 - 12.2m	greater than 70%
37. a. b.	10.9 5.7 16.6	RF4N	same	same	40 - 69%
38.	6.9	RF4P	same	same	20 - 39%
39.	7.3	RF4P /SR	same; riparian	same	same

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
40.	2.4	RF4S	predominantly red fir; lodgepole pine comprises at least 10% of the tree crown area	same	less than 20%
41.	16.2	RFLP3G	predominantly red fir; lodgepole pine comprises at least 10% of the tree crown area	3.8 - 7.5m	greater than 70%
42. a. b.	10.1 23.1 33.2	RFLP3N	same	same	40 - 69%
43.	8.5	RFMH2P	predominantly red fir; mountain hemlock comprises at least 10% of the tree crown area	1.8 - 3.8	20 - 39%
44. a. b.	10.9 35.6 46.5	RFMH3G	same	3.8 - 7.5m	greater than 70%
45.	9.3	RFMH3P	same	same	20 - 39%
46.	11.3	RFPP3N	predominantly red fir; ponderosa pine comprises at least 10% of the tree crown area	same	40 - 69%
47.	12.5	RFPP4N	same	7.5 - 12.2m	same
48.	45.3	RFPP4P	same	same	20 - 39%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
49. a. b.	3.2 2.8 6.0	RFWF4G	predominantly red fir; white fir comprises at least 10% of the tree crown area	same	greater than 70%
50.	17.4	RFWF4N	same	same	40 - 69%
51. a. b.	17.8 6.9 24.7	RFWP3P	predominantly red fir; western white pine (*P. monticola*) comprises at least 10% of the tree crown area	3.8 - 7.5m	20 - 39%
52.	29.1	RFWP4N	same	7.5 - 12.2m	40 - 69%
53. a. b. c. d. e. f. g.	10.5 11.3 4.9 7.3 8.0 3.6 5.3 50.9	SR	riparian, stream-side or bordering wet meadows	?	?
54.	7.7	WF1N	predominantly white fir; no other tree species comprises 10% of tree crown area	1.8m or smaller	40 - 79%
55. a. b.	12.1 4.9 17.0	WF2N	same	1.8 - 3.8m	same
56.	6.5	WF2P	same	same	20 - 39%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
57.	8.5	WF2S	same	same	less than 20%
58. a. b. c. d.	3.6 6.5 7.7 6.1 23.9	WF3G	same	3.8 - 7.5m	greater than 70%
59. a. b. c. d. e. f.	29.9 12.5 4.0 12.1 8.9 5.3 72.7	WF3N	same	same	40 - 69%
60. a. b. c.	21.0 7.3 4.0 32.3	WF3P	same	same	20 - 39%
61.	2.0	WF3S /SM	same; montane brush ground cover	same	less than 20%
62.	20.2	WF3S /SR	predominantly white fir; no other tree species comprises 10% of the tree crown area; riparian	same	same

Table Al. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
63.	8.9	WF4N	predominantly white fir; no other tree species comprises 10% of the tree crown area	7.5 - 12.2m	40 - 69%
64.	8.9	WFPP2P	predominantly white fir; ponderosa pine comprises at least 10% of the tree crown area	1.8 - 3.8m	20 - 39%
65. a. b. c. d. e.	65.6 9.7 55.8 38.9 39.3 209.3	WFPP3G	same	3.8 - 7.5m	greater than 70%
66. a. b. c. d. e. f. g. h. i.	7.3 10.9 17.4 18.6 11.3 15.0 16.2 7.3 12.1 116.1	WFPP3N	same	same	40 - 69%
67. a. b. c. d.	27.9 22.3 10.1 13.0 73.3	WFPP3P	same	same	20 - 39%
68.	8.1	WFPP3S /SR a	same; riparian	same	less than 20%

Table A1. Legend for Tree Species, Size and Density Map--continued

Map Symbol	Area (ha)	Type Label	Species Composition	Crown Diameter's Size Class	Canopy Cover Density
69. a. b.	8.9 24.7 33.6	WFPP4G	predominantly white fir; ponderosa pine comprises at least 10% of the tree crown area	7.5 - 12.2m	greater than 70%
70. a. b.	10.5 8.9 19.4	WFPP4N	same	same	40 - 69%
71.	9.3	WFPP4P	same	same	20 - 39%
72.	5.3	WFRF3N	predominantly white fir; red fir comprises at least 10% of the tree crown area	3.8 - 7.5m	40 - 69%
TOTALS 169 map units	2444.4 ha	19 tree species combinations			

---

[a] A conflict exists between the meanings of these coding symbols. They mean that at least 10% of crown area is occupied by less abundant of the species and yet that total canopy density is less than 20%.

Table A2. Equations for Estimating Tree Biomass[1]

Species Portion of Tree	Biomass (oven-dry wt) (kg) Diameter at Base Height (cm)	Sample	
		dbh range (cm)	size
Abies concolor (white fir) & A. magnifica (red fir)			
foliage	$\ln Y = -3.4662 + 1.9278 \ln dbh$	8.7-111.0	25^a
live branches	$\ln Y = -4.8287 + 2.5585 \ln dbh$	8.7-111.0	26^b
stem wood	$\ln Y = -3.7389 + 2.6825 \ln dbh$	8.7-111.0	20^c
stem bark	$\ln Y = -6.1918 + 2.8796 \ln dbh$	8.7-111.0	20^c
Pinus contorta (lodgepole pine)			
foliage	$\ln Y = -3.6187 + 1.8362 \ln dbh$	2.5-28.7	19^d
live branches	$\ln Y = -4.6004 + 2.3533 \ln dbh$	2.5-28.7	19^c
stem wood & bark	$\ln Y = -2.9849 + 2.4287 \ln dbh$	2.5-28.7	19^c
stem bark	$\log Y = 3.025 + 2.207 \log dbh^e$	10.0-32.0	13^f
stump & roots	$\log Y^g = -1.88 + 1.0221 \log(dbh^h)^2 ht^i$	10.0-33.5	85^j
roots	$\log Y^g = -2.1045 + 1.0704 \log(dbh^h)^2 ht^i$	10.0-33.5	85^j
Pinus jeffreyi (jeffrey pine) & P. ponderosa			
foliage	$\ln Y = -4.2612 + 2.0967 \ln dbh$	15.5-79.5	9^a
new foliage	$\ln Y = -6.3022 + 2.300 \ln dbh$	15.5-79.5	9^c
live branches	$\ln Y = -5.3855 + 2.7185 \ln dbh$	15.5-79.5	9^c
dead branches	$\ln Y = -2.5766 + 1.444 \ln dbh$	15.5-79.5	9^c
stem wood	$\ln Y - -4.4907 + 2.7587 \ln dbh$	15.5-79.5	9^c
stem bark	$\ln Y = -4.2063 + 2.2312 \ln dbh$	15.5-79.5	9^c

Table A2. Equations for Estimating Tree Biomass (continued)

Species Portion of Tree	Biomass (oven-dry wt) (kg)	Diameter at Base Height (cm)	Sample	
			dbh range (cm)	size
Tsuga mertensiana	(mountain hemlock)			
foliage	$\ln Y = -3.8169 + 1.9756 \ln dbh$		17.0-76.2	11[a]
live branches	$\ln Y = -5.2581 + 2.6045 \ln dbh$		17.0-76.2	11[k]
dead branches	$\ln Y = -9.9449 + 3.2845 \ln dbh$		17.0-54.6	6[c]
stem wood	$\ln Y = -4.8464 + 2.9308 \ln dbh$		17.0-76.2	14[c]
stem bark	$\ln Y = -5.5868 + 2.7654 \ln dbh$		17.0-76.2	14[c]

a. Waring et al. 1978.

b. Gholz et al. 1979 citing Krumlik 1974, Fujumori et al. 1976 and Satoo 1974.

c. Gholz et al. 1979.

d. Reid et al. 1974.

e. Dbh units are meters.

f. Kimmins 1974.

g. Biomass units are pounds.

h. Dbh units are inches.

i. Height units are feet.

j. Johnstone 1970.

k. Gholz et al. 1979 citing Krumlik 1974.

l. The correlation coefficients of all the equations are high (20 of 21 range from .84 to .99) and statistically significant.

the reverse, as well) of western white pine (WP), western hemlock, LP, and ponderosa pine (PP) than canopy length or tree height. While DBH-crown diameter relationship is undoubedly more complex than the rule-of-thumb, its simplicity, general validity and wide usage makes it adequate for my estimation purposes.

Whole tree biomass regression equations are rarer than those for different portions of individual trees--foliage, branches, trunk wood, trunk bark, roots. Separate estimates of the biomass and nutrients in portions of trees is useful because: results are more accurate and understandable when not aggregated; nutrient content information is more readily available and dependable for parts than for whole trees (e.g., nutrient content of branch wood and bark is significantly higher than for trunks; Appendix Table A3); and feasible nutrient management options are very different for foliage and branches than for trunk wood and bark.

I limit my calculations to the above-ground portion of biomass because harvesting the stump root biomass is probably an economically infeasible nutrient management option which would cause more environmental quality damage than protection. Roots and stumps may contain 20 percent of the biomass of whole trees (Young, 1977 p. 8) and may be more important than litter fall in placing nutrients in soils (Swank and Wade, 1980 p. 143). Thus they are not inconsequential and contain a mass of site nutrients not included in my estimation of either soil or biomass nutrients. Their mangement objectives and options are clearly the same as those of soil nutrient stocks.

I did not locate a matched pair of equations for lodgepole pine trunk bark and wood which use DBH as the independent variable. Subtracting the results of the LP stem bark equation of Kimmins (1974)

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
a. Pinus ponderosa (PP) and P. jeffreyi (JP)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
foliage					
	0.668	5	0.160	10	JP 0-1yr old needles, 3/70 Stark 1973 p261
	0.916	5	0.134	10	JP 0-1yr 3/71
	1.124	5	0.054	10	JP 0-1yr 3/72
	1.091	5	0.123	10	JP 0-1yr 6/70
	1.137	5	0.129	10	JP 0-1yr 6/71
	1.275	5	0.085	10	JP 0-1yr 6/72
	1.149	5	0.149	10	JP 0-1yr 9/70
	1.268	5	0.183	10	JP 0-1yr 9/71
	1.030	5	0.117	10	JP 0-1yr 12/70
	1.209	5	0.138	10	JP 0-1yr 12/71
a	1.98	4	0.174	4	JP Ward Creek Zinke & Stangenberger 1975
	1.48	2	0.191	2	PP 0-1yr old needles Clayton & Kennedy 1980
	1.58	2	0.136	2	PP 1-2
	1.60	2	0.151	2	PP 2
a	1.07	78	0.126	78	PP 0-1yr old needles Zinke et al. 1979
	1.07	27	0.111	27	PP 0-1yr old needles Zinke 1963
	1.06	25	0.057	26	PP 1-2
a	1.08	10	0.087	10	PP 1-2 Zinke et al. 1979
	0.95	24	0.049	25	PP 2-3 Zinke 1963
	0.84	21	0.048	21	PP 3-4
	0.71	9	0.045	9	PP 4-5
	0.64	4	0.066	4	PP 5-6
	0.65	1	0.026	1	PP 6-7
	1.141		0.131		PP 0-1yr, granite & rhyolite Powers 1981
	1.231		0.121		PP 0-1yr, basalt soil parent material p 153
	1.024		0.114		PP 0-1yr, metamorphic
	0.947		0.134		PP 0-1yr, sedimentary
	0.921	12	0.117	12	PP 0-1yr p 160
	1.173	142	0.119	142	PP 0-1yr
	1.292	15	0.096	15	PP 0-1yr
	0.744	3			PP 0-1yr

---

[a] These values are not included in the averages from this Table A3 used to calculate tree biomass nitrogen and phosphorus because they were located after I made all the calculations for other tables.

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
a. *Pinus ponderosa* (PP) and *P. jeffreyi* (JP) (continued)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
	1.63				PP 0-lyr, live p 129
	1.50				PP lyr, live
	0.73				PP old needles, dead
	———		———		MEANS
	1.103		0.132		JP new needles
	1.150		0.126		PP new needles
	1.065		0.072		PP old needles
bark	0.210	25	0.088	10	JP trunk, inner bark, 3/70 Stark 1973 p261
	0.366	25	0.103	10	JP trunk, inner bark, 3/71
	0.372	25	0.082	10	JP trunk, inner bark, 3/72
	0.297	25	0.070	10	JP trunk, inner bark, 6/70
	0.352	25	0.078	10	JP trunk, inner bark, 6/71
	0.357	25	0.071	10	JP trunk, inner bark, 6/72
	0.455	25	0.096	10	JP trunk, inner bark, 9/70
	0.366	25	0.088	10	JP trunk, inner bark, 9/71
	0.358	25	0.085	10	JP trunk, inner bark, 12/70
	0.355	25	0.102	10	JP trunk, inner bark, 12/71
a	0.36	4	0.033	4	JP trunk, Ward Cr. Zinke & Stangen. 1975
	0.734	2	0.033	2	PP trunk, surpressed tree Clayton & Kennedy 1980
	0.509	2	.01	2	PP trunk, dominant tree
	0.63				PP branch, new Powers 1981 p 131
	0.58				PP branch, old
	0.56				PP trunk
	0.12		0.003		PP trunk Bollen 1969
			0.020	25	PP trunk Zinke 1963
	———		———		MEANS
	0.481		0.017		PP trunk
	0.605				PP branch
	0.349		0.086		JP trunk, inner bark

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
a. Pinus ponderosa (PP) and P. jeffreyi (JP) (continued)

Portion of Plant	Nitrogen aver. value (%)	n	Phosphorus aver. value (%)	n	Notes and References
branches					
a	0.37	4	0.023	4	JP Ward Creek Zinke & Stangenberger 1975
wood	0.073	50	0.009	10	JP trunk, outer 10 cm 3/70 Stark 1973
	0.080	50	0.011	10	JP trunk, outer 10 cm 3/71 p 261
	0.079	50	0.014	10	JP trunk, outer 10 cm 3/72
	0.073	50	0.005	10	JP trunk, outer 10 cm 6/70
	0.078	50	0.019	10	JP trunk, outer 10 cm 6/71
	0.077	50	0.014	10	JP trunk, outer 10 cm 6/72
	0.089	50	0.012	10	JP trunk, outer 10 cm 9/70
	0.072	50	0.013	10	JP trunk, outer 10 cm 9/71
	0.093	50	0.009	10	JP trunk, outer 10 cm 12/70
	0.072	50	0.007	10	JP trunk, outer 10 cm 12/71
a	0.14	2	0.004	4	JP trunk, Ward.Cr. Zinke & Stangen. 1975
					Clayton & Kennedy 1980
	0.291	2	0.01	2	PP trunk, heart., surpressed tree, 30.5 cm dbh
	0.323	2	0.01	2	PP trunk, heart., intermediate, 48.3 cm dbh
	0.315	2	0.01	2	PP trunk, heart., dominant, 78.7 cm dbh
	0.524	2	0.01	2	PP trunk, sapwood, surpressed, 30.5 cm
	0.286	2	0.01	2	PP trunk, sapwood, intermediate, 48.3 cm
	0.304	2	0.01	2	PP trunk, sapwood, dominant, 78.8 cm
	0.149	24	0.014	24	PP trunk Zinke 1963
	0.28				PP trunk Powers 1981 p 132
	0.29				PP branch, young
	0.24				PP branch, old
			MEANS		
	0.079		0.011		JP trunk
	0.371		0.01		PP trunk, sapwood
	0.313		0.01		PP trunk, heartwood
	0.257		0.012		PP trunk, all wood
	0.265				PP branch

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
b. *Abies concolor* (white fir, WF) & *A. magnifica* (red fir, RF)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
foliage					
	1.374	32	0.116	32	WF Camino plantation Isik 1974 p 247
	1.413	32	0.115	32	WF Blodgett plantation p 248
	1.132	32	0.178	32	WF Hoopa plantation p 249
	1.245	15	0.092	15	WF Powers 1981 p 160
	1.65				WF 0-1yr old needles p 129
	2.51				WF 1yr old, live
	1.79				WF 1yr old, dead
a	1.48	6	0.090	6	WF Ward Creek Zinke & Stangenberger 1975
	0.710	21			RF 0-1yr old needles Stangenberger 1979 p76
	0.751	22			RF 1-2
	0.737	22			RF 2
					MEANS
	1.588		0.130		WF weighted mean, all needles
	0.733				RF weighted mean, all needles
bark	0.96				WF young branch Powers 1981 p 131
	0.80				WF old branch
	0.58				WF trunk
a	0.528	12	0.085	12	WF trunk, Ward Cr. Zinke & Stangen. 1975
	0.337	7			RF core ends, cambium Stangenberger 1979 p76
	0.240	5			RF inner bark
	0.158	5			RF outer bark
	0.150	8			RF dead bark
	0.155				RF value used in his model p 108
wood	0.58				WF young branch Powers 1981 p 132
	0.33				WF old branch
	0.20				WF trunk
a	0.203	10	0.004	12	WF trunk, Ward Cr. Zinke & Stangen. 1975

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
b. _Abies concolor_ (white fir, WF) & _A. magnifica_ (red fir, RF)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
	0.048	25			RF live wood Stangenberger 1979 p 76
	0.235	17			RF decomposing wood p 76, p 78
	0.300				RF branch wood & bark, model value p 108
	0.37		0.009		RF large undecomposed branch appendix p1A
branches					
a	0.55	6	0.042	6	WF Ward Creek Zinke & Stangenberger 1975

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
c. *Pinus contorta* (Lodgepole Pine, LP)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
foliage					
	1.348	80	0.165	80	LP 0-1 yr old needles DeByle 1980
	1.233	80	0.120	80	LP 1 yr
	0.978	80	0.145	80	LP 0-1 yr old terminal shoots
			0.165		LP Beaton et al. 1965
			0.105		LP older trees
a	2.01	6	0.108	6	LP 100 yr old Zinke & Stangenberger 1975
					MEAN
	1.291		0.139		LP needles, all ages
wood	0.558	80	0.090	80	LP bark & wood of 5 yr old seedling stems DeByle 1980
	0.48	80	0.11	80	LP root wood & bark of seedlings
a	0.14	4	0.003	5	LP 100 yr old Zinke & Stangenberger 1975 Ward Creek banks
bark					
a	0.75	5	0.038	5	LP 100 yr old Zinke & Stangenberger 1975
branches					
a	0.56	5	0.035	5	LP 100 yr old Zinke & Stangenberger 1975

Table A3. Nitrogen and Phosphorus Concentrations of Foliage Bark & Wood
d. *Tsuga mertensiana* (Mountain Hemlock, MH)

Portion of Plant	Nitrogen		Phosphorus		Notes and References
	aver. value (%)	n	aver. value (%)	n	
foliage					
	1.414		0.198		*T. canadensis* Stark 1973 p 260
	1.47	3	0.16	3	*T. heterophylla* (TH) van den Driessche 1976 0-1 yr old needles on 13 yr old trees
	1.23		0.14		TH 1 yr
a	1.15		0.09		TH 1-2 yr Zinke 1981
a	1.26		0.13		TH 0-1 yr
	1.17		0.16		TH 0-1 yr old needles on Beaton et al. 1965 60 yr old trees, February
	1.21		0.18		TH 1-2 yr
	1.22		0.18		TH 2-3 yr
	0.91		0.11		TH 0-1 yr, 140-150 yr old trees, April
	0.86		0.19		Th 0-1 yr, 8-185 yr old trees, August
	0.84		0.21		TH 1-2 yr
	0.88		0.22		TH 2-3 yr
	1.34		0.21		TH 12-17 yr old trees, November Baker 1969
	1.58		0.14		TH
	1.32		0.24		TH
	1.1		0.09		TH Smith et al. 1968
	1.36		0.17		TH unthinned stands Strand & Rottink 1976
	1.32		0.14		TH thinned, 30-40 yr old trees
					van den Driessche 1976 citing Webber 1973
	1.09		0.14		TH 0-1 yr old needles
	0.96		0.18		TH 1 yr, 15-20 yr old trees
	1.182		0.170		MEANS all species & needle ages
wood	0.13				Th trunk Ovington 1957

from the LP stem wood and bark equation of Gholz et al. (1979) produces improbably high proportions of stem bark to wood (Appendix Table A4). The regression equations of Kimmins and Gholz et al. are obviously incompatable; the equations of the former gave biomass values 2-4 times those of Gholz and much higher than obtained for the other species. Bark as a proportion of stem biomass weight was consistently greater using the equation of Kimmins than the proportion indicated for this species by Brickel (1970) and Lange (1971). Therefore I estimated LP trunk bark biomass by using the percentage of bark in PP stems for corresponding trunk sizes. These figures for the separate weight of bark and of wood on individual different-sized LP trees are used in appendix Table A5 to calculate the biomass per hectare of those materials.

Biomass Per Hectare

Using interpretations derived from the vegetation cover mapping specification, I estimate the number of trees per hectare for stands of each crown size and canopy density (Appendix Table A6). To develop that information, I assume that whole forest type units are of the predominate crown diameter for that type and determine how many crowns of different sizes cover a hectare. Such average-tree approaches to biomass estimation are not nearly as accurate as those obtained by discrete treatment of the different size classes in a mixed stand (Dice, 1970 p. 8-10, Baskerville, 1965)--information not available for the Tahoe Vegetation Cover maps. However, average-tree approaches are useful when only a rough estimate of total biomass is desired (Baskerville 1965)--as for the purposes of this chapter. For comparison purposes, the four right columns in Appendix Table A6

Table A4. Tree Species Biomass by DBH and Portions of Plant

Species	DBH	Foliage		Branches			Stem Wood	Stem Bark and Wood	Stem Bark	Stump and Roots
	(cm)	new (kg)	total (kg)	live (kg)	dead (kg)	total (kg)	(kg)	(kg)	(kg)	
Abies concolor & *Abies magnifica*	6.4									
	22.9		13.0	24.0			105		16.8	
	47.0		52.2	152			726		133	
	82.6		154.7	641			3292		676	
Pinus contorta	22.9		8.39	15.9				101	50.8	
	47.0		31.5	86.4				581	200	
	82.6		88.6	325				2283	694	
Pinus ponderosa & *Pinus jeffreyi*	22.9	2.45	9.97	22.7	6.97	29.6	62.9		16.0	
	47.0	12.8	45.2	161	19.7	181	459		80.1	
	82.6	46.9	147	744	44.5	788	2173		282	
Tsuga mertensiana	22.9		10.6	18.0	1.40	19.4	77.8		21.5	
	47.0		44.2	118	14.9	133	643		158	

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH	foliage		branches		stem wood		stem bark	
			(cm)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
2 LP2P 479	LP 29.5%	479	22.9	8.4	4024	15.9	7616	79.3	37985	21.7	10394
3 LP2S 244	LP 15%	244	22.9	8.4	2050	15.9	3880	79.3	19349	21.7	5295
4 LP3G 399	LP 85%	399	47.0	31.5	12589	86.4	34474	495	197505	86.0	34314
5 LP3N 217	LP 54.5%	217	47.0	31.5	6836	86.4	18749	495	107415	86.0	18862
6 LP3P 118	LP 29.5%	118	47.0	31.5	3717	86.4	10195	495	58410	86.0	10148
7 LP3S 60	LP 15%	60	47.0	31.5	1890	86.4	5184	495	29700	86.0	5160
8 LP3S/SR 60	LP 15%	60	47.0	31.5	1890	86.4	5184	495	29700	86.0	5160
9 LPPP3N 217	LP 44.5%	177	47.0	31.5	5576	86.4	15293	495	87615	86.0	15222
	PP 10%	40	47.0	45.2	1808	181	7240	459	18360	80.1	3204

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH	foliage		branches		stem wood		stem bark	
			(cm)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
10 LPRF3N 217	LP 44.5%	177	47.0	31.5	5576	86.4	15293	495	87615	86.0	15222
	RF 10%	40	47.0	52.2	2088	152	6080	726	29040	134	5360
11 LPRF3P 118	LP 19.5%	78	47.0	31.5	2457	86.4	6739	495	38610	86.0	6708
	RF 10%	40	47.0	52.2	2088	152	6080	726	29040	134	5360
12 MH2N 885	MH 54.5%	885	22.9	10.6	9381	19.4	17169	77.8	68853	21.5	19028
13 MH3P 118	MH 29.5%	118	47.0	44.2	5216	133	15694	643	75874	158	18644
14 MHLP2P 479	MH 19.5%	317	22.9	10.6	3360	19.4	6150	77.8	24663	21.5	6816
	LP 10%	162	22.9	8.4	1361	15.9	2576	79.3	12847	21.7	3515
15 MHLP3N 217	MH 44.5%	177	47.0	44.2	7823	133	23541	643	113811	158	27966
	LP 10%	40	47.0	31.5	1260	86.4	3456	495	19800	86.0	3440

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
18 PP3P 118	PP 29.5%	118	47.0	45.2	5334	181	21358	459	54162	80.1	9452
19 PP45/SR 26	PP 15%	26	82.6	147	3822	788	20488	2173	56498	282	7332
20 PP6G 1195	PP 12.8%	22	82.6	147	3234	788	17336	2173	47806	282	6204
	PP 72.3%	1173	22.9	9.97	11695	29.7	34832	62.9	73782	16.1	18885
21 PPLP4N 94	PP 44.5%	77	82.6	147	11319	788	60676	2173	167321	282	21714
	LP 10%	17	82.6	88.6	1506	325	5525	2019	34323	263	4471
22 PPRF4P 51	PP 19.5%	34	82.6	147	4998	788	26792	2173	73882	282	9588
	RF 10%	17	82.6	155	2635	641	10897	3292	55964	676	11492
23 PPWF2P 479	PP 19.5%	317	22.9	9.97	3160	29.6	9383	62.9	19939	16.0	5072
	WF 10%	162	22.9	13.0	2106	24.0	3888	105	17010	16.7	2705

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
24 PPWF2S /NG 325	PP 10%[a]	163	22.9	9.97	1625	29.7	4841	62.9	10253	16.0	2608
	WF 10%[a]	162	22.9	13.0	2106	24.0	3888	105	17010	16.8	2722
25 PPWF3G 339	PP 75%	224	47.0	45.2	10125	181	40544	459	102816	80.1	17942
	WF 10%	115	47.0	52.2	6003	152	17480	726	83490	133	15295
26 PPWF3N 217	PP 44.5%	177	47.0	45.2	8000	181	32037	459	81243	80.1	14178
	WF 10%	40	47.0	52.2	2088	152	6080	726	29040	133	5320
27 PPWF3P 118	PP 19.5%	78	47.0	45.2	3526	181	14118	459	35802	80.1	6248
	WF 10%	40	47.0	52.2	2088	152	6080	726	29040	133	5320
28 PPWF3S 80	PP 10%	40	47.0	45.2	1808	181	7240	459	18360	80.1	3204
	WF 10%[a]	40	47.0	52.2	2088	152	6080	726	29040	133	5320

[a] I use 10% for each because of conflict between coded information (i.e., 10% of cover is less abundant species but total is less than 20%).

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH	foliage		branches		stem wood		stem bark	
			(cm)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
29 PPWF4G 147	PP 75%	130	82.5	147	19110	788	102440	2173	282490	282	36660
	WF 10%	17	82.5	155	2635	641	10897	3292	55964	676	11492
30 PPWF4N 94	PP 44.5%	77	82.5	147	11319	788	60676	2173	167321	282	21714
	WF 10%	17	82.5	155	2635	641	10897	3292	55964	676	11492
31 PPWF4P 51	PP 19.5%	34	82.5	147	4998	788	26792	2173	73882	282	9588
	WF 10%	17	82.5	155	2635	641	10897	3292	55964	676	11492
32 PPWF4S 35	PP 10%[a]	18	82.5	147	2646	788	4184	2173	39114	282	5076
	WF 10%[a]	17	82.5	155	2635	641	10897	3292	55964	676	11492
33 RF2N 885	RF 54.5%	885	22.9	13.0	11505	24.0	21240	105	92925	16.8	14868
34 RF3G 339	RF 85%	339	47.0	52.2	17696	152	51528	726	246114	133	45087

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
35 RF3N 217	RF 54.5%	217	47.0	52.2	11327	152	32984	726	157542	133	2886
36 RF4G 147	RF 85%	147	82.6	155	22785	641	94227	3292	483924	676	99372
37 RF4N 94	RF 54.5%	94	82.6	155	14570	641	60254	3292	309448	676	63544
38 RF4P 51	RF 29.5%	51	82.6	155	7905	641	32691	3292	167892	676	34476
39 RF4P/SR 51	RF 29.5%	51	82.6	155	7095	641	32691	3292	167892	676	34476
40 RF4S 26	RF 15%	26	82.6	155	4030	641	16666	3292	85592	676	17576
41 RFLP3G 60	RF 10%	30	47.0	52.2	1566	152	4560	726	21780	133	3990
	LP 10%	30	47.0	31.5	945	86.4	2592	495	14850	86.0	2580

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
42 RFLP3N 217	RF 44.5%	195	47.0	52.2	10179	152	29640	726	141570	133	25935
	LP 10%	22	47.0	31.5	693	86.4	1901	495	10890	86.0	1892
43 RFMH2P 479	RF 19.5%	431	22.9	13.0	5603	24.0	10344	105	45255	16.8	7241
	MH 10%	48	22.9	10.6	509	19.4	931	77.8	3734	21.5	1032
44 RFMH3G 339	RF 75%	335	47.0	52.2	17487	152	50920	726	243210	133	44555
	10%	34	47.0	44.2	1503	133	4522	643	21862	158	5372
45 RFMH3P 118	RF 19.5%	106	47.0	52.2	5533	152	16112	726	76955	133	14098
	MH 10%	12	47.0	44.2	530	133	1596	643	7716	158	1896
46 RFPP3N 217	RF 44.5%	195	47.0	52.2	10179	152	29640	726	141570	133	25935
	PP 10%	22	47.0	47.1	1036	181	3982	459	10098	80.1	1762

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
47 RFPP4N 94	RF 44.5%	85	82.6	155	13175	641	54485	3292	279820	676	57460
	PP 10%	8	82.6	147	1323	788	7092	2173	19557	282	2538
48 RFPP4P 51	RF 19.5%	45	82.6	155	6975	641	28845	3292	148140	676	30420
	PP 10%	5	82.6	147	735	788	3940	2173	10855	282	1410
49 RFWF4G 147	RF 75%	142	82.6	155	22010	641	91022	3292	467464	676	95992
	WF 10%	15	82.6	155	2325	641	9615	3292	49380	676	10140
50 RFWF4N 94	RF 44.5	85	82.6	155	13175	641	54485	3292	279820	676	57460
	WF 10%	9	82.6	155	1395	641	5769	3292	29628	676	6084
51 RFWP3P 118	RF 19.5%	106	47.0	52.2	5533	152	16112	726	76956	133	14098
	WP[b] 10%	12	47.0	31.5	387	86.4	1037	495	5940	86.0	1032

[b] I use LP values because no biomass equations were found for WP.

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH	foliage		branches		stem wood		stem bark	
			(cm)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
52 RFWP4N 94	RF 44.5%	85	82.6	155	13175	641	54485	3292	279820	676	57460
	WP[b] 10%	9	82.6	88.6	797	325	2925	2019	18171	263	2367
54 WF1N 8566	WF 54.5%	8566	6.35	1.10	9423	1.11	9508	3.39	29039	2.38	20387
55 WF2N 885	WF 54.5%	885	22.9	13.0	11505	24.0	21240	105	92925	16.8	14868
56 WF2P 479	WF 29.5%	479	22.9	13.0	6227	24.0	11496	105	50295	16.8	8047
57 WF2S 244	WF 15%	244	22.9	13.0	3172	24.0	3856	105	25620	16.8	4099
4058 WF3G 339	WF 85%	339	47.0	52.2	17696	152	51528	726	246114	133	45087
59 WF3N 217	WF 54.5%	217	47.0	52.2	11327	152	32984	726	157542	133	2885

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH (cm)	foliage		branches		stem wood		stem bark	
				per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
60 WF3P 118	WF 29.5%	118	47.0	52.2	6160	152	17936	726	85668	133	15694
61 WF3S/SM 60	WF 15%	60	47.0	52.2	3132	152	9120	726	43560	133	7980
62 WF3S/SR 60	WF 15%	60	47.0	52.2	3132	152	9120	726	43560	133	7980
63 WF4N 94	WF 54.5%	94	82.6	155	14570	641	60254	3292	309448	676	63544
64 WFPP2P 479	WF 19.5%	431	22.9	13.0	5603	24.0	10344	105	45255	16.8	7241
	PP 10%	48	22.9	9.97	479	29.7	1426	62.9	3019	16.1	773
65 WFPP3G 339	WF 75%	305	47.0	52.2	15921	152	46360	726	221430	133	40565
	PP 10%	34	47.0	45.2	1537	181	6154	459	15606	80.1	2723
66 WFPP3N 217	WF 44.5%	197	47.0	52.2	10283	152	29944	726	143022	133	26201
	PP 10%	22	47.0	45.2	994	181	3982	459	10098	80.1	1762

Table A5. Tree Cover Biomass

Map Key Type Label Trees per ha	Species and Canopy Cover Density	Trees of Sp.	DBH	foliage		branches		stem wood		stem bark	
			(cm)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)	per tree (kg)	per ha (kg)
67 WFPP3P 118	WF 19.5%	106	47.0	52.2	5533	152	16112	726	76956	133	14098
	PP 10%	12	47.0	45.2	542	181	2172	459	5508	80.1	961
68 WFPP3S /SR 60	WF 10%	30	47.0	52.2	1566	152	4560	726	21780	133	3990
	PP 10%	30	47.0	45.2	1356	181	543	459	3770	80.1	2403
69 WFPP4G 147	WF 75%	132	82.6	155	20460	641	84612	3292	434544	676	89232
	PP 10%	15	82.6	147	2205	788	11820	2173	32595	282	4230
70 WFPP4N 94	WF 44.5%	85	82.6	155	13175	641	54485	3292	279820	676	57460
	PP 10%	9	82.6	147	1323	788	7092	2173	19557	282	2538
71 WFPP4P 51	WF 19.5%	46	82.6	155	7130	641	29486	3292	151432	676	31096
	PP 10%	5	82.6	147	735	788	3940	2173	10865	282	1410
72 WFRF3N 217	WF 44.5	195	47.0	52.2	10179	152	29640	726	141570	133	25935
	RF 10%	22	47.0	52.2	1148	152	3344	726	15972	133	2926

Table A6. Trees per Hectare and Basal Area According to Crown Size and Canopy Density

Crown		Trees per Hectare	Canopy Density		Breast Height			Forest Inventory[a]			
dia (m)	area (m^2)		(%)	trees per hectare	diam (cm)	area (cm^2)	basal-area (m^2/ha)		trees/ha <1.2m	>1.2	key
0.9	0.64	15718	54.5	8566	6.35	31.7	27.3	b			MPL
2.8	6.16	1624	15	244	22.9	410	10.0	37.7	803	556	L3P
								15.2	855	553	M2N
			29.5	479			19.7	45.0	333	883	R2N
			54.5	885			36.3	48.2	1623	956	L3G
								15.2	855	553	M2N
			85	1380			56.6	45.0	333	883	R2N
5.7	25.1	399	15	60	47.0	1734	10.4	37.7	803	556	L3P
								21.0	953	361	M3P
			29.5	118			20.5	23.3	846	201	R3P
			54.5	217			37.6	48.2	1623	956	L3G
								47.9	1329	1014	M3G
			85	339			58.8	56.9	553	582	R3G
9.9	57.9	173	15	26	82.6	5352	13.9	37.7	803	556	L3P
								21.6	521	380	M4P
			29.5	51			27.3	30.5	515	380	R4P
			54.5	94			50.3	48.2	1623	956	L3G
								53.3	1102	696	M4G
			85	147			78.7	59.4	1844	612	R4G

a. 1980 Tahoe National Forest Inventory. Preliminary Data. Stratum Summary (unpublished computer printouts dated 28 May, 1981). Values include all live trees: commercial conifer and hardwoods growing stock and other conifers and hardwoods.

b. No inventory data are given for this stratum.

summarize the average basal area and trees per hectare data of the forest inventory data for the nearby Tahoe National Forest. Similar Tahoe Basin data were not yet available at the time this was written. The Tahoe National Forest data are for stands at about 2,000 feet lower elevation than the lake; hence they contain more trees and biomass. The data have standard errors of about ± 50 percent for the number of trees greater than 1.2 m tall and ± 15-30 percent for basal area, so variability is great within their "Land Management Planning Vegetation Strata."

A 1.2 m conifer has a crown diameter of about 2.8 m;* this is the smallest size recorded in the canopy cover of the forest types on the vegetation map--except for map unit 54. The Tahoe Forest data show that the number of trees greater than 1.2 m tall per hactare varies greatly depending on species as well as size class. I assumed that the number of trees per hectare was constant for a given crown diameter class. My estimates of the number of trees are greatly lower except for the two highest densities of 2.8 m diameter crowns. The extent of the discrepancy increases with increasing crown diameter, approaching an order of magnitude in the largest size class. This large discrepancy suggests that there is considerably more biomass, and hence more nutrients, in the forest stands than my estimates indicate.

The large number of trees less than 1.2 m tall in the Tahoe Forest data particularly indicates additional biomass overlooked by my

---

* Philip Aune, Tahoe National Forest Timber Management Officer (personal communication)

estimate, as I do not include understory vegetation. Information enabling estimation of the amount of understory vegetation biomass is not available for the watershed. None of the type labels for the vegetation cover map indicate the presence of large amounts of understory shrubs. I assumed that the understory probably contained an insignificant portion of the biomass and nutrients. Several studies (Dice 1970 p. 124, Patric and Smith 1975 p. 4) found that understory vegetation contains less than 5 percent of the biomass nutrients on sites covered by dense mature stands. However, where shade tolerant conifers such as mountain hemlock (MH) and white fir (WF) (Fowells 1965), are present, use of average tree or similar short cut methods for estimating biomass can lead to gross errors (Baskerville 1965)--probably part of the explanation for the large discrepancy between Tahoe Forest stem numbers and my numbers.

The basal area values are more similar, indicating that my average tree approach makes up some of the underestimation of tree numbers by assuming that all trees are the size of the predominate crown diameter. For 2.8, 5.7, and 9.9 m crown diameters respectively, their values range from 15-48 m^2/ha and mine from 10-57, 10-59, and 14-79 m^2/ha. The remaining discrepancy, still usually an underestimate, is not serious given the great amount of averaging and non-adjustment for species differences that go into my estimates. Given the similarity between our basal area figures and the expectedly greater values for the lower elevation stands, my estimates are adequate for calculating the biomass per hectare.

A few other assumptions I had to make to overcome problems also may affect the biomass results. These problems mainly are caused by the need to more specifically interpret tree cover type labels. Sometimes the labels imply conditions that conflict with the mapping specifications. For example, two species are listed in some labels also indicating a canopy cover density of 10-20 percent. However, the mapping specifications state that a second species label should be used only when it occupies 10 percent or more of the canopy cover. I assumed that both species were 10 percent of the cover in these contradictory instances. Where two species are indicated for greater canopy cover densities, I assumed that the second is only 10 percent of the total cover because no more specific value is given. Where two species are indicated by the type label, I assumed both have the same crown diameter, since only one size class label is given. In the single instance (map unit 20) where a two-storied canopy is indicated, I assume both layers are the same species as no other indication is given. I also assume that the overstory occupied 10-20 percent of the crown area with 7.5-12.2 m diameter crowns and the understory 70 percent with 1.8-3.8 m crowns. These latter assumptions are based on the minimum mapping specifications for designation two-storied units.

The biomass per hectare for the component parts of trees on each forest cover map unit are calculated in Appendix Table A5 and used in Appendix Tables A7 and A8 respectively to calculate nitrogen and phosphorus contents.

Nutrient Mass in Tree Biomass

Foliage, branches, stem wood and stem bark contain respectively 18.8, 31.1, 32.8 and 17.3 percent of the above-ground biomass nitrogen and 24.7, 27.0, 33.6 and 14.6 percent of the phosphorus. Thus the

Table A7. Mass of Nutrients in Tree Cover: Nitrogen

Map Key	Sp	Foliage			Branches			Stem Wood			Stem Bark			Tl.
		bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha		mass kg/ha	bio-mass kg/ha	%	mass kg/ha	kg/ha
2	LP	4024	1.29	52	7616	.558	42	37985	.304	115	10394	.569	59	270
3	LP	2050	1.29	26	3880	.558	22	19349	.304	59	5295	.569	30	137
4	LP	12589	1.29	162	34474	.558	192	197505	.304	600	34314	.569	195	1149
5	LP	6836	1.29	88	18749	.558	105	107415	.304	327	18662	.569	106	626
6	LP	3717	1.29	48	10195	.558	57	58410	.304	178	10148	.569	58	341
7	LP	1890	1.29	24	5184	.558	29	29700	.304	90	5160	.569	29	172
8	LP	1890	1.29	24	5184	.558	29	29700	.304	90	5160	.569	29	172
9	LP	5576	1.29	72	15293	.558	85	87615	.304	266	15222	.569	87	
	PP	1808	1.09	20	7240	.585	42	18360	.079	15	3204	.481	15	
				92			127			281			102	602
10	LP	5576	1.29	72	15293	.558	85	87615	.304	266	15222	.569	87	
	RF	2088	.733	15	6080	.300	18	29040	.048	14	5360	.155	8	
				87			103			280			95	565
11	LP	2457	1.29	32	6739	.558	38	38610	.304	117	6708	.569	38	
	RF	2088	.733	15	6080	.300	18	29040	.048	14	5360	.155	8	
				47			56			131			46	280
12	MH	9381	1.18	111	17169	.634	109	68853	.13	90	19028	.17	32	342
13	MH	5216	1.18	62	15694	.634	99	78874	.13	103	18644	.17	32	296
14	MH	3360	1.18	40	6150	.634	39	24663	.13	32	6816	.17	12	
	LP	1361	1.29	18	2576	.558	14	12847	.304	39	3515	.569	20	
				58			53			71			32	214
15	MH	7823	1.18	92	23541	.634	149	113811	.13	148	27966	.17	48	
	LP	1260	1.29	16	3456	.558	19	19800	.304	60	3440	.569	20	
				108			168			208			68	552
18	PP	5334	1.09	58	21358	.585	125	54162	.079	43	9452	.481	45	271
19	PP	3822	1.09	42	20488	.585	120	56498	.079	45	7332	.481	35	242
20	PP	3234	1.09	35	17336	.585	101	47806	.079	38	6204	.481	30	
	PP	11695	1.09	127	34838	.585	204	73782	.079	58	18885	.481	91	
				162			305			96			121	684
21	PP	11319	1.09	123	60676	.585	355	167321	.079	132	21714	.481	104	
	LP	1506	1.29	19	5525	.558	31	34323	.304	104	4471	.569	25	
				142			386			236			129	893
22	PP	4998	1.09	54	26792	.585	157	73882	.079	58	9588	.481	46	
	RF	2635	.733	19	10897	.300	33	55964	.048	27	11492	.155	18	
				73			190			85			64	412
23	PP	3160	1.09	34	9383	.585	55	19939	.079	16	5072	.481	24	
	WF	2106	1.59	33	3888	.710	28	17010	.20	34	2705	.58	16	
				67			83			50			40	240
24	PP	1625	1.09	18	4841	.585	28	10253	.079	8	2608	.481	13	
	WF	2106	1.59	33	3888	.710	28	17010	.20	34	2722	.58	16	
				51			56			42			29	178
25	PP	10125	1.09	110	40544	.585	237	102816	.079	81	17942	.481	86	
	WF	6003	1.59	95	17480	.710	124	83490	.20	167	15295	.58	89	
				205			461			248			175	1089

Table A7. Mass of Nutrients in Tree Cover: Nitrogen (continued)

		Foliage			Branches			Stem Wood			Stem Bark			Tl.
Map Key	Sp	bio-mass kg/ha	%	mass kg/ ha	bio-mass kg/ha	%	mass kg/ ha	bio-mass kg/ha		mass kg/ ha	bio-mass kg/ha	%	mass kg/ ha	kg/ ha
26	PP	8000	1.09	87	32037	.585	187	81243	.079	64	14178	.481	68	
	WF	2088	1.59	33	6080	.710	43	29040	.20	58	5320	.58	31	
				120			230			122			99	571
27	PP	3526	1.09	38	14118	.585	83	35802	.079	28	6248	.481	30	
	WF	2088	1.59	33	6080	.710	43	29040	.20	58	5320	.58	31	
				71			126			86			61	344
28	PP	1808	1.09	20	7240	.585	42	18360	.079	15	3204	.481	15	
	WF	2088	1.59	33	6080	.710	43	29040	.20	58	5320	.58	31	
				53			85			73			46	257
29	PP	19110	1.09	211	02440	.585	599	282490	.079	223	36660	.257	94	
	WF	2635	1.59	42	10897	.710	77	55964	.20	112	11492	.58	67	
				63			676			335			161	1235
30	PP	11319	1.09	123	60676	.585	355	167321	.079	132	21714	.257	56	
	WF	2635	1.59	42	10897	.710	77	55964	.20	112	11492	.58	67	
				165			432			244			123	964
31	PP	4998	1.09	54	26792	.585	157	73882	.079	58	9588	.257	25	
	WF	2635	1.59	42	10897	.710	77	55964	.20	112	11492	.58	67	
				96			234			160			92	582
32	PP	2646	1.09	29	14184	.585	83	39114	.079	31	5076	.257	13	
	WF	2635	1.59	42	10897	.710	77	55964	.20	112	11492	.58	67	
				71			160			143			80	454
33	RF	11505	.733	84	21240	.30	64	92925	.048	45	14868	.155	23	216
34	RF	17696	.733	130	51528	.30	155	246114	.048	118	45087	.155	70	473
35	RF	11327	.773	83	32984	.30	99	157542	.048	76	2886	.155	4	262
36	RF	22785	.733	167	94227	.30	283	483924	.048	232	99372	.155	154	836
37	RF	14570	.733	107	60254	.30	181	309448	.048	149	63544	.155	98	535
38	RF	7905	.733	58	32691	.30	98	167892	.048	81	34476	.155	53	290
39	RF	7905	.733	58	32691	.30	98	167892	.048	81	34476	.155	53	290
40	RF	4030	.733	30	16666	.30	50	85592	.048	41	17576	.155	27	148
41	RF	1566	.733	11	4560	.30	14	21780	.048	10	3990	.155	6	
	LP	945	1.29	12	2592	.558	15	14850	.304	45	2580	.569	15	
				23			29			55			21	128
42	RF	10179	.733	75	29640	.30	89	141570	.048	68	25935	.155	40	
	LP	693	1.29	9	1901	.558	11	10890	.304	33	1892	.569	11	
				84			100			101			51	336
43	RF	5603	.733	41	10344	.30	31	45255	.048	22	7241	.155	11	
	MH	509	1.18	6	931	.634	6	3734	.13	5	1032	.17	2	
				47			37			27			13	124
44	RF	17487	.733	128	50920	.30	153	243210	.048	117	44555	.155	69	
	MH	1503	1.18	18	4522	.634	29	21862	.13	28	5372	.17	9	
				146			182			145			78	551
45	RF	5533	.733	41	16112	.30	48	76955	.048	37	14098	.155	22	
	MH	530	1.18	6	1596	.634	10	7716	.13	10	1896	.17	3	
				47			58			47			25	177

Table A7. Mass of Nutrients in Tree Cover: Nitrogen (continued)

		Foliage			Branches			Stem Wood			Stem Bark			Tl.
Map Key	Sp	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha		mass kg/ha	bio-mass kg/ha	%	mass kg/ha	kg/ha
46	RF	10179	.733	75	29640	.30	89	141570	.048	68	25935	.155	40	
	PP	1036	1.09	11	3982	.585	23	10098	.079	8	1762	.481	8	
				86			112			76			48	322
47	RF	13175	.733	97	54485	.30	163	279820	.048	134	57460	.155	89	
	PP	1323	1.09	14	7092	.585	41	19557	.079	15	2538	.481	12	
				111			204			149			101	565
48	RF	6975	.733	51	28845	.30	87	148140	.048	71	30420	.155	47	
	PP	735	1.09	8	3940	.585	23	10865	.079	9	1410	.481	7	
				59			110			80			54	303
49	RF	22010	.733	161	91022	.30	273	467464	.048	224	95992	.155	149	
	WF	2325	1.59	37	9615	.71	68	49380	.20	99	10140	.58	59	
				198			341			323			208	1070
50	RF	13175	.733	97	54485	.30	163	279820	.048	134	57460	.155	89	
	WF	1395	1.59	22	5769	.71	41	29628	.20	59	6084	.58	35	
				119			204			193			124	640
51	RF	5533	.733	41	16112	.30	48	76956	.048	37	14098	.155	22	
	WP	378	.76	3	1037	.407	7	5940	.179	11	1032	.335	3	
				44			55			48			25	172
52	RF	13175	.733	97	54485	.30	163	279820	.048	134	57460	.155	89	
	WP	797	.76	6	2925	.407	12	18171	.179	33	2367	.335	8	
				103			175			167			97	542
54	WF	9423	1.59	150	9508	.71	68	29039	.20	58	20387	.58	118	394
55	WF	11505	1.59	183	21240	.71	150	92925	.20	186	14868	.58	86	605
56	WF	6227	1.59	99	11496	.71	82	50295	.20	101	8047	.58	47	329
57	WF	3172	1.59	50	5856	.71	42	25620	.20	51	4099	.58	24	167
58	WF	17696	1.59	281	51528	.71	366	246114	.20	492	45087	.58	262	1401
59	WF	11327	1.59	180	32984	.71	234	157542	.20	315	2885	.58	17	746
60	WF	6160	1.59	98	17936	.71	127	85668	.20	171	15694	.58	91	487
61	WF	3132	1.59	50	9120	.71	65	43560	.20	87	7980	.58	46	248
62	WF	3132	1.59	50	9120	.71	65	43560	.20	87	7980	.58	46	248
63	WF	14570	1.59	232	60254	.71	428	309448	.20	619	63544	.58	369	1648
64	WF	5603	1.59	89	10344	.71	73	45255	.20	91	7241	.58	42	
	PP	479	1.09	5	1426	.585	8	3019	.079	2	773	.481	4	
				94			81			93			46	314
65	WF	15921	1.59	253	46360	.71	329	221430	.20	443	40565	.58	235	
	PP	1537	1.09	17	6154	.585	36	15606	.079	12	2723	.481	13	
				270			365			455			248	1338
66	WF	10283	1.59	163	29944	.71	213	143022	.20	286	26201	.58	152	
	PP	994	1.09	11	3982	.585	23	10098	.079	8	1762	.481	8	
				11			236			294			160	701
67	WF	5533	1.59	88	16112	.71	114	76956	.20	154	14098	.58	82	
	PP	542	1.09	6	2172	.585	13	5508	.079	4	961	.481	5	
				94			127			158			87	446

Table A7. Mass of Nutrients in Tree Cover: Nitrogen (continued)

		Foliage			Branches			Stem Wood			Stem Bark			Tl.
Map Key	Sp	bio-mass kg/ha	%	mass kg/ ha	bio-mass kg/ha	%	mass kg/ ha	bio-mass kg/ha		mass kg/ ha	bio-mass kg/ha	%	mass kg/ ha	kg/ ha
68	WF	1566	1.59	25	4560	.71	32	21780	.20	44	3990	.58	23	
	PP	1356	1.09	15	5430	.585	32	13770	.079	11	2403	.481	12	
				40			64			55			35	194
69	WF	20460	1.59	325	84612	.71	601	434544	.20	869	89232	.58	518	
	PP	2205	1.09	24	11820	.585	69	32595	.079	26	4230	.481	20	
				349			670			895			538	2452
70	WF	13175	1.59	209	54485	.71	387	279820	.20	560	57460	.58	333	
	PP	1323	1.09	14	7092	.585	41	19557	.079	15	2538	.481	12	
				223			428			575			345	1571
71	WF	7130	1.59	113	29486	.71	209	151432	.20	303	31096	.58	180	
	PP	735	1.09	8	3940	.585	23	10865	.079	9	1410	.481	7	
				121			232			312			187	852
72	WF	10179	1.59	162	29640	.71	210	141570	.20	283	25935	.58	150	
	RF	1148	.733	8	3344	.30	10	15972	.048	8	2926	.155	5	
				170			220			291			155	836

Table A8. Mass of Nutrients in Tree Cover: Phosphorus

Map Key	Sp	Foliage bio-mass kg/ha	Foliage %	Foliage mass kg/ha	Branches bio-mass kg/ha	Branches %	Branches mass kg/ha	Stem Wood bio-mass kg/ha	Stem Wood	Stem Wood mass kg/ha	Stem Bark bio-mass kg/ha	Stem Bark %	Stem Bark mass kg/ha	Tl. kg/ha
2	LP	4024	.139	6	7616	.09	7	37985	.019	7	10394	.027	3	23
3	LP	2050	.139	3	3880	.09	3	19349	.019	4	5295	.027	1	11
4	LP	12589	.139	17	34474	.09	31	197505	.019	38	34314	.027	9	95
5	LP	6836	.139	10	18749	.09	17	107415	.019	20	18662	.027	5	52
6	LP	3717	.139	5	10195	.09	9	58410	.019	11	10148	.027	3	28
7	LP	1890	.139	3	5184	.09	5	29700	.019	6	5160	.027	1	15
8	LP	1890	.139	3	5184	.09	5	29700	.019	6	5160	.027	1	15
9	LP	5576	.139	8	15293	.09	14	87615	.019	17	15222	.027	4	
	PP	1808	.088	2	7240	.024	2	18360	.011	2	3204	.017	1	
				10			16			19			5	50
10	LP	5576	.139	8	15293	.09	14	87615	.019	17	15222	.027	4	
	RF	2088	.130	3	6080	.025	2	29040	.004	1	5360	.013	1	
				11			16			18			5	50
11	LP	2457	.139	3	6739	.09	6	38610	.019	7	6708	.027	2	
	RF	2088	.130	3	6080	.025	2	29040	.004	1	5360	.013	1	
				6			8			8			3	25
12	MH	9381	.170	16	17169	.046	8	68853	.023	16	19028	.033	6	46
13	MH	5216	.170	9	15694	.046	7	78874	.023	18	18644	.033	6	40
14	MH	3360	.170	6	6150	.046	3	24663	.023	6	6816	.033	2	
	LP	1361	.139	2	2576	.09	2	12847	.019	2	3515	.027	1	
				8			5			8			3	24
15	MH	7823	.170	13	23541	.046	11	113811	.023	26	27966	.033	9	
	LP	1260	.139	2	3456	.09	3	19800	.019	4	3440	.027	1	
				15	3		14			30			10	69
18	PP	5334	.088	5	21358	.024	5	54162	.011	6	9452	.017	2	18
19	PP	3822	.088	3	20488	.024	5	56498	.011	6	7332	.017	1	15
20	PP	3234	.088	3	17336	.024	4	47806	.011	5	6204	.017	1	
	PP	11695	.088	10	34838	.024	8	73782	.011	8	18885	.017	3	
				13			12			13			4	42
21	PP	11319	.088	10	60676	.024	15	167321	.011	18	21714	.017	4	
	LP	1506	.139	2	5525	.09	5	34323	.019	7	4471	.027	1	
				12			20			25			5	62
22	PP	4998	.088	4	26792	.024	6	73882	.011	8	9588	.017	2	
	RF	2635	.130	3	10897	.025	3	55964	.004	2	11492	.013	1	
				7			9			10			3	29
23	PP	3160	.088	3	9383	.024	2	19939	.011	2	5072	.017	1	
	WF	2106	.130	3	3888	.059	2	17010	.017	3	2705	.048	1	
				6			4			5			2	17
24	PP	1625	.088	1	4841	.024	1	10253	.011	1	2608	.017	0	
	WF	2106	.130	3	3888	.059	2	17010	.017	3	2722	.048	1	
				4			3			4			1	12
25	PP	10125	.088	9	40544	.024	10	102816	.011	11	17942	.017	3	
	WF	6003	.130	8	17480	.059	10	83490	.017	14	15295	.048	7	
				17			20			25			10	72

Table A8. Mass of Nutrients in Tree Cover: Phosphorus (continued)

		Foliage			Branches			Stem Wood			Stem Bark			Tl.
Map Key	Sp	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha		mass kg/ha	bio-mass kg/ha	%	mass kg/ha	kg/ha
26	PP	8000	.088	7	32037	.024	8	81243	.011	9	14178	.017	2	
	WF	2088	.13	3	6080	.059	4	29040	.017	5	5320	.048	3	
				10			12			14			5	41
27	PP	3526	.088	3	14118	.024	3	35802	.011	4	6248	.017	1	
	WF	2088	.13	3	6080	.059	4	29040	.017	5	5320	.048	3	
				6			7			9			4	26
28	PP	1808	.088	2	7240	.024	2	18360	.011	2	3204	.017	1	
	WF	2088	.13	3	6080	.059	4	29040	.017	5	5320	.048	3	
				5			6			7			4	22
29	PP	19110	.088	17	102440	.024	25	282490	.011	31	36660	.017	6	
	WF	2635	.13	3	10897	.059	6	55964	.017	10	11492	.048	6	
				20			31			41			12	104
30	PP	11319	.088	10	60676	.024	15	167321	.011	18	21714	.017	4	
	WF	2635	.13	3	10897	.059	6	55964	.017	10	11492	.048	6	
				13			21			28			10	72
31	PP	4998	.088	4	26792	.024	6	73882	.011	8	9588	.017	2	
	WF	2635	.13	3	10897	.059	6	55964	.017	10	11492	.048	6	
				7			12			18			8	45
32	PP	2646	.088	2	14184	.024	3	39114	.011	4	5076	.017	1	
	WF	2635	.13	3	10897	.059	6	55964	.017	10	11492	.048	6	
				5			9			14			7	35
33	RF	11505	.13	15	21240	.025	5	92925	.004	4	14868	.013	2	26
34	RF	17696	.13	23	51528	.025	13	246114	.004	10	45087	.013	6	52
35	RF	11527	.13	15	32984	.025	8	157542	.004	6	2886	.013	0	29
36	RF	22785	.13	30	94227	.025	24	483924	.004	19	99372	.013	13	86
37	RF	14570	.13	19	60254	.025	15	309448	.004	12	63544	.013	8	54
38	RF	7905	.13	10	32691	.025	8	167892	.004	7	34476	.013	4	29
39	RF	7905	.13	10	32691	.025	8	167892	.004	7	34476	.013	4	29
40	RF	4030	.13	5	16666	.025	4	85592	.004	3	17576	.013	2	14
41	RF	1566	.13	2	4560	.025	1	21780	.004	1	3990	.013	1	
	LP	945	.139	1	2592	.09	2	14850	.019	3	2580	.027	1	
				3			3			4			2	12
42	RF	10179	.13	13	29640	.025	7	141570	.004	6	25935	.013	3	
	LP	693	.139	1	1901	.09	2	10890	.019	2	1892	.027	1	
				14			9			8			4	35
43	RF	5603	.13	7	10344	.025	3	45255	.004	2	7241	.013	1	
	MH	509	.170	1	931	.046	0	3734	.023	1	1032	.033	0	
				8			3			3			1	15
44	RF	17487	.13	23	50920	.025	13	243210	.004	10	44555	.013	6	
	MH	1503	.170	3	4522	.046	2	21862	.023	5	5372	.033	2	
				26			15			15			8	64
45	RF	5533	.13	7	16112	.025	4	76955	.004	3	14098	.013	2	
	MH	530	.170	1	1596	.046	1	7716	.023	2	1896	.033	1	
				8			5			5			3	21

Table A8. Mass of Nutrients in Tree Cover: Phosphorus (continued)

Map Key	Sp	Foliage			Branches			Stem Wood			Stem Bark			Tl.
		bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha		mass kg/ha	bio-mass kg/ha	%	mass kg/ha	kg/ha
46	RF	10179	.13	13	29640	.025	7	141570	.004	6	25935	.013	3	
	PP	1036	.088	1	3982	.024	1	10098	.011	1	1762	.017	0	
				14			8			7			3	32
47	RF	13175	.13	17	54485	.025	14	279820	.004	11	57460	.013	7	
	PP	1323	.088	1	7092	.024	2	19557	.011	2	2538	.017	0	
				18			16			13			7	54
48	RF	6975	.13	9	28845	.025	7	148140	.004	6	30420	.013	4	
	PP	735	.088	1	3940	.024	1	10865	.011	1	1410	.017	0	
				10			8			7			4	29
49	RF	22010	.13	29	91022	.025	23	467464	.004	19	95992	.013	12	
	WF	2325	.13	3	9615	.059	6	49380	.017	8	10140	.048	5	
				32			29			27			17	105
50	RF	13175	.13	17	54485	.025	14	279820	.004	11	57460	.013	7	
	WF	1395	.13	2	5769	.059	3	29628	.017	5	6084	.048	3	
				19			17			16			10	62
51	RF	5533	.13	7	16112	.025	4	76956	.004	3	14098	.013	2	
	WP	378	.12	0	1037	.033	0	5940	.016	1	1032	.023	0	
				7			4			4			2	17
52	RF	13175	.13	17	54485	.025	14	279820	.004	11	57460	.013	7	
	WP	797	.12	1	2925	.033	1	18171	.016	3	2367	.023	1	
				18			15			14			8	55
54	WF	9423	.13	12	9508	.059	6	29039	.017	5	20387	.048	10	33
55	WF	11505	.13	15	21240	.059	13	92925	.017	16	14868	.048	7	51
56	WF	6227	.13	8	11496	.059	7	50295	.017	9	8047	.048	4	28
57	WF	3172	.13	4	5856	.059	3	25620	.017	4	4099	.048	2	13
58	WF	17696	.13	23	51528	.059	30	246114	.017	42	45087	.048	21	116
59	WF	11327	.13	15	32984	.059	19	157542	.017	27	2885	.048	1	62
60	WF	6160	.13	8	17936	.059	11	85668	.017	15	15694	.048	8	42
61	WF	3132	.13	4	9120	.059	5	43560	.017	7	7980	.048	4	20
62	WF	3132	.13	4	9120	.059	5	43560	.017	7	7980	.048	4	20
63	WF	14570	.13	19	60254	.059	36	309448	.017	53	63544	.048	31	139
64	WF	5603	.13	7	10344	.059	6	45255	.017	8	7241	.048	3	
	PP	479	.088	0	1426	.024	0	3019	.011	0	773	.017	0	
				7			6			8			3	24
65	WF	15921	.13	21	46360	.059	27	221430	.017	38	40565	.048	19	
	PP	1537	.088	1	6154	.024	1	15606	.011	2	2723	.017	0	
				22			28			40			19	109
66	WF	10283	.13	13	29944	.059	18	143022	.017	24	26201	.048	13	
	PP	994	.088	1	3982	.024	1	10098	.011	1	1762	.017	0	
				14			19			25			13	71
67	WF	5533	.13	7	16112	.059	10	76956	.017	13	14098	.048	7	
	PP	542	.088	0	2172	.024	1	5508	.011	1	961	.017	0	
				7			11			14			7	39

Table A8. Mass of Nutrients in Tree Cover: Phosphorus (continued)

Map Key	Sp	Foliage			Branches			Stem Wood			Stem Bark			Tl.
		bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha	%	mass kg/ha	bio-mass kg/ha		mass kg/ha	bio-mass kg/ha	%	mass kg/ha	kg/ha
68	WF	1566	.13	2	4560	.059	3	21780	.017	4	3990	.048	2	
	PP	1356	.088	1	5430	.024	1	13770	.011	2	2403	.017	0	
				3			4			6			2	15
69	WF	20460	.13	27	84612	.059	50	434544	.017	74	89232	.048	43	
	PP	2205	.088	2	11820	.024	3	32595	.011	4	4230	.017	1	
				29			53			78			44	204
70	WF	13175	.13	17	54485	.059	32	279820	.017	48	57460	.048	28	
	PP	1323	.088	1	7092	.024	2	19557	.011	2	2538	.017	0	
				18			34			50			28	130
71	WF	7130	.13	9	29486	.059	17	151432	.017	26	31096	.048	15	
	PP	735	.088	1	3940	.024	1	10865	.011	1	1410	.017	0	
				10			18			27			15	70
72	WF	10179	.13	13	29640	.059	17	141570	.017	24	25935	.048	1	
	RF	1148	.13	1	3344	.025	1	15972	.004	1	2926	.013	0	
				14			18			25			1	58

Table A9. Estimates of Percent Nutrient Concentrations of Tree Species' Foliage, Branches and Trunks

	Foliage				Branches						Trunk			
	new		all ages		wood		bark		overall		wood		bark	
	N	P	N	P	N	P	N	P	N	P	N	P	N	P
PP	1.15	.126	1.091^{a}	$.088^{a}$	.265	$.018^{b}$	.605	$.021^{b}$	$.585^{c}$	$.024^{c}$	.257	.012	.481	.017
JP	1.10	.132	1.091^{d}	$.088^{d}$	$.265^{d}$	$.018^{d}$	$.605^{d}$	$.021^{d}$	$.585^{d}$	$.024^{d}$	.079	.011	$.481^{d}$	$.017^{d}$
LP			1.291	.139	$.314^{e}$	$.028^{e}$	$.716^{e}$	$.033^{e}$	$.558^{f}$	$.090^{f}$	$.304^{e}$	$.019^{e}$	$.569^{e}$	$.027^{e}$
WP			0.76^{g}	$.12^{g}$	$.185^{e}$	$.025^{e}$	$.421^{e}$	$.029^{e}$	$.407^{e}$	$.033^{e}$	$.179^{e}$	$.016^{e}$	$.335^{e}$	$.023^{e}$
WF			1.588	.130	.455	$.038^{h}$	.88	$.073^{i}$	$.710^{j}$	$.059^{j}$	.20	$.017^{h}$	.58	$.048^{i}$
7F			0.733	$.130^{d}$	$.109^{h}$	$.009^{l}$	.455	$.038^{i}$	$.300^{k}$	.025	.048	$.004^{h}$	.155	$.013^{i}$
MH			1.182^{d}	$.170^{d}$	$.287^{e}$	$.035^{e}$	$.655^{e}$	$.041^{e}$	$.634^{e}$	$.046^{e}$	.13	$.023^{e}$	$.17^{d}$	$.033^{e}$

a. Sum of .3 times new foliage percent and .7 times older foliage. New needle biomass averages .307 of PP total according to regression equations in Appendix Table A2.

b. Based on proportional concentration of nutrient in same material on another portion of tree species.

c. Clayton and Kennedy 1980.

d. Assumed to be same value as for another species in genus.

e. Assumed to be proportional to nutrient concentrations in foliage of species and to those for PP.

f. DeByle 1980. I assume nutrient concentrations in whole stems of 5 year old seedlings is same as for branches.

g. Tarrant et al. 1951.

h. Assumed to have same proportional composition as pair of known values for other species in genus.

i. Assumed to have same proportional composition as wood for species.

j. Assumed to be proportional to sum of branch wood and bark nutrient concentration for species.

k. Value Stangenberger (1979) used for branches in his model.

l. Value for a large, undecomposed branch on forest floor reported in Stangenberger's appendix p. 1A.

nutrient mass is almost evenly divided between the trunks, containing 50.1 and 48.3 percent of the N and P respectively, (removable by harvesting) and the branch and foliage slash (almost always left on logging sites and sometimes piled and burned). However my values for trunks include portions of the bole tops above 4 to 8 inches DBH which are usually added to the slash deposits.

The total above-ground biomass nutrients in each of the 72 vegetation cover types has 62 different values of nitrogen mass and 46 of phosphorus mass. These are too many distinctions to retain for land classification purposes.

The difference between adjacent values (Tables 13 and 14) ranges from barely detectable (1 kg/ha) to huge (804 kg/ha). The difference between some values is so slight as to be insignificant given the numerous approximations I use in biomass and nutrient concentration estimation procedures. Therefore, the values must be regrouped into a much smaller number of classes.

Class Boundary Principles and Approaches

The most desirable basis for placing boundaries between classes is to establish some functional relationship between values of variables and the magnitude of their effects. While constantly intriguing, the search for such threshold values has usually proved fruitless--being frustrated by the discovery that concentration controlled cause-effect relationships are almost always continous rather than step functions over most of their range. The effect of nutrient concentrations on phytoplankton biomass (hence water color) is a good example of one of these elusive values--additionally complicated because many other variable conditions affect biomass growth (Chapters 7 and 15). The direct connection between the amount of nutrients stored on sites, the amount in waters draining from sites and via stream flow into the lake, and production of biomass in the lake is even more difficult to establish because of the greatly vascillating concentrations introduced by streams (Coats 1974 p. 150) and the important role of nutrient recycling processes in lakes (Axler et al. 1981).

Another commonly used strategy for establishing class boundaries is to look for clusters of values or for breaks in the continuity of variable values. The latter approach enables analysts to establish capability classes separated by relatively large numeric differences. It is also desirable for my purposes because of the broad generalizations and assumptions used in developing estimates. Having capability zones with numerically similar values at their point of separation is likely to provoke many challenges and much discontent because of the slight differences that may greatly affect land use options of individuals.

Natural breaks in continuity may not be obvious, not exist or exist only for portions of a variable's range. There are several fundamental ways to search for them; all involve rank ordering of values and examening the ordered column for differences between adjacent and cumulative values on absolute and percentage bases (see Tables 13 and 14). The advantage of using percent differences is their compensation for magnitudinal differences between values, e.g., so that small differences between small values are not treated the same as small difference betweeen large values. This approach is particularly useful when a great range of values is present--as for biomass nitrogen.

Cumulative differences are advantageous for attaining an even distribution of values in and between different classification categories; e.g., 200 units in each class. The advantage of using the difference between adjacent values is its ease when obvious beaks in continuity occur. Analysis may require the use of a combination of all these approaches to identify a desirable number of break points along a series of values--as some approaches will work in some places but not others. When the rational, objective approaches fail in some portions of the range, essentially arbitrary decisions on class break points have to be made.

Another general principle guiding placement of boundaries between classes is that the size interval within classes ought to be about the same--if no functional bases can be established for boundaries. This principle need not be so rigidly adhered to near either end of the range, where it is reasonable to extend class ranges to include outlying extreme values rather than having single value classes. Generally it is undesirable to have single value classes because they represent too small a portion of the total diversity to justify separate treatment. It is desirable to have even-sized class intervals because uneven divisions place uneven importance on different value ranges when presumably there are not functionally defensible bases for giving special significance to certain values. Some compromise between the aforementioned principles guides my selection of classes.

Litter Deposit Nutrient Storage

I proportionately adjust reported maximum litter deposit values for dense old stands of each species to compensate for lower canopy

Table A10. Estimated Nitrogen and Phosphorus Mass in Forest Litter Deposits

Sp.	Crown Dia. (m)	Canopy Density %	Deposit Weight (kg/ha)[c]	Nitrogen (%)	Nitrogen (kg/ha)	Phosphorus (%)	Phosphorus (kg/ha)	Map Unit Numbers
LP	2.8	15	3132[b]	1.07[d]	34	.08[d]	3	3
		29.5	6159		66		5	2
	5.7	15	6264[b]	1.07	67	.08	5	7,8
		29.5	12319		132		10	6,11
		54.5	22758		244		18	5,9,10
		85	35494[a]		380		28	4
MH	2.8	29.5	6159	.61[d]	38	.14[d]	9	14
		54.5	11379		69		16	12
	5.7	29.5	12319	.61	75	.14	17	13
		54.5	22758[a]		139		32	15
PP	2.8	15	1694	.72[d]	12	.075[d]	1	24
		29.5	3332		24		3	23
	5.7	15	3389	.72	24	.075	3	28
		29.5	6665		48		5	18,27
		54.5	12313		89		9	26
		85	19204		138		14	25
	9.9	15	6778	.72	49	.075	5	19,32
		29.5	13330		96		10	22,31
		54.5	24626		177		19	21,30
		85	38408[a]		277		29	20,29
RF	2.8	29.5	17248	.854	147	.08[e]	14	43
		54.5	31866		272		25	33
	5.7	29.5	35117	.854	300	.08	28	45,51
		54,5	64870		554		52	35,42,46
		85	101173		864		81	34,41,44
	9.9	15	31009	.854	265	.08	25	40
		29.5	60985		521		49	38,39,48
		54.5	112668		962		90	37,47,50,52
		85	175720[a]		1501		141	36,49

Table A10. Estimated Nitrogen and Phosphorus Mass in Forest Litter Deposits (continued)

Sp.	Crown Dia. (m)	Canopy Density %	Deposit Weight (kg/ha)	Nitrogen (%)	Nitrogen (kg/ha)	Phosphorus (%)	Phosphorus (kg/ha)	Map Unit Numbers
WF	0.9	54.5	6147	1.7[d]	105	.16[d]	10	54
	2.8	15	5263	1.7	89	.16	8	57
		29.5	10351		176		17	56,64
		54.5	19123		325		31	55
	5.7	15	10656	1.7	181	.16	17	61,62,68
		29.5	20959		356		34	60,67
		54.5	38716		658		62	59,66,72
		85	60382		1026		97	58,65
	9.9	29.5	36397	1.7	619	.16	58	71
		54.5	67613		1149		108	63,70
		85	104874[a]		1783		168	69

a. The maximum deposit weights for RF, WF, PP and LP are from reported values in Table A11. The deposit weight values in Table A11 for RF are increased by the woody debris loads reported by Stangenberger (1979 p. 102); WF by the WF:RF litter deposit proportion times RF woody debris load; PP by the average woody debris loads for eastside forest PP type reported by Brown and See (1981 p. 6). I use LP values for MH.

b. Deposit weight for different crown sizes is reduced directly proportionally to diameter--assuming that size reflects the relative productivity of sites and comparative length of time trees have to produce litter and woody debris deposits.

c. The deposit weight for maximum crown diameter and canopy density for a species is proportionally reduced (i.e., by 15/85, 29.5/85 or 54.5/85) to account for the affect of lesser canopy densities.

d. Values for the percent nitrogen and phosphorus in LP, PP, MH, and WF are averages from Appendix Table A11. The JP average is used for PP because it is the species under that label in Ward Creek watershed. The RF nitrogen value is the average of the weighted averages for the three reported deposits and is proportionally reduced by the average percent nitrogen of woody debris deposits in various stages of decomposition reported by Stangenberger (1979 p. 78 & 102).

e. The percent phosphorus for RF is assumed to be .08 from comparison to its value for other species.

Table A11. Reported Values for Litter Deposit Weights and Nitrogen and Phosphorus Concentrations

Sp.	N (%)	P (%)	Deposit Weight (kg/ha)	Notes and References
PP	.78	.097		100yr. old stand, newly fallen Tarrant et al. 1951
	.57	.09		newly fallen litter Daubenmire 1953
	1.7	.12		300yr. old stand Kittredge 1948 p 183
			27181	preclimax stand Kittredge 1948 p 173 citing Bodin
JP	.65	.052		L layer Stark 1973 p 262
	.87	.060		F layer
a	1.06	.064	4625	L layer Ward Creek Zinke & Stangenberger 1975
a	2.27	.076	43425	F layer
a	2.33	.083	34850	H layer

			82900	
LP	.98	.078		newly fallen Tarrant et al. 1951
	.59	.04		newly fallen Daubenmire 1953
	1.30	.096	35494	incl. debris 7.6 cm dia., overmature, DeByle 1981
	1.42	.110		decadent, 2.6 cm deep, 2850 m elev.
			12113	3.6cm deep Reynolds & Knight 1973
a	1.53	.065	9338	L layer, 100 yr old Zinke & Stangenberger 1975
				Ward Creek
a	2.78	.319	39274	F layer
a	2.36	.096	37944	H layer

			86556	
WP	.76	.12		newly fallen Tarrant et al. 1951
	.54	.07		newly fallen Daubenmire 1953
WF	1.7	.16		300 yr old stand Kittredge 1948 p 183
			74624	undercrowns, 3.8 cm deep, 1585 m Kittredge 1955
				elev. immature stand
			13343	openings, .3 cm
			68447	stand average 3.6 cm
			51891	old growth Kittredge 1948 p 173 citing Bodin

Table A11. Reported Values for Litter Deposit Weights and Nitrogen and Phosphorus Concentrations (continued)

Sp.	N (%)	P (%)	Deposit Weight (kg/ha)	Notes and References
RF	.413		11250	L layer, 70 yr old stand Stangenberger 1979 p 89
	.776		50710	F layer

			62000	
	.862		26270	L old growth, Ward Creek, Waca soil
	1.87		57330	F layer

			91190	
a	0.89	.035	26270	L layer, old growth Zinke & Stangenberger 1975 Wark Creek, Waca soil
a	1.87	.071	57333	F layer
a	.83	.072	37960	H layer

			121563	
	.66		14010	L & F_1 layers 150 yr old stand Stangen. 1979 p. 89
	1.01		53360	F_2 layer

			67360	
			58068	under crowns, 3.6 cm deep 1908 m Kittredge 1955 elev., mature, near Pine Crest
			42501	in openings, 2.3 cm
			54856	stand average, 3.3 cm
MH	.77	.11		*T. heterophylla*, newly fallen Tarrant et al. 1951
	.45	.17		newly fallen Daubenmire 1953

[a] These values are not included in the averages from this Table A11 used to calculate litter deposit nitrogen and phosphorus masses because they were located after I made the calculations for other tables.

densities and smaller tree sizes. I then multiply the resulting adjusted deposit weights for each crown diameter size and canopy density by the average nitrogen and phosphorus concentration of the litter deposits of species. My estimates also include the nitrogen and phosphorus stored in such large wood debris when it is unclear in reported values whether they were included in deposit weights. More details of my estimation approach are given in footnotes of Appendix Table A10. Figures 15 and 16 show the distribution of estimated litter nitrogen and phosphorus mass, respectively, in Ward Creek watershed.

My estimated values range from 12 to 1783 kg/ha of nitrogen and from 1 to 168 kg/ha of phosphorus. For the same tree size and canopy density (e.g., 2.8 m. and 29.5%), the relative amount of nitrogen in species litter deposits, in order of decreasing abundance, is WF, RF, LP, MH, PP (176, 147, 66, 38, 24 kg/ha). For phosphorus the order is WF, RF, MH, LP, PP (17, 14, 9, 5, 3 kg/ha).

Stangenberger (1979 p. 64) reports that Zinke measured 1359 kg/ha of litter deposit nitrogen on Waca soil under old growth red fir in Ward Creek watershed. Stangenberger (1979 p. 91) measured 418 and 607 kg/ha of nitrogen in litter deposits under 70 and 150 year old red fir stands respectively, growing on Waca soils near Quincy. He also measured 225 kg/ha of nitrogen in the large woody debris on the latter for a total litter deposit of 832 kg/ha.

Zinke et al. (1979) report total litter nitrogen and phosphorus values of 2210 and 76 kg/ha respectively for 100 year-old lodgepole pines in Ward Creek watershed. Zinke (1963 p. 37) reports measurements of 485 and 268 kg/ha of nitrogen in litter deposits under ponderosa pine growing respectively on soils with andesite and granite parent materials. His first value is 75% greater than my highest estimate for ponderosa pine but his other value fits my estimates well. It appears that my estimation approach produces reasonable results, certainly values adequate for my purpose of quantitatively rating different zones of nitrogen and phosphorus storage.

Soil Nutrient Storage

I estimate the amount of nitrogen stored in the soils by multiplying together four quantities of the depth zones given in Tables 16 and 17 of the Soil Report (Rogers 1974); interval size, bulk density, portion of particles with diameters smaller than 2 mm, and nitrogen concentration. I then sum the results of all depth zones (Appendix Table A12). Stored nitrogen values of 12813 and 3496 kg/ha are obtained for Tallac (to 79 cm) and Waca (to 53 cm) soils respectively.

Zinke and Stangenberger (1974a) report nitrogen and phosphorus measurements of 2946 and 25.1 kg/ha (to a depth of 122 cm) on a Ward Creek Waca soil under old growth red fir. Stangenberger's measurements (1979 p. 106) of soil nitrogen under old growth red fir on Waca series soils (op. cit. p. 64) average 5672 kg/ha. Zinke and Stangenberger (Sierra Cooperative Pilot Project 1978) report nitrogen and phosphorus values of 9010 and 1 kg/ha respectively for Waca soils under a young fir stand and 6060 and 9 kg/ha for Tallac soils under a mixed conifer stand--both in Ward Creek watershed. They also report (1974a) values for soil nitrogen and phosphorus on a glacial outwash-white fir site of 7358 and 0 kg/ha, on a moraine-fir site of 6715 and 113.6 kg/ha, on a moraine-white fir site of 5839 and 0 kg/ha and on a dense white fir

Table A12. Nitrogen Stored in Soils

Soil Series	Depth		Bulk Density	Fine Fraction		Nitrogen	
	Zone (in)	Interval (cm)	(g/cm^3)	(%)	(kg/m^2)	(%)	(kg/ha)
Tallac	0-15	38.1	1.35	86	442	.195	8627
	15-21	15.2	1.40	57	121	.162	1965
	21-30	25.4	1.50	53	202	.110	2221
							12813
Waca	0-9	22.9	0.91	56[a]	117	.178[b]	2077
	9-14	12.7	0.63	62[a]	50	.109[b]	541
	14-21	17.8	0.88	63[a]	99	.089	878
							3496

[a] Data from representative profile description (Rogers 1974 p.36) in Soil Report.

[b] These values are 1.78 & 1.09 in Soil Report Table 17. Obviously this is an error due to a misplaced decimal point because they are 10 times larger than any other values for nitrogen in the table and the carbon-nitrogen ratio given for their depth zones were calculated using nitrogen values one tenth as large.

[c] Calculations: interval thickness x bulk density = weight of whole soil in interval x percent of interval which is fine fraction = weight of fine fraction in interval (g/cm^3) x 10,000 = weight of fines in interval per square meter x percent nitrogen in fines = weight of nitrogen in interval per square meter x 10,000 = weight of nitrogen in interval per ha.

site of 6168 and 130 kg/ha--all in Ward Creek watershed.

Zinke (1963 p. 37) reported soil nitrogen storage values (to 122 cm depth) of 5372 kg/ha on andesite and 7092 kg/ha on granite parent materials and covered by ponderosa pine stands. Neither location was in the Tahoe Basin nor on soil series occuring in the basin. Zinke and Stangenberger (1974a) report values for soil nitrogen and phosphorus on a moraine-ponderosa pine site of 3448 and 88 kg/ha and at the edge of a cutover site boundary of 7730 and 18 kg/ha--both in Ward Creek watershed.

My 3496 kg/ha value for Waca soils is 20% greater than Zinke and Stangenberger' 2946 value but for only 43% of their sampling depth. As soil nitrogen concentration typically decreases rapidly with depth and the values obtained by Stangenberger range from 3630 to 7720 kg/ha my value is within the normal range of variability for this soil series. Zinke and Stangenberger (1974b) calculated nitrogen values of 12728 and 8241 kg/ha from Soil Conservation Service data for Tallac soils. The former is only 0.6% less than the value I calculated. Stangenberger's values are understandably higher because they are for a 160 year old stand while Tahoe stands are about 100 years old, and his are for an area of the highest red fir site class (Stangenberger 1979 p. 66).

The 1,213 kg/ha value for Tallac soils is considerably larger than Stangenberger's highest value but does not exceed those reported in the summary by Moore and Norris (1974 p. C-6) for forest ecosystem studies of douglas-fir, red alder and alder-conifer (13138, 18698, and 14169 kg/ha respectively). None of the values in Table 17 of the Soil Report (Rogers 1974) is obviously incorrect as they are for Waca (see Appendix Table All footnote), therefore, I use my calculated Tallac value for mapping the total nitrogen in watershed soils.

Nitrogen Storage by Soil Map Units

I make adjustments only for differences occurring in the depth zones for which nitrogen values are given in Table 17 of the Soil Report (Rogers 1974). No nitrogen analysis results are given for Meiss soils; I assume they contain a third as much as Waca soils because the Soil Report states they are similar, and the latter is three times deeper. Inclusions of Meeks soil occur in Tallac soil units, but no nitrogen information is provided on the former. The report states they are similar to Celio soils but better drained (Rogers 1974 p. 26); I use the nitrogen values given for Celio adjusted for differences in their content of coarser particles to estimate nitrogen for Meeks soils.

APPENDIX B

SUPPLEMENTARY INFORMATION FOR CHAPTER 12

POTENTIAL SUSPENDED SEDIMENT QUANTITIES

Soil Type Particle Contents

The number of estimates I develop for each soil is determined by the availability of different particle size analyses in the Soil Report. Consequently I developed three separate estimates are developed for the Tallac and Waca soils and one for Meiss soils. The fine particle analyses given in Soil Report Tables 2 and 16 (my Appendix Tables B1 and B2 respectively) were independently determined--as can be seen by the variability in the amounts shown, sampling depth intervals and the different laboratories performing analyses. However, the bulk density values needed to make calculations are available only in Table 17 (Rogers 1974)(my Appendix Table B3), preventing my estimates of suspended sediment from being completely independent determinations.

General Calculation Procedure

I generally use a five-step procedure in Tables B4 through B10 to estimate the weight per unit area and volume of fine particle fractions. First I multiply the percentage of the whole soil in the

Table B1. Selected Data from Tahoe Basin Soil Survey Report "Table 2. Engineering Test Data"

Soil Name	Depth Interval	Mechanical Analysis								
		percentage passing sieve[b]							percentage smaller than	
		no. 8	no. 10	no. 16	no. 30	no. 40	no. 50	no. 200		
	inches	2.38 mm	2.00 mm	1.19 mm	.595 mm	.420 mm	.297 mm	.074 mm	.005 mm	.001 mm
Tallac (TcC)	0-21	66	64[a]	59	50	44[a]	39	21	3	1
	21-42	56	53[a]	51	42	36[a]	32	17	2	1
	42-65	54	51[a]	44	35	31[a]	29	14	2	1
Waca (WaF)	13-29	51	49[a]	46	40	36[a]	33	21	-	-

[a] Value for data missing from Table 2 in these categories were obtained by linear interpolations based on proportional difference between missing value's particle size and adjacent values.

[b] U.S. Standard Sieve Series opening sizes in millimters according to the Handbook of Chemistry and Physics--36th edition, Chemical Rubber Publishing, Cleveland, p. 3079.

Table B2. Selected Data from Tahoe Basin Soil Survey Report "Table 3. Estimates of Soil Properties Significant in Engineering"

Soil Name and Map Symbols	Depth to Bedrock inches	Depth Interval inches	Percentage of Particles Greater Than 3 Inches	Percentage of Particles Less Than 3 in. Passing Sieves			
				no. 4 4.76mm	no. 10 2.00mm	no. 40 0.42mm	no. 200 0.074mm
Meiss	12 - 18	0 - 13	5 - 20	65-80	60-75	55-60	30-40
MxE MxF	average for fraction		(13)	(73)	(68)	(58)	(35)
	average for whole soil[a]			(64)	(59)	(50)	(30)
Tallac	60+	0 - 42	5 - 65	55-65	45-60	30-45	15-25
TcB TdD TeG TcC TeE TkC	average for fraction		(35)	(60)	(53)	(38)	(20)
	average for whole soil			(39)	(34)	(25)	(13)
		42 - 65	30[b]	60-75	45-65	25-40	10-25
	average for fraction		(30)	(68)	(55)	(33)	(18)
	average for whole soil			(48)	(39)	(23)	(13)
Waca	18 - 42	0 - 36	5 - 30	45-60	35-50	25-40	15-25
WcE WcF	average for fraction		(18)	(53)	(43)	(33)	(20)
	average for whole soil			(43)	(35)	(27)	(16)

[a] Sieve fraction times fine fraction's proportion of whole.

[b] Value missing from Table 3. Figure obtained from series representative profile description for this depth interval (p.33).

Table B3. Selected Data from Tahoe Basin Soil Survey Report "Tables 16 and 17.

Depth in.	Bulk Density gm/cc	Particle-size (mm.) Distribution in Fine Fraction percent by weight								
		<.002	.002-.02	.02-.05	.05-.1	.1-.25	.25-.5	.5-1	1-2	>2
Tallac gravelly coarse sandy loam (TcC)										
0-15	1.35	5.1	13.3	13.1	13.2	16.7	10.5	16.9	11.2	14
15-21	1.40	4.2	13.8	14.7	13.5	16.9	10.8	17.0	9.1	43
21-31	1.50	4.2	17.1	15.1	11.7	14.4	9.8	16.9	10.8	47
31-42	1.50	3.8	9.2	10.5	8.4	14.8	12.7	23.2	17.4	48
42-65	1.70	3.1	10.2	13.1	13.5	20.4	13.5	18.7	7.5	35
Waca cobbly coarse sandy loam (WaF)										
0-9	0.91	4.7	17.3	11.6	10.8	14.1	7.8	14.5	19.2	44[a]
9-14	0.63	4.8	17.5	11.6	12.4	15.8	9.1	14.1	14.7	38[a]
14-21	0.88	4.7	16.6	12.1	13.2	16.2	9.1	14.0	14.1	37[a]
21-31	0.76	4.0	17.2	11.2	12.7	17.2	9.9	15.1	12.7	48[a]
31-36	0.71	4.2	16.9	10.7	11.4	17.6	10.7	17.4	11.1	48[a]

[a] Data from representative profile description (p. 36) in soil report.

Table B4. Percentage of Whole Soil in Particle Size Ranges

	Total Fines	Fine Fragment Fragments								Transport Type		
										wash load b	empirical c	impact law d
depth in.	≤2 mm	1.19-2.00 mm	.595-1.19 mm	.42-.595 mm	.297-.42 mm	.074-.297 mm	.005-.074 mm	.001-.005 mm	<.001 mm	.35 mm	.35-1 mm	1-2 mm
Tallac soil type												
0-21	64%	5%[a]	9%	6%	5%	18%	18%	2%	1%	41%	15%	8%
21-42	53%	2%[a]	9%	6%	4%	15%	15%	1%	1%	33%	15%	5%
42-65	51%	7%[a]	9%	4%	2%	15%	12%	1%	1%	30%	11%	10%
Waca soil type												
13-29	49%	3%[a]	6%	4%	3%	12%	21%	-	-	34%	10%	5%

[a] Partially based on interpolated data

[b] Wash load particles calculated from .43 of .297-.42 mm particles percentage plus all particles smaller than .297 mm.

[c] Empirical formula particle value based upon total fines percentage minus percentage of wash load plus percentage of impact law particles.

[d] Impact law's 1-2 mm particles calculated from 1.19-2 mm particles percentage plus .32 of percentage of .595-1.19 mm particles.

Table B5. Tallac (TcC) Soil Fine Fragment Weight Based on Data in Table 2 of the Tahoe Basin Soil Report

Layer in.	Percent (Weight) of Whole Soil	Bulk Density of Soil kg/m^3	Fraction Weight Per Soil Volume kg/m^3	Layer Thickness m	Fine Fraction Weight Per Soil Area kg/m^2
Colloidal particles, size range 0 -.001 mm.					
0-21	1%	1364[a]	14	.533	7
21-42	1%	1500	15	.533	8
42-65	1%	1700	17	.584	10
			15[b]		total 25
Wash load transport particles, size range .001-.35mm.					
0-21	41%	1364[a]	559	.533	298
21-42	33%	1500	495	.533	264
42-65	30%	1700	510	.584	298
			521[b]		total 860
Empirical transport rule particles, size range .35-1.00mm.					
0-21	15%	1364[a]	205	.533	109
21-42	15%	1500	225	.533	120
42-65	11%	1700	187	.584	109
			205[b]		total 338
Impact law transport particles, size range 1.0-2.0mm.					
0-21	8%	1364[a]	109	.533	58
21-42	5%	1500	75	.533	40
42-65	10%	1700	170	.584	99
			120		total 197

[a] Weighted average from values in Soil Report's Table 17.

[b] Weighted average for full soil depth.

Table B6. Waca (WaF) Soil's Fine Fragment Weight Based on Data in Table 2 of the Tahoe Basin Soil Report (13 - 29 inch depth)

Transport Type	Size Range mm	Percent (Weight) of Whole Soil	Bulk Density of Soil kg/m^3	Fraction's Weight Per Soil Volume kg/m^3	Layer Thick -ness m	Fraction's Weight Per Soil Area kg/m^{2b}
wash load	0-0.35	34%	809[a]	275	.91	250
empirical	0.35-1.0	10%	809[a]	81	.91	74
impact law	1.0-2.0	5%	809[a]	40	.91	36
				396		360

[a] Weighted average from Soil Report Table 17.

[b] Calculated assuming characteristics of 13-29 in sample extend through full 36 in. of soil (.91 m) depth.

Table B7. Percentage of Whole Soil in Particle Size Ranges

Depth Interval	Whole Soil	Fine Fragment Fractions			Transport Type		
	≤2 mm	2.00-0.42 mm	0.42-0.074 mm	<.074 mm	washload	empirical	impact law
inches	%				0-.35 mm	.35-1.0mm	1-2.0 mm
Meiss soil series							
0 -13	59	9%	20%	30%	50%	4%	6%
Tallac soil series							
0 - 42	34	9%	12%	13%	25%	4%	6%
42 - 65	39	16%	10%	13%	23%	6%	10%
Waca soil series							
0 - 36	35	7%	11%	17%	28%	3%	4%

Table B8. Soil Fine Fragment Weight Based on Data in Table 3 of the Tahoe Basin Soil Report

Soil Layer Size Range	Whole Soil % by Weight	Bulk Density of Soil kg/m^3	Fraction Weight Per Soil Volume kg/m^3	Layer Thickness m	Fine Fraction Weight Per Soil Area kg/m^2
<u>Meiss Series</u>					
0-13 inches		800[b]		0.330	
0-0.35 mm	50%		400		132
0.35-1.0 mm	4%		32		11
1.0-2.0 mm	6%		48		16
		totals	480		159
<u>Tallac Series</u>					
0-42inches		1430[a]		1.067	
0-0.35 mm	25%		358		382
0.35-1.0 mm	4%		57		61
1.0-2.0	6%		86		92
42-65inches		1700[a]		0.584	
0-0.35 mm	23%		391		228
0.35-1.0 mm	6%		102		60
1.0-2.0 mm	10%		170		99
		totals	558[c]		922
<u>Waca Series</u>					
0-36inches		800[a]		0.914	
0-0.35 mm	28%		224		205
0.35-1.0 mm	3%		24		22
1.0-2.0 mm	4%		32		29
		totals	280		256

[a] Weighted average from Table 17 of Soil Survey Report.

[b] Data missing. Waca's bulk density was used because Report (p.28) says soils are similar.

[c] Weighted average for 0-65 inch depth.

Table B9. Percentage (Weight) of Whole Soil in Particle Size Ranges[a]

Depth in.	Whole Soil % of Fines	Particle-size (mm) Distribution in Fine Fraction percent by weight							
		0-.002	.002-.02	.02-.05	.05-.1	.1-.25	.25-.5	.5-1	1-2
Tallac gravelly coarse sandy loam (TcC)									
0-15	86	4.4	11.4	11.3	11.4	14.4	9.0	14.5	9.6
15-21	57	2.4	7.9	8.4	7.7	9.6	6.2	9.7	5.2
21-31	53	2.2	9.1	8.0	6.2	7.6	5.2	9.0	5.7
31-42	52	2.0	4.8	5.5	4.4	7.7	6.6	12.1	9.0
42-65	65	2.0	6.6	8.5	8.8	13.3	8.8	12.2	4.9
Waca cobbly coarse sandy loam (WaF)									
0-9	56	2.6	9.7	6.5	6.0	7.9	4.4	8.1	10.8
9-14	62	3.0	10.9	7.2	7.7	9.8	5.6	8.7	9.1
14-21	63	3.0	10.5	7.6	8.3	10.2	5.7	8.8	8.9
21-31	52	2.1	8.9	5.8	6.6	8.9	5.1	7.9	6.6
31-36	52	2.2	8.8	5.6	5.9	9.2	5.6	9.0	5.8

[a] Product of percentage of individual fine fractions (Table B4) and total fines percentage of whole soil.

Table B10. Particle Transport Class Weights Based on Soil Report Table 16

Depth	Layer Thick-ness	Bulk Density	Wash Load			Empirical Rule			Impact Law		
in.	m	kg/m^3	% <.35 mm	volume kg/m^3	area kg/m^2	% .35-1 mm	volume kg/m^3	area kg/m^2	% 1-2 mm	volume kg/m^3	area kg/m^2
Tallac gravelly coarse sandy loam (TcC)											
0-15	.381	1350	56.5	763	290	19.9	269	102	9.6	130	50
15-21	.152	1400	38.5	539	82	13.4	188	29	5.2	73	11
21-31	.254	1500	35.2	528	134	12.1	182	46	5.7	86	22
31-42	.279	1500	27.0	405	113	16.1	242	68	9.0	135	38
42-65	.584	1700	42.7	726	424	17.5	298	174	4.9	83	48
				632	1043		254	419		102	169
Waca cobbly coarse sandy loam (WaF)											
0-9	.229	910	34.5	314	72	10.7	97	22	0.8	98	22
9-14	.127	630	40.8	257	33	12.1	76	10	9.1	57	7
14-21	.178	880	41.9	369	66	12.2	107	19	8.9	78	14
21-31	.254	760	34.3	261	66	11.0	84	21	6.6	50	13
31-36	.127	710	33.9	241	31	12.4	88	11	5.8	41	5
				292	268		91	83		67	61

fine fraction* times the percent passing each sieve analysis category to convert the latter to percent of whole soil values. Secondly I subtract the percent of the whole soil passing through succeedingly finer meshes from the immediately preceding coarser ones to obtain the percent of the whole soil particles in each fine fraction size range. I then regroup the percent in the standard sieve size ranges into three size ranges of particular import for assessing suspended sediment transport. To enable subdivision I assume an even distribution of different sized particles between sieve sizes. Next I multiply percent of particles in each suspended sediment transport category by the bulk density** of the soil, obtaining the weight of each per cubic meter of soil. Lastly I multiply the latter value by the thickness of the sampled soil interval to obtain the weight of each suspended sediment fraction per square meter of soil depth interval.

When using the information of others for unintended purposes, data gaps are usually found. Therefore, to calculate in some instances I use interpolations and make assumptions necessary to fill in missing information. One serious gap in the Soil Report data is the absence of soil bulk density values for Meiss soils. I assume that Meiss and Waca soil bulk density are as similar as the rest of their descriptions indicates. Rogers (1974 p. 28) also states that the two soils are

---

* Particles passing through the largest mesh used to sieve soils (usually 2.00 mm) are referred to as the "fine soil fraction." Those failing to pass through are the "coarse fraction" and are generally referred to as gravel, cobble and other size and shape names for stones in or on soils.

** Bulk density is the weight of a unit volume of the whole, undisturbed soil including all soil material contents and natural air spaces. (Buckman & Brady 1969, p 602).

similar. If my assumption is incorrect, the consequence would be an underestimate of the weight of potential suspended sediments present in Meiss soils. The unusual lightness of Waca soils makes it unlikely that Meiss is of even lower bulk density.

Particle Contents of Land Types

Rocklands (Ra)

> Rock outcrop and stones cover 50 to 90 percent of the surface area. In the crevices is a thin mantle of soil material generally less than 10 inches deep. Included in mapping are scattered areas of ... Waca soils, and Rock outcrop and Rubble land (Rx). (Rogers 1974 p. 29)

Soil materials in pure Ra type areas only exit in crevices between rock outcrops and stones. The description gives no values for the percent of the area which is crevices. To develop estimates of fine fraction abundances I assume that 10 percent of pure Ra lands are crevices filled with Waca soils. Assuming that on the average 70 percent of Ra map units are covered by bedrock, rock outcrops and stones, 30 percent could be inclusions of Waca soils either in the crevices or in scattered patches too small to map as separate units.* I also assume that the Waca soils in Ra map units are the shallow form of that type because conditions are not favorable for the development of deep soils, and the Series description gives a range of 0.508 to 1.16 m deep.

I proportionately adjusted the average values given in Appendix Table B6 for full depth Waca soils to discount for shallower and

---

* The minimum mapping area is 10 acres.

rockier soils and the large portion of the area where soil is totally absent, yielding* values of 66.8 kg/m^2 and 73.5 kg/m^3 for Ra units.

Rock Outcrop and Rubble Lands (Rx)

> Rock outcrop consists of areas of rock left bare by the scouring of glaciers or of large bare faces of ... rock. There is little or no soil material in the crevices. Rubble land consists of stony colluvium ... . It is more than 90% stones and boulders. Included in mapping are scattered areas of ... Waca soils; areas of Tallac soils, shallow variant; and areas of Rock land (Ra) and Stony colluvial land (Sm). (Rogers 1974 p. 30)

I assume that the Rock outcrop portions of the unit contain no fine particles and are the same as stony colluvial lands but are 90 percent coarse fragments rather than 50 percent. My adjustment process** yields estimates of 202.7 kg/m^2 and 169.9 kg/m^3 for Rx units.

---

* Estimated by calculations shown below. (1) = weight of pure soils materials, (2) = proportion of total area, (3) = depth difference correction factor, (4) = excess coarse fragment correction factor, (5) = cracks proportion of total area.

	(1) (2) (3) (4) (5)		(1) (2) (3) (4) (5)	
Ra	343x.70x8/36x.63x.10	= 3.4	375x.70x8/36x.63x.10	= 3.7
	343x.70x2/36x.83x.10	= 1.1	375x.70x2/36x.83x.10	= 1.2
Rx	72 x.15	= 10.8	82 x.15	= 12.3
Wa	343x.15	= 51.5	375x.15	= 56.3
		66.8kg/m^2		73.5 kg/m^3

** The calculations using these assumptions are given below.

	(1)	(2)	(4)		(1)	(2)	(4)	
Rockland	0 x	.35		= 0.0	0 x	.35		= 0.0
Rubbleland	238 x	.35	x .6	= 50.0	261 x	.35	x .6	= 54.8
Wa	343 x	.08		= 27.4	375 x	.08		= 30.0
Tc	1324 x	.08		= 105.9	798 x	.08		= 63.8
Ra	5 x	.08		= 0.4	5 x	.08		= 0.4
Sm	238 x	.08		= 19.0	261 x	.08		= 20.9
				202.7 kg/m^2				169.9 kg/m^3

Stony Colluvial Land (Sm)

> Stony colluvial land (Sm)occurs in areas of colluvium from ... highly fractured volcanic flow. This land is associated ... in ... volcanic areas with ... Waca soils. Large cobblestones, stones, and boulders cover 50 to 90 percent of the surface area. Coarse fragments make up more than 50 percent of the volume.* The texture generally ranges from sandy to gravelly sandy loam. The depth to bedrock is 30 to more than 60 inches. Included in mapping are areas of Rock land, Rock outcrop and Rubble land, and ... Waca ... soils. (Rogers 1974 p. 31)

Under the pavement of large stones there evidently is a considerable weight of fine fragments. As small patches of Waca soils are included in Sm mapping units, I assume that the soil materials in the pure Sm areas are proto- or skeletonal Wacas or strongly related to Waca and therefore have similar fine fragment abundances. However some obvious discrepancies result from using this assumed relationship too rigidly. For example, analyses of Waca soils show they are more than 50 percent coarse fragments**--consistent with the minimum coarse fragment value for the deposits underlying the pavement given in the Sm Descriptions . However, I expect that Sm areas must be significantly rockier lands than Waca or they would have been mapped as that type of soil.

Another relationship producing conflicting results is soil depth.

---

* I assume soil mineral particle densities are about the same whether gravel, sand, salt or clay (Buckman and Brady 1969 p. 51) (U.S. Forest Service 1966 p. 118). Therefore, in the following calculations I use the "Descriptions" coarse fragment volume percent figures as if they were percent by weight determinations.

** The Waca coarse fragment contents reported in my tables B4, B7, and B9 are respectively 49%, 65%, and 43.5% (a weighted average for 5 depth intervals), averaging 52.5%. Thus the proportion of coarse fragments in Waca soils is not necessarily exceeded by the value of 50% given in the Sm Description. However, the 90% coarse fragments in the top 8 inches of miscellaneous land types is 37% greater than Waca value.

Typical Waca soils are 20-40 inches deep while the soil materials under the pavement are 30-60 inches deep. Using Waca fine particle contents and making adjustments for lesser or equally coarse fragment content and deeper depth to bedrock results in more fines in Sm than Waca areas--a highly unlikely situation. In the case of Sm areas, more reasonable results are produced by assuming that the coarse fragment content of the portions below eight inches are somewhere between 50-90* percent--rather than using the minimum content figure as I did for the Ra miscellaneous land type. My adjustment process yields estimates of 280.4 kg/m^2 and 307.o kg/m^3 for Sm units.

Gravelly Alluvial Land (Gr)

> Gravelly alluvial land (Gr) consists of small areas of recent gravelly alluvium adjacent to stream channels and in meadows. ...this land is more than 60 inches deep. ...it is stratified gravelly sandy loam, gravelly loam, and gravelly silt loam that generally becomes very gravelly with increasing depth. ...included in mapping are scattered areas of loamy alluvial land and Marsh; and in the Paige Meadows are areas of this land where the surface layer is ... stony loam and the substratum is ... gravelly clay loam. (Rogers 1974 p. 16).

Not enough quantitative information is provided to estimate the fine particle content in this unit. Knowing that the surface soils materials are gravelly and the deeper levels very gravelly means that they are 20-50 and 50-70 percent coarse fragments respectively.

---

* The calculations using this assumption are given below.

	(1) (2) (3) (4)		(1) (2) (3) (4)	
Sm	343x.70x 8/36x.63	= 33.6	375x.70x 8/36x.63x	= 36.9
	343x.70x37/36x.83x	= 204.8	375x.70x37/36x.83x	= 223.9
Ra	4.5x.10	= 0.5	4.9x.10	= 0.5
Rx	72x.10	= 7.2	82x.10	= 8.2
Wa	343x.10x 1 x 1	= 34.3	375x.10x1 x 1	= 37.5
		280.4kg/m^2		307.0 kg/m^3

However, the depth at which coarse fraction abundance increases is not stated. Hence I am unable to adjust the fine fraction weights of the analogous soil to account for coarse fragment content differences.

Some indication of the size distribution of fine particles in Gr units can be obtained from the soil textures present in it; i.e., silt loam, clay loam and sandy loam. The content of sand-size particles (2-.05 mm) ranges from 0 percent in silt loam to equal to or greater than 52 percent in sandy loams. Silt-size particle (.05-.002 mm) abundance ranges from 15 percent in clay loam to 80 percent in silt loam. Clay particle (less than .002 mm) abundance ranges from less than 7 percent in silt loams to 40 percent in clay loams. However, without information on what proportion of the Gr area is the various soil texture types, I cannot make use of the fine particle abundance and size distribution information to arrive at a figure for Gr.

I assume that Tallac soils (bordering all but a small portion of Gr units perimeters) are probably most similar to the Gr units. Lacking any usable indications of fine particle contents in the Gr Description, I assume that the fine particle abundances of those land types are the same as those of the Tallac soils surrounding them--i.e., 1324 kg/m^2 and 798 kg/m^3.

Particle Content of Soil Type Map Units

For each soil type, phase or land type in each map unit category I calculated estimates of the average fine particle content for the whole unit from the weight per unit area and volume of the pure types, and their percent coverage of the unit. When the inclusions vary in depth and/or coarse fragment abundance from the pure type, I also made proportional adjustments correcting for these factors which affect fine particle abundances. The sum of the particle weights for all the types in a map unit yields the average value for the unit.

When inclusions occurred for which particle content values were not already calculated, I developed estimates using the same approach as for soil or land types. Specifically no bulk density values are given in the Report for Meeks soils. Therefore, I adjusted the values for the similar Tallac soil for depth and coarse fragment content differences to obtain estimates for Meeks. The Report description (Rogers 1974 p. 16) for gravelly alluvial lands (Gr) states that there are some loamy alluvial land and marsh land inclusions and that the coarse fragment content increases from 20-50 percent in the surface soil to 50-90 percent with increasing depth. However, no quantitative values are given enabling adjustment of the estimate for the pure type.

Some Neglected Types of Fine Particles

The typically low density of organic particulates (1.2-1.7 versus 2.65 gm/cm^3 for mineral particles) (Buckman and Brady 1969 p. 51, U.S. Forest Service 1966 p. 118) renders them readily suspendable, transportable and persistent in the lake water column, once made susceptible to fluvial processes. Most soil organic particles are added to stream waters during high flow periods. Because of their rapid passage downstream during such events soil organic particles are altered only by leaching and in size by turbulent mechanical forces in the stream. However, during low flow periods, introduced soil organic particles are greatly altered by biological processes in the stream environment--fungal and bacterial decay, digestion by stream invertebrates. Consequently during low flows soil organic particles seldom reach the lake. However, when converted to dissolved organic matter (DOM) by leaching and biologic processing soil organic matter may have an impact on water color and transparency much greater (Black & Christman 1963, Wilen 1975) than indicated by the relatively small mass of DOM coming from that source. Such substances are very persistent but currently do not significantly affect Lake Tahoe water color and transparency.

Depending upon the depth zone, Tallac soils are 0.29 to 3.92 percent organic carbon and Waca 1.44 to 4.85 (Rogers 1974 p. 76). On a weighted average based on depth intervals, the soils are respectively 1.66 and 2.45 percent organic carbon. Most organic matter in soil is considered to be in the form of humus, which is 58 percent carbon. This relationship yields a conversion factor of 1.724 (conventionally rounded to 1.7) for obtaining an estimate of percent organic matter (Foth 1978 p. 156, Brady 1974 p. 154). Using the 1.7 conversion factor, Tallac soils average 2.8 percent organic matter and Waca soils 4.2. Converting percent by weight to weight per square meter as I did for mineral particles, Tallac soils may have an additional 47.6 kg/m^2 of fine organic particulates and Waca soils 33.6 kg/m^2. These values are respectively 3.6 and 9.8 percent of the fine mineral particle contents of those soils. This relationship is calculated on a relative weight basis, but water color and transparency are affected mainly by the number of particulates and their size (Edmondson 1980). The average density of mineral particles in the soil is 1.8 times organic ones. Therefore, possibly 6.5 percent of the total number of fine particles in Tallac soils and 17.6 percent of Waca soils may be organic--assuming the size distribution of the two types of particles is the same.

Particle Size Relative Transportability Relationships

The scheme Krumbein and Sloss (1963 p. 196-198) is based upon the behavior of particles settling in fluids, with the categories defined by the established relationships between particle dimensions (size, specific gravity) water properties (viscosity, density), and gravity. These relationships are formally expressed by particle behavior laws--Stokes' Law, the Impact Law and the Empirical Rule.

The suspension of particles smaller than 0.001 mm (i.e., colloids) is maintained by buffeting collisions with turbulent water molecules. The viscosity and density of water and gravity play no role in the settling behavior of cohesionless colloids. As the Soils Report contains little data on soil content of colloid-size particles, I merged any such data with the next larger particle size category. This regrouping is reasonable because both categories exhibit essentially identical transportability properties; both are part of the wash load-sized particles and hence are transported directly and fully to the lake once waterborne in channels. Also, the theoretical perpetual suspension of colloid particles only occurs if they are truly cohesionless, a state which rarely exists as they rapidly flocculate (Einstein 1964 p. 17 - 40). In the flocculated state, their settling behavior more closely resembles the next larger category than it does cohesionless colloidal particles.

The settling behavior of particles with diameters between 0.1 and .001 mm is largely determined by the viscous resistence of the fluids.

Table B11. Settling Velocity of Particles in Still Water[a]

	Particle Diameter mm	Settling Velocity mm/sec	Time to Settle 1 Meter	Time to Settle Below Maximum Secchi Depth 37 [b]
Impact Law	2.0			
	1.0	100	10 secs	6.2 mins
	0.8	83	12 secs	7.4 mins
Empirical Rule	0.6	63	16 secs	9.9 mins
	0.5	52	19 secs	11.7 mins
	0.4	42	24 secs	14.8 mins
	0.35	37	27 secs	16.7 mins
	0.3	32	31 secs	19.1 mins
	0.2	21	48 secs	29.6 mins
Wash Load	0.15	15	1.1 mins	40.7 mins
	0.10	8	2.1 mins	1.3 hrs
	0.08	6	2.7 mins	1.7 hrs
	0.06	3.8	4.4 mins	2.7 hrs
	0.05	2.9	5.8 mins	3.6 hrs
	0.04	2.1	7.9 mins	4.9 hrs
	0.03	1.3	12.8 mins	7.9 hrs
Stoke's Law	0.02	0.62	26.9 mins	16.6 hrs
	0.015	0.35	47.6 mins	29.4 hrs
	0.010	0.154	1.8 hrs	2.8 days
	0.008	0.098	2.8 hrs	4.3 days
	0.006	0.065	4.3 hrs	6.6 days
	0.005	0.0385	7.2 hrs	11.1 days
	0.004	0.0247	11.2 hrs	17.3 days
	0.003	0.0138	20.1 hrs	31.0 days
	0.002	0.0062	44.8 hrs	69.1 days
	0.0015	0.0035	3.3 days	122.1 days
	0.001	0.00154	7.5 days	277.5 days

---

[a] Adapted from American Water Works Association 1951 Water quality and treatment. 2nd edition p.172. Based on water temperature = 10°C, particle specific gravity = 2.65, fall velocity for particles equal to or greater than 0.1 mm from Hazen 1904, for 0.02 mm and smaller from Wiley's formula, intermediate values interpolated from a connecting curve.

[b] Tahoe Regional Planning Agency 1971a p.7.

The settling rate relationship between the particle and fluid dimensions is a function of the particle diameter squared as described by Stoke's Law.*

The sediments in these smallest sizes are more likely than larger ones to indirectly affect water color because their long settling time provides attachment substrates for bacteria to feed and multiply on thereby increasing nutrient recycling rates, hence enabling growth of a larger phytoplankton population (Paerl 1975, Jannasch & Pritchard 1972). Depending upon the relative amount of suspended sediment to nutrients in inflowing stream water masses, the reduction of light intensities in the surface layers can also result in a net gain in phytoplankton population size by eliminating light inhibition of photosynthetic activity in the surface waters of Lake Tahoe (Tilzer, Goldman & Richards 1976).

The settling of particles with diameters greater than 1 mm is controlled largely by inertial conditions. They are too heavy for viscous resistence to greatly affect their sinking rate. The settling rate relationship between particle and fluid dimensions is largely a function of the square root of particle diameter as described by the Impact Law.**

---

* Stoke's Law is $v = \frac{gd^2(p_1-p_2)}{18u}$ where v = falling velocity, g = gravitational constant, d = particle diameter, p_1 = particle density, p_2 = water density, and u = fluid viscosity.

** The Impact Law is $v = (2/3\ gd\ (p_1 - p_2)/p_2)^{1/2}$

I use 2 mm as the upper limit for particle quantities in the Impact Law category in my calculation because it is the upper limit of soil fines, the largest sand particle size, and commonly the largest particle size separated by mechanical sieve analyses of soils. Larger particles also settle very rapidly (at least 0.1 m /sec.). Hence they are suspended sediments for only a short time and fall entirely past the maximum observed Secchi depth of 37 m in no more than 6 minutes and 10 seconds. Thus they can have only minor and ephemeral effects on lake water color and transparency except in shallow waters where their suspension may be perpetuated and renewed by wave turbulence.

Krumbein and Sloss categorize the settling behavior of .1-1 mm particles as being an average of those of Stokes and of the Impact Law--a set of relationships between the physical dimensions of settling particles and water they call the Empirical Rule. On plots of particle diameter versus settling velocity,* the Empirical Rule zone shows up clearly as the inflection segment joining two curves closely following the two settling laws.

Wash load suspended sediments are a particularly important category to isolate when classifying relative transportability of particles, because once water-borne in channels, they are carried directly to the lake unless trapped in transit by drying up waters--a quantitatively uncommon fate. Thus I subdivided the .1-1 mm size range of Krumbein and Sloss because the smaller particles in it are part of the wash load.

---

* E.g., see Krumbein & Sloss (1963 p. 198 figure 6.2 for a non-log plot and Einstein (1964 p. 17 - 42 Figure 17-II-1) for a log-log plot.

The reported maximum particle size at which suspended sediments behave as wash load varies. Lane (1938) pointed out the relative rarity in stream sediment deposits of particles smaller than 0.1 mm --even though large quantities of such particles were being transported in suspension. Similarly, Sundborg (1956 p. 219) found that particles smaller than 0.15-.20 mm were relatively rare in stream channel sediment deposits, Inman (1949 p. 57), 0.18 mm particles and Einstein et al. (1940), 0.35 mm particles. Because of the great reputation of the latter, I use 0.35 mm as the wash load boundary and as the small end of the Empirical Rule particle size range. On a log-log graph of settling velocity versus particle size (Einstein 1964 p. 17 - 42), 0.35 mm occurs almost exactly in the middle of the inflection zone where the descriptive accuracy of Stokes' Law and the Impact Law are exactly balanced. Thus settling behavior of smaller particles is increasingly better described by Stokes' Law and larger ones by the Impact Law.

APPENDIX C

SUPPLEMENTARY MATERIAL FOR CHAPTER 17
LAND CAPABILITY CLASSIFICATION TO PROTECT WATER COLOR AND TRANSPARENCY

Mapping Method Decisions

In this section I discuss my reasons for favoring conversion of units in natural factor maps from their typically irregular, curvilinear shapes to square grid cell shapes before developing a composite LCC map. Then I explain my recommendations for grid cell size and orientation of the grid cell network. Lastly I state how the mechanics of converting curvilinear map units to grid cells affects the accuracy of composite maps.

Grid Map-Polygon Map Advantages and Disadvantages

A composite map to establish LCC is created by the superimposition of separate maps showing the spatial distribution of different variables. The shape of mapped units containing an essentially homogeneous quantity or quality of some spatially varying natural factor is almost always curvilinear and irregular. Techniques for handling mapped data which retain these irregular shapes are referred to as polygon approaches. The only other common technique for handling mapped data--the grid cell approach--initially converts the natural shapes to stepped outlines by transforming boundary lines to conform to a regular network of uniform-sized grid squares. Both terms originate from computer jargon, but they are also commonly applied to noncomputerized techniques for developing composite maps. Both methods have advantages and disadvantages, and neither is clearly superior to the other in all situations (Phillips 1974, Wehde 1979).

Distortions of Shape and Area

The main advantage of the polygon approach is its preservation of the irregular curvilinear shapes, spatial distributions and areal magnitude of the original map units. Preservation of shape is desirable primarily because it is obvious to the general public and other technically unsophisticated observers that computer or hand-drawn representations are reproductions of original maps. The conversion of map unit shapes to the stepped outline of grid cell formats may produce shapes bearing little obvious resemblance to the originals. Some change of the spatial location of unit types also inevitably occurs as shapes are distorted to conform to the grid. The amount of area occupied by a polygon map unit may also be changed by the gridding decision rules needed to classify a cell when more than one type of polygon map unit occurs in that location. All of these problems are readily overcome by using grid cell sizes which are small in comparison to the irregularity of shape outlines and to the smallest of the original map units.

Impractically Small Classification Units

Approaches for combining polygon maps encounter a problem which is difficult to resolve in a generally acceptable manner. When the curvilinear shapes of map units are superimposed to form composite maps, some of the new units are narrow, discontinuous strips parallel to and between the boundaries of larger units, and some are very small isolated units. As more natural factor maps are added to form the final composite LCC map, these two types of units rapidly become very numerous, occupy a significant portion of the total area and are difficult to keep track of because of their extreme compositional diversity and scattered locations. Such units are too small or narrow to retain as separate land classification units on the final composite map, and they are also too difficult to locate on the ground for land use regulation and administration purposes. Hence, the particular problem caused by their generation concerns the basis and method of their disposal; how can they easily be integrated into the larger and wider LCC units in a rational, readily understandable manner?

Capability classification map developers commonly assume the very narrow units are largely the result of field boundary definition and map drawing technique errors and so devise some means for subsuming them into the larger capability classification units they border. Dividing them evenly down the middle and adding them to the adjacent, larger LCC units on each side is one disposal approach. In theory the boundaries of such commonly included variables as rock, soil and vegetation types ought to coincide. In fact, their mapped edges frequently are separated by considerable distances because of such factors as canopy overhangs, gradual separation by downslope mass movement processes and differing detail of mapping. Thus that method for disposing of too small units is frequently misleading.

One important reason I favor converting map polygons to grid cell forms is that creating composite maps from grid maps does not produce units too small or narrow to retain. However, a different problem must be faced--i.e., deciding how to categorize units when more than one natural factor occurs in one grid location. The choices associated with this problem are comparatively easy to make and to execute and their underlying bases are readily understood and usually acceptable.

When more than one mapped type is in one grid location, some geographic information analysts, particularly those using cell sizes very large in comparison to map units, solve this problem by recording the fraction of the different land types in such cells. However, it is much more convenient, particularly when developing composite maps, to use grid cells considerably smaller than map unit polygon sizes and to treat each cell as being of only the arealy dominant type or a particularly important type.

To convert polygons to grid cell shapes in a consistent manner, simple rules typically are developed for deciding how to classify cells when more than one mapped type occurs in them on the original maps (Henderson, 1980). The grid approach makes such reclassification decisions during the initial conversion of natural polygon maps to cell format maps. Once these gridding decisions are made, units too small to retain no longer occur.

I am particularly concerned with the type and significance of distortions created by decisions reclassifying and merging the numerous small units produced by the compositing processes. My concern is not that one ends up with a larger total area or number of such units using the polygon rather than the grid cell representation method. Many more disposal decisions are made when all the different polygon maps are converted to grid formats, while they are only made on a single map when using the polygon approach. However, disposal principles are simpler to develop, use and defend when individual resource map polygons are converted to grid shapes. Making the grid cell type assignments on the individual maps also makes it much easier to identify and record the specific natural factors whose existence must be ignored or compromised because they cause impractically small units. Identification of the specific variables causing such units is difficult on a final composite LCC map.

Locating Classified Parcels

The location of particular grid cells can readily be specified in legal and other written references and easily located by giving their coordinates. These properties facilitate the administration of land use regulations and aid land owners, developers and other users to recognize where their particular parcels are located in a zoning map, how they are classified and which use regulations apply to them. Polygon approaches could also provide coordinate references, but they never show the fine resolution grid lines of a grid cell geographic coordinate system. Consequently, determining and specifying locations is a more difficult process.

Comparative Costs

Cost of execution is also a factor favoring use of the grid cell approach, especially when a computer is used. Computer programs for handling polygon map units are a more recent and more sophisticated development than those for handling gridded information. Consequently the former are more expensive to run (Bryant and Zobrist 1976; Henderson 1980; Smith, G. et al. 1973) and require more computer expertise. For example, to produce the vegetation types polygon map of the Ward Creek Watershed (Figure 12) required a computer run compositing two different types of polygon maps; one showing the watershed boundary and one showing the timber type polygons for the Tahoe Basin portions of the Homewood and Tahoe City quadrangle maps--U.S. Geological Survey 7.5 minute series. The timber type maps are fairly complex and detailed compared to most resource base maps, containing 169 map units of 72 different types for a 2,445 ha area. However, the watershed boundary is the simplest of all possible maps, as the entire study area is classified as one unit. Hence compositing the two results in no increase in the number of land type units in the area. The cost of the computer run and plotting to produce a single composite map was $120. Grid maps are less expensive because much less computer memory is needed to record the spatial location of each cell than for recording the constantly changing coordinates of polygon unit boundaries. The grid approach needs for computer memory are also less because no small units are created whose existence must be recorded until eventually merged with larger units.

Ease of Quantification

When the process of map generation and compositing is completely computerized, both mapped data handling approaches are accompanied by quantifications of the area of individual map units. However, quantification is not accomplished with equal ease when maps are drawn by hand. The area of polygons can be measured using mechanical devices, such as compensating polar planimeters, but their use is tedious and cumulative errors are large when many small units must be measured. Quantification of map units using the grid cell approach is extremely simple, requiring only multiplying a count of the cells times the area represented by each cell.

To summarize, I strongly favor the grid cell approach for developing hand-drawn composite LCC maps because it is comparatively easy to quantify manually, it does not produce classification units which are impractically small and narrow, and it is easy to refer to specific locations by coordinates. Its major potential shortcomings--distortion of the shape and areal extent of individual map units--can be readily overcome by using sufficiently small grid cell sizes.