July 1990

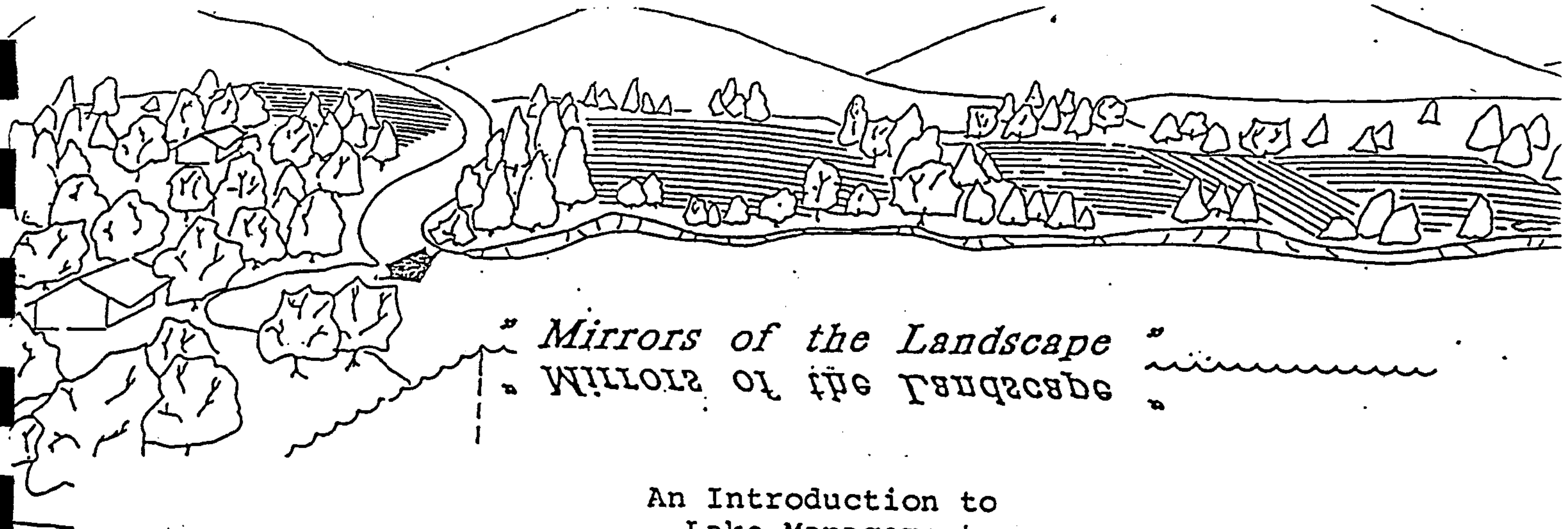
Mirrors of the Landscape : an Introduction to Lake Management

R. W. Kortmann

D. Dickenson Henry

CONNECTICUT INSTITUTE OF WATER RESOURCES

The University of Connecticut
Storrs, Connecticut 06268



Mirrors of the Landscape

An Introduction to
Lake Management

by

R. W. Kortmann
D. D. Henry

The research on which this report is based was financed in part by the United States Department of the Interior as authorized by the Water Research and Development Act of 1978 (P.L. 95 - 467).

Editor

P. H. Rich

2nd Printing and Addendum July, 1990

FOREWORD

The key to effective lake management is a comprehensive approach. Management, restoration, and preservation of lake ecosystems require the concerted use of (1) scientific (physical, chemical, and biological) methods with lakes and (2) social (organizational, political, and legal) methods with people and institutions. To be successful, a management plan also must be specific. Every lake and community is unique, and the efficiency of management techniques often depends upon very particular circumstances which need to be carefully examined and verified.

The first major task in lake management is to define the problems and establish the criteria for their successful solution. Objective science and subjective consensus are equally important factors in the process. A lake manager must have objective goals in order to know when progress is being made, when the job is finished, and when efforts are being made to fix something which isn't broken.

The second task is a technical determination of the causes of the problems. (Beware! This step appears to be the prime criterion for a successful solution of all problems. It is not. Do not attempt a technical assessment until the first step is well advanced.) Generally, algal and weed problems derive from excess or mis-placed nutrients. When the specific, in-lake problems are well understood, the importance of external factors, such as watershed nutrient loads, can be assessed meaningfully.

The third task is a comprehensive and detailed plan for lake management (the "feasibility plan") in which the goal is long term effectiveness of treatment. Techniques should be employed to prevent the reestablishment of controlled organisms, or the appearence of even more troublesome pests. Complete annihilation of weeds and algae should not be the objective of management. The target is a "balance" between fish, zooplankton, and plant communities.

An ounce of prevention is often worth pounds of cure. Lake ecosystem preservation is more cost-effective than restoration. One must also avoid being "penny wise and pound foolish". The relative benefits of a treatment method should be evaluated in both the long-term and short-term. For example, repeated treatments with chemicals which accumulate in lake sediments, such as copper sulfate, may foreclose the future option of sediment removal.

The best management approach manages the "ecosystem", not just the "organisms". The ecosystem approach corrects the cause; an organism approach treats the symptoms. The ecosystem approach usually is more expensive in the short run, but more permanent.

This handbook has guidelines for organizing and funding a lake management project, a description of how lakes work, some methods for diagnosing lake problems, and some restoration and preservation techniques appropriate in a variety of circumstances. It should be a useful guide and overview for an informed lakefront owner, a member of a lake association, a town or municipal official faced with a lake issue, etc. It is not intended as a substitute for the professional services of trained and experienced lake ecosystem specialists. There is no simple "cure-all" for lake problems.

ACKNOWLEDGEMENTS: This handbook is the product of contributions from many participants. Preparation of text and illustrations was made possible by an author stipend from the Jessie Smith Noyes Foundation. The Lake Waramaug Task Force enthusiastically supported the project as the sponsoring institution and by contributing in-kind services for the preparation of "Chapter 1: Getting Organized".

The Connecticut Institute of Water Resources provided funds for outside review, editing, and production. Special thanks are due Prof. Carroll Burke of The University of Connecticut and past Director of the Institute of Water Resources for her careful review of the manuscript and her many efforts over several years to see the handbook to completion.

We gratefully acknowledge technical review of the manuscript by Dr. Jack Vallentyne of the Ministry of the Environment, Canada. We also thank all those who have contributed directly and indirectly to our efforts, including the Connecticut Department of Environmental Protection, the Connecticut Agricultural Experiment Station, the Northwestern and Northeastern Connecticut Regional Planning Agencies, and many individual reviewers.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Cont.)

SECTION 1
GETTING ORGANIZED

By D. Dickenson Henry

CHAPTER 1

GETTING ORGANIZED

Even with the best science and adequate funding, lake projects still must function within the realm of local, state, and often federal politics. Fundamental principles of organization are often overlooked in the heat of an environmental crisis. Basic concepts of management often spell the difference between a sustained, successful effort, and an ephemeral burst of environmental enthusiasm.

Forming an Association

A lake project has three major phases: planning, implementation, and maintenance. To reach the third phase may take many years, so the Association must plan for the long haul.

If a lake is to be managed, the Association must deal with two basic tasks. First, the Association must understand the limits of use and abuse that the lake can sustain. And second, the Association must reach out to the entire lake community and incorporate all interests in the planning and managment process.

In most cases it makes sense to address not only the lake proper but also its entire watershed. In this way a plan can be developed that will address problems both in the lake and those caused by the watershed. Trying to do one without the other is a prescription for failure. By covering both the lake and the watershed, the physical area addressed by the Association will be much larger. That is good because many more people will become involved in the lake's restoration. Right from the start, public access to the lake through beaches and landing sites, for example, should be emphasized and encouraged. Access not only increases public support, but is a key factor in gaining governmental funding and favorable tax status for the lake group itself.

Regulatory Power

In defining a new organization, there often arises the question of enforcement power. Should your organization have it? In my personal experience, it is not an advantage. First an organization with regulatory power is much more difficult to set up. Second, enough regulatory agencies usually exist, and they will do their job if they are informed of problems and know your group is keeping tabs. Third, as an educational body, your group acts as a unifying force bringing together all sectors of the

community to learn about, plan, monitor, and implement your lake project.

Why is an Association more effective as an advisory and educational body than a regulatory one? So many different interests are associated with a lake that sooner of later you will step on someone's toes. Better to do it as an educational body and be listened to, than as a regulatory one and be resented forever. For example, swimmers and water skiers would like to see all weeds out of a lake; fishermen would like to see more weeds in a lake. No single answer will satisfy both groups. A well thought out and agreed upon compromise designating different areas of the lake for different activities may be agreed upon readily by all parties <u>if</u> they are part of its development. A regulatory edict would be resented by all, even if identical to the solution described above. Further, voluntary compliance puts the burden of enforcement on the individual interest groups, in the long run a more effective solution.

How to Incorporate

The question of a formal identity for the lake group arises when individuals originally concerned with lake restoration have decided that community support and funding prospects are sufficient to begin studying the lake's problems. At that point, select a lawyer who has had experience organizing and advising nonprofit groups, preferably environmental ones. Working with the lawyer, you will first have to decide whether to establish your group as a separate entity for organizational and tax purposes or to associate yourself with an existing tax-exempt organization. Should you decide on a separate identity, incorporation (a process taking place at the state level), is the most likely route.

Your lawyer will assist you in resolving the preliminary issues such as selecting a corporate name, designing the Board of Directors, and deciding whether the organization will have members. Once these matters are settled, he then can draft all the necessary corporate documents, comply with all the state filing and reporting requirements, and apply for a state sales tax exemption, if appropriate.

Once corporate status has been achieved, the lake group must turn its attention to gaining federal tax-exempt status as a charitable organization. Retaining a lawyer and an accountant well versed in federal tax process will help found your new corporation as a credible and serious organization. Without delving into the ever changing intricacies of federal tax law, two points must be made. First, the corporation must decide what type of charitable tax status to seek. Second, you then must be certain to operate in a fashion that maintains the favorable designation by the IRS. The message here is to think through what your federal tax status

means to the organization, have a well-qualified attorney file the necessary documents to obtain that status, and then be certain your organization complies with all the relevant IRS requirements on paper and in fact. When your lawyer advises you that your federal tax status is assured, you are all set to begin your fundraising effort as a charitable organization. Your lawyer also should advise the Board of Directors, once it is selected, on its legal responsibilities.

The Board of Directors

What should the role of your Board be? Primarily, a Board should set policy and be responsible for the financial stability of the organization. Board members also act as a liason between the public and the professional staff of the organization. In order to do this, Board members must be clear on three things: why they are here?, how they got here?, and where we are going? A clear sense of the purpose of an organization makes it much easier for the organization to attain its goals. Confusion or disagreement over goals inevitably leads to great inefficiency at best, and demise of the organization at worst. It is worth the time in the beginning to carefully define your objectives. Considerable help from the community may be required to establish a common vision for your lake's future, and the process may be slow and painful. But, having reached a consensus and written down the objectives of the organization, the job of choosing Board members and actually moving towards restoring the lake becomes much easier.

If you have adopted a watershed approach, your Association probably will cover more than one town and, sometimes, more than one state. It is important that the people on your Board fairly represent the entire watershed and not just one particular group, such as the lake front landowners. Participation by and communication with all interest groups are vital to vigorous and credible advocacy of the lake's restoration. All Board members should be genuinely interested in the welfare of the lake, however. Beware of possible conflicts of interest. Local real estate agents, for instance, may feel that serving on your Board will help their work. That is not a good reason to be on your Board.

Choose only Board members who are willing to work. It is tempting for a new organization to pick figure-head names, but in the long run they don't help and may, in fact, drain energy away from the project. The old saw says that Board members should have one of the three W's: Work, Wealth, or Wisdom.

A useful approach is to ask people who already serve on other important boards in town, such as zoning or inland wetlands, to become Board members of the new lake Association. These people will carry information back and forth between established bodies

and the lake project. That process is educational, helps municipal agencies understand the development of a lake plan, and will make then more effective in regulating activities affecting the lake. Similarly, homeowner groups, boaters, and fishermen should all have a part in developing the plan. In general, it is better to have those people part of the group effort rather than isolated from it.

Another potential source of Board members is technical people. Lawyers, accountants, businessmen, bankers, scientists, engineers, etc. are all useful. Bear in mind, however, what and how much work you want them to do. Volunteers make poor consultants, particularly if you decide to disagree with them. It is better to have the engineer on your Board review the engineering plans of your consultant. Having technically skilled people on your Board is a good way to complement the work of the staff and to bring valuable perspectives to the planning process. It is rarely a substiture for good staff work.

Keep the Board a reasonable size. Twelve to twenty is a good number. Much larger than that and the whole process becomes too cumbersome. Committees can be a useful way to take maximum advantage of the diverse skills of the Board. They allow the Board to work in small groups of three to eight and present their findings to the full Board. An Executive Committee, for example, can meet monthly and formulate problems for the full Board to address. If every Board member is on some committee, mutual confidence in Board members' skills grows, and Board members will readily accept a subcommittee's findings. This makes the whole management process much more efficient, and allows the entire Board to concentrate on major policy matters while giving everyone an opportunity to play a significant role.

Make the terms of Board members of limited duration, say three years, and stagger the terms so a third of the Board is up for re-election each year. This helps eliminate people who are not working or have lost interest, and allows the Board to include new, active people.

Be clear that all Board members <u>must</u> contribute money to the project annually and that at least one third of the Board will be actively engaged in fund raising. If you have any hope of raising money from others, every Board member must believe in the project enough to support it financially at whatever level is reasonable for the individual. It is a reality of life that fundraising is one of the prime responsibilities of the Board.

A Full-time Director

From the start, try to hire a full-time Director. The coordination of a large lake project is really more than any one

volunteer can handle. As I mention below, there are a great many resources available to lake clean-up efforts if you have someone looking for them, but it is a full-time job. A good Director should be a good public speaker, fund raiser, work well with volunteers, and be able to communicate well with scientists. He does not have to be technically expert on lake matters, he can learn that on the job. He should be a good organizer and have the ability to motivate people. A genuine enthusiasm for the project may be his single most important attribute. A full-time Director may seem like an extravagance at first, but in the long run a Director will pay handsome dividends.

Scientists

A good lake management project must have a plan, and the plan must be based on good science. Every lake is unique, so don't trust yours to a fast talking salesman. There are a large number of bunko artists trying to sell communities lake cures. If someone tells you that his patented formula will clean up your lake, don't believe him. If anyone promises his system will work on your lake; and he has never seen your lake, don't believe him. Have a reputable scientist with a good track record study your lake and collect data for at least one year. No one can give a reasonable diagnosis in less time. The analysis of your lake's problems will be the basis of a long term plan which should cover both in-lake and watershed problems. Don't cut corners at this stage as you will be spending a lot of money later to implement the solutions. Remember, an elegant answer to the wrong question is still "the wrong answer"!

Once you have found your scientist, remember to protect him. Let him do science. He is not a public orator, nor a politician. It is your job to sell and implement the plan, not his. On the other hand, the scientist should be able to answer the Director's questions about the lake in meaningful and useful terms.

Make a Management Plan

Once you have formed your Association, elected the Board of Directors, hired a Director, and identified the lake's problems, it is time to make a feasible plan of management for preservation and/or restoration. That may seem simple, but it isn't. The variety of interests associated with a lake is staggering. Reaching some consesus on what people really want can be difficult. It will be necessary to give all groups a chance to express their needs. Write up the resulting plan and circulate it widely for comments. Then re-write the plan before adopting it. The whole process is long, frustrating, and involved. But until everyone feels he has had a chance to give input and make his voice heard, the project will not succeed. In the middle of

developing the plan, while looking at a green lake, it is hard to remember that the process is almost as important as the result. This is the first time the Association has to establish its credibility. If the plan is developed thoughtfully and fairly, it sets the tenor of the project for years to come. If the plan is arbitrary, it will end up gathering dust on yet another shelf in the town hall. Try to get as much agreement as possible and then go to work.

A suggested list of topics to be considered is:

Introduction:
- community goals
- statement of problem
- criteria for success

History:
- geological
- biological
- cultural

Planning and Zoning: policies designed to protect the lake.

Forestry

Agriculture

Recreation
- present uses
- projected uses

Roads

Specific watershed problems

Specific in-lake problems

Policy for the future: what to expect when it works.

Plans can and should be changed, but having one printed and available to anyone who is interested gives the project real legitimacy. It is also a powerful fundraising tool.

Public Education

Public awareness of your project is essential to its long-term success. Newsletters are an effective way of keeping everyone interested. At a minimum, publish two a year, one at the beginning of the recreational season and one before Thanksgiving as part of an annual giving campaign. Treat everyone who has ever

shown any interest in the project as a member of "the club". Don't send mailings just to people who have asked for them. Develop a comprehensive list and include everyone who should know what you are doing, who you may ask for help to support the lake in any way, and who may vote, for example, on town appropriations. Don't save a 22 cent stamp and miss a large contribution or a crucial vote of confidence. Be sure to tell about the bad as well as the good. You can build a lot of credibility by telling people why the lake just turned green. It is also useful for future fund raising to establish that you do understand and can explain the lake's problems. People need to be constantly reminded that you are doing something important.

Talk to anyone who will listen: scouts, garden clubs, the Rotary, high school science classes, and home owners around the lake. Distribute materials and posters widely in post offices, stores, laundromats, etc. Emphasize your policy of improving the lake for everyone, and stress the need for everyone to help.

Cultivate the press. A good relationship with the press is most useful. Keep them informed. Send out releases and talk with reporters. Remember, especially for weekly papers, you are an ongoing story that will run for years.

Run tours of your project. If you are doing any construction, run several tours as the construction progresses. People love to see their money at work.

Workshops are another useful way of getting important information across to a particular audience. For example, dairy farmers in the area may be interested in how a manure storage program can save them money and improve the lake at the same time. Maybe you can promote such a program with your local extension agent for additional credibility.

A telephone "hotline" is also a good idea. Helping someone now with reference material or a personal visit may make the difference come fundraising time.

In short, make the Association as accessible as possible. Avoid membership fees and anything else that tends to be exclusionary; you are, after all, cleaning up the lake for everyone.

Fundraising: In-Kind Services

Many areas have a wide variety of resources helpful to a lake project. Some colleges have excellent limnology programs anxious to work on "real problems". You may be able to snare several students and their professor if you offer reasonable support structure.

Many states have departments of environmental protection that may offer technical as well as monetary support. Often the land grant colleges have a research arm (Institute of Water Resources) and/or an extension service interested in water quality. A variety of federal agencies such as the Soil Conservation Service, Agricultural Stabilization and Conservation Service, United States Geological Survey, and the United States Environmental Protection Agency may be able to help with some aspect of your project. Having a comprehensive plan is a great help in soliciting support from these agencies.

If you have a specific construction effort to complete, many local businesses may be able to supply material if they can get a tax deduction and some kind of publicity. Be careful to check with each individual company, however. Some want the publicity and some don't. Given a specific task, public utilities may also chip in with supplies and manpower. Don't overlook the National Guard and the various scouting organizations.

Towns are an extremely valuable source of manpower and equipment. They need to have participated in developing the plan and have access to the lake, but they often will help.

Many of the above organizations have some types of useful equipment which they will loan to the project. Don't buy anything when an indefinite loan will do.

Volunteers, either private individuals or those supplied by a company, can be most useful if handled properly. I have found that to get the most out of a voluteer and to avoid wasting a lot of the Director's time, it is a good idea to draw up a "contract of expectations" before the volunteer begins work. The document outlines the amount of time and the skills a volunteer is willing to provide, and that which the Director or the Association will provide. Make these initial "contracts" of short duration, say two weeks or a month, then sit down and review the results. If everyone is happy, the contracts can be extended. If not, they can be adjusted or terminated gracefully with a minimum of personal disappointment and resentment. The last thing anyone wants is a pestiferous volunteer who is wasting everyone's time and feels as though he is doing the organization a great favor.

Fundraising: Money

The primary sources of money are federal, state, and local government grants, foundation grants, and private gifts from corporations and individuals. They are listed roughly in order of restrictions: federal grants being the most difficult to comply with, and private donations having few if any restrictions. One could write a book on raising money from each of these sources, but here are some general rules.

Take a rifle, not a shotgun, approach to your fundraising. Find out everything you can about a source, then pursue it with all your resources. It is easy to mail out two hundred requests and get two hundred refusals. It takes more time and thought to seek and get one donation. Try to focus your fundraising on specific tangible projects. Raising money for research or building something is much easier than raising it for heat and light. Therefore, build your operating costs into the project costs in reasonable fashion. Avoid hammers costing eight hundred dollars.

Try not to ask for too little money. You cannot insult someone in America by believing they can give you more than they planned to. They still might not give you as much as you would like, but you won't have hurt their feelings by expecting they could have.

Never guarantee results. First of all you can't and, second, cleaning up a lake is an inexact science at best. And that is what you are doing, your best. Of course, you always hope to learn more.

Who should do what kind of fundraising? The Director should be primarily responsible for federal, state, local, and foundation grants. He should write most of the proposals and make the presentations. When making a presentation he should always be accompanied by a Board member, preferably an officer unless another board member has a personal contact with the organization being approached. In general, don't send Board members out alone to the above groups. They usually will not be sufficiently up to date on the technical details of the project to make a good presentation.

Do send Board members out for individual appeals. This is not the place to use the Director. It invariably looks as though he is trying to raise his own salary. Your Director can of course make a group presentation to a gathering of likely donors. He can then answer technical questions about the project, but he should not be put in the position of telling an individual how much he should give.

The actual request for support should come from a Board member or other volunteer who knows the potential donor well and can accurately gauge his potential for giving. Use the "white knuckle" approach. If their knuckles don't turn white in shock, your haven't asked for enough!

Some Parting Thoughts

What makes organizations work? Usually one or two key people launch the project, not from any technical or professional knowledge, but from a fierce commitment to clean up the lake. That individual's commitment is a crucial force which will

motivate an organization for many years. Recognize from the start that the committed person or persons are essential to the project's success. There must be someone whose attitude is, "Come Hell or high water, we are going to clean up this lake."

Let people involved with the project do what they do best, and keep them away from what they do poorly. For instance, don't ask a scientist to write your newsletter. Keep your engineer from making presentations at town meeting. Search for someone, preferably a paid Director, to orchestrate the project. There are a tremendous number of resources available for this kind of environmental work, but they must be coordinated to be most effective.

Finally, remember your job -- the Association represents the lake first, last, and always. You understand that individual abuses inflicted upon your lake are usually small. Rarely is there an isolated, single factor causing the lake's demise. Therefore, the Association works on many fronts simultaneously. After awhile, people will come to the Association first and say, "May I do this or that?" Generally it is possible to protect the lake's welfare while showing an individual how to meet his goals. But the day will come when the Association must say, "No! We cannot support that because it will harm the lake." That is a difficult decision to make even when the case is clear-cut. But it must be done, and the Association, on behalf of the lake, must be willing to make the arguments forcefully to the regulatory agencies involved. For example, as the lake improves more and more people will want to convert summer cottages around the lake to year-round dwellings. It is essential that septic systems for those dwellings meet the rigorous standards set for new dwellings. Building the systems can be expensive, and everyone would like an exception made in "their case". The Association must insist that everyone, even your most generous donor, meet the same rigorous standard.

In taking clear positions, the Association cannot play favorites. It must stand firm in its knowledge that the little degradations of the lake do, in fact, add up to a significant problem -- whoever is involved. You will be respected if you have done your homework and can substantiate the course you recommend. You may lose some friends temporarily, and may be accused of being picayune. But your job is to defend the lake, and incremental degradation of the resource is one of the most insidious forces threatening it.

Even those occasional disputes will not overshadow the joy of cleaning up a lake. Few environmental tasks are so tangible and so clearly beneficial to people throughout a community. Lake restoration is a comparatively new science, and the solutions are not intuitively obvious. But the rewards of restoring your lake will be felt immediately, and popular support will be strong. Be of good cheer, dive in, and get to work.

— D. Dickenson Henry

SECTION 2
INTRODUCTION TO LAKES AND LAKE MANAGEMENT

By Robert W. Kortmann, Ph.D.
Ecosystem Consulting Service, Inc.

CHAPTER 2

INTRODUCTION TO LAKE MANAGEMENT

Lakes: What Are They?

The behavior of lakes depends largely upon the physical and chemical properties of water. A water molecule consists of two hydrogen atoms and one oxygen atom in a structural configuration which confers unique properties on the molecule. Water is the "universal" **solvent**: atmospheric gases and most chemicals (polar and non-polar) readily dissolve in water. Water also has tremendous heat-absorbing and heat-retaining properties which buffer seasonal changes in lakes, creating a much more stable environment than exists on land.

Perhaps the most extraordinary behavior of lakes results from the fact that water is most dense at 4 degrees Centigrade (about 40 degrees Fahrenheit). Water both colder and warmer than 4°C is lighter, and ice is about 9% lighter than liquid water. In winter, as a result, lakes freeze from the top down rather than from the bottom up because ice and the coldest water (less than 4°C) float. In contrast, during **summer stratification** the warmest water (above 4°C) floats above the cold water (nearer 4°C) beneath. Above 4°C the decrease in water density per unit temperature increase becomes larger as temperature rises. Thus, even small, warm lakes are capable of strong summer stratification.

Among the important effects of summer stratification is the isolation of the cold bottom layer (**hypolimnion**) beneath the warm surface layer (**epilimnion**). The overlying epilimnion prevents the uptake of oxygen from the atmosphere by the hypolimnion and blocks light which could produce oxygen by photosynthesis in the hypolimnion. Thus, oxygen removed by respiration of organisms living in the hypolimnion cannot be replaced, and hypolimnetic oxygen may be exhausted during summer stratification. Thermal stratification has such a profound effect upon lakes that it is the basis for the technical distinction between lakes and ponds. Lakes stratify for the entire summer. Ponds only stratify during hot days, and then mix at night.

Important physical and chemical properties of water and their effects on lakes are illustrated in Figures 1 and 2.

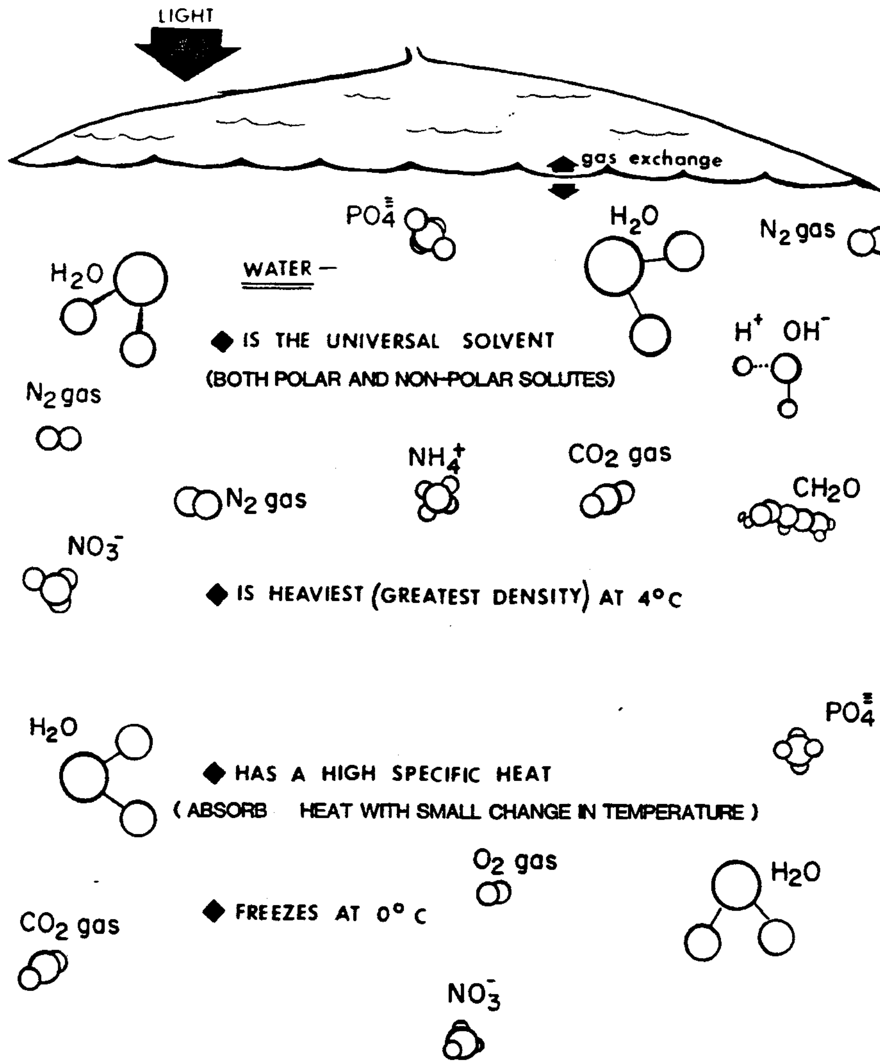


Figure 1. Properties of Water.

The molecular structure of water confers unique physical and chemical properties which are important in the behavior of lakes and ponds. The water molecule contains one oxygen atom asymmetrically bonded to two hydrogen atoms. The asymmetrical covalent bonds confer a small positive charge on the hydrogen side of the molecule and an equal but negative charge on the oxygen side. The resulting polarity is sufficient to dissolve other **polar compounds**, but not too polar to prevent solubility with most **non-polar compounds** as well. Thus, water is the "universal solvent", able to dissolve more substances (including nutrient compounds) than any other common solvent.

Figure 1. Properties of Water (cont.)

Gases dissolved in water at the surface of a lake are near **equilibrium** with the composition of the atmosphere (ca. 79% nitrogen, 20% oxygen, & 1% others). The proportion of carbon dioxide dissolved in water (particularly hard water) tends to be higher than the 0.3% in air. Deeper in the lake the proportions of dissolved gases depend more on biological processes occurring in the lake and less upon atmospheric composition.

The asymmetry of the water molecule also permits the formation of unusually strong **"hydrogen bonds"** among water molecules. H-bonds hold water molecules apart as well as together, and create the crystalline structure and unusual properties of ice. Ice is different from most other solids in being less dense than its liquid. Most H-bonds are broken when ice melts, but enough remain to make water less dense at 0 C than at 4 C. Above 4 C water becomes less dense because the increasing **thermal motion** of water molecules becomes more important than effects of residual H-bonds. Because water is lighter above and below 4 C, lake undergo a remarkable annual cycle of circulation and thermal stratification (see Fig. 2).

Other effects of the exceptionally strong H-bonds in water are high "**specific heat**" and high "**latent heats**". Specific heat is the amount of heat required to raise the temperature of a gram of water one degree Centigrade. Water has the highest specific heat (one calorie per gram) of any common substance. As a result, water is well known to "hold" heat or cold, and to moderate the environment in and around large bodies of water. The latent heats of water (heat required for transition from solid to liquid or liquid to gas phases) are also higher than those of any other common substance, and further buffer lakes from violent changes in temperature. Evaporation cools lakes in summer, and ice formation "warms" lakes in winter.

A final property of water of great importance is its **transparency** to **visible** and **photosynthetically active radiation (= PAR)**. In contrast, water is opaque to **infra-red** and **ultra-violet radiation** which tend to interfere with photosynthesis in terrestrial plants. Unfortunately for lakes, substances dissolved and suspended (including their own algae) in water tend to absorb light. Thus, the amount of light penetrating into lakes during both summer and winter stratification frequently is insufficient to produce enough photosynthesis to maintain dissolved oxygen near the bottom. The absence of oxygen limits fisheries, creates tastes and odors in drinking water, and stimulates eutrophication by accelerating internal re-cycling of phosphorus (see Figs. 9 and 11).

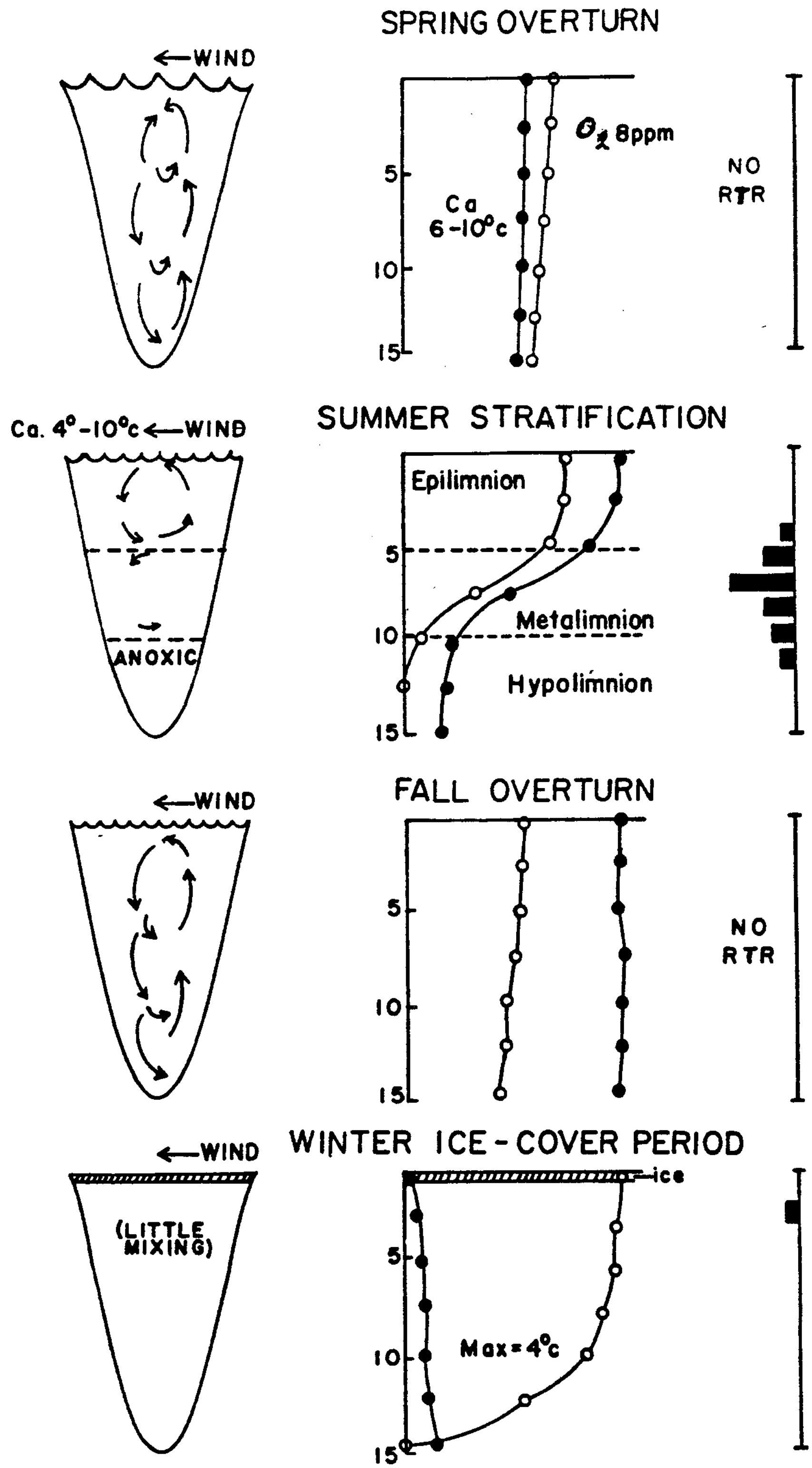

SPRING OVERTURN
←WIND
O2 8ppm
Ca
6-10°c
NO
RTR
5
10
15
SUMMER STRATIFICATION
Ca. 4°-10°c ←WIND
ANOXIC
Epilimnion
Metalimnion
Hypolimnion
5
10
15
FALL OVERTURN
←WIND
NO
RTR
5
10
15
WINTER ICE-COVER PERIOD
←WIND
(LITTLE
MIXING)
ice
Max=4°c
5
10
15

Figure 2. Thermal Stratification.

In winter the coldest part of a lake is the surface, 0 C or colder. The lake gets progressively warmer with depth, up to 4 C (maximum density) at the bottom. Although the thermal gradient is only 4 C between top and bottom, the lake is effectively stratified because ice protects the water from wind. Following ice-out and warming of the surface water by sunlight, the lake circulates from top to bottom ("**spring overturn**") in response to wind-induced motion. As the surface of the lake warms beyond 4 C, the lake again stratifies, but the effect of wind on the lake surface prevents a continuous temperature gradient from top to the bottom as occurs in winter.

Instead, **summer stratification** divides the lake into three distinct layers. The surface layer, the "**epilimnion**", is heated by solar radiation, wind mixed, and uniformly warm. Beneath the epilimnion is the "**metalimnion**" where warm, less dense epilimnetic water rubs against cold, dense water at the bottom of the lake. Technically, the metalimnion is the zone where the temperature gradient is at least 1 degree C per meter of depth. (The "**thermocline**", the depth of maximum temperature change with depth, occurs within the metalimnion.) Beneath the metalimnion is the "**hypolimnion**" where the water is closest to the temperature of maximum density, 4 C. The hypolimnion is effectively isolated from sunlight and air by overlying water. When a lake either produces too much organic matter in its surface waters or receives too much from its drainage basin, bacterial decomposition exhausts dissolved oxygen and concentrates carbon dioxide in the hypolimnion. In the autumn, cooling destroys summer stratification and permits another period of circulation ("**fall overturn**") before winter freeze-up and a return to winter stratification.

A sidelight on the temperature/density function of water important in southern New England is the fact that density changes more at high temperatures than low temperatures. Thus, a warm, shallow lake in Connecticut can experience severe density stratification in the summer with only a few degrees temperature difference between top and bottom.

There are over 200 natural and man-made lakes in the State of Connecticut. Most occupy basins left by the last glaciation. Many are so small that they fail to thermally stratify every summer, or stratify only intermittently during a summer. Many of Connecticut's lakes are **impoundments** created during the development of industrial water power in the 19th Century. The levels of many natural lakes were raised for the same purpose. The largest lake in the State, Candlewood, was impounded in the 20th Century for hydro-electric power. Many of the larger, deeper lakes are drinking water reservoirs. The majority of Connecticut's lakes have **soft water**. Some have medium-hard water, and a very few have very **hard water** with marl (calcium carbonate) sediments.

Lakes are unique and fragile natural resources. They offer habitats for a long list of desirable and endangered species. They are the setting for many active and passive kinds of recreation. Unfortunately, lakes also have become an early-warning system, signalling environmental changes induced by the activities of man. Lakes and surface water quality must now be managed.

Lakes age and die. Many have have filled-in and been obliterated in the 10,000 years since the glacier retreated. Those which remain are "survivors", unique biogeochemical entities balanced between the external geological forces which tend to fill-in lakes by erosion and the internal biological forces which stabilize and maintain lake **ecosystems**. Our attempts to manage lakes and watersheds, to regain stability, and to increase longevity must be patient, subtle, and enduring. Then the results will be well worth the effort.

Drainage Basins: How They Affect Lakes

Lakes receive water from their **drainage basins**. North American **limnologists** use **"watershed"** interchangeably with "drainage basin". Everyone else uses "watershed" to mean the dividing line between drainage basins. A better term coming into use is "**paralimnion**", emphasizing the fact that the lake comes from the drainage basin.

The quality of water which enters a lake is influenced by what is happening in the drainage basin. Water draining from an undisturbed woodland is different than water draining from agricultural or urbanized areas. Specifically, the amount of **phosphorus** contained in the runoff from agricultural land is generally an order of magnitude greater than that exported from forested land. Urban land-use generally causes even more phosphorus to be carried into a lake (up to another order of magnitude), particularly during construction and when housing density is high. Watershed disturbance also increases

concentrations of other constituents in runoff, but phosphorus is almost always the controlling (limiting) factor in lake eutrophication.

Phosphorus entering lakes is rapidly taken up (used) by living organisms. What happens to the phosphorus incorporated in their organic matter then depends upon the fate of the organisms. The fate of most organisms (and their predators) is to die and sink to the bottom of the lake. Thus, phosphorus is rather quickly and efficiently trapped in lake sediments. Under certain circumstances, however, phosphorus again becomes available to the lake. For instance, phosphorus in **littoral** sediments will be taken up by the roots of higher aquatic plants, be incorporated into the plant tissues, and be once more an active part of the lake ecosystem. Sediments deeper in a lake subjected to hypolimnetic **anoxia** also can release phosphorus, as will be described later in this chapter (see Management).

We shall refer to all external sources (e.g. tributary streams, erosion/runoff, wildfowl, etc.) as "watershed sources" to distinguish them from internal sources created by recycling from sediments. The role of watershed sources as the primary supply of all phosphorus in lakes makes watershed management a basic step in lake management.

Succession, Eutrophication, and Balance

Most of the natural lakes in Connecticut were formed during the last glaciation by physical forces associated with movement and melting of ice masses. When forces which form lake basins decline or cease, lakes begin to be overtaken by erosion and sedimentation in a geological process called "**succession**". Waves and ice cut a terrace along the edge of lakes, creating a beach and shallow littoral zone. Weathering of rocks and erosion of soils in the drainage basin release minerals and nutrients which are carried into lakes by runoff and streams, causing further filling of the lake basin and more aquatic plant and animal life.

The succession of lakes from deep, sterile basins to shallow, fertile ponds to wet meadows or forest is not inevitable. Limnologists draw a distinction between lake succession, a geological process, and lake "**eutrophication**", the biological response to nutrient enrichment. The two processes often proceed simultaneously because the geological maturation of a landscape generally involves the release of nutrients through mineral weathering as well as erosion of mineral material into the lake basin. Where minerals in the drainage basin are deficient in nutrients, however, lakes succeed to ponds and wetlands without nutrient enrichment and without eutrophication. On the other hand, lakes which are very large and deep may go through episodes of nutrient enrichment, eutrophication, and recovery without

significant geological succession.

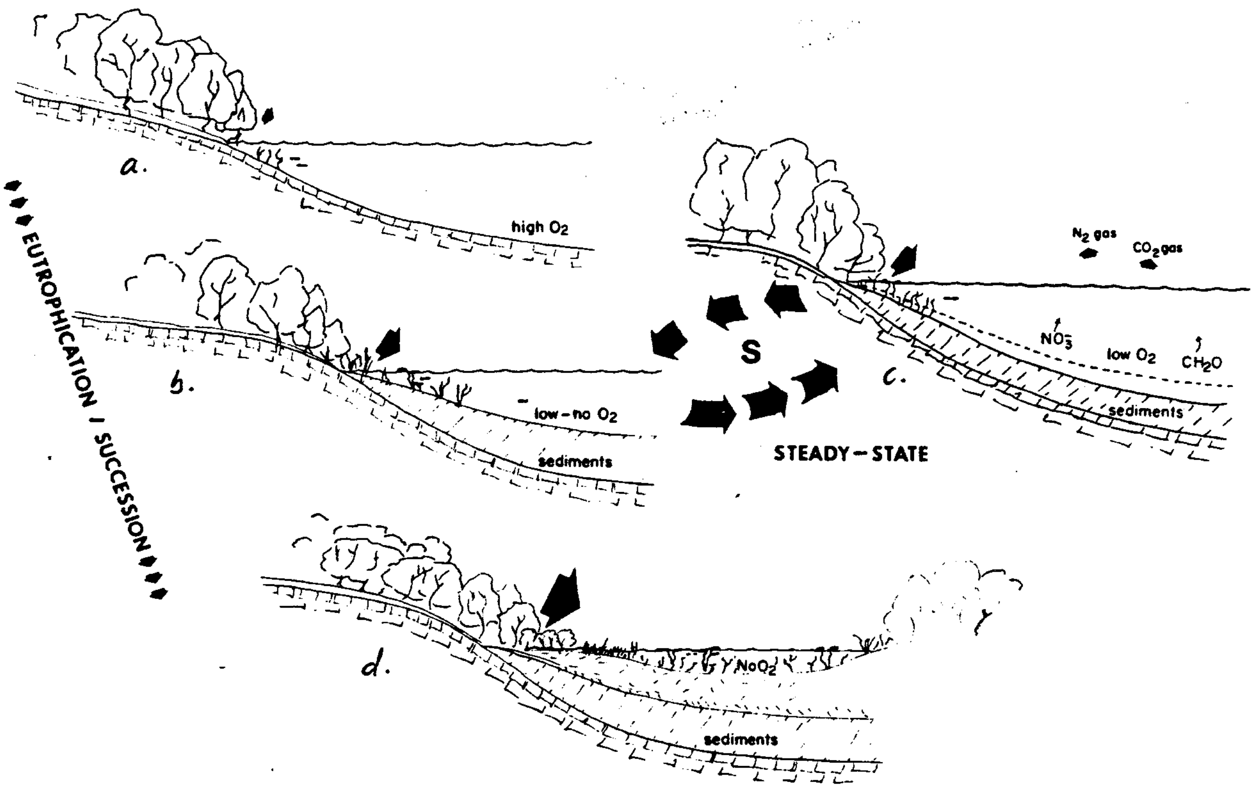


Figure 3

Figure 3. Lake Succession and Eutrophication.

The effect of nutrients on lakes depends upon the amount of nutrients available from the watershed and the amount (depth) of water in the lake with which the nutrients and their effects are diluted. A lake may have low nutrient concentrations (a. "**oligotrophic**"), because the watershed is poor in nutrients and/or because the lake is large and deep. On the other hand, a lake may be fertile ("**eutrophic**") because the watershed is releasing nutrients, because the lake is re-cycling nutrients from its sediments (c.), and/or because the lake is small and shallow (b.). "**Mesotrophic**" refers to lakes transitional between oligotrophic and eutrophic. A pond (d.) is so shallow that aquatic plants grow even in the deepest part and the water column does not thermally stratify.

The process of **lake succession** is caused by geological forces which tend to flatten watersheds and fill lake basins. The term "**eutrophication**" refers to the biological response to increasing nutrient "loading" on a per area basis. Thus, a deep lake receiving large amounts of nutrients may be eutrophic, technically, but "morphometrically oligotrophic" because of dilution in a deep basin. Similarly, a shallow lake may be technically oligotrophic but appear eutrophic because of a well developed littoral zone.

Modern limnologists classify lakes according to their nutrient supplies, specifically the annual input ("**loading**") of phosphorus per unit area of a lake. Phosphorus loading is reflected in the concentration of phosphorus in lake water in the spring of the year during **spring overturn**. Our experience indicates that an "**oligotrophic**" lake contains less than 15 milligrams (mg) of phosphorus per cubic meter (m^3) of water, a "**mesotrophic**" lake between 15 and 30 mg/m^3, and a "**eutrophic**" lake over 30 mg/m^3 of phosphorus after spring thaw. The effects of increased phosphorus loadings, i.e. advancing eutrophication, include progressive loss of dissolved oxygen in the hypolimnion and increasing frequency of **algae blooms**.

Note: Lakes "choked" with organic material are not necessarily eutrophic. Eutrophic lakes deposit more organic material in their sediments than oligotrophic lakes, but the largest amounts of organic matter are deposited by "**dystrophic**" lakes. Dystrophy is a deviation from the oligotrophic to eutrophic progression, and results from the inability of lakes to decompose their organic sediments. Dystrophic lakes generally do not produce the excess organic matter with which they are burdened. Rather, the organic matter is of terrestrial or littoral origin.

Although extinction may be the ultimate destiny of lakes, most lakes are in some degree of "steady-state" in which biological forces in the watershed and lake tend to resist the mostly geological aging process. A mature watershed conserves mineral soil and nutrients extremely efficiently, keeping them out of the lake. Nutrients, nutrient re-cycling, and the production of organic matter they cause are subject to several kinds of control within lakes. Ultimately, bacterial decomposition in lakes and lake sediments has the potential to turn almost all organic matter into gases and water. Thus, the destruction of lakes through culturally accelerated succession, eutrophication, and dystrophy may be greatly delayed and even reversed in some cases.

The degree of steady-state (how constant is the lake from year to year) and the point in succession where the steady-state develops (oligotrophic, mesotrophic, or eutrophic) are characteristics unique to each individual lake. Knowledge of the stage of eutrophication, the rate of succession, and the degree of steady-state stability is the basis of lake management. Although knowledge of the <u>cause</u> of eutrophication (phosphorus loading) is the best basis for estimating eutrophication in the greatest variety of circumstances, the <u>effects</u> of eutrophication (productivity and hypolimnetic oxygen consumption) are the basis for individual lake diagnostics.

Table 1. Phosphorus Concentration and Hypolimnetic Oxygen Consumption.

Trophic stages of lakes with respect to both phosphorus (concentration of total P at spring overturn) and dissolved oxygen (areal uptake per month) in the hypolimnion. (The concentration of phosphorus is given in parts per billion (ppb), which is the same as milligrams per cubic meter and easier to abbreviate.) The major effect of phosphorus is the stimulation of plant and algal photosynthesis in the part of the lake which receives solar radiation (epilimnion). However, increased productivity in the upper part of the lake causes increased respiration and decomposition in the lower, dark part of the lake (hypolimnion). Thus, the concentration of phosphorus in the epilimnion is inversely related to the concentration of dissolved oxygen in the hypolimnion.

Because lakes of greater depth have larger hypolimnia, the effects of eutrophication (hypolimnetic oxygen concentrations) are "diluted" in a large, deep lake (i.e. morphometrically oligotrophic). For that reason oxygen consumption is calculated on an areal basis in the table.

TROPHIC STAGE	TOTAL PHOSPHORUS	OXYGEN CONSUMPTION
Oligotrophic	<15 ppb	<0.75 mg $O_2/cm^2/mo$
Mesotrophic	15 - 30	0.75-1.65
Eutrophic	>30	>1.65

Determinations of hypolimnetic oxygen consumption (best done with simultaneous determinations of carbon dioxide production) may be a more precise method than phosphorus determinations for diagnosing earlier trophic stages. The stimulatory effects of phosphorus on the production of organic matter are not always unambiguous. Two considerations are involved: 1.) what is the **productivity** (rate of production of organic matter)?, and 2.) what is the "**standing crop**" (net amount of primary production)? Some highly productive eutrophic lakes do not exhibit "nuisance" algal or weed accumulations. The point is that different amounts of plant productivity can exist without accumulation when autotrophic production is balanced by heterotrophic consumption. Changes in the occurance of organisms result from changes in the balance of the food web as well as changes in eutrophication and ecosystem productivity.

Water Quality Problems

Two general categories of water quality problems occur in Connecticut lakes: (1) eutrophication resulting from excess nutrient inputs, and (2) contamination with toxic and/or other troublesome substances.

Eutrophication involves the excessive growth of aquatic weeds and/or algae. As described above, eutrophication may occur gradually under natural conditions. However, activities within a watershed that increase nutrient transport to the lake may greatly stimulate eutrophication. The value of algal and aquatic weed growth depends upon the point of view. Fishermen consider algae and weed beds a healthy attribute of lakes because they contribute to the production of warm-water fish species such as bass and pickerel. On the other hand, swimmers and recreational boaters look at algae and weeds as a problem.

Massive growths of algae and/or weeds result in large amounts of organic matter decomposing in the lake. A large amount of decomposing organic matter exhausts oxygen dissolved in the hypolimnion, adversely affecting fish populations and profoundly changing lake water chemistry. Loss of oxygen leads to accumulations of dissolved, **chemically reduced** iron (see Section F.), manganese, hydrogen sulfide, and other products of **anaerobic respiration**. Hydrogen sulfide is particularly toxic, more toxic than cyanide on a weight for weight basis. Loss of oxygen also increases internal re-cycling of phosphorus (see Section F.), accelerating eutrophication. Excessive growth ("blooms") of certain **blue-green algae** also produces toxins, as well as tastes, odors, foam, and discolored water.

The second major category of water quality problems in Connecticut is contamination by bacteria, septic materials, and chemicals such as PCB's, dioxin, TCA, TCE, EDB, road salt, petroleum products and

leachates from sanitary landfills. The distinction between eutrophication and contamination is often overlooked. In general, eutrophication of a lake is not related to the health of the people using the lake, but rather to the health of the lake ecosystem. Contamination (bacterial or chemical) damages both the lake ecosystem and organisms (including people) using the lake. This handbook deals primarily with eutrophication and its relationship to water quality.

Available Information vs. Need for Testing

The first step in a technical analysis of lake problems is a compilation of existing information about the lake and its watershed. Lake watershed boundaries can be defined on **topographic maps** available from the United State Geological Survey (USGS). Topographic maps also can be used to find total area of the drainage basin and certain physical characteristics such as elevations and slopes. Drainage basin area and rainfall information, often available from environmental agencies (see Appendix I), will provide an estimate of the annual **water budget** of a lake.

Soil maps from the U. S. Department of Agriculture (USDA) Soil Conservation Service provide very useful information for watershed management. Combined with the information on topographic maps, soil maps permit a competent consultant to estimate erosion at any point in the drainage basin and to predict the total sediment load entering a lake. Detailed information on soils and slopes is the basis for good land-use management, planning and zoning, and lake watershed management. Erosion control, road design, storm runoff, development, septic systems, wetland protection, and virtually all land-uses must be managed to achieve lake watershed nutrient control.

Bathymetric maps which show depth contours are very important for developing lake management strategies. Bathymetric maps for many of the larger lakes in Connecticut are available in Frink and Norvell's 1984 publication <u>Chemical and Physical Properties of Connecticut Lakes</u> (Bulletin 817) available from the Connecticut Agricultural Experiment Station (see Appendix 1.). In other states bathymetric maps are available in similar reports or in sports fishing publications. Smaller lakes for which bottom surveys have not been made are conveniently mapped and sounded in the winter during ice cover. (Be sure the ice is safe!!)

A bathymetric map for a small lake makes a good "do-it-yourself" project for Association members. A grid or radial pattern is easily laid out on the ice with a surveyor's optical level and tape measure. Tie the pattern into a number of known points along the shore so the lake outline will be apparent on your map. Drill holes at measured intervals along the lines, and measure water

depths through the holes with a weight and marked line (or tape measure). If the ice has some water on it (during a brief thaw, for instance), a fisherman's sonar unit will read depths right through the ice (operate the unit only when the transducer is in water). Be careful to keep track of what depths go with what points on the lines. Plot the pattern you created on the ice on a large piece of sturdy paper which will withstand many erasures. (You can ink a neat copy on tracing paper later.) Draw in the outline of the lake. Write in the depths at the appropriate points on the lines you have plotted. Select a **contour interval**. Three feet (one meter) is good for small lakes). Interpolate and plot the depths of the contours (3, 6, 9, 12, etc. feet) on the plotted lines, then draw in the contours through the points of equal depth.

A professional consultant can help you with the details of a bathymetric map. He will need one to determine the volume of water in the lake and the surface area of sediments located at each depth. Once those volume and area relationships are defined, a general description of the lake can be formulated which indicates flushing rate, the area where aquatic plants are expected to grow (littoral zone), the percentage of the lake bottom likely to become oxygen deficient during thermal stratification, etc.

Existing biological and chemical information about a lake then can be incorporated by the "pro" into the physical description. For instance, if spring phosphorus concentrations are known, a prediction can be made regarding the trophic status of the lake. If oxygen concentrations have been observed, rates of oxygen depletion in the bottom waters can be calculated. Likewise, if nutrient concentrations are known, they can be applied to determine mass balances between inflow and outflow of the lake, and potential accumulation rates in the lake.

The next step in the technical analysis of a lake ecosystem is a testing program to measure lake nutrient supplies and the effects of metabolism (photosynthesis and respiration) on lake water and sediments. The testing program is best broken into two segments. The first task is an intensive examination of the annual cycle of seasonal changes in the lake ecosystem, including both lake and watershed. Chemical, physical, and biological characteristics of water at different depths in the lake, of water entering from the watershed, and of water leaving via the lake outlet must be recorded at different times of year, under different weather conditions, during storm events, etc. When that testing is completed, analyzed, and incorporated into a management plan, the stage is set for the second phase of testing: long-range monitoring to observe changes in the lake, including the effects of management efforts.

Lake Ecosystem Management

Management of a lake ecosystem involves controlling nutrients in both watersheds and lakes. The watershed is the ultimate source of most of the nutrients in the lake (excluding only atmospheric precipitation directly on the lake), and is the first (and most cost-effective) line of defense against future phosphorus loading. Watershed nutrient control involves erosion abatement and management of agriculture, residential development, septic systems, wastewater disposal, stormwater drainage, and any other significant land-use in the watershed.

In-lake control of nutrients generally involves suppression of re-cycling from sediments. Direct techniques include removing sediments, removing nutrient-rich water immediately overlying sediments, and covering sediments with an impervious material. Indirect techniques include the maintenance of dissolved oxygen in water over-lying sediments and adding substances which make phosphorus insoluble.

Note: Oxygenating water overlying sediments retards the diffusion of dissolved phosphorus from sediments because iron is present in lakes and lake sediments. In the presence of a few parts per million (ppm = mg/L) molecular oxygen, iron oxide assumes its oxidized form (ferric iron = Fe^{+++}) and becomes ferric hydoxide in the presence of water. Ferric hydroxide is itself insoluble, and combines with phosphorus in an insoluble complex. Ferric hydroxide is a major part of the "**oxidized microzone**" found on sediments overlain by oxygenated water. Only a few millimeters thick, the oxidized microzone consists of hydrated metal oxides in a gel-like matrix which adsorbs many nutrient ions. When dissolved oxygen in the water overlying the sediment surface is exhausted by respiration, the ferric iron in the oxidized microzone is chemically reduced to soluble ferrous iron (Fe^{++}), the oxidized microzone disappears, and the diffusion of phosphorus from sediments to overlying water increases sharply.

MAJOR NUTRIENT PATHWAYS IN LAKES

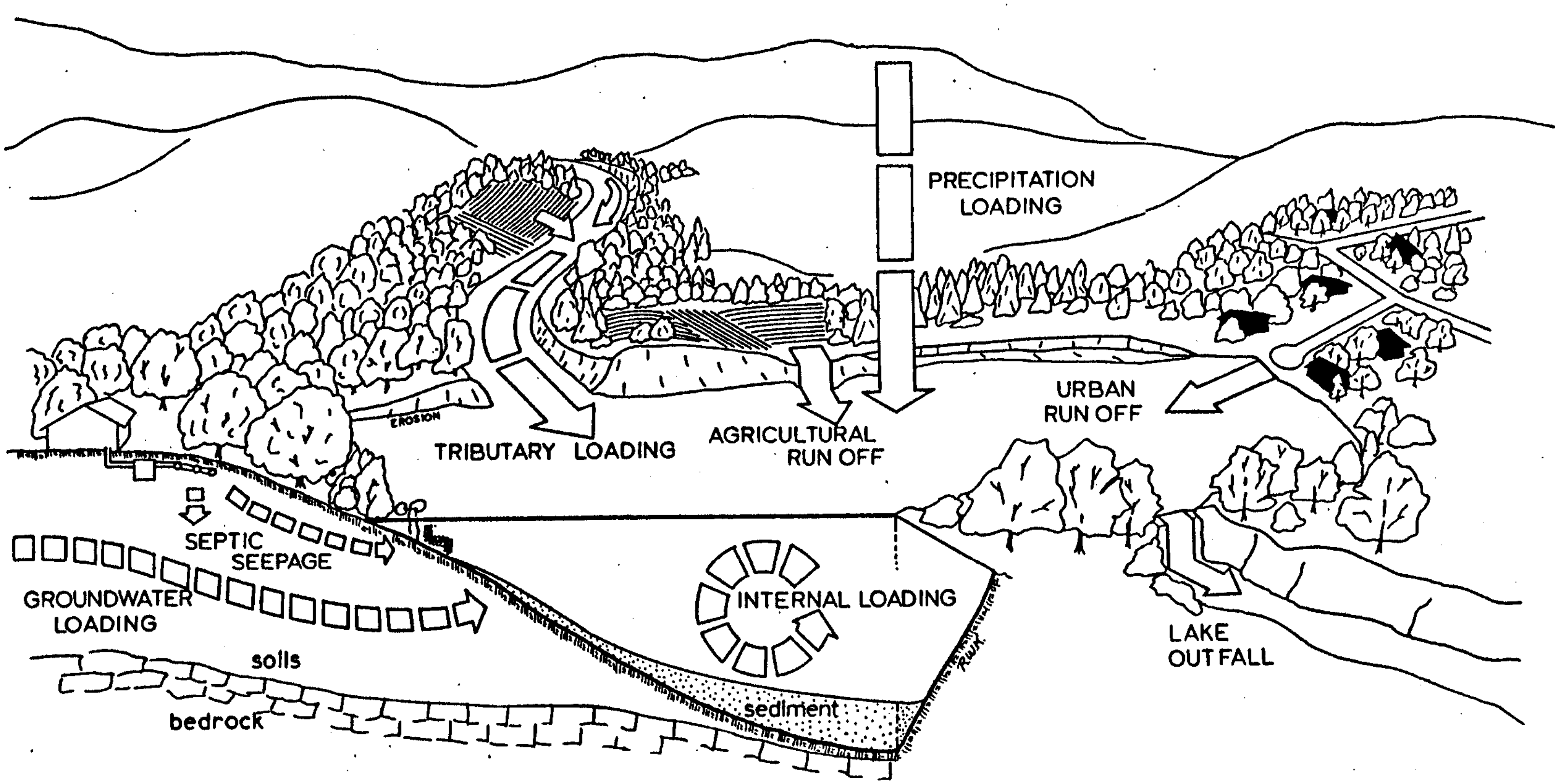


Figure 4. Major Nutrient Pathways in the Lake Ecosystem.

A lake ecosystem consists of a lake drainage basin, its lake, the lake's sediments, and the organisms that inhabit them. Lake succession is the geological process which tends to make lakes shallower by filling them with mineral material from their drainage basin. Eutrophication is the biological response of lakes to increasing nutrient inputs.

Erosion of both mineral soil and nutrients is accelerated by disturbance of the drainage basin. The most important potential sources of nutrient input from drainage basins tend to be diffuse (**non-point sources**): small tributary streams and storm drains, **groundwater**, **septic seepage**, **runoff**, and **precipitation**. **Point sources** tend to be more noticeable, easier to fix technically (but more difficult financially and politically), and to be associated with impoundment lakes on large rivers.

Internal nutrient re-cycling ("**internal loading**") occurs when nutrients which have already entered lakes, been incorporated into living material, and fallen to the bottom re-enter lake water by diffusion from lake sediments during anoxia. Anoxia in water overlying lake sediments and nutrient recycling occur during thermal stratification, particularly in the summer.

The relative contributions of nutrient sources must be examined and understood to guide management efforts.

CHAPTER 3

LAKE ECOSYSTEMS: NUTRIENTS AND ENERGY

"**Ecosystem**" is the unit of natural organization in which living organisms interact collectively with basic physical and chemical processes in the environment. The operation of an ecosystem depends upon available energy and nutrients. Plants have the ability to divert energy from solar radiation (a physical process) to photosynthesis (a biological process). Energy diverted to photosynthesis is stored in the organic matter of plants which is preyed upon by animals. Animals then use the diverted energy to live, to grow, to pass on to their predators, and to do things like read a lake handbook. The energy originally captured as sunlight by plants is returned to the physical world as very low temperature heat released by biochemical reactions in all living organisms. The amount of biological activity in a lake ecosystem depends ultimately upon the amount of energy available for photosynthesis and the amount of biochemical "machinery" (for both photosynthesis and respiration) which can be constructed from available nutrients. When energy is limited and nutrients are abundant, biochemical machinery only does as much as energy permits. When energy is abundant and nutrients are limited, biochemical machinery is inadequate to use the energy available.

In small, soft water lake ecosystems most energy enters the ecosystem through terrestrial photosynthesis in the watershed. Photosynthesis in the lake, itself, is limited by physical and chemical characteristics of the water. About one half of photosynthetically active radiation is reflected and refracted at the lake surface, and much of the rest may be absorbed by "tea colored" (humic) organic matter dissolved in the lake water. Energy from terrestrial photosynthesis helps lakes by creating the terrestrial community which takes up nutrients and prevents erosion of the drainage basin into the lake. However, large amounts of particulate and dissolved organic matter may be washed and blown into lakes from land. Terrestrial organic material affects physical/chemical properties and processes of lakes, combines with products of aquatic photosynthesis to support lake **food-webs**, and accumulates in lake sediments.

Water is the medium which connects the components of lake ecosystems: drainage basin, littoral zone, lake water, and lake sediments. Interactions among ecosystem components are studied by observing the volume and composition of water moving among them. Lakes are driven by energy received as organic matter from their drainage basins and as sunlight driving their own photosynthesis using nutrients entering from the drainage basin. Periodically, organic matter and nutrients from the watershed may be

supplemented by inputs from the littoral zone and lake sediments. The flow of nutrients and energy through a lake ecosystem will be explored in this section.

Watershed Contributions

The most effective approach to understanding lake eutrophication is to assess of the flow of phosphorus from the watershed through the lake on an annual basis. Phosphorus is important in lake eutrophication because it is a limiting nutrient in most lakes. The reasons for this are several-fold. First, phosphorus appears to have a unique role in biochemistry which cannot be duplicated by any other atom. Second, phosphorus is a rather scarce element relative to the others needed in large amounts by living organisms, i.e. carbon, hydrogen, oxygen, nitrogen, and sulfur. Finally, unlike other important nutrients, phosphorus has neither a gaseous phase nor a common gaseous compound. Unlike sulfur, for instance, phosphorus cannot form a gas such as hydrogen sulfide that can escape from lake sediments as bubbles. In fact, most compounds of phosphorus are insoluble as well as **non-volatile.** Once an atom of phosphorus has been covered by an inch or so of sediment, the probability of it again participating in lake ecosystem activity declines sharply.

Quality of lake water depends upon natural characteristics of the drainage basin and upon uses for which the land has been employed by man. Research has shown that the amount of watershed phosphorus reaching a lake can be predicted from the size and shape of the lake, the volume of watershed discharge to the lake, and the fractions of watershed which are urbanized, agricultural, or left in natural vegetation. The greatest export of phosphorus comes from urban watersheds. Agricultural watersheds export only about a third as much phosphorus. Forested watersheds lose about one fifth as much phosphorus as agricultural watersheds.

During most of the 19th century, much of New England was pasture or cropland. Stone walls from that era are now found in secondary forest or suburban houselots. Material eroded during 19th Century agriculture is being covered by material eroded during 20th Century roadbuilding, industrial, and residential development. The amounts and types of sediments which have entered lakes historically, plus current inputs, set the stage for what happens in lakes during the summer stratification.

Watershed Contributions: Watershed Soils

Soils around lakes have four properties important to the management of lakes: renovation capacity, clay content, depth to bedrock, and drainage. "**Renovation capacity**" is the ability of soil to remove contaminants (including nutrients) from water

passing through it. Wastewater renovation is the property of soils which make backyard septic systems work. Renovation capacity is commonly confused with "**percolation**". Percolation describes the rate at which water moves through soil. The distinction between renovation and percolation becomes important in very sandy soils. When particles of soil are large and coarse, with relatively large air spaces between them, the quality of water moving through the soil remains relatively unchanged. Percolation occurs without renovation.

Lakes associated with sandy, very well-drained soils (Fig. 5a.) are generally oligotrophic if their watersheds are undisturbed. Such lakes receive abundant groundwater and little surface runoff. If groundwater in the watershed is degraded by wastewater disposal, excessive fertilizer applications, salts, etc., the lake may become contaminated because groundwater seepage is rapid and renovation is poor.

The Congamond Lakes are located in excessively drained soil which forms part of the border between Suffield, Connecticut, and Southwick, Massachusetts. The Lakes lie in a belt of coarse sand and gravel, washed and deposited by meltwater from the last glacier. The watershed has a long history of agricultural use, most intensively for tobacco crops. The immediate lakefront, first developed as a seasonal recreational community, has become a setting for high density, year-round residences. These land uses have exceeded the renovation capacity of the rapid and shallow groundwater system, increasing the nutrient load on the lakes.

The second property of soil important for watershed management is the presence of compact soil layers associated with high "**clay content**". Clay particles are much smaller than those of sand and gravel, hence have greater surface area and less air space between them. These characteristics give clay soils renovative powers much superior to those of sand. Nutrients such as phosphorus come in contact with more soil surface and are more likely to be **adsorbed** by clay particles. Clay is sometimes present in compact and impermeable layers which impede soil water drainage. As depicted in Figure 5b., the water table in clay areas is high in the spring when water is often "perched" on clay **strata** which prevent downward seepage. In contrast to the potential for groundwater contamination in soils which are too sandy, soils which have too much clay are able to purify water but are unable to accept enough. Thus, septic system failure (backup) and soil erosion are problems on clay soils, while groundwater contamination is a problem in gravelly soils.

The third important property of soils is "**depth to bedrock**" (Fig. 5c.). Very little purification occurs in water seeping through shallow soils. Further, the renovation and flow of water over rock layers and through cracks in rock are very difficult to assess. When ground water flowing through fractured rock becomes

contaminated by domestic, agricultural, or industrial sources, trouble can be anticipated in wells and surface water for a large radius.

The fourth property of watershed soils vital to lake quality is "**drainage**". "Poorly drained" and "very poorly drained" soils (Fig. 5d.) are commonly defined as inland wetlands. Wetland soils are waterlogged much of the time, causing an absence of oxygen that results in anaerobic respiration and an accumulation of organic matter in the soil. Water draining through organic wetland soils acquires dissolved organic ("**humic**") materials which stain the water "tea-color". That coloration has an important effect on of underwater light. Loss of blue light, strongly absorbed by the yellow-brown stain, interfers with germination and photosynthesis in aquatic plants in deeper water. In general, light energy is absorbed in a shallower stratum, reducing aquatic photosynthesis, and causing stronger, shallower thermal stratification because solar radiation is absorbed closer to the surface. During the growing season, wetland plants and soils take up nutrients from surface and groundwater, causing wetlands to be **nutrient sinks** in general. However, wetlands periodically become nutrient sources, particularly during and after extreme changes in water level.

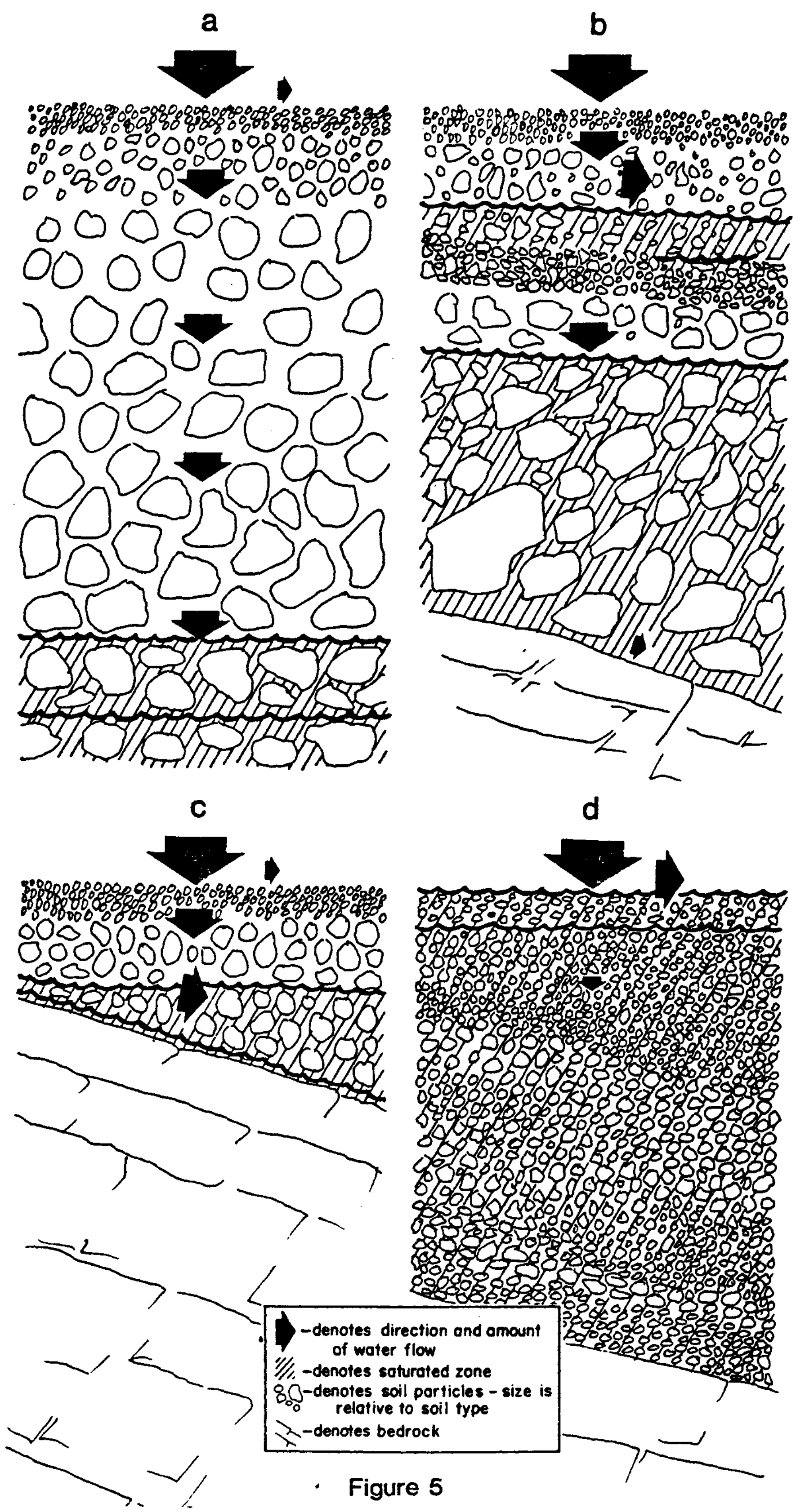

a
b
c
d
-denotes direction and amount of water flow
-denotes saturated zone
-denotes soil particles - size is relative to soil type
-denotes bedrock

Figure 5

Figure 5. Typical Soil Profiles (magnified schematic view).

Smaller soil particles generally mean better nutrient removal and poorer drainage. Soil A used for wastewater disposal is likely to have poor renovation capacity and produce nutrient enrichment in nearby lakes. Soils B, C, and D used for wastewater disposal are likely to fail because they are unable to accept enough water, leading to blockage and surface breakout. The best type of soil for wastewater disposal is a mixture of sand and smaller particles (sandy and fine sandy loam) which will accept the required quantity of wastewater while providing good purification. In general, the size of the wastewater distribution system (leaching field) should be based on field tests performed during the wettest part of the year. Also, the "effective lifetime" of phosphorus removal should be maximized by increasing setback distances from lakes and tributary streams.

a. A Coarse, Sandy Soil - such as Hinkley, Merrimac, or Terrace Escarpments.

Precipitation and wastewater penetrates the soil and flows to the watertable readily. The watertable remains deep even during the spring groundwater maximum. The quality of groundwater moving through this soil type remains relatively unaltered because travel time is short and relatively few soil particles are encountered.

b. Effect of a Compact Soil Layer - hardpan.

Groundwater accumulates in a saturated zone (shaded) perched on a compact layer. During wet seasons groundwater moves down slope on the hardpan. The watertable remains relatively close to the surface throughout the year.

c. Shallow Bedrock.

Groundwater moves through the shallow soil and then flows down slope along the bedrock surface.

d. Poorly Drained Organic (Wetland) Soil.

The watertable remains close to the surface throughout the year. Particle size is very small relative to excessively drained soils illustrated in a.

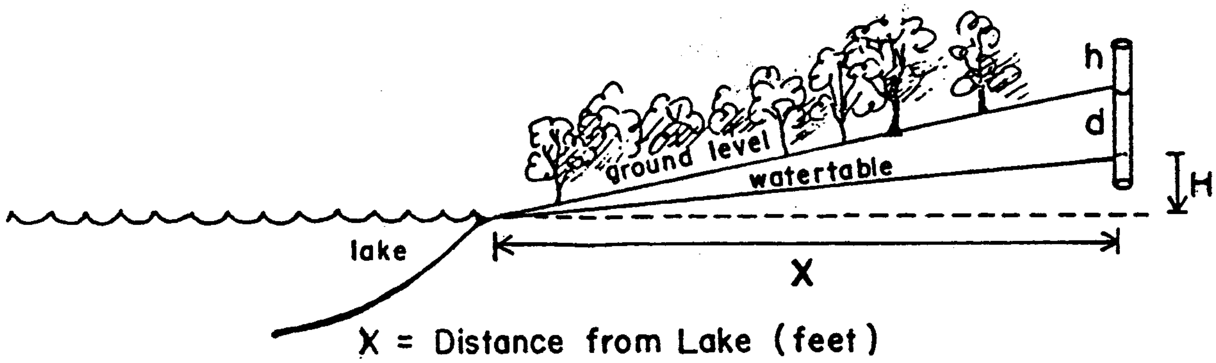
Watershed Contributions: Topography

Important topographic features in watershed landscapes include slopes, drainage divides, runoff patterns, and landscape formations such as wetlands. Figure 6 illustrates two approaches to mapping watershed topography which are useful to lake managers. The first approach is to use land surface contours to delineate a surface drainage basin, subbasins, and areas of steep slopes (Fig. 6a.). Topographic maps available from the USGS have contour intervals of ten feet (their next map series will have contours in metric units). When the surface of the drainage basin has been "read" from the topographic maps, soil groups may be superimposed on the topography with Soil Conservation Service (SCS) soil maps. Superimposing topographic and soil maps permits rapid identification of areas where unstable slopes and fragile soils create "hotspots" of erosion in a watershed.

The second mapping approach needed by lake managers defines subsurface features and drainage patterns of groundwater. Although surface features strongly influence groundwater flow, surface and subsurface drainage patterns are seldom identical. Groundwater is generally the dominant source of water for lakes occurring in sand and gravel. In such cases, the topography of the subsurface water table can be more important than surface topography. Identification of "watertable watersheds" requires technical assistance.

Groundwater drainage topography is estimated by installing water table observation wells and plotting the slope of the water table surface toward the lake. Groundwater discharge is a function of water table slope and the ability of the soil type to conduct water flow ("conductivity"). This method of calculating groundwater entering a lake, called the "Darcy Method", is illustrated in Figure 6b. Good practice in the Darcy Method requires the use of at least two observation wells (in addition to lake level) to define water table slope. The technique is easily computerized.

The Darcy method may be supplemented by two other approaches to estimating groundwater discharge. "Seepometers" (inverted buckets with bags to collect seepage water) may be installed in the lake to measure water coming through the lake bottom. When estimates of local evaporation are available, net groundwater input can be measured as the difference between surface inflows to a lake and lake outflow. When the volume of groundwater input is known and representative concentrations of nutrients in groundwater have been determined, the input of dissolved substances to the lake through groundwater can be calculated by multiplying concentration times volume.



X = Distance from Lake (feet)

h = Above ground height (cm)

d = Depth to watertable (cm)

H = Height (of W.T.) above lake level (cm)

Figure 6. Watershed Mapping.

a. Surface Topography.

Surface flow is at right angles to lines of equal elevation (contour lines). Using this axiom to visualize the flow of an imaginary drop of water, an outline of the surface drainage basin of a lake is rather easily plotted on a USGS topographic map. Superimposing a Soil Conservation Service soil map on the topographic map of the lake drainage basin quickly identifies wetland areas, areas where fragile soils coincide with steep slopes, and other features of interest for watershed nutrient budgets. A small, softwater lake and red maple swamp ecosystem in northeastern Connecticut is shown.

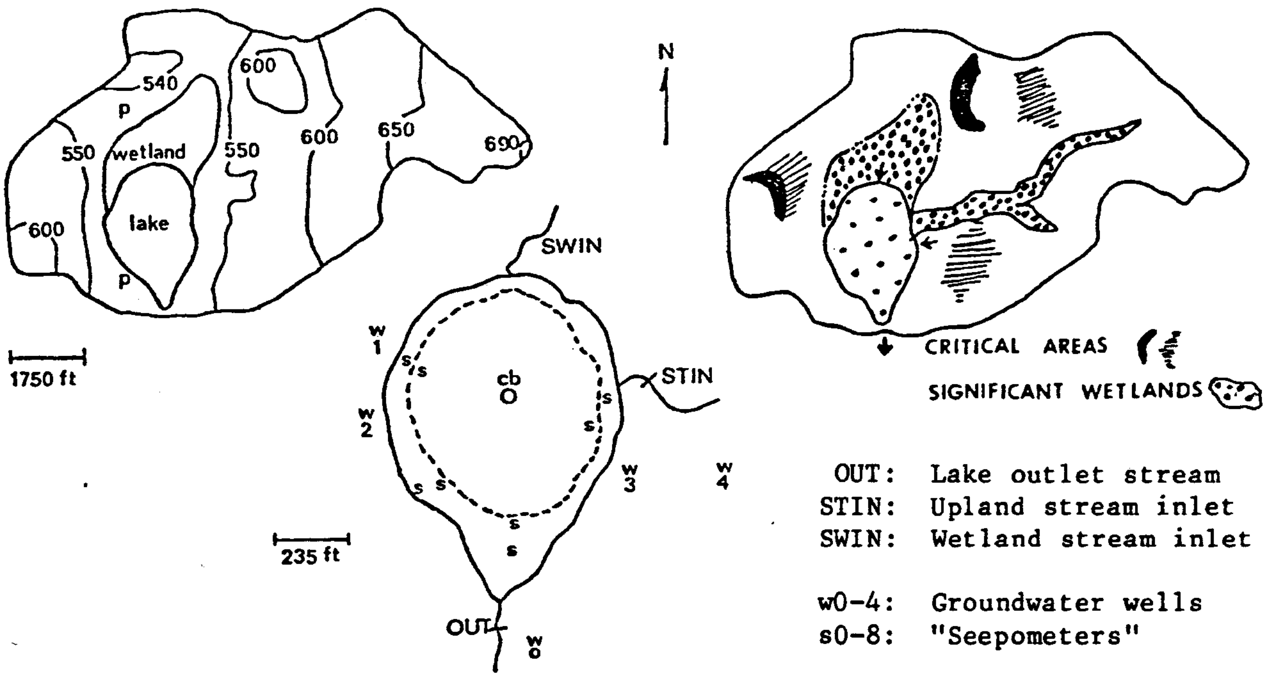


Figure 6. Watershed Mapping (cont.)

b. Subsurface Topography - Groundwater.

The Darcy method computes groundwater inputs to a lake from information on the slope of the watertable around the lake and the hydrologic conductivity of associated soils. Particularly in areas of excessively drained sands and gravel, the topography of the watertable can be very different from the land surface.

In most New England lakes, surface and groundwater topography and drainage boundaries are similar enough to ignore any differences. However, lakes which are known to be groundwater or "spring" fed require an analysis of both surface and subsurface drainage patterns.

Watershed Contributions: Lake and Stream Hydrology

The ultimate source of lake water is precipitation. The first step in defining a lake's hydrology is to determine watershed area and multiply that area by the amount of effective rainfall to estimate how much water flows through the lake in an average year. In Connecticut one may reasonably assume an annual total rain and snow fall of 48 inches. About one half of this amount returns to the atmosphere as water vapor ("**evapo-transpiration**"), and the balance ("**effective precipitation**") flows downhill as surface runoff or groundwater. Mean annual effective precipitation is about one half (24 inches) of total annual precipitation, but the proportion of effective to total precipitation varies seasonally due to changes in the water demands of terrestrial plant communities.

Mean precipitation is distributed very evenly thoughout the year (Fig. 7b.), but lakes receive most of their water between December and May because of water demands during the growing season by the terrestrial plant community. A method of estimating effective precipitation from a given rainstorm is illustrated in Figure 7a. The calculation requires knowledge of the length of the storm, the amount of precipitation, and the amount of precipitation in the weeks preceeding the storm.

The discharge of water from a drainage basin has a characteristic response pattern, called its "**unit hydrograph**", between the time precipitation occurs and the time runoff returns to pre-storm levels (Fig. 7c.). Defining a unit hydrograph for a lake drainage basin and each discernable subbasin greatly increases the ease and accuracy of estimating discharge and nutrient budgets. For instance, the highest phosphorus content of runoff occurs in the part of the runoff hydrograph where flow increases most rapidly. At peak flow phosphorus concentrations begin to decline, and minimum concentrations occur at "**base flow**" when groundwater contributes most to discharge. A unit hydrograph when applied to a storm event (intensity and duration) can be used to construct a runoff hydrograph which tells the investigator what he is sampling and when he should sample it. By determining representative phosphorus concentrations for each flow stage of each lake inlet in each season of the year, one can convert inches of rainfall directly into net phosphorus delivered to the lake. The combination of unit hydrographs, rainfall/runoff relations, and efficient sampling at critical times is a reliable way to identify specific subbasins requiring nurtient control, to provide direct

assessments of lake nutrient loading, and to accurately monitor progress in management.

Precipitation directly on the lake surface can be a significant portion of the lake's nutrient budget at certain times of year. For instance, the fraction of total phosphorus and nitrate entering a lake from direct precipitation increases markedly in the summer when runoff is at a minimum (Fig. 7h.). In contrast, atmospheric deposition of acids ("**acid rain**") accumulates with snow during the coldest part of the winter, and has the greatest effect on lake pH when the snow melts at ice-out and runoff is at a maximum.

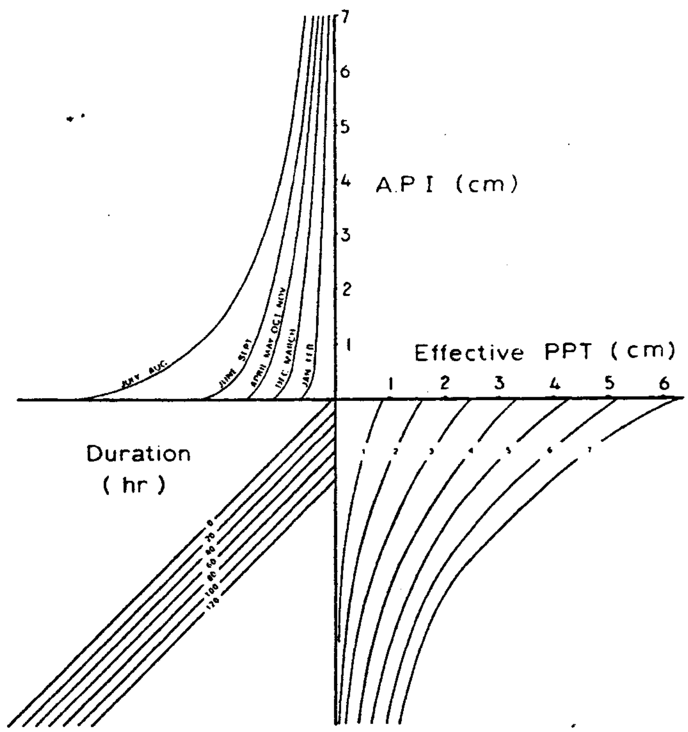


Figure 7. Hydrology.

Repeated sampling of all lake inflows is difficult and expensive. If major tributaries are studied carefully through several storm events, certain relationships can be defined which simplify and improve estimates of runoff in future storms.

a. Rainfall-Runoff Relationships.

The proportion of actual precipitation which becomes runoff (effective precipitation) depends upon seasonal demands on groundwater by terrestrial plants and then upon the duration of the storm (degree of saturation of the watershed). The nomogram was drawn from field data from a small lake/swamp system in NE Connecticut (Fig. 6a.). Similar nomograms may be constructed for other areas by observing seasonal variations of rainfall and runoff for a variety of storm events. To use the nomogram, one must know 1) the amount of precipitation in the previous two weeks (antecedent precipitation = API), 2) the date of the storm, 3) the duration of the rain, and 4) the amount of precipitation. The example uses 3 cm of antecedent precipitation, a storm in June, 60 hours of rainfall, and 4 cm actual precipitation. The effective precipitation is just under 2 cm.

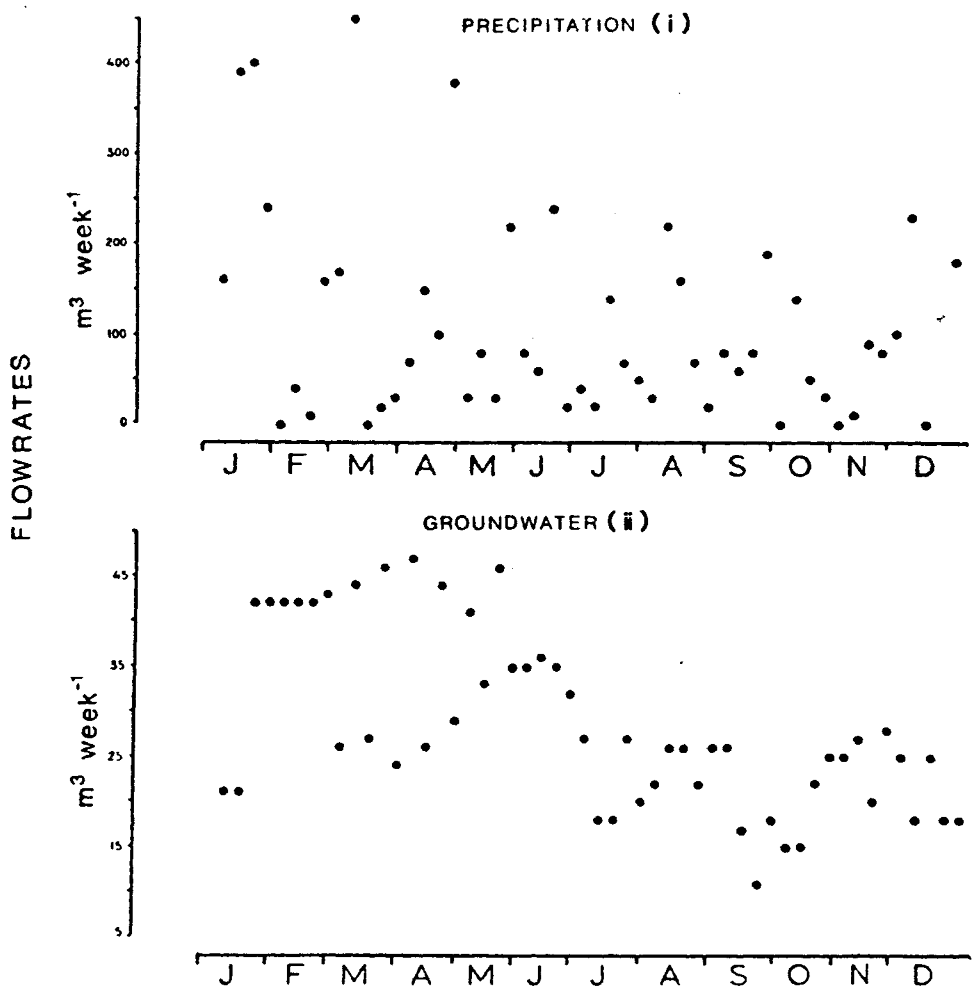


Figure 7. Hydrology (cont.)

b. Seasonal Precipitation and Runoff.

The relationship between precipitation (i) and groundwater (ii) flow in a small lake/swamp system in NE Connecticut. Precipitation is rather uniform throughout the year in Connecticut, but evapo-transpiration by terrestrial plants causes groundwater to decline through the growing season.

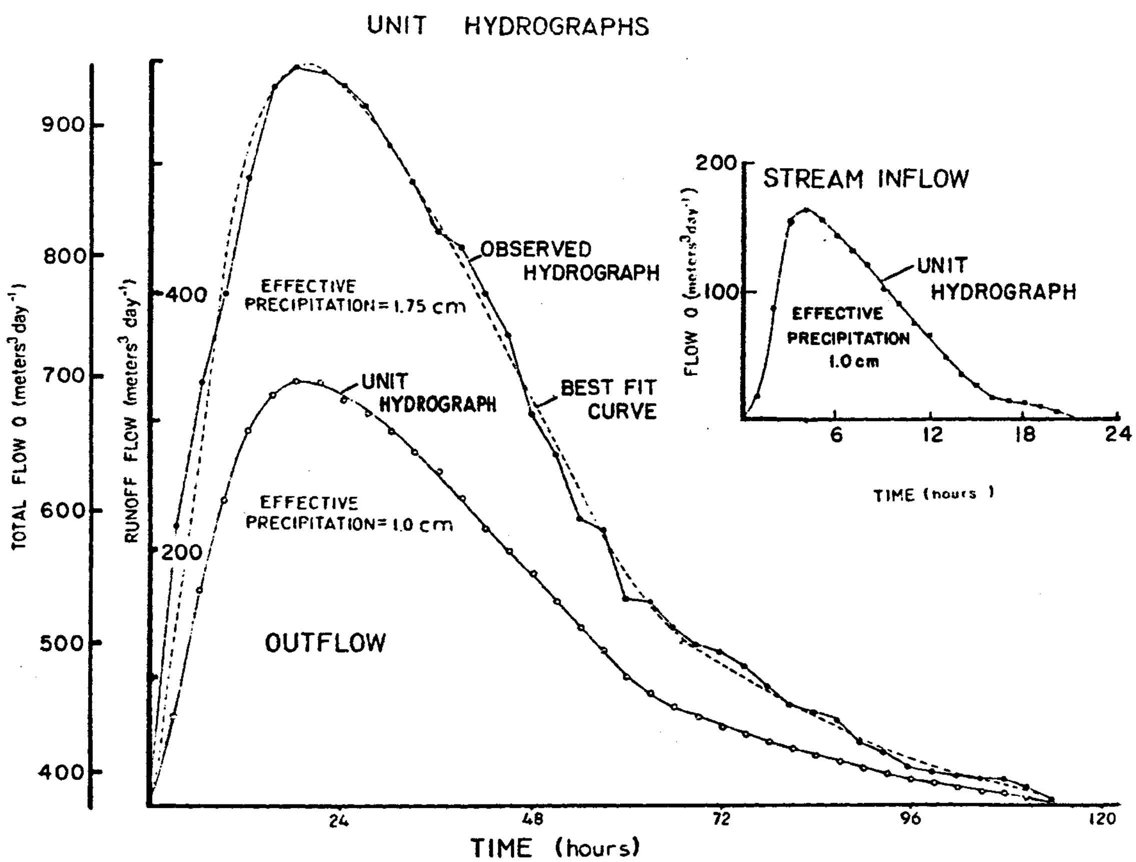


Figure 7. Hydrology (cont.)

c. Unit Hydrograph.

In addition to simplifying sampling and analysis of stream runoff, a unit hydrograph can be used in conjunction with the calculation of effective precipitation to estimate the relative amounts of surface and groundwater runoff in a stream at any given time. A unit hydrograph is constructed either by observing a time series of runoff volumes for a "unit storm" (i.e. 1 inch or 1 cm effective precipitation) in the field or by "synthetic modeling" techniques available from the Soil Conservation Service and in hydrology textbooks.

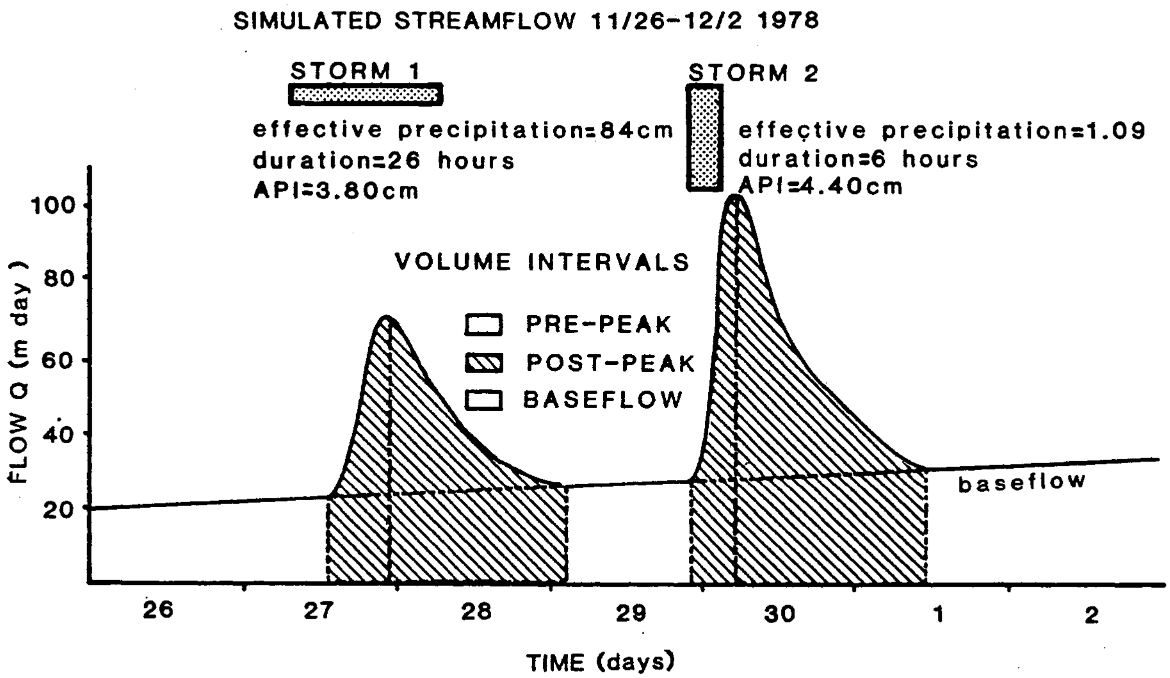
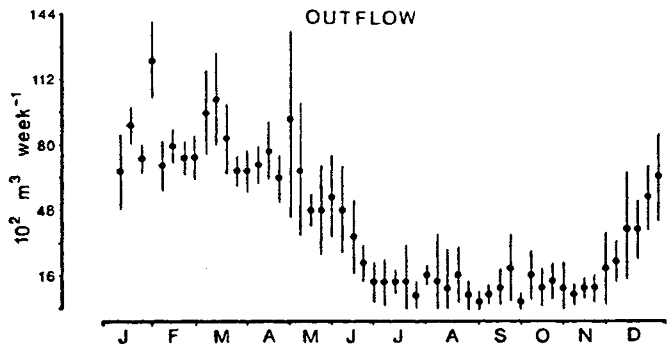


Figure 7. Hydrology (cont.)

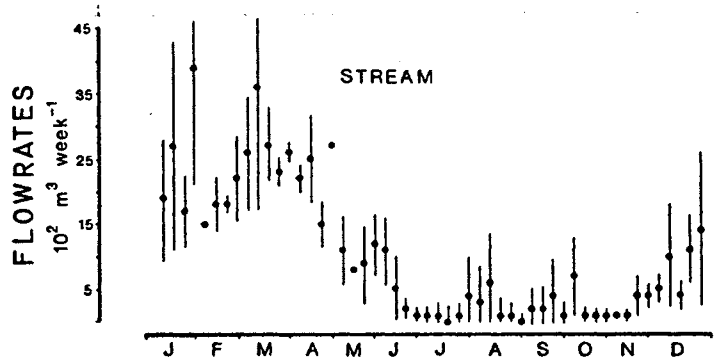
d. Simulated Streamflow.

Streamflow predicted from precipitation records and the unit hydrograph of a small stream in NE Connecticut.



e. Discharge from a Small Lake.

The lake receives discharges from a small upland stream and from a red maple swamp wetland. The lake discharges through a small stream to the Willimantic River.



f. Discharge from a Small Upland Stream.

Discharge from the upland stream into the lake (e.). Discharge almost stops in summer due to water demands by the terrestrial plant community.

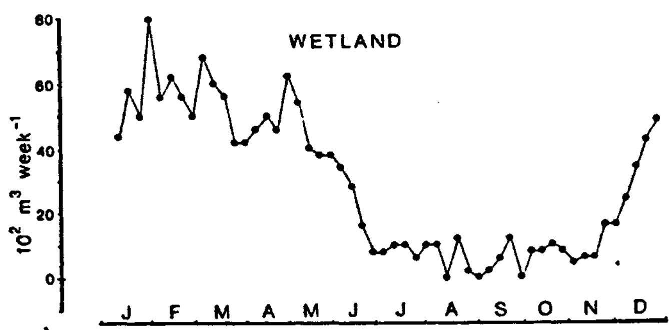


Figure 7. Hydrology (cont.)

g. Discharge from a Small Wetland.

Discharge from the wetland (red maple swamp) into the lake (e.) changes less abruptly than discharge from the upland.

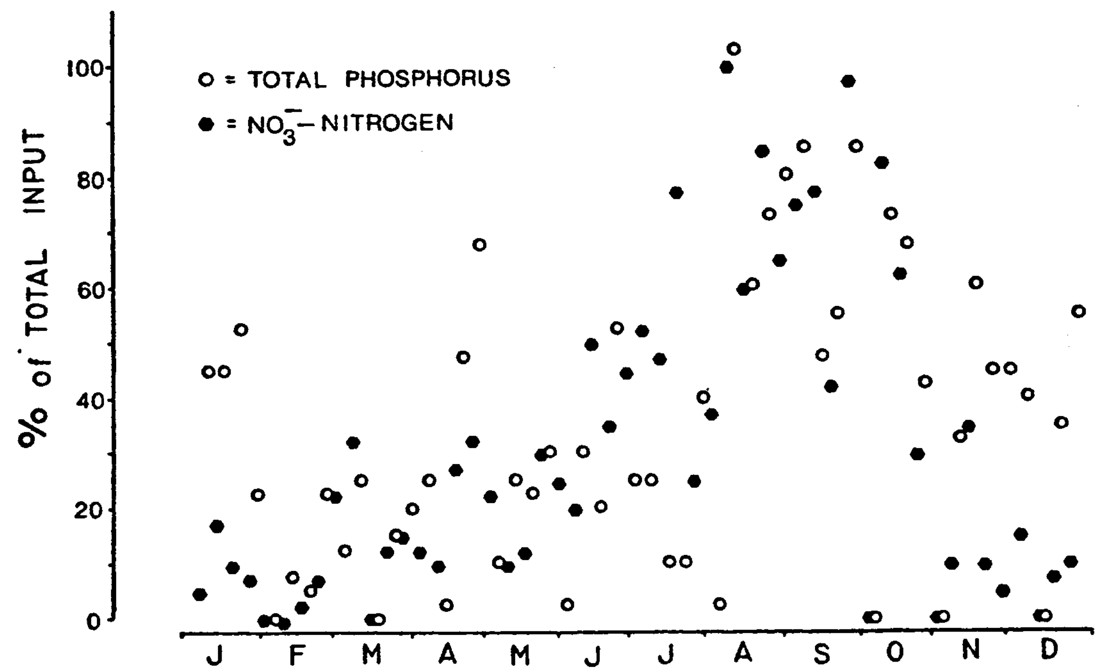


Figure 7. Hydrology (cont.)

h. Percentage Nutrient Input from Precipitation.

The relative amount of nutrients entering a lake directly as precipitation increases rather dramatically in some lakes during the growing season. This pattern results from the even distribution of rainfall during the uneven seasonal distribution of groundwater runoff.

Nutrient Budgets

A **nutrient budget** is much like a household budget. Both itemize income and outgo, and both tell you what's left. The concept is based on the principle that material (and money) is neither created nor destroyed. Thus, the amount of a nutrient in a lake depends upon the balance between summed inputs and outputs (the "input-output budget model").

Input-output budgets for total phosphorus, total nitrogen, dissolved and particulate organic matter, and several other substances are extremely useful for a lake manager. The first objective of nutrient budgeting is to itemize and estimate the relative importance of nutrient sources (inputs). An important distinction exists between external (watershed) sources and internal (in-lake release) sources. External nutrient sources are susceptible to more direct and cost-effective management than internal sources!!! The second objective of nutrient budgeting is to estimate the balance of nutrient residuals in the lake. This aspect of nutrient budgets is a major new chapter in limnology (the study of lakes).

Basic research over the last 20-30 years in the theory and practice of estimating lake nutrient budgets and their effects has created a series of useful "models" for important nutrients. The models are detailed mathematical expressions which estimate a critical piece of very difficult to obtain information from several pieces of much easier to obtain information. Essentially, the models use one or more very well tested correlations between what is known and what needs to be known about a lake. Thus, a lake manager can "plug into the model" what he knows about his specific lake, "run the model", and obtain the benefit of computations based on intensive research done elsewhere that he could never hope to duplicate on his own lake. Models have the potential to mislead, of course, and a responsible lake manager hedges his bets with some research on his own lake. Phosphorus models based on lake characteristics and land-use practices, models based on **synoptic field sampling**, unit hydrographs models, septic performance models, etc. are extremely efficient applications of basic science to practical problems, and they give a skillful lake manager tremendous predictive and diagnostic powers.

Nutrient Budgets: Spring Phosphorus Model

Several models have been derived which relate the concentration of phosphorus in a lake in spring (ice-out) to "**phosphorus tolerance**" of a lake, and "**allowable phosphorus**" inputs. In addition to a determination of the concentration of total phosphorus at ice-out, these models use readily available information about lakes such as mean (average) depth, lake surface

area, drainage basin area, etc. (Fig. 8a.).

The Dillon-Rigler Model, the most popular type of spring phosphorus model, uses only the spring phosphorus concentration, the annual water budget, and some general dimensions of the lake. The model serves several applications. First, it provides an estimate of the total annual phosphorus load on your specific lake. Second, this estimate can be compared to annual phosphorus loads at other lakes to establish a criterion for watershed performance and potential management. Third, the model can be "run backwards" to find the concentration of spring phosphorus which must be achieved to reach a particular management goal. Finally, the estimate of phosphorus loading from the model can be compared to actual input measurements to verify that all sources have been found and controlled.

The chief weakness of the Dillon-Rigler Model is its total focus on watershed sources. Later in the growing season when evapo-transpiration by the terrestrial plant community is at a maximum and watershed discharge to the lake is at a minimum, the concentration of phosphorus in lakes begins to be influenced by in-lake factors such as recycling from the sediments. These complications are likely in very shallow lakes, lakes with anoxic hypolimnia, and lakes susceptible to mixing by wind. Recent research on the effects and modelling of internal events such as hypolimnetic anoxia and mixing offer some promise for future management of lake nutrient recycling. The new models are still being tested and refined, and are not yet ready for inclusion in a general lake management guide.

Figure 8. Nutrient Budgets.

Three useful models to estimate the nutrient status of lake ecosystems based on external (watershed) inputs. They use an annual time scale and tend to be insensitive to seasonal effects. These models focus on external nutrient sources, hence do not work for internal nutrient sources.

a: $TP = \frac{L(1-Rp)}{\bar{z}\rho}$; $Rp = \frac{13.2}{13.2} + qs$

- TP = total phosphate ppb
- L = phos. load per area
- $\bar{z}$ = mean depth
- ρ = flushing rate
- qs = annual water load relative to surface area
- Rp = phos. retention fraction

a. Kirchner and Dillon Model.

A spring phosphorus model derived by W. B. Kirchner and P. J. Dillon, this is a variant of the "Dillon-Rigler" type model. The model predicts phosphorus content of a lake based upon hydrology (flushing rate and water load) and dimensions of the lake such as area and mean depth. The model can be manipulated algebraically for a number of uses, including a comparison of computed and observed phosphorus concentrations to detect internal phosphorus loading by re-cycling in the lake.

Nutrient Budgets: Land-use Models

Efforts to reduce lake eutrophication by managing watersheds are more effective when contributions of nutrients from specific land-uses are known. Figure 8b. illustrates a model which predicts export of phosphorus from a unit surface area of watershed in either urban, agricultural, or woodland use. When verified in the field by comparing predicted to observed phosphorus concentrations, this approach establishes the relative importance of various parts of the watershed for control.

Another method for measuring the relative importance of various parts of the watershed is a watershed model which estimates the phosphorus contribution from non-point sources. The model is described in detail in The Windham Regional Planning Agency Report, Lake Management Handbook: a guide to quantifying phosphorus inputs to lakes (see Appendix I). The method involves identification of erodible areas, use of the **universal soil loss equations**, and other techniques developed by the Soil Conservation Service and the Connecticut Agricultural Experiment Station to estimate sediment and phosphorus loads on lakes. This watershed land-use model distinguishes cropland, pasture, forest, urban, suburban, estate, wetland, and other land-uses. The model is very helpful for quiding watershed and nutrient management.

b: $$P = \frac{(Q + 1.2)}{Q + 12}(170\,U + 54\,A + 10W)/D$$

- P = phos. conc. ppb
- Q = meters of water per year of load relative to surface area
- D = water export from entire watershed in meters per year
- U,A,W = fractions of watershed in urban, agricultural and woodland areas

Figure 8. Nutrient Budgets (cont.)

b. Connecticut Agricultural Experiment Station Model.

A land-use model derived for Connecticut lakes by W. A. Norvel, C. R. Frink, and D. E. Hill. The model predicts the concentration of phosphorus from watershed use, i.e. the amount in urban, agricultural, or woodland classifications.

Nutrient Budgets: Unit Hydrograph Model

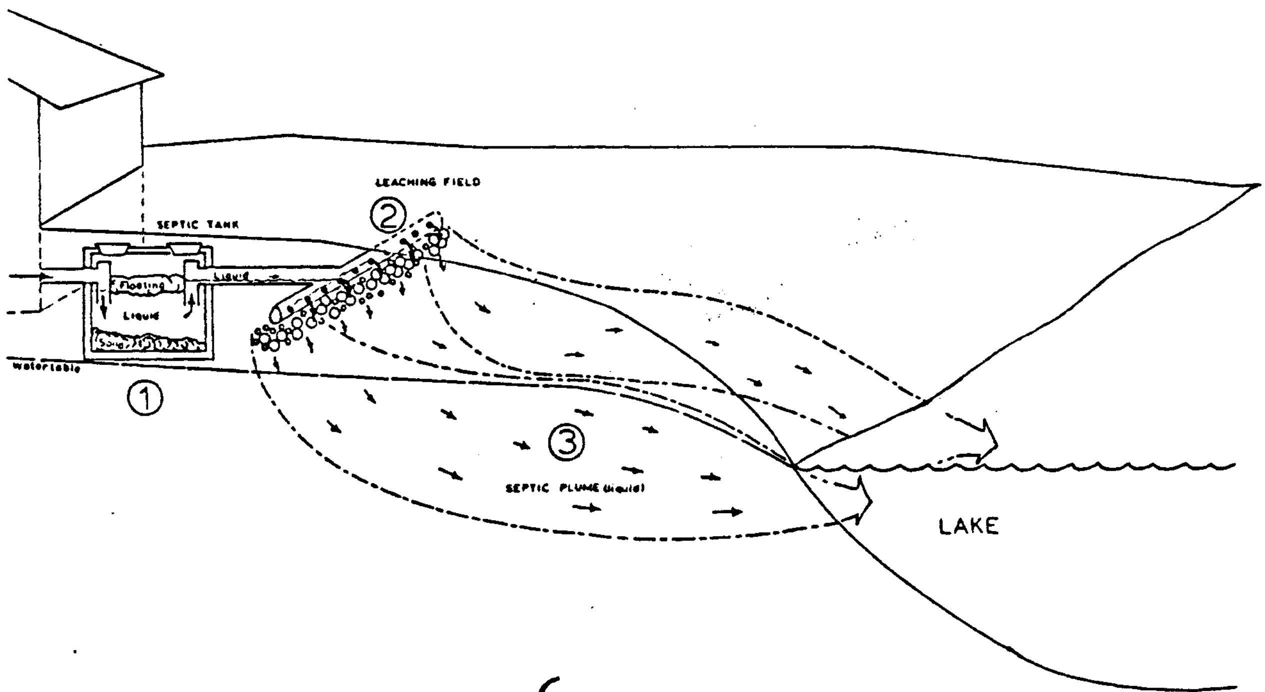
Runoff from a storm occurs with a characteristic distribution through time (the "unit hydrograph") for a given drainage basin or subbasin. Determining typical seasonal nutrient concentrations at different flow stages in a drainage system is an extremely cost-effective investment in sampling effort and nutrient budget accuracy. Figures 7c. and 7d. illustrates the three characteristic flow stages of a unit hydrograph. Immediately following the onset of a storm is the "**prepeak flow**" stage when flow is increasing and phosphorus concentration is generally highest. After a characteristic period of time flow peaks and then diminishes in the "**postpeak flow**" stage. "**Base flow**" occurs between precipitation events and consists entirely of the groundwater contribution to surface flow. The relationship between total phosphorus concentration and flow stage is statistically significant, with postpeak concentrations generally about three times baseflow, and prepeak about 20% higher than postpeak. Improved accuracy and sampling efficiency comes from knowing the flow stage at which samples are taken and the relative amounts of discharge which occur in each flow stage.

Nutrient Budgets: Septic Performance Models

A septic system is composed of three "processing components": the septic tank, the leaching field, and the septic plume. In the **septic tank** solid materials which either settle or float are separated from liquid wastes. The solid materials are stored and, to a degree, digested by bacteria. More material is put into septic systems than can be digested. The accumulation of solid materials must be pumped out at regular intervals. Liquid waste flows from the septic tank to a **leaching field** where the liquid is distributed over beds of stone, gravel, and sand. Bacteria also live on these materials and further digest the dissolved organic material. Liquid leaving the leaching field flows downhill on top of the watertable. The wastewater forms a **septic plume** containing high levels of nutrients which may reach a nearby lake. The dissolved nutrients tend to "stick" to soil particles, and the wastewater plume undergoes further treatment as it moves, depending on soil type and depth to watertable.

The important considerations for septic systems are how much phosphorus enters the system and how well the soils remove dissolved phosphate from the plume. Those aspects can be estimated for a septic system in a lake watershed by determining (a) the average use of the system, (b) the volume of soil through which the plume moves, and (c) the ability of the soil to remove dissolved phosphate (Fig. 8c.). That information permits a calculation of the effective lifetime of a septic system, and an estimate of how much phosphorus enters a lake from a system when effective lifetime has been exceeded. The procedure can be used

to estimate phosphorus produced by residential land, including phosphorus from septic systems which have not failed by health code standards. The methodology is found in the Windham Regional Planning Agency Report, "Lake Management Handbook: a guide to quantifying phosphorus inputs in lakes."



c: $V \times C \div S = T$ (years)

- V = soil volume
- C = phos. adsorption coefficient specific to soil type
- S = annual phos. load of waste
- T = lifetime of the septic system for phos. removal

Figure 8. Nutrient Budgets (cont.)

c. Septic System Lifetime Model.

The model predicts the useful lifetime (in years) of the phosphorus removal function in septic systems. The model requires information on the distance the septic plume must travel to reach a lake, the amount of phosphorus the soil can remove from wastewater, and the estimated amount of phosphorus put into the septic system each year. The model is used to estimate when and how much phosphorus reaches a lake from septic systems. The model is most useful when used in conjunction with the above models for overall phosphorus inputs.

Some Watershed Nutrient Sources

Nutrients enter lakes from watersheds as either "point" or "non-point sources". Point sources are focused, easily observed inflows such as inlet streams, drainage culverts, conduits, pipes, etc. Non-point sources are diffused inflows such as surface erosion, groundwater, septic system plumes, wet and dry atmospheric fallout directly on lakes, waterfowl wastes, etc. Point sources generally are easier to analyze and control than non-point sources. Samples are conveniently obtained from point sources, discharge can be measured directly, and the calculation of total input from concentrations times volumes is unambiguous.

Watershed Nutrient Sources: Storm Runoff

Storm drains must be sampled quickly, either during or immediately following a rainfall event. The very first part of storm runoff contains accumulated atmospheric "dry-fall" washed from exposed surfaces. Dry-fall is known to include phosphorus (probably in excess of 100 milligrams of phosphorus per square meter per year in Connecticut) plus sulfur and nitrogen compounds which cause "acid rain". Areas of pavement, rooftops, and other impervious surfaces collect significant amounts of dry-fall during periods of dry weather. A watershed largely in commercial or dense residential use can produce enough phosphorus runoff after a summer thunderstorm to nourish an algal bloom. The phosphorus in storm runoff from urban areas is effectively treated by collecting the first flush of storm water in dry wells. The latter part of storm runoff has much less phosphorus and can be allowed to by-pass the dry well system. Water in the dry wells can be allowed to seep into the ground, thus treating the water and recharging the groundwater table.

Watershed Nutrient Sources: Agriculture

The amount of nutrient input to a lake watershed from raising livestock can be calculated from the number of lifestock animals of specific kinds which are present. For instance, a dairy cow produces as much waste as twenty people, and a beef animal about as much as fourteen people. A simple method of calculating "animal units" of waste and equivalent nutrient export is found in the Windham Regional Planning Agency Handbook.

Table 2. Animal Units of Phosphorus Waste.

Feedlot Identifier: Farm on North Main Street, Greenwater, CT

Animal Units	Number of Animals	Number of Units
0.7 Dairy Cows	140	200.0
1.0 Beef Cows	20	20.0
2.5 Hogs	10	4.0
1.0 Horses	2	2.0
10.0 Sheep	15	1.5
50.0 Turkeys	25	0.5
	Total Animal Units:	228.0

Phosphorus Load Computation: Yi = R x N x A x Ci x Ld

Where:

R = Direct Runoff (e.g. 0.27 m/yr)
(= ca. 11 inches runoff from storms exceeding 0.5 inches).

N = Animal Units (e.g. 228.0)(from above).

A = Average Effective Feeding Area
(e.g. 20 sq. meters per animal unit).

Ci = Average Total Phosphorus Concentration in Runoff
(e.g. 0.60 g P/liter from feedlots).

Ld = Delivery Ratio (e.g. 0.9)
(ranges from 0.7 for very large areas to 0.9 for small areas close to streams).

Estimated Total Phosphorus Load from Identified Source =

66 kg P per year.

Source: Windham Regional Planning Agency. Lake Management Handbook - A guide to quantifying phosphorus inputs to lakes. March 1982.)

Croplands are a significant source of both nutrients and sediments through soil loss after plowing and tilling. Total export can be estimated using the universal soil loss equations found in the Windham Regional Planning Agency Handbook. The soil loss equations yield an estimate of soil volume mobilized from its location. Because much of the mobilized soil is redeposited prior to reaching a stream of lake, the model yields an overestimate of lake sediment load. However the model is useful for estimating a "worst case" load rate and for identifying critical areas needing management. Control practices include contour plowing, minimum tillage, no-till planting, manure and fertilizer management, etc.

Watershed Nutrient Sources: Fertilizers

When large areas of watershed are in cropland (including lawns), fertilization practices become a significant factor in watershed nutrient export. The fate of fertilizer nutrients depends upon how and when fertilizers are applied. Application of chemical fertilizers and manure is best done after frost has left the ground, and the land should be tilled immediately following application. Manure is often spread on frozen ground because facilities for winter storage of manure are inadequate and because normally wet areas are accessible. Winter application of manure results in large losses of nutrients in surface runoff. Construction of winter manure storage facilities has economic benefits for both the farmer (more efficient use of nutrients by crops and storage during summer when a crop prevents application) and the lake manager (better nutrient retention by croplands and less entering lakes).

Fertilization of lawns immediately adjacent to lakes also is an opportunity for nutrient enrichment of runoff. For lawns within about 300 feet of a lake, low phosphorus fertilizers and grass species requiring small amounts of phosphorus should be used. An inexpensive soil test will provide specific fertilizer recommendations, and prevent over-fertilization (a common occurrence thanks to advertising campaigns). In lake areas fertilizers should be applied in early summer (after spring storms), and washed into the soil by moderate sprinkling after application. These precautions will result in a greener lawn and a cleaner lake.

Watershed Nutrient Sources: Waterfowl

The preferred diet of Canada Geese is new grass sprouts and high nutrient grasses. Thus, they seek areas where grass is mowed frequently and heavily fertilized (such as golf courses). They also readily accept handouts from people and quickly become semi-domesticated. People feeding geese near a body of water will tend to keep geese at that location even when natural food in the

vicinity is not abundant.

Another factor which appears to attract Canada Geese to certain lakes and ponds is an open view from the water to feeding or resting areas on land. Behavioral research on Canada Geese indicates that a clearly seen feeding area reduces their fear of attack by predators on land. Thus, the combination of a small lake or pond, an open view of a large potential grazing area, the presence of nutrient-rich grass or agricultural fields, and food handouts from people are the major attraction for flocks of geese large enough to be a nuisance. A major problem created by large flocks of geese inhabiting a lake for long periods is the nutrients in their wastes. One goose excretes approximately 50 grams of phosphorus per month.

Flocks of geese reach nuisance proportions primarily in the fall and winter. Their behavior and habitat preferences during the spring and summer nesting season are significantly different. Nesting apparently requires more solitude, more cover, irregular shorelines, and/or small islands.

The display of styrofoam swans is a method having some success discouraging geese from establishing themselves on golf courses and family ponds. Swans are the only waterfowl Canada Geese avoid, although they will coexist on the same pond under some circumstances. The styrofoam swans must be in a threatening posture which consists of having the wings folded but in a raised position. Swans normally adopt this posture when guarding a mate and/or their young. The technique works best when at least two adult and one or two young (cygnets) styrofoam models are deployed. Other devices and suggestions for habitat modifications to control nuisance geese are available from the U. S. Fish and Wildlife Service (USFWS).

Lake Ecosystems

Lakes contain many life forms (Fig 9a.) which work in concert to produce (Fig. 9b.) and use (Fig. 9c.) material and energy in a highly ordered system. Energy enters the lake ecosystem by photosynthesis either in the lake or the lake drainage basin (Fig. 10.). **Autotrophs** capture solar energy radiating through air or water, and store ("fix") the captured energy in the products of **photosynthesis:** oxygen and organic matter. The fixed energy is recovered by animals and bacteria when oxygen and organic matter are recombined in **respiration.** The products of respiration, water and carbon dioxide, are once again available for photosynthetic conversion to oxygen and organic matter.

The organic matter and energy fixed by autotrophs ("**primary producers**"), are passed on to the first tier of **heterotrophs** ("**herbivores or primary consumers**"). Herbivory is a difficult

biochemical step involving the conversion of plant (carbohydrate) material to animal (protein) material. In fact, herbivory is so inefficient that much plant matter goes uneaten, and is left at the end of the growing season to be decomposed by bacteria. In contrast to plants, bacteria are a good source of nutrition, and a large number of aquatic animals called "**filter feeders**" prey on bacteria as well as algae. The term "**detritus**" is used to distinquish organic matter decomposed by bacteria (which are subsequently the prey of filter-feeders) from organic matter preyed upon while alive ("**grazed**").

Omnivorous filter-feeders make the products of both aquatic (algae) and terrestrial photosynthesis (particulate and dissolved terrestrial detritus) available to aquatic predators (secondary consumers) which eat the primary consumers. Each step in the "**food chain**" from primary producers to the highest predators involves losses of organic matter and energy to respiration, incomplete digestion, etc. Thus, the collective mass ("**biomass**") of autotrophs is larger than the biomass of primary consumers, and the biomass of primarary consumers is larger than the biomass of secondary consumers, etc. The term "**ecological pyramid**" alludes to this phenomenon.
Lakes which "tap" into the terrestrial food chain via the the use of terrestrial detritus have anomalous consumer biomasses. Crossing-over between food sources by animals makes the term "food-web" more accurate than "food-chain", and reminds us that a lake is but part of a much larger ecosystem.

Anaerobic metabolism in lakes is an extension of the detrital side of the "food-web". Bacteria decomposing and respiring detrital organic matter do not stop when oxygen is exhausted. Instead, bacteria switch from **aerobic respiration** to **anaerobic respiration** and **fermentation**. In the absence of oxygen, not all the energy can be recovered from organic matter by respiration. Thus, the products of anaerobic respiration and fermentation (inorganic and organic, respectively) contain residual energy subject to subsequent reactions. That is the energy which drives "**chemolithotrophy**", a process which synthesizes organic matter in the absence of even dim light. The bacteria which grow by chemolithotrophic metabolism can re-enter the grazer food chain via filter-feeders just like aerobic bacteria. A number of planktonic and sediment dwelling animals have evolved ways to "hold their breath" while hunting in anoxic water.

Lake ecosystems are complex, involving both terrestrial and aquatic photosynthesis, external and internal nutrients, grazer and detrital food-webs, and aerobic and anaerobic metabolism. Manipulation of a lake ecosystem involves a myriad of causes and effects which operate through the seasons and the years. Lake management which is not comprehensive, not carefully tailored to a specific lake ecosystem, and not well understood by lakeside and

watershed residents has little hope for ultimate success.

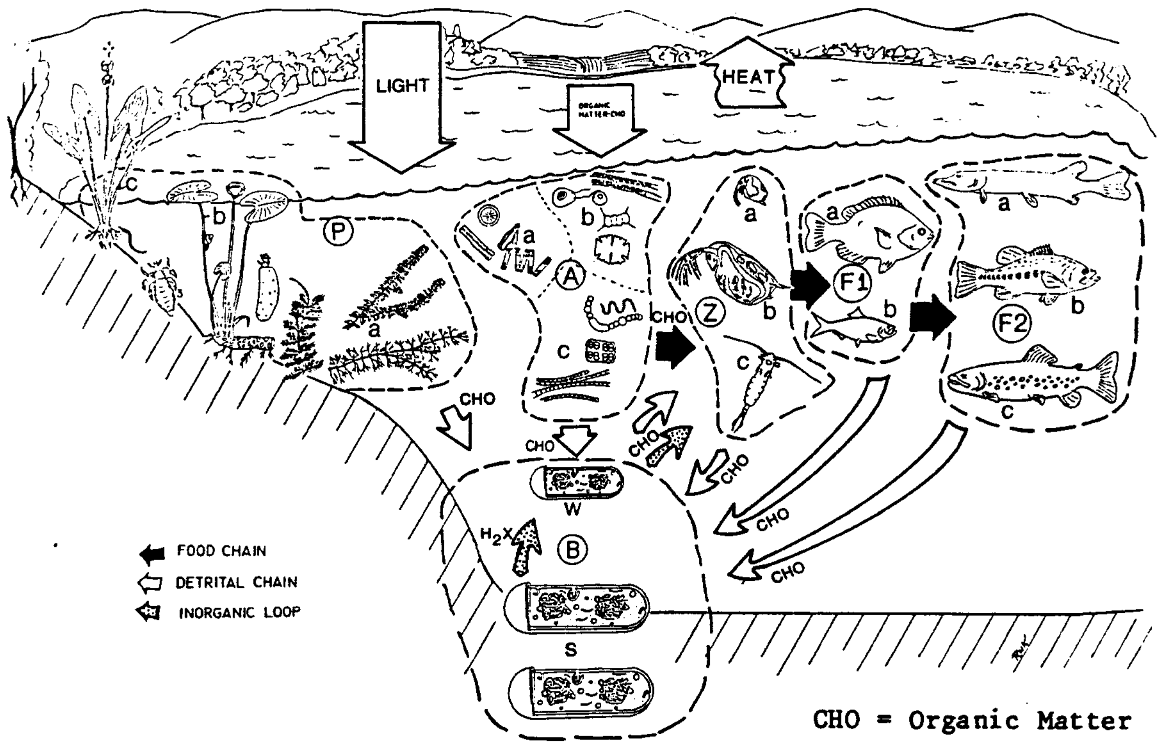


Figure 9. Biology of Lakes.

a. Life Forms in Lakes.

Plants are identified as "**P**"**lants** and "**A**"**lgae**. Large aquatic **plants** (P) generally have roots and internal vascular systems to transport nutrients and products of photosynthesis. Plants grow

in the littoral zone of lakes where the bottom receives sufficient light to promote germination and photosynthesis. Some very specialized aquatic plants (a) have lost their need for roots, and have the ability to drift just under the water surface. Plants less evolved for aquatic life have roots but weak stems and floating leaves (b). Least evolved aquatic plants simply have the ability to root in shallow water, while the rest of the plant emerges into the air (c).

Algae (A) are one-celled, filamentous, or colonial plants which grow attached to things (**periphyton**) or drift free in the water (**phytoplankton**). Diatoms (a), which are one-celled plants with glass walls, are abundant in the winter and early spring. Green algae (b) become numerous later in the spring and may remain dominant during most of the growing season in oligotrophic lakes. Blue-green algae (c) can occur at any time of year, but most often appear in summer and late summer. Blue-green algae have the ability to use nitrogen from the air (like a legume), and they become a problem when other kinds of nitrogen are exhausted in a lake and phosphorus is still plentiful. Blue-green algae are more like bacteria (B) than algae, and they often grow in the cool, dim depths of lakes.

Collectively, plants and algae are called "**autotrophs**" (self-feeders), and create the energy base of organic matter for other organisms ("**heterotrophs**" = other-feeders) to eat. However, most lakes in Connecticut also receive much terrestrial organic matter which also enters lake food-webs. Dead organic matter (both aquatic and terrestrial) supports the bacteria (B) which decompose it. Bacteria are most abundant at the sediment-water interface where particulate organic matter accumulates. However, bacteria also live on dissolved organic material in the water column (w), and on both organic and inorganic (iron, nitrogen, sulfur, etc.) compounds in the sediments (s).

Small, often microscopic, animals called "**zooplankton**" (**Z**) graze on aquatic plants, algae, and the bacteria decomposing terrestrial material. Three types of zooplankton are found in open water (many more exist in plant beds and on the lake bottom). Small zooplankton such as Bosmina (a) and copepods (c) tend to dominate lakes having unstable algal communities subject to nuisance "algae blooms". Large zooplankton like Daphnia (b) tend to be found in lakes where algal densities remain under control. The possiblity of managing the effects of lake eutrophication by manipulating zooplankton is a current research topic.

Zooplankton are eaten by small fish (F1) such as sunfish (a) and landlocked alewife (b). Small fish are eaten by big fish (F2) such as pickeral (a), bass (b), and trout (c).

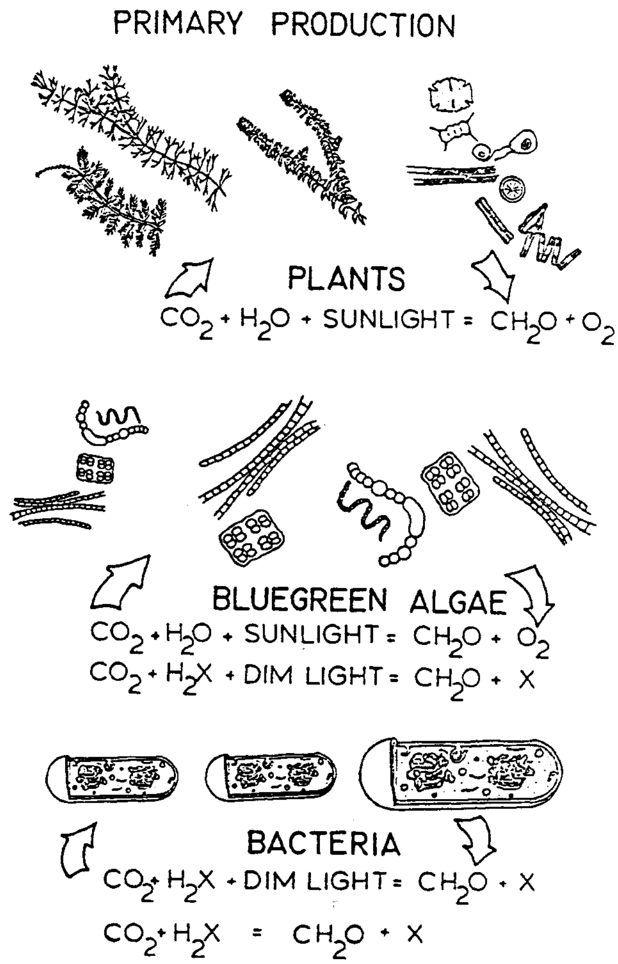


Figure 9. Biology of Lakes (cont.)

b. Primary Production.

Higher plants and algae produce organic matter and oxygen from sunlight and nutrients by **photosynthesis**. Blue-green algae and bacteria are more versatile. In light too dim for photosynthesis, blue-green algae and bacteria produce organic matter but no oxygen in a process called "**photolithotrophy**". In absolute darkness, bacteria produce organic matter from chemical energy, only, by "**chemolithotrophy**". "Lithotrophic" organisms are important in lakes having severe anoxia during summer or winter stratification, and have the effect of creating organic matter in unexpected places.

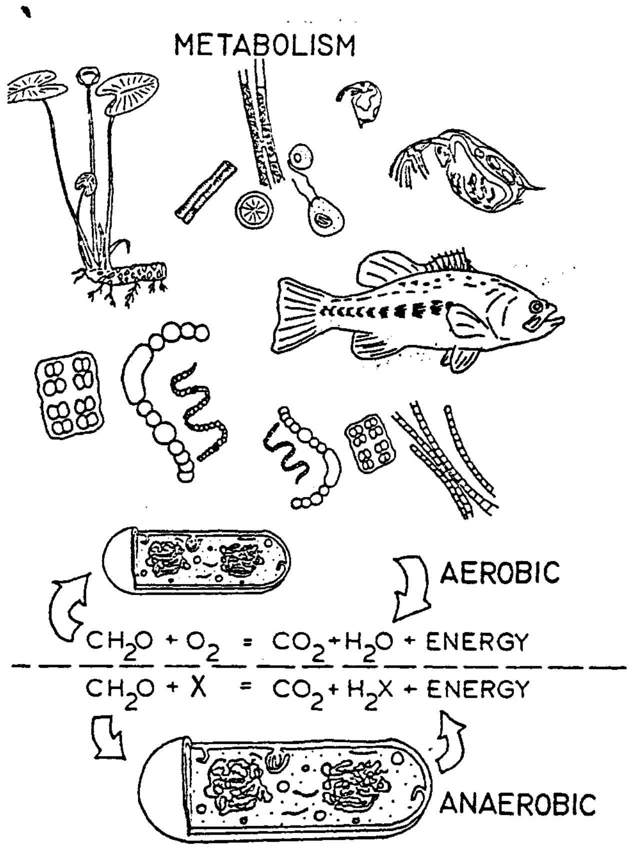


Figure 9. Biology of Lakes (cont.)

c. Metabolism.

Metabolism refers to all biochemical activities by living organisms. Metabolism involving oxygen is called **aerobic** or **oxic**, and includes **photosynthesis** and **aerobic respiration.** Metabolism occuring in the absence of oxygen is called **anaerobic** or **anoxic**, and includes the "lithotrophies" described above, **anaerobic respiration** (inorganic endproducts), and **fermentation** (organic endproducts). Small lakes are dominated by anoxic metabolism because oxygen is not very soluble in water, and because the balance between aquatic photosynthesis and respiration is overwhelmed by demands for oxygen for respiration of imported terrestrial organic matter.

The supply of oxygen to lake sediments is limited by thermal stratification and the limitation of aquatic photosynthesis by the reflection, refraction, and absorption of light by lake water. The anaerobic metabolism of **iron** in Connecticut lakes has the potential to remove or release **phosphorus** in the water overlying sediments.

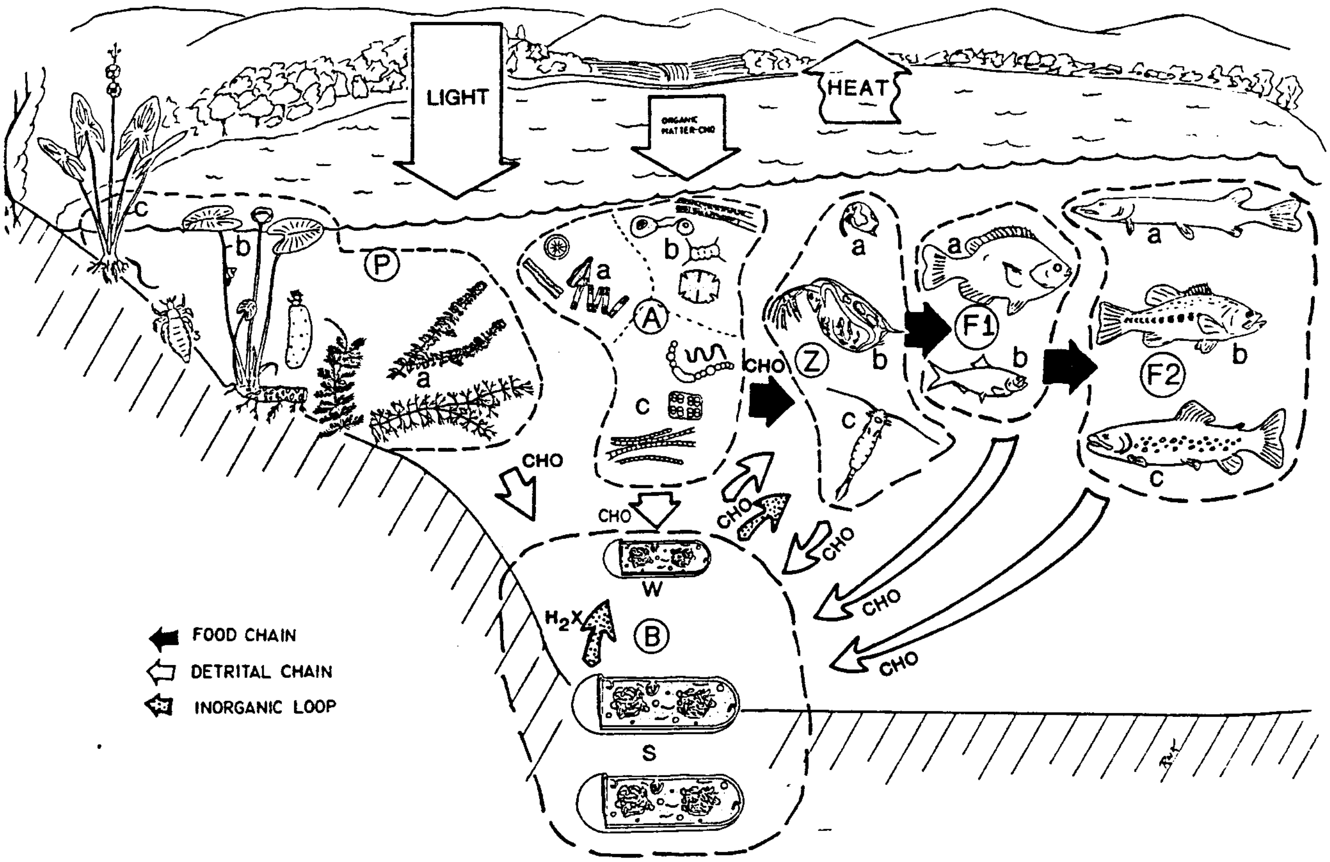


Figure 10. Energy Flow in a Lake Ecosystem.

Energy enters the lake ecosystem by photosynthesis either in the lake or the lake drainage basin. Autotrophs (**P** and **A**) capture solar energy (**Light**) radiating through air or water, and store or "fix" the captured energy in the products of photosynthesis: oxygen and **Organic** Matter (CHO: **C = carbon, H = hydrogen, and O = oxygen**). The fixed energy is recovered by the **food chain** when animals (**Z, Fl, and F2**) and bacteria (**B**) recombine oxygen and organic matter in respiration. The products of respiration, water, carbon dioxide, and nutrients (**Inorganic** Loop) are once again available for photosynthetic conversion to oxygen and organic matter.

The organic matter and energy fixed by autotrophs, the primary producers, are passed on to the first tier of heterotrophs (**Z**), the herbivores or primary consumers. However, much plant matter goes uneaten, and is left at the end of the growing season to be decomposed by bacteria. **Filter feeders** (Z) prey on bacteria as well as algae. The term "detritus" (**Detrital** Chain) is used to distinguish organic matter decomposed by bacteria (which are subsequently the prey of filter-feeders) from organic matter preyed upon while alive ("grazed"). Omnivorous filter-feeders make the products of both aquatic (algae) and terrestrial photosynthesis (particulate and dissolved terrestrial detritus) available to aquatic predators (secondary consumers) which eat the primary consumers.

Lake Ecosystems: In-Lake Models

The most precise way to determine the amount of a substance in a lake is to compute a "**mass-balance**" (Fig. 11a.) for the substance. A mass balance requires a bathymetric map (or a **hypsographic curve**) from which the area of lake at each depth interval is obtained. Area times depth gives the volume of water in each depth interval. Volume of water times the concentration of substance sampled at each depth gives the amount of substance in each interval. The sum of substance at each depth interval is the total amount of substance in the lake. Mass balances are computed at regular time intervals for metabolic products such as dissolved oxygen or carbon dioxide to measure photosynthesis and respiration, for nutrients such as total phosphorus to measure inputs and losses, and for temperature to measure strength and effects of thermal stratification. Mass balances not only provide estimates of changes in total lake contents, but indicate the changes at each depth. When a lake is thermally stratified into distinct compartments (epilimnion, metalimnion, and hypolimnion) one is reasonably certain that a change in the concentration of something at a specific depth occurs because of processes at that depth. For instance, an increase in phosphorus coinciding with hypolimnetic anoxia is strong evidence of the conversion of ferric iron (phosphorus compounds insoluble) to ferrous iron (phosphorus compounds soluble) by anaerobic respiration. Similarly, a sudden increase in temperature in the metalimnion indicates a downward mixing of warm epilimnetic water and an equal upward mixing of phosphorus-rich hypolimnetic water.

Changes in the mass balance of heat during thermal stratification are the basis for a very useful estimate of vertical transport of substances by wind energy in lakes. The transport of heat by diffusion downward in the a lake is used to calculate a "**coefficient of eddy diffusion**" (Fig. 11b.). The method depends upon the fact that mixing warm, light water downward into cold, dense water requires work. Essentially, a lake with water of uniform density has a higher center of gravity than a lake with dense water on the bottom and light water at the surface. Energy must be expended in mixing to raise the center of gravity of the lake.

The coefficient of eddy diffusion (CED) is computed when the lake is heating during the first part of the growing season (before the middle of July). When the change in temperature at each depth stratum is plotted on semi-log graph paper three heating zones are found. The epilimnion heats quickly because it is exposed to sunlight and at the same rate throughout because it is entirely mixed by the wind. The hypolimnion hardly heats at all. Between the epilimnion and the hypolimnion is the metalimnion where heating decreases exponentially with depth. The slope of the decrease, the CED, is a measure of the energy expended in mixing warm and cold water.

The CED times the temperature gradient in the metalimnion equals the transport of heat through the metalimnion to the hypolimnion. Similarly, the CED times the concentration gradient (either up or down) of any dissolved substance is an estimate of the transport (from high to low concentration) of the substance by wind-induced mixing. The CED must be corrected for other sources of heating and mixing such as underwater light and bottom currents. The CED may vary over the course of a heating season and from year to year (see Lake Waramaug results for 1977 and 1980, Fig. 11c.).

Storms and episodes of high winds cause sudden, short term mixing in susceptible lakes by disrupting the metalimnetic boundary between the epilimnion and the hypolimnion. The amount of mixing produced by an event is measured as mixing ratios (R_z) between the epilimnion and each depth stratum in the metalimnion (modified from Stauffer and Lee, 1974). A mixing ratio is calculated as the temperature change ($T_2 - T_1$) of a stratum divided by the difference between the average initial epilimnetic temperature (T_{e1}) and the final temperature of the stratum (T_1). Total vertical transport of a substance due to a mixing event is obtained as the sum of direct capture by epilimnion expansion (F_e), and the sum of the products of volume (V_z), concentration differences ($C_z - C_e$), and mixing ratio (R_z) for each depth stratum (Z) below the epilimnion depth (D_e).

Two mixing events in Lake Waramaug in the summer of 1980 are illustrated in (Fig. 11c.). The events produced direct capture of metalimnetic water by the epilimnion, and a corresponding expansion of the epilimnetic volume. The September event caused an input of phosphorus to the epilimnion equal to 25% of the mean annual external load.

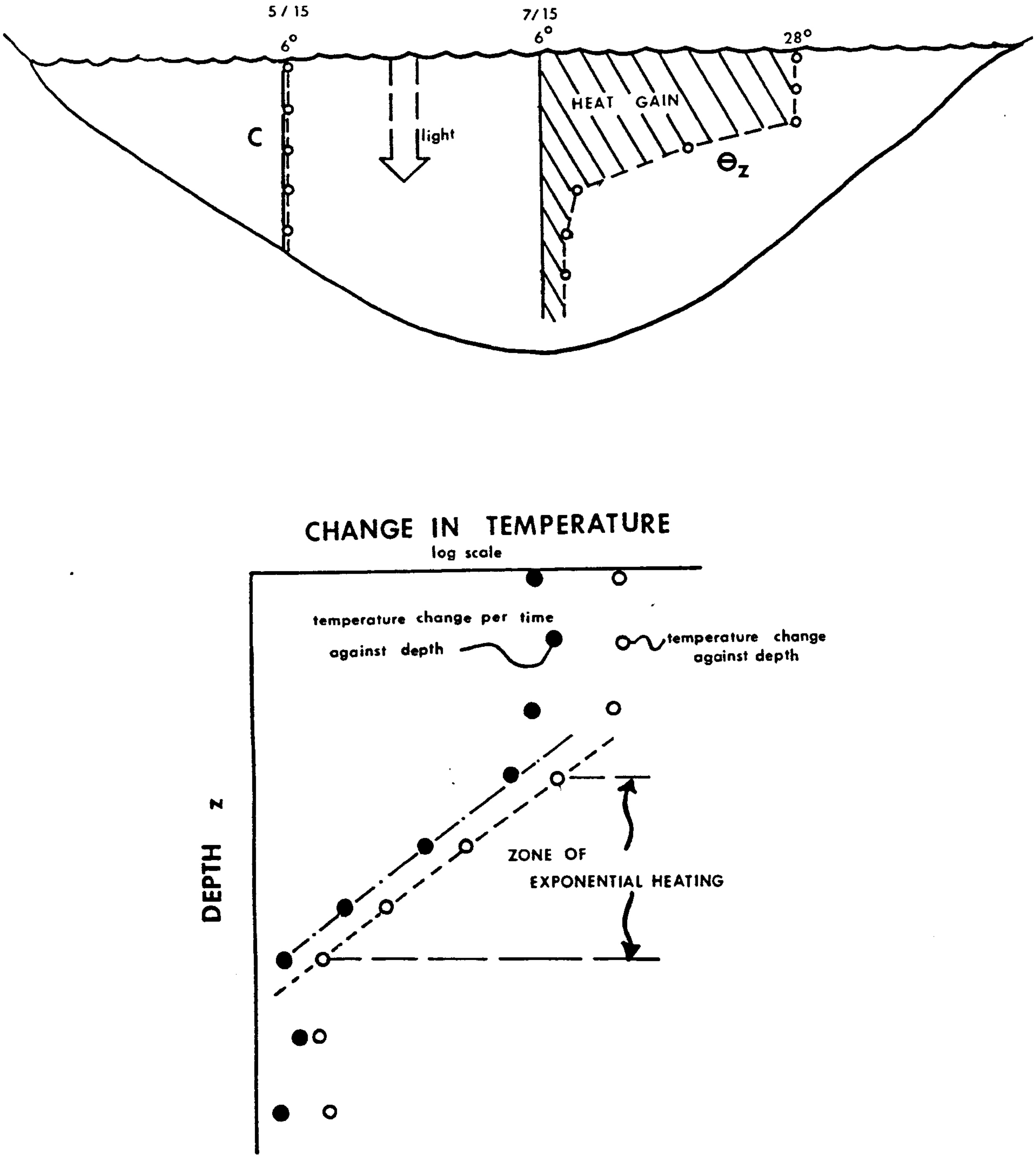
DEPTH(m)	AREA	VOLUME %
>10	42.50	101.14
9-10	38.80	65.07
8-9	32.70	93.92
7-8	32.70	115.71
6-7	32.60	173.79
5-6	34.80	202.36
4-5	38.80	260.20
3-4	42.90	245.74
2-3	40.90	318.04
1-2	40.90	361.73
0-1	32.70	375.88
SUM	410.30	2313.58

OXYGEN(mg/l)	OXYGEN MASS T1	CO 2 (mg/l)	CO 2 MASS T1
3.43	346.91	5.24	529.97
4.33	281.75	4.50	292.82
5.20	488.38	3.74	351.26
5.65	653.76	3.35	387.63
6.54	1136.59	2.95	512.68
6.99	1414.50	2.56	518.04
7.50	1951.50	2.27	590.65
8.00	1965.92	1.98	486.57
9.00	2862.36	1.69	537.49
9.50	3436.44	1.40	506.42
9.55	3589.65	1.25	469.85
75.69	18127.76	30.93	5183.38

Figure 11. In-Lake Models.

a. Mass-Balance Model.

A mass balance requires a bathymetric map (and/or hypsographic curve) from which the area of lake (**AREA**) at each depth interval (**DEPTH**) is obtained. Area times depth gives the volume of water in each depth interval (**VOLUME**). Volume of water times the concentration of substance (**OXYGEN (mg/L** and **CO 2 (mg/L)** sampled at each depth gives the amount of substance (**OXYGEN MASS T1** and **CO 2 MASS T1**) in each interval. The sum (**SUM**) of substance at each depth interval is the total amount of substance in the lake. Mass balances are computed at regular time intervals for metabolic products such as dissolved oxygen or carbon dioxide to measure photosynthesis and respiration, for nutrients such as total phosphorus to measure inputs and losses, and for temperature to measure strength and effects of thermal stratification.



$$-a = \frac{1/z \ln \Theta_z C}{C_1} \qquad A = \frac{d\Theta/dt\ (sec)}{a^2(\Theta - C)}$$

Figure 11b.

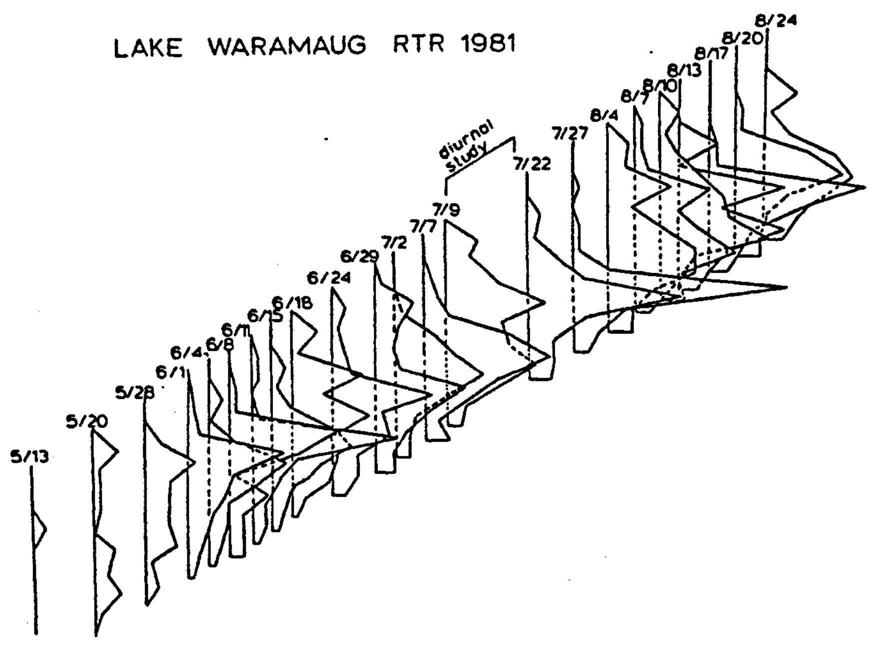
Figure 11 In-Lake Models (cont.)

b. Eddy Diffusion.

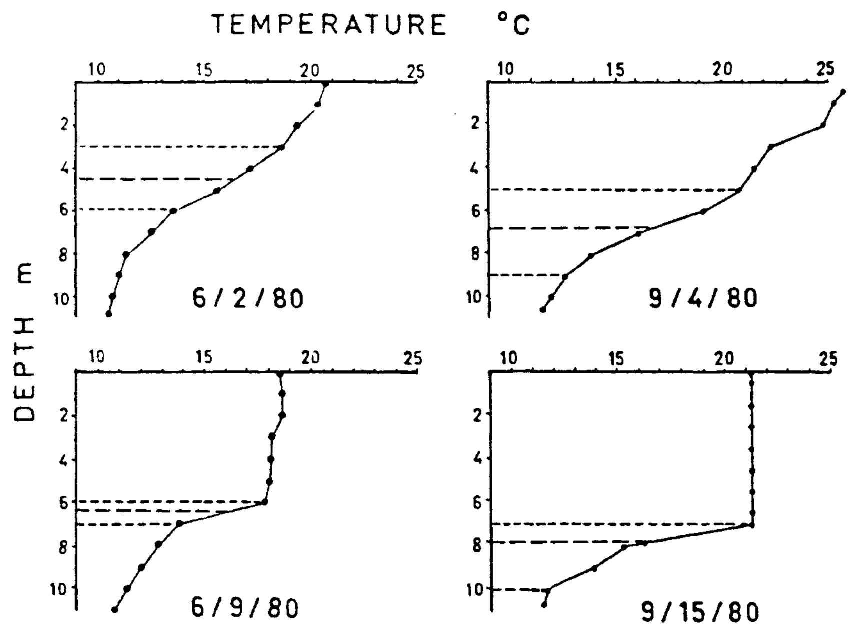
Transport of heat by diffusion downward in a lake may be used to calculate a "**coefficient of eddy diffusion**" **(= A)**. The CED is computed when the lake is heating during the first part of the growing season, in this case between **5/15** and **7/15**. **Change in temperature** (log scale) plotted against **depth** indicates three heating zones are found. The upper **epilimnion** heats quickly and at the same rate throughout because it is exposed to sunlight and wind. The **hypolimnion** at the bottom hardly heats at all. Between the epilimnion and the hypolimnion is the **clinolimnion** where heating decreases **exponentially** with depth.

The slope of the exponential decrease, the CED, is a measure of the energy expended in mixing warm and cold water. The CED times the temperature gradient in the metalimnion equals the transport of heat through the metalimnion to the hypolimnion. Similarly, the CED times the concentration gradient (either up or down) of any dissolved substance is an estimate of the transport (from high to low concentration) of the substance by wind-induced mixing.

The CED must be corrected for other sources of heating and mixing such as underwater light and bottom currents. The CED varies over the course of a heating season and from year to year (see Lake Waramaug results for **1977** and **1980**).



Another way to estimate the "strength" or "stability" of the thermocline is to plot a "Relative Thermal Resistance" curve (RTR). The maximum RTR value identifies both intensity and location of the thermoline.



$$R_z = (T_2 - T_1) / (T_{e1} - T_2)$$

$$F = F_e + \sum V_z \cdot (C_z - C_e) R_z \ldots$$

Figure 11. In-Lake Models (cont.)

c. Mixing Events in Lake Warmaug.

Temperature/Depth plots of two mixing events in Lake Waramaug in the summer of 1980, one in June (between **6/2** and **6/9**) and the other in September (between **9/4** and **9/15**). The events produced direct capture of metalimnetic water by the epilimnion, and a corresponding expansion of the epilimnetic volume. The September event caused an input of phosphorus to the epilimnion equal to 25% of the mean annual external load.

The amount of mixing produced by an event is measured as mixing ratios (R_z) between the epilimnion and each depth stratum in the metalimnion (modified from Stauffer and Lee, 1974). A mixing ratio is calculated as the temperature change ($T_2 - T_1$) of a stratum divided by the difference between the average initial epilimnetic temperature (T_{e1}) and the final temperature of the stratum (T_1). Total vertical transport of a substance due to a mixing event is obtained as the sum of direct capture by epilimnion expansion (F_e), and the sum of the products of volume (V_z), concentration differences ($C_z - C_e$), and mixing ratio (R_z) for each depth stratum (Z) below the epilimnion depth (D_e).

CHAPTER 4
CONTROL OF EUTROPHICATION

PERSPECTIVES on LAKE MANAGEMENT

Managing Ecosystem Processes

Lake managers eager to correct the problems which plague our lakes (algae blooms, dense weed infestations, habitat loss, water quality degradation) can lose sight of fundamental ecosystem processes. We have focused on nutrients, particularly phosphorus, and with good reason. Phosphorus plays a central role in the biochemical processes performed by all living organisms (recall ATP, substrate level phosphorylation, cyclic and non-cyclic photophosphorylation), a role which no other atom can duplicate. Phosphorus is typically the nutrient in shortest supply to aquatic plants -- hence it tends to be "limiting". Even when a system is not phosphorus limited when diagnosed, it is usually easier to control phosphorus and "make it limiting" than attempt to induce nitrogen limitation. However, the emphasis on phosphorus has perhaps obscured our view of other aspects of the lake ecosystem where potential for effective management exists. One aspect of lake ecosystems too often neglected is "ecosystem energetics" -- the flow of energy through the ecosystem. The following discussion of ecosystem energetics is intended as a "primer" for those wishing to learn more about their lake, as a reminder to lake managers that "life is energy", and perhaps to spark an idea for an innovative management technology.

Fundamental Biochemical Processes: Respiration

"Life is energy." Living organisms consist of a highly ordered arrangement of matter that takes advantage of chemical energy released in the "combustion" of organic material. Fundamentally, the reason life exists on earth is because living organisms synthesize catalysts for chemical reactions. These catalysts are called **enzymes**. Enzymes provide the energy required to initiate chemical reactions (activation energy) which subsequently yield far more energy than the original investment in enzyme synthesis made by organisms. Hence, "life" provides the activation energy (via enzymes) needed to obtain greater energy yield (positive Gibbs free energy change) which supports life. Simply put, we burn organic matter in a slow, controlled way. All living organisms perform this combustion process called **respiration.** In this respect the only differences between the variety of living organisms are:

* the source of the fuel (whether it is made by the organism (autotrophic) or another organism (heterotrophic), and

* the specific process used to combust the fuel.

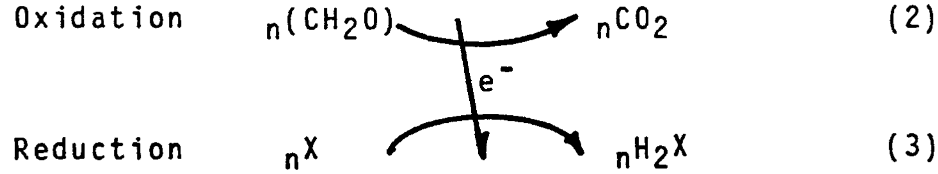
The respiration process performed by all living organisms can be simply depicted by the following formula:

$$(CH_2O)_n + X \longrightarrow CO_2 + H_2X \quad (1)$$

where $(CH_2O)_n$ represents the fuel (organic matter) and "X" represents the substance used to combust it. Respiration is an "oxidation-reduction" reaction where organic matter is "oxidized" to carbon dioxide and another substance is "reduced". **The process involves the**

breaking and reformation of chemical bonds -- transfer of energy -- which yields life-giving energy. Separating the "oxidation" from the "reduction", the respiration formula (1) becomes:

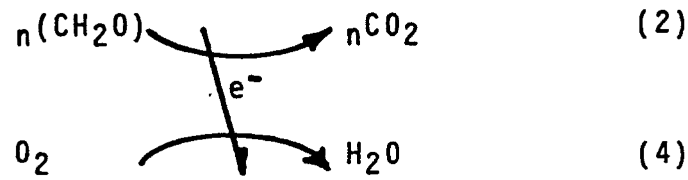
Respiration



All organisms do this. The only differentiating feature is the substance ("X") used to accept the transferred energy ("terminal electron acceptor").

Organisms that require oxygen to combust organic matter (such as humans) perform **aerobic respiration**:

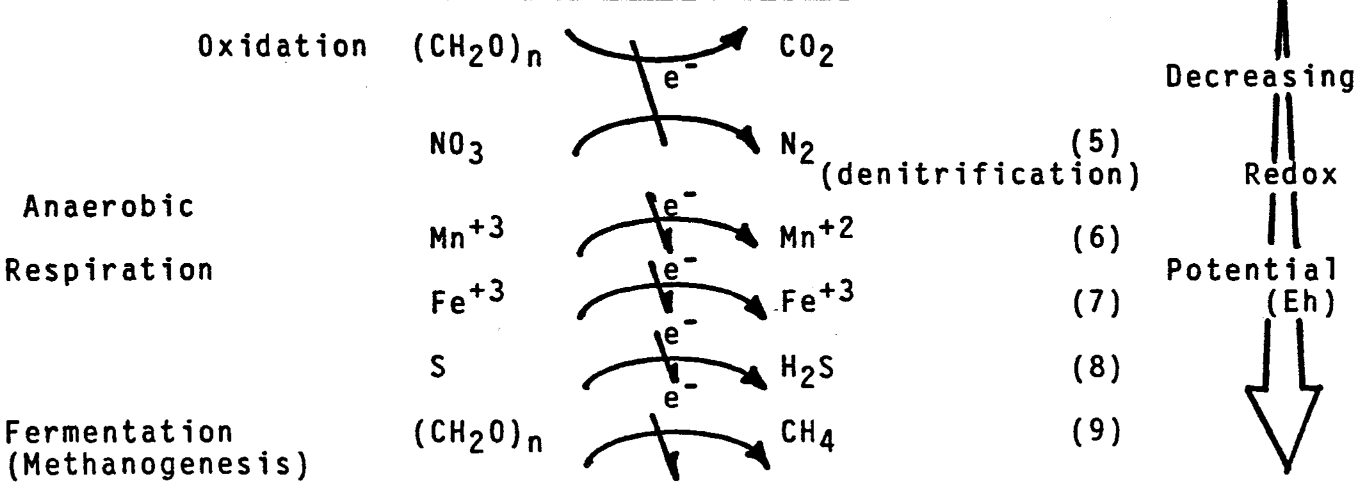
Aerobic Respiration



In aerobic respiration organic matter is oxidized to carbon dioxide, and oxygen (the terminal electron acceptor) is reduced to water. Oxygen is the "X" in equations (1) and (3) for aerobic respiration.

Many organisms do not require oxygen to combust organic matter. Indeed, we humans perform intermediary steps before oxygen is used (e.g., lactic acid production). **Anaerobic respiration** is the process by which organic matter is combusted (oxidized) using an alternate to oxygen (alternate terminal electron acceptor). The "alternate" can be a variety of substances ("X") which become reduced. Some examples include:

Anaerobic Respiration



These "alternates" are shown in the sequence in which they are used after oxygen is depleted (first nitrate, then metals, and finally other organic compounds in fermentation). In the absence of oxygen, not all of the energy can be recovered from organic matter by respiration. Hence, the products of anaerobic respiration (inorganic products) and fermentation (organic products) contain residual energy subject to subsequent reactions.

Production

As discussed above, all living organisms (plant and animal) obtain the "energy of life" by combustion of organic matter. **Autotrophs** capture solar energy radiating through air or water and store ("fix") the captured energy in the products of **photosynthesis**: oxygen and organic matter. (More accurately, the energy captured by photosynthesis is not stored in the products of photosynthesis but, rather, as environmental redox potential between the photosynthetic products.) Autotrophs essentially "make their own fuel" in a process the reverse of respiration (1):

$$_n(CH_2O) + X \xleftarrow{\text{Solar Energy } h\nu} {}_nCO_2 + {}_nH_2X \qquad (10)$$

This "photosynthetic process" (phototrophy) is also an oxidation-reduction reaction, but uses solar energy to "photo-reduce" carbon dioxide to organic matter. The oxidation-reduction couple is:

Reduction $\quad {}_nCO \rightarrow {}_n(CH_2O) \qquad (11)$

e^-

Oxidation $\quad {}_nH_2X \rightarrow {}_nX \qquad (12)$

In photosynthesis the "X" is oxygen; water is oxidized to oxygen. In a sense, water is the chemically reduced state of oxygen. Photosynthesis oxidizes water to oxygen (this is how our oxygen-rich atmosphere evolved). Aerobic respiration reduces oxygen to water. However, this is not the only process that produces organic matter. The "X" can also be the products of anaerobic respiration. For example, where the "X" is sulfur, hydrogen sulfide is oxidized while carbon dioxide is reduced to organic matter. This process is called **chemolithotrophy** and synthesizes organic matter in the absence of light. Other, very similar processes occur such as **chemoorganotrophy** where an organic "X" is used, and "photo-assisted" organo- and lithotrophy where some (dim) solar energy is needed.

Organisms which do not produce their own fuel are dependent on organic matter produced by autotrophs. These are called **heterotrophs**.

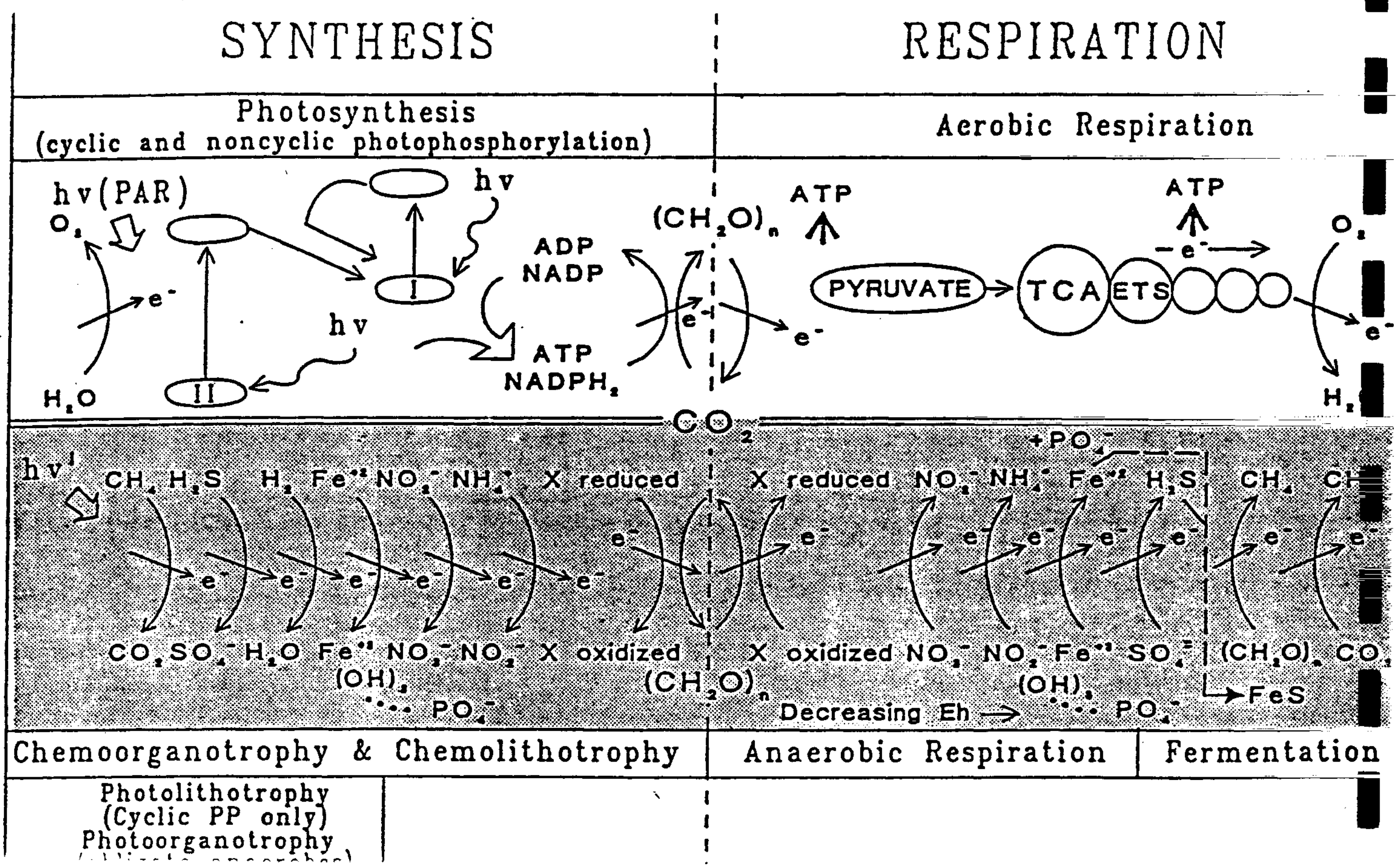
Fundamental Ecosystem Processes

Now that we have discussed the basic biochemical processes of life, it is time to discuss the relationships between energy and matter in the ecosystem.

Ecosystem is the unit of natural organization in which living organisms interact collectively with basic physical and chemical processes in the environment. The operation of an ecosystem depends upon available energy and nutrients. Plants have the ability to divert energy from solar radiation (a physical process) to photosynthesis (a biological process). Energy diverted to photosynthesis is stored in the organic matter of plants (simple sugars which are subsequently polymerized into starch and cellulose), which is eaten by animals. Animals use the diverted energy to live, to grow, to pass on to their predators. The energy originally captured as sunlight by plants is returned to the physical world as very low temperature heat released by biochemical reactions in all living organisms. The amount of biological activity in a lake ecosystem depends ultimately upon the amount of energy available for photosynthesis, and the amount of biochemical "machinery" (for both photosynthesis and respiration) which can be constructed from available nutrients. When energy is abundant and nutrients are limited, biochemical machinery is inadequate to use the energy available.

Figure 12 illustrates the fundamental energetics of organisms and ecosystems. All life is based on carbon. In this figure synthesis of organic matter is shown on the left half, respiration of organic matter is illustrated on the right. The upper half depicts "aerobic processes", the lower half "anaerobic processes". Hence, four quadrants are identified:

FIGURE 12. FUNDAMENTAL ENERGETICS OF ORGANISMS and ECOSYSTEMS



"**Aerobic Photosynthesis**" (upper left): Photosynthetically active radiation (PAR) is captured by photosystems I and II (cyclic and non-cyclic photophosphorylation, respectively), used to create reducing power ($NADPH_2$ and ATP), which is used to create organic matter from carbon dioxide. The electron donor is water; oxygen is the oxidized product.

"**Aerobic Respiration**" (upper right): Organic matter is oxidized; the terminal electron acceptor is oxygen. The "reducing energy" contained in the organic matter is used to produce energy-rich compounds (e.g., ATP) in the Krebs Cycle (Tricarboxylic Acid Cycle) and the Electron Transport System. These are biochemical, enzyme mediated systems contained in organisms which perform aerobic respiration.

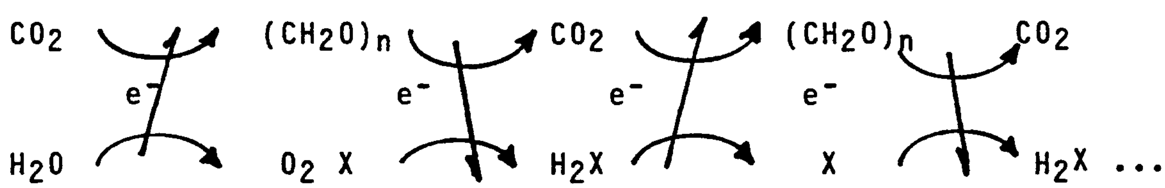
"**Anaerobic Respiration and Fermentation**" (lower right): There are many organisms which can oxidize organic matter to obtain energy without using oxygen as the terminal electron acceptor. The first "alternate terminal electron acceptor" used is nitrate, which is reduced to nitrite, nitrogen gas, or ammonia. Dissimilatory nitrate reduction is a particularly important process in anaerobic environments (also called "denitrification"). Nitrate becomes an electron acceptor at a redox potential (Eh) of about 220 mv. The products of denitrification are all gaseous; N_2O, N_2, and CO_2. Because of the importance to lake management, nitrogen transformations will be discussed in greater detail.

Once all available oxygen and nitrate has been depleted (by use as electron acceptors in respiration), the redox potential continues to decrease. At about 200 mv manganic manganese is used as an alternate electron acceptor, being reduced to manganous compounds. As the redox potential decreases further, insoluble ferric iron is used as an electron acceptor producing soluble ferrous iron. This reaction is reached at a redox potential of approximately 120 mv. Ferric iron binds with orthophosphate (Mayer, et al., 1983; Hutchinson, 1957; Einsele, 1938). Bacterial reduction of ferric hydroxy-phosphate complexes results in large amounts of diffusing soluble inorganic phosphorus and ferrous iron across the sediment-water interface (Kortmann, 1980). The internal load of phosphorus which results is important to the trophic status of lakes (Nurnberg, 1987, 1984; Kortmann et al., 1981). If redox potential continues to decrease (below -100 mv), sulfates are reduced to sulfides and organic compounds become electron acceptors (fermentation).

The oxidation-reduction system depicted in the lower right quadrant of Figure 1 is an "ecological analog" to the electron transport system of an individual organism. The reduced products, however, enter and accumulate in the anaerobic environment. Some of these processes can be performed by the same organisms. For example, some organisms have enzyme complexes capable of "switching" from oxygen to nitrate and, finally, to iron (facultative anaerobic bacteria).

"Chemotrophy" (lower left): The reduced products of anaerobic respiration (and the reducing energy they contain) are not lost from the ecosystem. Upon diffusing to an oxidized environment, the reduced products can be further oxidized, yielding energy for the reduction of carbon dioxide to synthesize organic matter. Chemolithotrophy and chemoorganotrophy are processes which synthesize organic matter using only the reducing energy of the products of anaerobic respiration and fermentation, respectively. When some light supplements the reduced chemical energy, the processes are called photolithotrophy and photoorganotrophy. Only photosystem I is involved (cyclic photophosphorylation), no oxygen is generated.

Anaerobic metabolism in lakes is an extension of the detrital side of the "food-web". Bacteria decomposing and respiring detrital organic matter switch from **aerobic respiration** to **anaerobic respiration** and **fermentation** when oxygen is exhausted. In the absence of oxygen, not all the energy can be recovered from organic matter by respiration. Thus, the products of anaerobic respiration and fermentation (inorganic and organic, respectively) contain residual energy which is subject to subsequent reactions. That is, the energy which drives **"chemolithotrophy"**, a process which synthesizes organic matter in the absence of light. The bacteria which grow by chemolithotrophic metabolism enter the food-web via filter-feeders, just like aerobic bacteria. The energy used in chemolithotrophy is residual energy from anaerobic respiration, energy originally fixed by either in-lake or terrestrial photosynthesis:



(13)

Photosynthesis (In the lake & in the drainage basin) | Anaerobic Respiration | Chemolithotrophy

Hence, chemolithotrophy in a true sense is a heterotrophic process. The energy was originally fixed by phototrophy (either allochthonous or autochthonous).

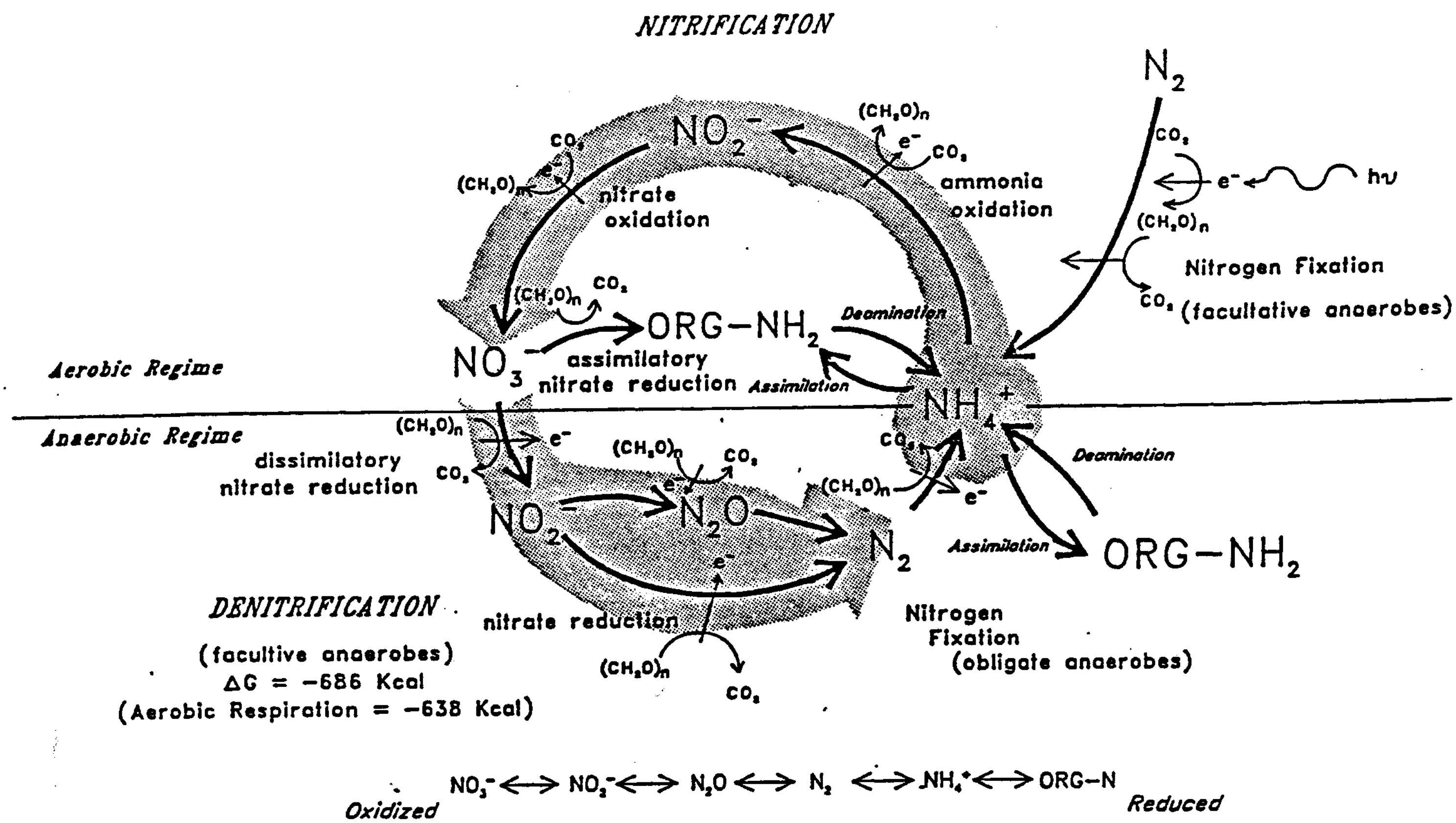
As discussed, Figure 12 depicts the fundamental energetic processes of organisms and ecosystems. The shaded portions of this figure identify reactions which are of particular interest to lake management and will be the focus of more detailed discussion.

Nitrogen Transformation

Although the availability of phosphorus is most often limiting to aquatic plants, the quantities and forms of nitrogen can influence phosphorus availability and the type of biotic response to a given phosphorus level. The nitrogen cycle offers significant management potential for lakes.

Figure 13 illustrates the transformations between various nitrogen compounds in aquatic ecosystems. Some organisms are capable of "fixing" nitrogen gas from the atmosphere and, hence, are not dependent on dissolved combined forms of nitrogen. It is interesting

Figure 13


NITRIFICATION
N_2
NO_2^-
$(CH_2O)_n$
e^-
CO_2
ammonia oxidation
nitrate oxidation
$h\nu$
Nitrogen Fixation
(facultative anaerobes)
ORG−NH₂
Deamination
NO_3^-
assimilatory nitrate reduction
Assimilation
NH_4^+
Aerobic Regime
Anaerobic Regime
dissimilatory nitrate reduction
N_2O
Deamination
Assimilation
ORG−NH₂
DENITRIFICATION
nitrate reduction
Nitrogen Fixation
(obligate anaerobes)
(facultive anaerobes)
ΔG = −686 Kcal
(Aerobic Respiration = −638 Kcal)
$NO_3^- \leftrightarrow NO_2^- \leftrightarrow N_2O \leftrightarrow N_2 \leftrightarrow NH_4^+ \leftrightarrow$ ORG−N
Oxidized
Reduced

to note that nitrogen fixation occurs only in bacterial cells (bluegreen algae are bacterial, unlike other phytoplankton). The enzyme that performs nitrogen fixation is nitrogenase. A substantial amount of energy (from ATP) and a hydrogen source (from reduced ferridoxin) is required to reduce nitrogen gas to ammonia and, subsequently, to organic ammonia (e.g. amine groups of amino acids). The nitrogenase enzyme complex is very sensitive to oxygen; nitrogen fixation is strictly anaerobic. Several adaptations have evolved to protect nitrogenase from oxygen in aerobic environments including:

"Respiratory protection" - consumption of oxygen by increased respiration,

"Conformational protection" - a change in protein structure to protect the enzyme from oxygen ("switched off").

Most phytoplankton which create nuisance bloom conditions are capable of nitrogen fixation. Both the vegetative cells and heterocysts of bluegreen algae (actually bluegreen bacteria) contain nitrogenase and can fix nitrogen. However, nitrogen fixation occurs only in heterocysts under aerobic conditions. Nitrogen fixation is inhibited by high cellular ammonia content.

Of the combined forms of nitrogen, the most important are ammonia and nitrate. Both can be assimilated to produce amino acids (amine groups). However, nitrate must first be reduced (assimilatory nitrate reduction), and this process is inhibited by ammonia. Decomposition of organic matter results in the release and accumulation of ammonia (via deamination, ammonification). Under aerobic conditions, ammonia is oxidized in a two-step process called nitrification (Phase I to nitrite; Phase II to nitrate). This is one of the chemolithotrophic processes discussed previously. The bacteria which perform these processes are obligate chemolithotrophs. Under anaerobic conditions nitrification of ammonia to nitrate does not occur, and ammonia accumulates.

As discussed previously, nitrate is the first alternate terminal electron acceptor used in anaerobic respiration when oxygen is exhausted. As shown in Figure 13 the energy yield using nitrate is very close to the yield for aerobic respiration (note the similar Gibbs free energy change, ΔG). Indeed, there are several potential advantages to the organism performing dissimilatory nitrate reduction rather than aerobic respiration (e.g., oxygen can poison important enzyme complexes). As long as nitrate remains available, the redox potential remains above that required for iron reduction and subsequent sediment phosphorus release from ferric hydroxy-phosphate complexes.

Because ammonia accumulates to high concentrations in anaerobic environments, enhancing nitrification to nitrate, and subsequent use of nitrate in denitrification, can stabilize redox potential and reduce internal phosphorus loading. These processes have contributed to the improvement of Lake Waramaug, Connecticut. The use of lake-generated ammonia, converted to nitrate by low level or "anaerobic aeration", stabilizing redox potential above the ferric-ferrous couple, offers substantial management potential (maintaining Eh near 200 mv without detectable oxygen concentration).

Sulfur - Iron - Phosphorus Interaction

Figure 14 illustrates the sulfur cycle and transformations as they relate to the iron-phosphorus dynamics of aquatic ecosystems. The use of sulfate, or elemental sulfur, as a terminal electron acceptor occurs when oxygen is exhausted and redox potential drops below about -75 mv. Reduction occurs in the water column and sediments. The end product of sulfate reduction is sulfide, which interacts readily with ferrous iron to produce ferrous sulfide (FeS), and subsequently pyrite (FeS_2) (Doyle, 1968). If ferrous sulfide precipitates from the water column and then forms pyrite, the ferrous iron is no longer susceptible to oxidation to ferric iron under aerobic conditions. Hence, phosphate binding capacity may be decreased.

The relationship between sulfur, iron, and phosphorus binding capacity raises questions about potential impacts from increased sulfate loading by algicide applications (copper sulfate), alum treatments (aluminum sulfate), and acid rain. The extent to which sulfide competes with orthophosphate for iron is a topic which warrants further research.

Much of the anaerobic respiration in Lake Waramaug is performed via ferric iron reduction. The reoxidation of lake-generated ferrous iron to ferric iron (bacterial and abiotic oxidation) has been used to precipitate water column phosphorus (from the lower metalimnion and upper hypolimnion) and decrease internal P load effects. Iron is a very effective precipitatnt for phosphorus (indeed some water utilities are converting from alum floculation to use of ferric chloride). The reoxidation of lake-generated ferrous iron has played a major role in water quality improvements at Lake Waramaug.

Ecosystem Dynamics - Nutrients and Energy

Figure 15 illustrates the energetic processes superimposed on a lake ecosystem. Note that the "lake ecosystem" consists of two major components; the "aquatic" component which is the water body itself, and the "paralimnetic" component which consists of the drainage basin or watershed. The paralimnetic component could be divided into a variety of land-use fractions (urban, agricultural, and wooded/wetland used here), soil groupings, slope classes, or other categories. Likewise, the aquatic component could be divided into littoral zone, pelagic zone, benthic boundary layer, sediments, and during summer stratification into epilimnion, metalimnion, and hypolimnion. Dividing the ecosystem into such categories enables the limnologist to apply compartment modeling techniques (donor control, recipient control) to evaluate structure and function (Kortmann, 1980).

In Figure 15 the lake ecosystem is divided into the basic compartments which interact by the flow of either nutrients or energy, or both. The compartments of Figure 15 are defined below:

Figure 14

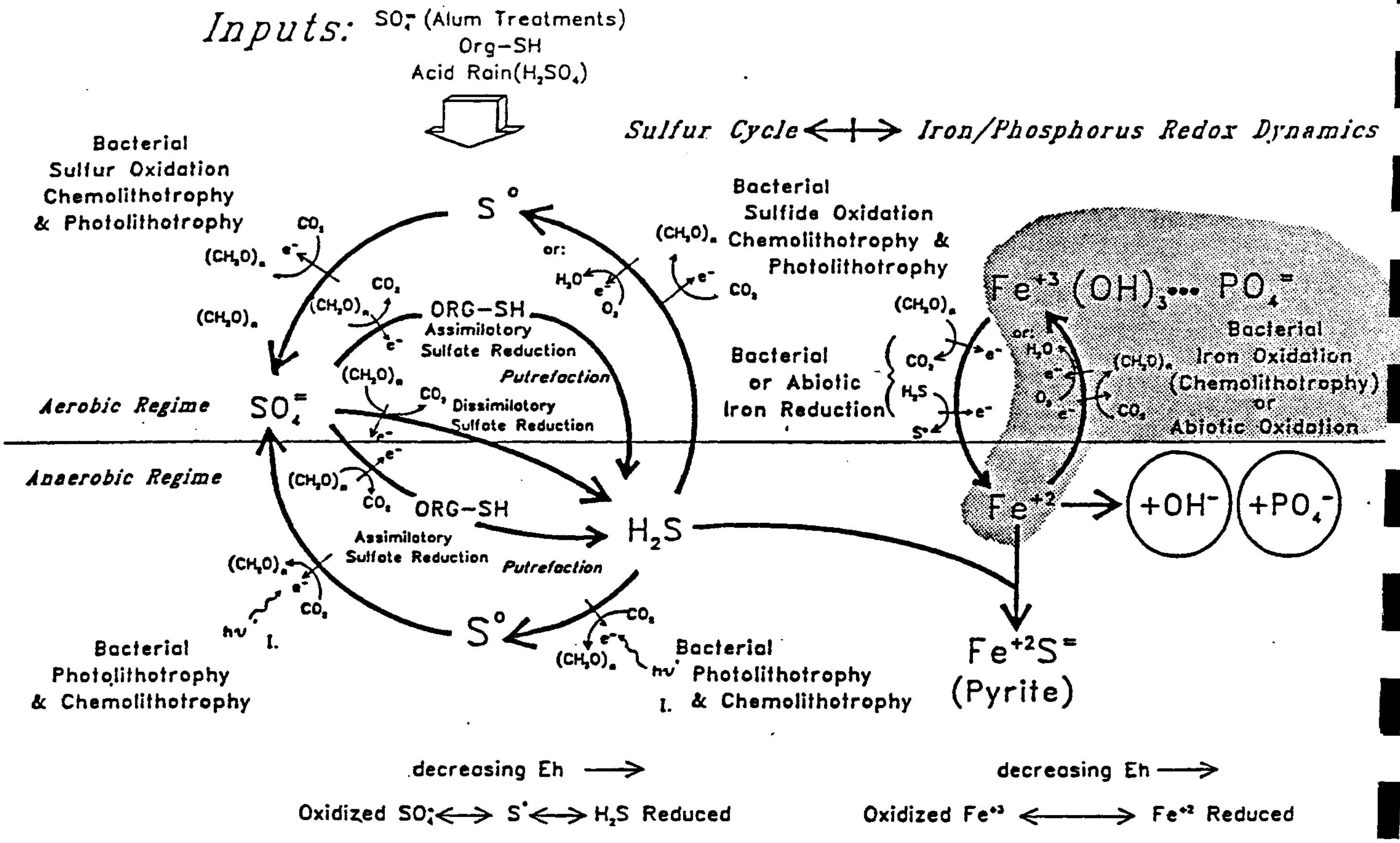
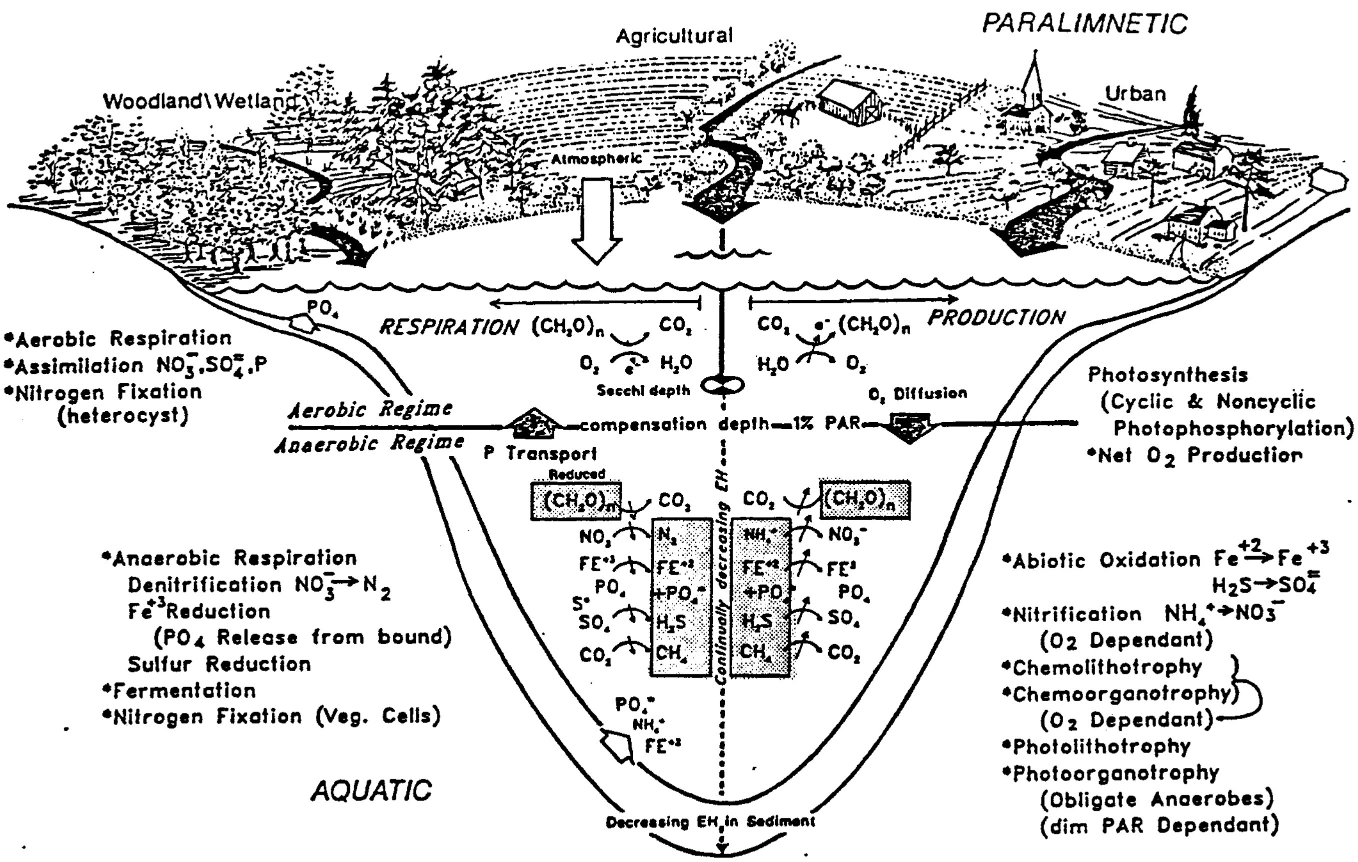

Inputs:
SO4= (Alum Treatments)
Org-SH
Acid Rain(H2SO4)
Sulfur Cycle ↔ Iron/Phosphorus Redox Dynamics
Bacterial Sulfur Oxidation Chemolithotrophy & Photolithotrophy
Bacterial Sulfide Oxidation Chemolithotrophy & Photolithotrophy
S°
ORG-SH
Assimilatory Sulfate Reduction
Putrefaction
Dissimilatory Sulfate Reduction
Aerobic Regime
SO4=
Anaerobic Regime
ORG-SH
Assimilatory Sulfate Reduction
Putrefaction
H2S
S°
Bacterial Photolithotrophy & Chemolithotrophy
Bacterial Photolithotrophy & Chemolithotrophy
Bacterial or Abiotic Iron Reduction
Fe+3 (OH)3 ••• PO4=
Bacterial Iron Oxidation (Chemolithotrophy) or Abiotic Oxidation
Fe+2
+OH-
+PO4-
Fe+2S=
(Pyrite)
decreasing Eh
Oxidized SO4= ↔ S° ↔ H2S Reduced
decreasing Eh
Oxidized Fe+3 ↔ Fe+2 Reduced

Figure 15


PARALIMNETIC
Agricultural
Woodland\Wetland
Urban
Atmospheric
PO4
RESPIRATION (CH2O)n CO2
O2 H2O
CO2 (CH2O)n PRODUCTION
H2O O2
Secchi depth
O2 Diffusion
*Aerobic Respiration
*Assimilation NO3-,SO4=,P
*Nitrogen Fixation
(heterocyst)
Aerobic Regime
Anaerobic Regime
compensation depth—1% PAR
P Transport
Photosynthesis
(Cyclic & Noncyclic
Photophosphorylation)
*Net O2 Production
Reduced
Continually decreasing EH
*Anaerobic Respiration
Denitrification NO3-→N2
Fe+3 Reduction
(PO4 Release from bound)
Sulfur Reduction
*Fermentation
*Nitrogen Fixation (Veg. Cells)
*Abiotic Oxidation Fe+2→Fe+3
H2S→SO4=
*Nitrification NH4+→NO3-
(O2 Dependant)
*Chemolithotrophy
*Chemoorganotrophy
(O2 Dependant)
*Photolithotrophy
*Photoorganotrophy
(Obligate Anaerobes)
(dim PAR Dependant)
AQUATIC
Decreasing EH in Sediment

Paralimnion

* WOODED/WETLAND fraction
* AGRICULTURAL fraction
* URBAN fraction.

Aquatic

* TROPHOGENIC Zone - net oxygen production; above the compensation depth.
* TROPHOLYTIC Zone - net oxygen consumption; below the compensation depth.
* SEDIMENTS.

In general, nutrient export from a unit area of the paralimnion is highest for the "urban" fraction and lowest for the "wooded/wetland" fraction. Nutrient loading is important because it generally controls production in the trophogenic zone of the aquatic component (autochthonous organic matter). Although nutrient inputs to the aquatic component are very important, the input of organic matter is too often overlooked. Terrestrial photosynthesis produces organic matter which enters the aquatic component as either particulate (POM) or dissolved organic matter (DOM). This allochthonous organic matter supports respiration in the aquatic component. The loading of allochthonous POM and DOM is as important to aquatic respiration, trophic dynamics, and ecosystem structure and function as the nutrient loading which supports autochthonous production.

The compensation depth is the depth at which photosynthetic oxygen production is balanced with respiratory demand for oxygen (as the terminal electron acceptor in aerobic respiration). This depth is controlled by light penetration because photosynthetically active radiation (PAR) is required to drive Photosystem II (noncyclic photophosphorylation) which uses water as the reducing agent and generates oxygen (see Figure 12). The depth to which 1% incident PAR penetrates identifies the compensation depth, which is the boundary between the trophogenic zone (above) and tropholytic zone (below). The compensation depth can be estimated by multiplying the Secchi disk depth by between 1.6 and 1.9, depending on the light attenuation due to color, dissolved organic matter, etc.

Below the compensation depth (in the tropholytic zone), net oxygen consumption occurs. As alternate terminal electron acceptors are consumed, the redox potential (Eh) decreases. The redox potential tends to decrease with greater depth in the water column and in the sediments (Figure 15). Once the redox potential of the ferric-ferrous iron couple is reached, both ferrous iron and phosphate accumulate. If Eh continues to decrease, sulfate is reduced to sulfide, which can remove iron and reduce phosphate binding capacity (as discussed previously).

Large quantities of dissolved phosphorus are released from sediments upon the reduction of iron, causing internal nutrient loading. Ferrous iron is reoxidized by the downward diffusion of oxygen (from the trophogenic zone), and tends to reprecipitate phosphorus. Accumulated hypolimnetic phosphorus can be transported to the trophogenic zone by eddy transport or wind mixing episodes, and can have dramatic effects on autochthonous production (Kortmann <u>et</u>

al., 1981). Note that carbon dioxide is a common product of all respiratory processes; aerobic, anaerobic, and fermentation. Measurement of dissolved inorganic carbon (DIC) increment yields a more accurate quantification of total hypolimnetic respiration than oxygen consumption rate.

The specific location of the compensation depth relative to the density and viscosity gradients in the metalimnion during thermal stratification is of particular interest. It tends to dictate the relative amounts of phosphorus transport to the trophogenic zone (increasing autochthonous production) compared to the reprecipitation of phosphorus with iron that is reoxidized by the downward diffusion of oxygen. When the compensation depth occurs in the metalimnion below the thermocline a greater fraction of phosphorus will coprecipitate with iron, and less reaches epilimnetic waters. The phosphorus input to metalimnetic waters supports metalimnetic layers of phytoplankton (especially bluegreen bacteria with low light requirements such as Oscillatoria sp.), chemolithotrophs, chemoorganotrophs, photolithotrophs, and photoorganotrophs. Production in the metalimnion tends to be favored over epilimnetic autochthonous production. When the transparency declines, compensation depth ascends, and epilimnetic production is favored.

The paralimnion is an integral part of the aquatic ecosystem. Terrestrial photosynthesis contributes to aquatic food webs, trophic dynamics, and internal nutrient cycling processes. The allochthonous input of DOM and POM represents a fraction, often a major fraction, of ecosystem production. Just as organic matter produced in the trophogenic zone of the lake is decomposed, the allochthonous DOM and POM support respiration in the lake. Nutrient loading from the paralimnion contributes to autochthonous production and subsequent respiration. Allochthonous DOM and POM contribute directly to the respiratory demand placed on the tropholytic zone.

Trophic Structure - "Food Web"

During the 1980's, an attempt was made by many limnological experts to make the point that eutrophication is a biological phenomenon, and that the biological component of a lake ecosystem can be "managed" in a way which manipulates the quality of the resource. **Eutrophication** is the biological response to increasing nutrient availability, either related to activities of man ("cultural eutrophication") or natural processes. This should not be confused with the filling of lake basins with sediment; primarily a geological process of **lake succession.** The filling of some lake basins with organic material is neither eutrophication nor lake succession. It is **dystrophication,** and tends to be caused by acidic conditions which limit microbial decomposition, and by a lack of available phosphorus and terminal electron acceptors rather than an overabundance. The point is that eutrophication is a biological phenomenon, and that biological management can control its effects. "Lake management" involves control of eutrophication, succession, dystrophication, contamination, and acidification. However, restoration methods for these are very different.

The focus of biological control methods has been aimed at the "Trophic Dynamic Structure", the growth of algae (phototrophy), grazing by zooplankton (especially large-bodied cladocera), and predation by zooplanktivorous and piscivorous fish populations. The principle of trophic manipulation is that increasing piscivorous fish (fish-eaters) decreases numbers of zooplanktivorous fish, increases grazer populations of zooplankton, and, hence, controls standing crop of phytoplankton by increased grazing efficiency. There is substantial evidence in the literature that this principle is sound. However, in practice the approach seems to produce inconsistent results. Perhaps the reason, and potential for ultimate success, lies not in the "Trophic Dynamic Structure", but rather in the "Detrital Dynamic Structure".

Trophic level manipulation relies on "recipient control", the receiving level controls donor level (e.g. grazers control phytoplankton). However, in nature, donor control usually prevails (Kortmann, 1980). Furthermore, the trophic dynamic structure (producer- grazer-predator-predator) operates at a relatively low efficiency. Only 10-15% of available energy from the donor trophic level is incorporated into biomass of the recipient level. The balance is <u>not</u> lost from the ecosystem.

Energy (in organic matter) that is not assimilated by the recipient trophic level goes into the detrital dynamic structure via "non-predatory losses" (Figure 5). The detrital dynamic structure makes this energy available to the food-web through heterotrophic bacteria, chemolithotrophic bacteria, etc. This is not a minor component of the ecosystem. Indeed, pure limnological research in the 1980's has demonstrated that bactivory (consumption of bacteria) can account for most trophic energy transfer at the primary consumer level (e.g. 50-80% of areal "grazing", and up to 98% of "grazing" at some depths (Sanders <u>et al.</u>, 1989). Ecosystem trophic efficiency is actually closer to 60%. Increasing the biomass of higher trophic levels will tend to increase the rate at which non-predatory losses enter the detrital dynamic structure, and will tend to accelerate the production of bacteria. In turn, it supports greater bactivory by flagellates, ciliates, rotifers, and some cladocerans, and supports greater biomass at higher levels. It also increases competition between bacteria (heterotrophic and chemolithotrophic) and phytoplankton (photolithotrophy) for available resources such as phosphorus (required by both bacteria and phytoplankton for their "biochemical machinery"). Observed low phytoplankton densities, high rotifer densities, and good transparency in lake waters with more than 30 ppb total phosphorus support this concept.

Biological management offers significant potential for controlling the effects of eutrophication. Consideration of both "Trophic Dynamic Structure" and "Detrital Dynamic Structure" may be the key to developing the utility of the method in the 1990's.

Lakes contain many life forms which work in concert to produce and use material and energy in a highly ordered system. Energy enters the lake ecosystem by photosynthesis either in the lake or the lake drainage basin. **Paralimnion** is the name for the drainage basin component of a lake ecosystem, and reminds us that the "Drainage

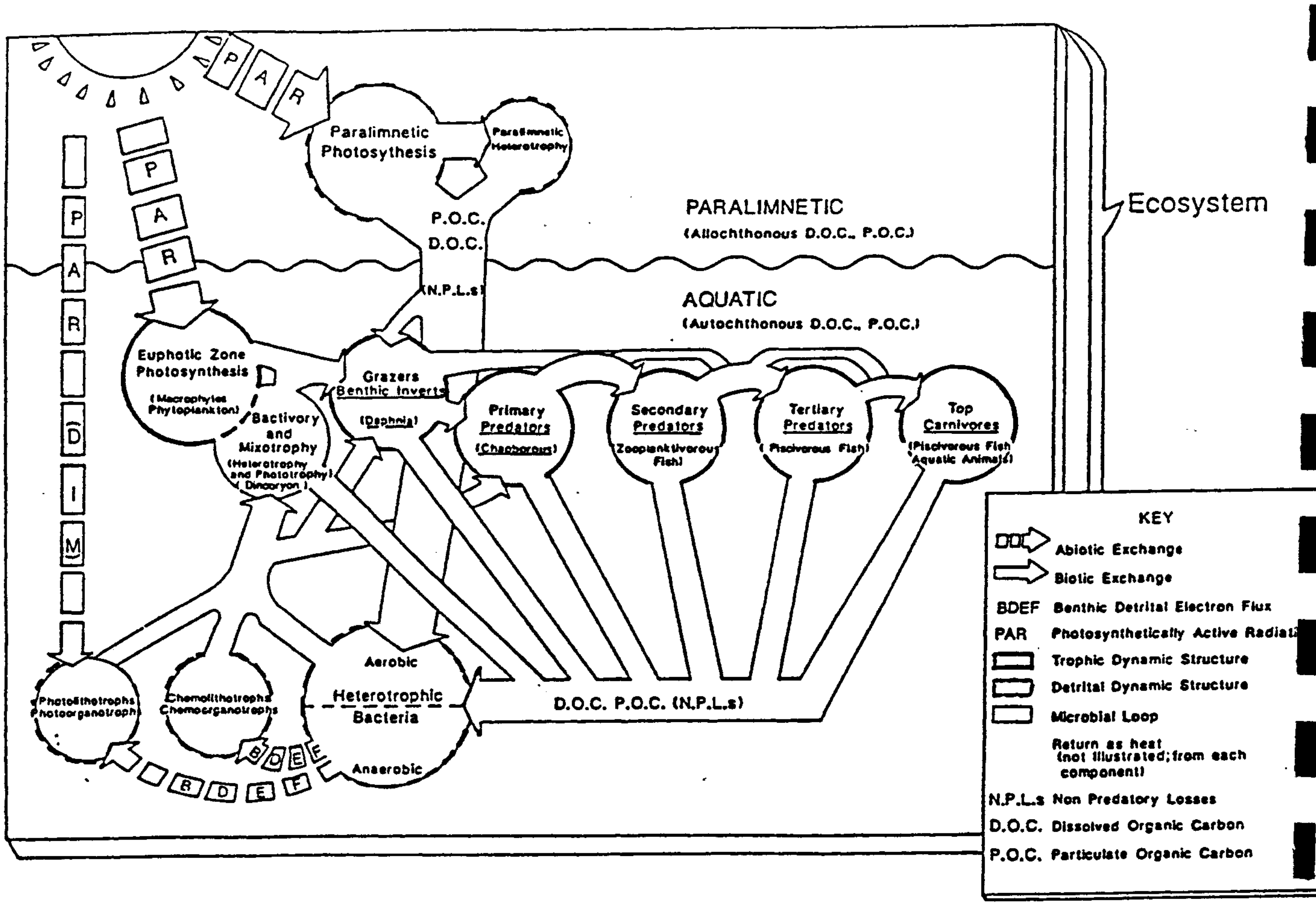
Basin" not only contributes substances to a lake via runoff, it is an **integral part of the ecosystem. Autotrophs** capture solar energy and store ("fix") the captured energy in the products of **photosynthesis**: oxygen and organic matter. The fixed energy is recovered by animals and bacteria when oxygen and organic matter are recombined in **respiration**. The products of respiration, water and carbon dioxide, are once again available for photosynthetic conversion to oxygen and organic matter.

The organic matter and energy fixed by autotrophs (**"primary producers"**), are passed on to the first tier of **heterotrophs** (**herbivores** or **primary consumers**) (Figure 16). Herbivory is a difficult biochemical step involving the conversion of plant (carbohydrate) material to animal (protein) material. In fact, herbivory is so inefficient that much plant matter goes uneaten, and is left to be decomposed by bacteria. In contrast to plants, bacteria are a good source of nutrition, and a large number of aquatic animals called **"filter feeders"** prey on bacteria as well as algae. The term **detritus"** is used to distinguish organic matter decomposed by bacteria (which are subsequently the prey of filter-feeders) from organic matter preyed upon while alive (**"grazed"**).

Omnivorous filter-feeders make the products of both aquatic and terrestrial photosynthesis (particulate and dissolved terrestrial detritus) available to aquatic predators (secondary consumers) which eat the primary consumers. Each step in the **"food chain"** from primary producers to the highest predators involves losses of organic matter and energy to respiration, incomplete digestion, etc. Thus, the collective mass (**"biomass"**) of autotrophs is larger than the biomass of primary consumers, and the biomass of primary consumers is larger than the biomass of secondary consumers, etc. The term **"ecological pyramid"** alludes to this phenomenon. Lakes which "tap" into the terrestrial food chain via the use of terrestrial detritus have anomalous consumer biomasses. Crossing-over between food sources by animals makes the term **"food-web"** more accurate than "food-chain", and reminds us that a lake is but part of a much larger ecosystem.

Lake ecosystems are complex, involving **both** terrestrial and aquatic photosynthesis, external and internal nutrients, grazer and detrital food-webs, and aerobic and anaerobic metabolism.

Most energy enters a small lake through terrestrial photosynthesis in the watershed (= paralimnion, part of the lake ecosystem). Photosynthesis in the lake itself is limited by physical and chemical characteristics of the water. About one half of the photosynthetically active radiation (PAR) is reflected and refracted at the lake surface, and much of the rest may be absorbed by lake water and organic matter dissolved in it. Energy from terrestrial photosynthesis helps lakes by creating the terrestrial community which takes up nutrients and prevents erosion of the drainage basin into the lake. However, large amounts of particulate and dissolved organic matter may be washed and blown into lakes from land. Terrestrial organic material affects physical/chemical properties and processes of lakes, combines with products of aquatic photosynthesis to support lake **food-webs**, and accumulates in lake sediments.


P A R
Paralimnetic Photosythesis
Paralimnetic Heterotrophy
P.O.C.
D.O.C.
(N.P.L.s)
PARALIMNETIC
(Allochthonous D.O.C., P.O.C.)
AQUATIC
(Autochthonous D.O.C., P.O.C.)
Ecosystem
P A R D I M
Euphotic Zone Photosynthesis
(Macrophytes Phytoplankton)
Bactivory and Mixotrophy
(Heterotrophy and Phototrophy) (Dinobryon)
Grazers
Benthic Inverts
(Daphnia)
Primary Predators
(Chaoborous)
Secondary Predators
(Zooplanktivorous Fish)
Tertiary Predators
(Piscivorous Fish)
Top Carnivores
(Piscivorous Fish Aquatic Animals)
Aerobic
Heterotrophic Bacteria
Anaerobic
Photolithotrophs Photoorganotrophs
Chemolithotrophs Chemoorganotrophs
B D E F
D.O.C. P.O.C. (N.P.L.s)
KEY
Abiotic Exchange
Biotic Exchange
BDEF Benthic Detrital Electron Flux
PAR Photosynthetically Active Radiation
Trophic Dynamic Structure
Detrital Dynamic Structure
Microbial Loop
Return as heat (not illustrated; from each component)
N.P.L.s Non Predatory Losses
D.O.C. Dissolved Organic Carbon
P.O.C. Particulate Organic Carbon

The overall flow of energy between trophic levels shown in Figure 16 is superimposed on a thermally stratified lake in Figure 17. Here, the compensation depth is shown within the metalimnion, which is often the case in deep thermally stratified temperate lakes. The "trophic dynamic structure" is widely recognized. It involves autochthonous production by aquatic macrophytes (littoral zone photosynthesis) and phytoplankton (pelagic photosynthesis), grazing by littoral invertebrates and zooplankton, zooplanktivorous predation, and piscivorous predation. This "trophic dynamic structure" prevails in the littoral zone and trophogenic pelagic zone.

The "detrital dynamic structure" of ecosystems is not as widely recognized or understood. It is generally considered to be the "decomposition process" but is rarely recognized for its role in ecosystem energetics. Most of the energy available in organic matter that is "grazed" or "preyed upon" is not assimilated by the consumer; it becomes non-predatory losses and enters the detrital system. Aerobic and anaerobic heterotrophic bacteria use non-predatory losses to support their respiration. Heterotrophic bacteria are consumed and the "detrital energy" reenters the trophic dynamic structure (food web).

As discussed previously, under anaerobic conditions alternate (to oxygen) terminal electron acceptors are used and reduced anaerobic respiration products are produced. These reduced products contain residual energy which supports photolithotrophy, photoorganotrophy, chemoorganotrophy, and chemolithotrophy. The transport of the reduced products of anaerobic respiration from sediments to overlying water represents an abiotic energy flow called benthic detrital electron flux (BDEF). The interaction between the detrital dynamic structure and trophic dynamic structure occurs via bactivory and represents a major component of ecosystem energetics (Rich, 1984; Bird and Kalff, 1986; Bloem and Bar-Gilissen, 1989; Sanders et al., 1989). Terrestrial photosynthesis and subsequent POC and DOC allochthonous loading is an important extension of the detrital dynamic structure. Terrestrial detritus supports heterotrophic bacteria, bacterial chemo- and phototrophies, and the higher food-web system via a "microbial loop" and bactivory.

Lake ecosystem energetics are summarized in a schematic illustration (Figure 18). Input of nutrients (from the paralimnion) and photosynthetically active radiation support internal primary production (autochthonous). Autochthonous production supports the food-web of the trophic dynamic structure. Input of allochthonous organic matter is an extension of the detrital system and supports heterotrophic bacteria which, in turn, contribute reducing power via BDEF to phototrophic and chemotrophic bacteria. The detrital dynamic structure is driven by non-predatory losses from the trophic dynamic structure and by terrestrial detritus. The detrital system supports the trophic dynamic structure via bactivory at the primary consumer level and by making nutrients available to support greater autochthonous production.

Figure 17

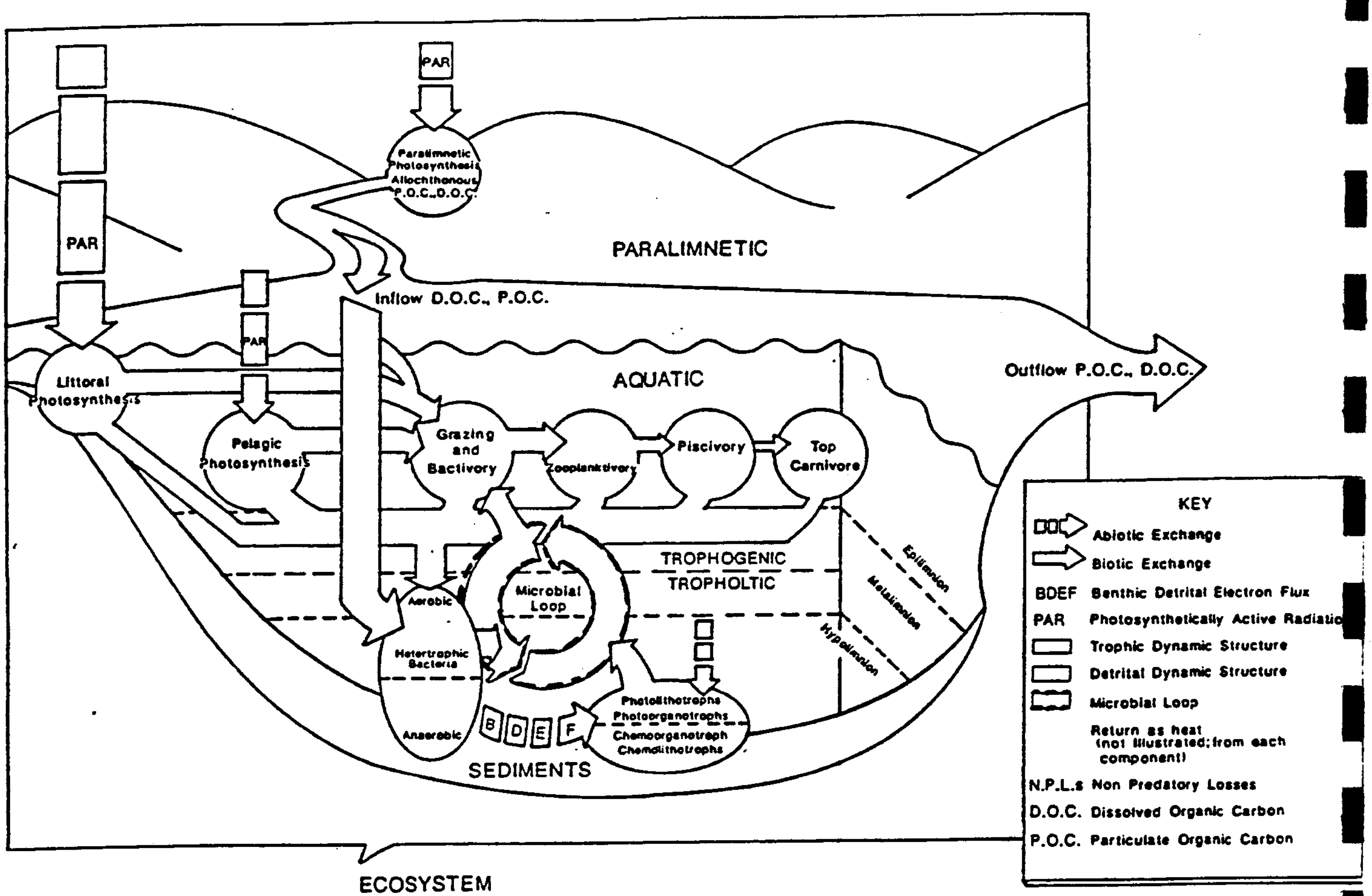
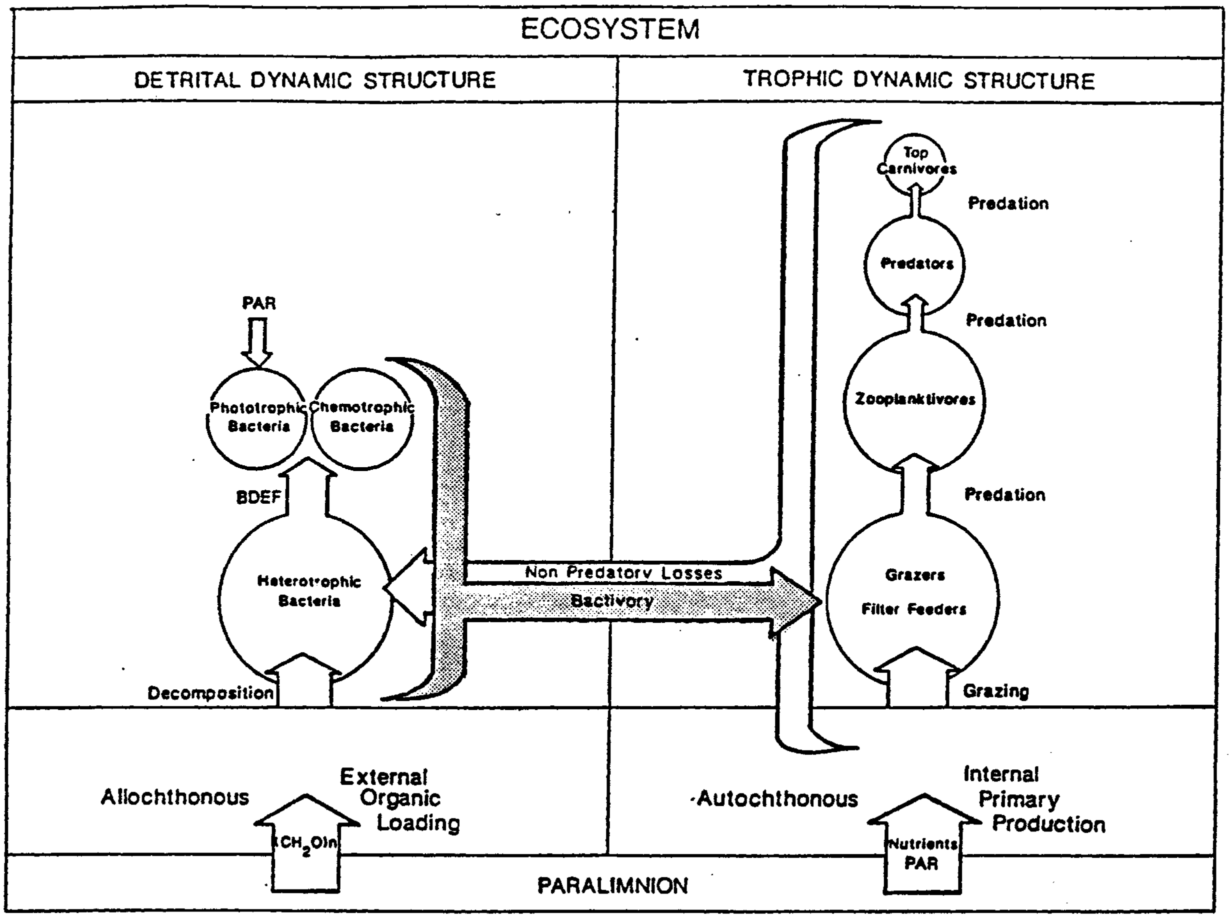

PAR
Paralimnetic Photosynthesis Allochthonous P.O.C., D.O.C.
PAR
PARALIMNETIC
Inflow D.O.C., P.O.C.
PAR
Littoral Photosynthesis
AQUATIC
Outflow P.O.C., D.O.C.
Pelagic Photosynthesis
Grazing and Bactivory
Zooplanktivory
Piscivory
Top Carnivore
TROPHOGENIC
TROPHOLTIC
Epilimnion
Metalimnion
Hypolimnion
Microbial Loop
Aerobic
Heterotrophic Bacteria
Anaerobic
B D E F
Photolithotrophs
Photoorganotrophs
Chemoorganotroph
Chemolithotrophs
SEDIMENTS
ECOSYSTEM
KEY
Abiotic Exchange
Biotic Exchange
BDEF Benthic Detrital Electron Flux
PAR Photosynthetically Active Radiatio
Trophic Dynamic Structure
Detrital Dynamic Structure
Microbial Loop
Return as heat (not illustrated; from each component)
N.P.L.s Non Predatory Losses
D.O.C. Dissolved Organic Carbon
P.O.C. Particulate Organic Carbon

Figure 18


ECOSYSTEM
DETRITAL DYNAMIC STRUCTURE
TROPHIC DYNAMIC STRUCTURE
Top Carnivores
Predation
Predators
Predation
PAR
Phototrophic Bacteria
Chemotrophic Bacteria
Zooplanktivores
BDEF
Predation
Heterotrophic Bacteria
Non Predatory Losses
Bactivory
Grazers
Filter Feeders
Decomposition
Grazing
Allochthonous
External Organic Loading
(CH2O)n
Autochthonous
Internal Primary Production
Nutrients
PAR
PARALIMNION

Ecosystem Symbiosis
"Detrital Management"

An "ecological symbiosis" exists between bacteria which use alternate terminal electron acceptors and those which rely on the used (chemically reduced) products of anaerobic respiration as an energy source for synthesis. The products of anaerobic respiration include nitrite nitrogen, ammonia nitrogen, ferrous iron, hydrogen sulfide, and methane:

nitrate → nitrite

nitrite → ammonia

ferric iron → ferrous iron

sulfate → hydrogen sulfide

carbon dioxide → methane.

These reduced, energy-rich compounds accumulate as extra cellular products of anaerobic respiration. They are transported by Fickian diffusion across the benthic boundary layer, a process called Benthic Detrital Electron Flux (BDEF). When the reduced products encounter an environment with either dim light (PAR), microaerophillic oxygen content, or both, the reducing energy they contain becomes available to other bacteria in photo- or chemolithotrophy:

ammonia → nitrite

nitrite → nitrate

ferrous iron → ferric iron

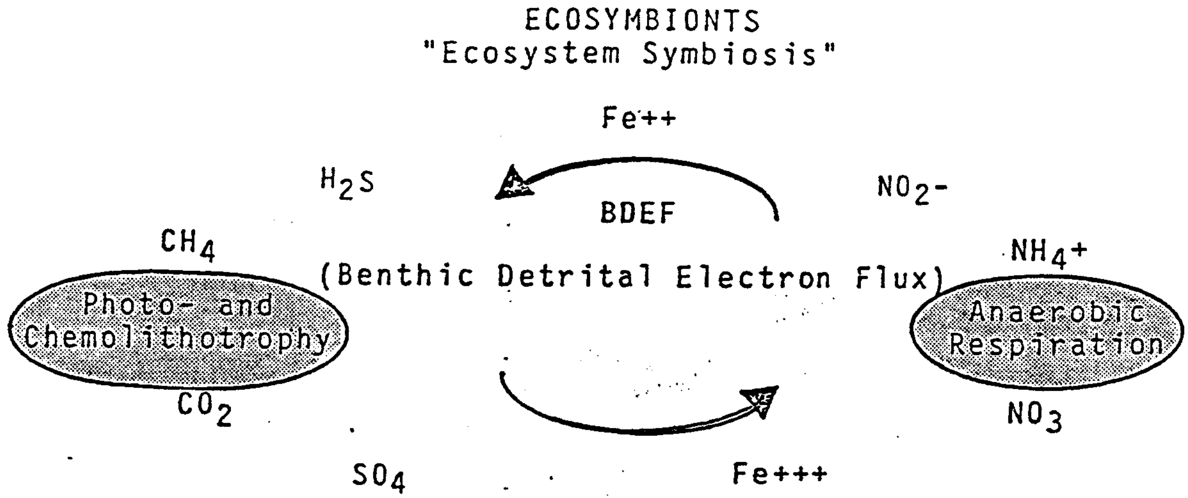
hydrogen sulfide → sulfate

methane → carbon dioxide.

Photo- and chemolithotrophs take advantage of the energy contained in reduced anaerobic respiration products to synthesize organic matter. Once reoxidized by these bacteria, the products (nitrate, nitrite, ferric iron, sulfate, carbon dioxide) once again are available as terminal electron acceptors for anaerobic respiration.

This "ecosystem symbiosis" provides a mechanism for energy flow from anaerobic environments to aerobic environments without "wasting" the energy resource. The reducing energy contained in the reactants of photo- and chemolithotrophy was originally derived from heterotrophic anaerobic respiration (ultimately, the "synthesis" took place as either aquatic or paralimnetic photosynthesis). Ecological communities evolve to exploit resources to full advantage (i.e. maximize the production of entropy). This component of the Detrital Dynamic Structure is a good example.

Figure 19



"Ecosystem symbiosis" between heterotrophic anaerobic bacteria, environmental BDEF, and photo- or chemolithotrophy can be enhanced to improve water quality and control the "expression" of eutrophication. Examples include:

Treatment System II at Lake Warámaug which provides a bacterial innoculum and environmental conditions of light and oxygen content which:

* enhance conversion of ammonia to nitrate and subsequent use of nitrate as a terminal electron acceptor in denitrification,

* cultures iron bacteria (in the system and in situ in the lake) which oxidizes ferrous iron (produced by anaerobic respiration in the hypolimnion) and returns it to the lake, in addition to abiotic oxidation. Ferric iron returned is again available as a terminal electron acceptor and as a precipitation agent for phosphorus.

Layer Aeration methods which enhance the interactions between trophogenic and tropholytic zones by redistributing oxygen (produced photosynthetically above the compensation depth) to enhance microaerophillic bacterial processes such as chemo- and photolithotrophy, as well as increasing abiotic coprecipitation of phosphorus with ferric hydroxy complexes (Kortmann, et al., 1988).

Lake management focus has traditionally been on "Trophic Dynamic Structure" (plant-grazer-predator). Improved understanding of the "Detrital Dynamic Structure" has resulted in the identification of management approaches which offer long-term, cost-effective control of eutrophication. Many such approaches are currently under development (i.e. alum surrogate, copper sulfate surrogate); others have been tested and improved upon (layer aeration methodologies, System II-Waramaug microbial processing). Several of the basic principles (goals) of these methods which focus on the Detrital Dynamic Structure include:

* favoring use of nitrate as a terminal electron acceptor to stabilize Eh, reduce sediment P release; using nitrification of lake-generated ammonia to provide the nitrate source (no chemical additions),

* favoring ferric iron in the ferrous-ferric couple to increase P precipitation,

* favoring heterotrophic bacteria, photo-, and chemolithotrophic bacteria in their competition with autotrophs for available phosphorus (reducing phytoplankton autochthonous production and promoting the decomposition of allochthonous POM and DOM),

* maintaining an adequate food-web base (via bactivory).

These are several approaches to "Detrital Management" already identified; much remains to be discovered.

Eutrophication: Compensation Depth

Eutrophication is the biological response to increasing nutrient availability. Greater nutrient availability supports increased internal primary production (of autochthonous organic matter). Phosphorus is typically the element in shortest supply relative to aquatic plant requirements; hence, it tends to be limiting. Phosphorus is essential to both autotrophic processes (e.g. cyclic and noncyclic photophosphorylation) and heterotrophic processes (e.g., ATP, substrate level phosphorylation). Autotrophs and heterotrophs compete for available phosphorus. Abiotic chemical reactions compete with both autotrophs and heterotrophs for phosphorus (e.g., ferric hydroxyl phosphate complex formation). Of greatest concern to "eutrophication abatement" is the availability of phosphorus in the trophogenic zone and its effect on internal primary production. In principal, the best lake ecosystem management approach is one that limits phosphorus availability to autotrophs (trophogenic zone; macrophytes and algae) while not limiting phosphorus availability to heterotrophs (tropholytic zone; decomposition maintained).

The effect of increasing nutrient availability, and the biological response of autotrophs, is illustrated in Figure 20. The history of eutrophication demonstrates changes in ecosystem structure and function in response to increased nutrient availability. As nutrient availability increases, primary production increases. External nutrient loading from watershed (paralimnetic) sources initiates the increase in phytoplankton production. As a result of increased phytoplankton densities, transparency declines and autochthonous organic matter increases. The compensation depth ascends; it is controlled by light attenuation in overlying H^2O.

Recall that the compensation depth identifies the boundary between trophogenic zone (above, net oxygen production) and tropholytic zone (below, net oxygen consumption). As nutrient availability increases, causing increased phytoplankton production and decreased transparency, the compensation depth becomes shallower. As compensation depth ascends, ultimately reaching the epilimnetic-metalimnetic boundary, a variety of changes occur, including those

identified in Figure 20. Eutrophication, initiated by increased external nutrient loading, perturbs and changes the internal structure of the lake. Greater areal and temporal duration of anoxia leads to increased anaerobic respiration, sediment nutrient release, and anaerobic synthetic and respiratory processes occurring at a shallower depth. Reprecipitation of sediment-released phosphorus decreases, transport to the trophogenic zone increases. Photosynthetic oxygen production occurs only in shallower waters. Hence, nitrification and subsequent denitrification in deeper strata declines.

The redox potential decreases further in deep strata resulting in greater internal P loading, greater sulfide generation, iron removal as pyrite, and reduced phosphorus binding capacity. Greater autochthonous production increases the organic load to the detrital dynamic structure, favoring bactivory (e.g., by Bosmina sp.) over phytoplankton grazing (e.g., by Daphnia sp.). The shift in dominance from the "Trophic" to "Detrital" dynamic structure is increased further by a decline in suitable habitat for piscivorous fish, an overabundance of zooplanktivorous fish, and decline in refuge habitat which facilitates diurnal vertical migration by grazing zooplankton. Watershed nutrient loading effects the entire structure and function of the lake ecosystem, not simply increased primary production.

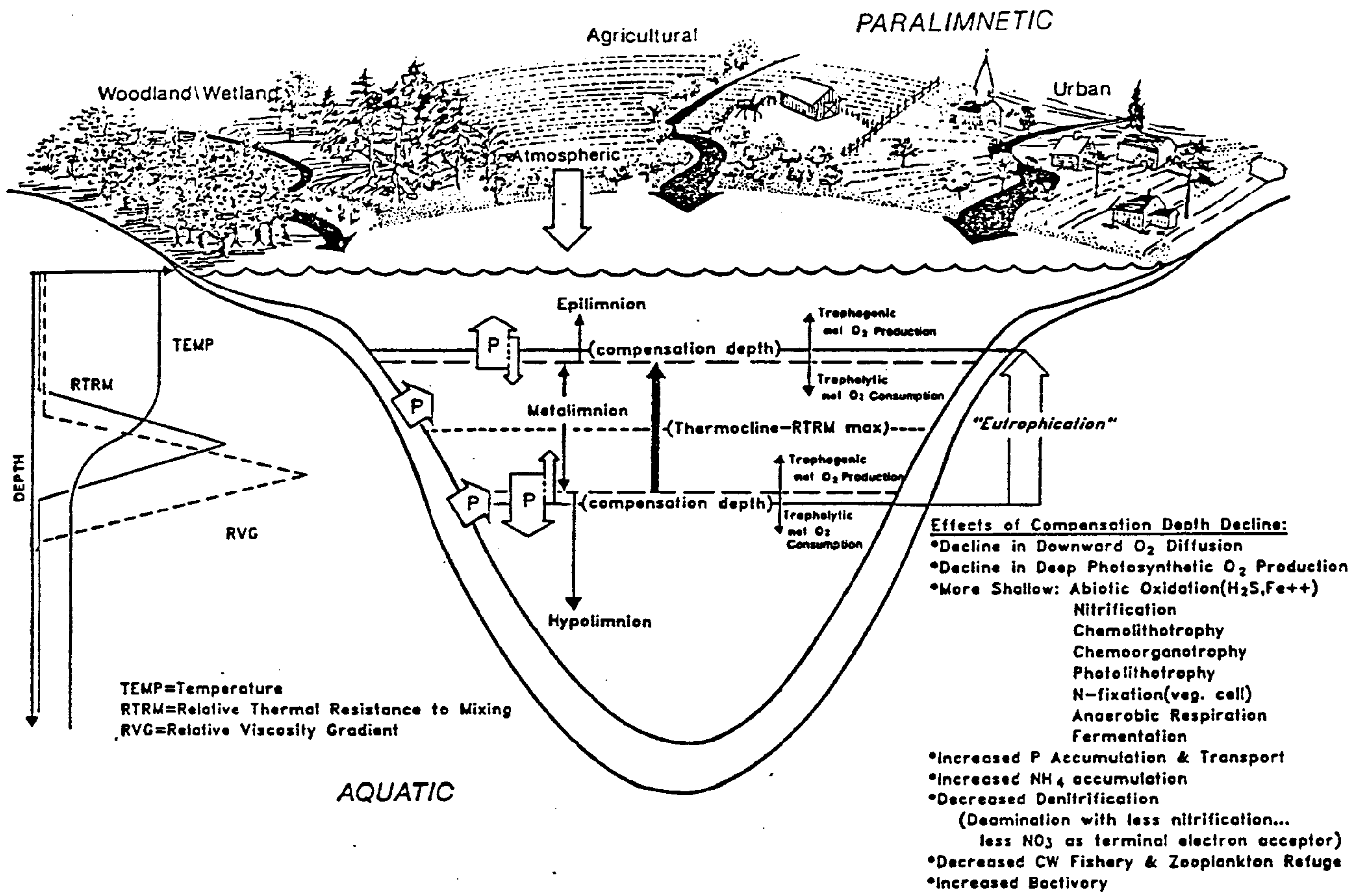
Restoration of a highly eutrophic lake is a difficult process because it involves reversal of the changes which were induced during eutrophication.

Ecosystem Management

Lakes are complex ecosystems. One system component interacts with others ... which interacts with others! Lakes truly are "Mirrors of the Landscape" -- their quality reflects the quality of the water they receive. It is for this reason I chose the title of this handbook.

Effective, long-term lake management involves correcting the causes of problems. Unfortunately, lake ecosystems, and eutrophication problems, cannot successfully be put into a single "cause-effect" relationship. Rather, a complex system of "cause-effect" emerges when one closely examines eutrophication and other lake ecosystem phenomena. A "cause" results in an "effect" ... which becomes a "cause" of another "effect", and so forth. These are, after all, ecosystems. For example, eutrophication almost always can be traced to an "ultimate cause": watershed nutrient, sediment, and organic loading. Nutrient enrichment (a "cause") results in increased weed and algae growth (an effect). Increased algae growth ("cause") results in more light attenuation ("effect"). Less light penetration causes less oxygen production at depth ... which causes more intense oxygen loss ... which causes habitat loss and more internal nutrient loading ... which causes more algae, less light penetration, and so on and so forth. In a sense, "eutrophication" caused ultimately by watershed nutrient enrichment becomes an "accelerating process" -- a "biological response" to nutrient enrichment. Eutrophication can be controlled, even reversed, by astute management of the system ... the ecosystem -- both land and water.

Figure 20


PARALIMNETIC
Agricultural
Woodland\Wetland
Urban
Atmospheric
Epilimnion
P
(compensation depth)
Trophogenic
net O_2 Production
Tropholytic
net O_2 Consumption
TEMP
RTRM
Metalimnion
(Thermocline–RTRM max)
"Eutrophication"
DEPTH
Trophogenic
net O_2 Production
(compensation depth)
Tropholytic
net O_2
Consumption
RVG
Hypolimnion
TEMP=Temperature
RTRM=Relative Thermal Resistance to Mixing
RVG=Relative Viscosity Gradient
AQUATIC
Effects of Compensation Depth Decline:
•Decline in Downward O_2 Diffusion
•Decline in Deep Photosynthetic O_2 Production
•More Shallow: Abiotic Oxidation(H_2S,Fe^{++})
Nitrification
Chemolithotrophy
Chemoorganotrophy
Photolithotrophy
N–fixation(veg. cell)
Anaerobic Respiration
Fermentation
•Increased P Accumulation & Transport
•Increased NH_4 accumulation
•Decreased Denitrification
(Deamination with less nitrification...
less NO_3 as terminal electron acceptor)
•Decreased CW Fishery & Zooplankton Refuge
•Increased Bactivory

An Action Plan

An action plan for lake ecosystem management has three parts: (a) a natural resource base, (b) a land use evaluation, and (c) a design and implementation plan based on (a) and (b). Homeowners can also do their part (Table 3).

Action Plan: Natural Resource Base

Sound management begins with a detailed data base describing the natural resources of the drainage basin. A good first step is a soils map indicating the natural soils groups as defined by the Soil Conservation Service. The soil evaluation is the basis for an assessment of erosion potential, potential nutrient contribution, and management techniques for specific areas of a watershed. Soils mapping will also define important wetland areas and streambelt corridors important for the protection of the lake ecosystem.

Critical natural features such as steep slopes, gradients (slopes) of tributary streams, and the general geologic composition of watershed sub-basins should then be described. Lakes which are otherwise similar but have different watershed geology exhibit very different characteristics. For instance, Lake Wononscopomuc in Salisbury, Connecticut, is in a limestone area. As a result, Wononscopomuc has hardwater, and its hypolimnion is dominated by sulfur. Lake Waramaug in Warren, Connecticut, is in a granite area, has softwater, and its hypolimnion is dominated by iron. Although both lakes are located in the northwestern corner of Connecticut, local geological differences make them very different.

When soils have been categorized and critical natural features identified, the entire lake drainage basin should be divided into its hydrologic sub-basins. The hydrology of each sub-basin then should be described with reference to soils and topography. A **unit hydrograph** for each sub-basin will maximize information and minimize effort and cost.

Finally, a description of the internal structure and metabolism of the lake through an entire summer stratification should be incorporated into the natural resource base. Such factors as consumption rate of dissolved oxygen, production rate of carbon dioxide, stratification dynamics, algal abundance, and weed distribution should be included.

Table 3. - How a homeowner living near a lake or near a stream entering a lake can help.

1. Use laundry, dish, dishwater and general purpose detergents which contain the lowest phosphorus content per use.

2. Avoid use of garbage disposals. They tend to overload septic systems with organic matter. If you have a garbage disposal, have your septic tank (the device designed to trap and store sinking and floating solids) pumped more frequently.

3. Have your septic system pumped regularly (every 2-5 years depending on system and use). Regular pumping will save the expense of major repairs in the long run.

4. Do not put grease, fats, etc. into your sink. They clog soils and lead to septic system failure.

5. Do not pour pesticides, disinfectants, acids, medicines, paint thinner, or other chemicals into your septic system. They are harmful to the bacteria which are at work in your septic system, and such substances can contaminate groundwater.

6. Minimize water use by installing water saving fixtures.

7. Keep heavy vehicles off the septic leaching area. Compacted soils will decrease the septic system's ability to accept wastewater.

8. Do not plant deep-rooted trees near the septic system. Maintain a buffer strip of evergreen plants between a septic system and a lake. Keep leaves from deciduous trees from entering a lake when possible.

9. Minimize fertilizer use, and use low phosphorus fertilizers. Apply fertilizer in summer (not spring) and after a rainfall (not before). Plant grass species having low nutrient requirements and evergreen trees and shrubs. Do not rake leaves and grass cuttings into a lake. If you rake weeds out of a lake - great! (but compost the aquatic plants away from the shoreline).

10. Stay informed about activities taking place to protect lake water quality. Participate in lake restoration activities and contribute to your lake association. Lake preservation in a long-term, perhaps permanent, effort.

Action Plan: Land Use Evaluation

The next step is to use the resource data base for an evaluation of various land uses in the watershed. The evaluation should consider land use practices past, present, and future, and their effects on the lake. Those effects can be estimated and predicted using models such as that contained in the Windham Regional Planning Agency Handbook and the land use model developed at the Connecticut Agricultural Experiment Station in New Haven.

A land use evaluation begins with general information regarding factors such as agricultural use and practices (including manure storage and spreading, use of fertilizers, etc.), construction, storm- and wastewater disposal, and other significant activities in the watershed. Erosion hazards among different land use areas should be identified, and specific erosion and sediment sources compared and rated.

Action Plan: Best Management Policies and Practices

Finally, management policies and practices based on the natural resource data base and land-use evaluation must be designed, optimized, and implemented. An organization (private lake association, town conservation commission, lake task force, etc.) appropriate to the particular situation should play the central role in implementing a watershed/lake management plan (see Chapter 1). Assistance may be obtained from a number of sources, including government agencies, universities, private companies, etc. (see Appendix I). Technical advice and assistance is available from Departments of Environmental Protection (Federal and State), Agricultural Experiment Stations, Regional Planning Agencies, the Soil Conservation Service, and Colleges/Departments of Agriculture, Forestry, Natural Resources, Civil Engineering, and Biology (ecology and limnology) at state and private universities. Assistance in development and implementation of regulations authorized by the Connecticut Inland-Wetland Act can be obtained from the Inland-Wetland Division of D.E.P., the Soil Conservation Service, local inland-wetland agencies, and private consultants. Assistance in designing Planning and Zoning policies and regulations is also available.

Education, public awareness, and citizen participation are often the most important aspects of lake restoration and preservation efforts. Programs such as workshops, slide presentations, nature walks, newsletter circulation, and other activities which involve people are vital parts of outreach. Table 3 offers some guidelines for homeowners which can help protect water quality.

Control of Eutrophication

Implementation of any lake preservation or restoration effort should start with watershed management to minimize future inputs of nutrients and sediment. The second step, when necessary, is in-lake management to suppress nutrients and the effects of nutrients already in the lake. In-lake treatments generally fall into two categories: (a) control of nuisance weed growth, and (b) reduction of algal blooms. Methods may involve long-term control of the causes of eutrophication or short-term treatment of the symptoms of eutrophication.

Control of Eutrophication: Weed Growth

The demand for control of undesirable aquatic plants increases as water bodies become developed and recreational uses become more intense. Factors contributing to the growth of aquatic plants involve both lake and watershed. Deposition of eroded silt and debris over a long period of time (succession) produces shallow lake basins and bays, and aquatic plant growth is stimulated where sunlight penetrates to the lake bottom. Extra nutrients from watershed disturbance (eutrophication) stimulate the growth of aquatic plants as well as algae. However, very high algal densities block enough underwater light to inhibit aquatic plants. (The first evidence of effective lake management often is increased aquatic plant growth caused by increased underwater light resulting from reduced algal density. Continued reduction of nutrients ultimately will bring the plants under control, too.) Finally, aquatic plant communities themselves may have cycles of relative abundance independent of habitat and nutrients.

Control of aquatic weeds begins, as does all lake management, with control of soil erosion and nutrient inputs from the watershed. Once current and future watershed inputs have been minimized, in-lake controls become feasible. Reliable and cost-effective control of aquatic plants requires knowledgeable management of natural forces. Drastic removal or destruction of nuisance plants does not always produce anticipated results. Chain reactions involving habitat and environmental changes and released nutrients may create conditions equally undesirable or worse. The possible consequences of any weed eradication program should be carefully assessed.

An aquatic "weed" may be defined simply as a plant that grows where it is not wanted. Waters with a variety of uses are likely to contain plants considered desirable by some and obnoxious by others. For instance, waterlilies offer an ideal habitat for some fish species. However, a patch of waterlilies clogging the area around a boat dock becomes a nuisance. Thus, aquatic plant communities must be balanced in a healthy biological system in which the levels of abundance match lake use. Some control

measures to limit aquatic weeds follows.

Weed Control: Herbicides

The advantages of chemical control are precision, specialization, and immediate results. However, control by herbicides usually is effective for a relatively short time, and repeated applications become expensive over the long term. Chemicals employed as aquatic herbicides may be categorized into two groups: a) those that kill outright by contact, and b) those that kill by disrupting normal growth.

Most contact herbicides are toxic to fish and other animals (including humans), although the concentrations used to kill aquatic plants are not considered dangerous. Fish kills occur when herbicides are not evenly distributed, when concentrations are miscalculated, when recently hatched fish are more susceptible than adults, when killed plants decay and deplete oxygen in the water, and when nutrients released by killed plants and anoxia produce further plant growth and decay. Those problems are minimized by treating small portions of a lake at a time and by spacing applications so that the decay process will not reduce dissolved oxygen to dangerous levels.

Herbicides such as 2,4-D stimulate abnormal plant growth that ultimately leads to exhaustion and death of the plant. "Growth-regulating" chemicals may control particular types of aquatic plants for several years at a time. Contact herbicides such as endothall, diquat, etc. are effective for control of submerged plants which are less susceptible to treatment with hormonal growth regulators.

Permits are required for chemical treatment, and the Pesticide Control Unit of the Connecticut Department of Environmental Protection offers advice regarding use and precautions for aquatic weed control by chemical herbicides. In the final analysis, chemical herbicides treat the symptoms of eutrophication rather than addressing the causes of eutrophication.

Weed Control: Mechanical Harvesting

Mechanical harvesting includes cutting, raking, or otherwise physically removing aquatic plants. A garden rake or hand pulling is effective for small areas around docks and bathing beaches. For larger areas special machines are available which may be adjusted to cut at various depths. Weeds that are cut should be removed from the water and disposed of away from the lake to prevent decay, anoxia, and nutrient release in the lake. Plant biomass consists primarily of the elements carbon, hydrogen, and oxygen. Nitrogen and phosphorus are present in very small

amounts. Removal of plants from lakes, therefore, is negligible in terms of total lake nutrient budgets. Mechanical harvesting produces immediate reduction in weed abundance. However, some plants will grow more rapidly when cut, and usually several cuttings are required each summer. Mechanical harvesting can be an effective management tool for lakes in which other control techniques are either impossible or economically prohibitive.

Weed Control: Lake Level Management

Lake level drawdown is a commonly practised technique in the southern United States, but has been less common in southern New England. During drawdown aquatic plants and their perenniating organs are killed by drying and freezing. Lake and pond fisheries often are improved at the same time. Drawdown increases mortality in fish subject to crowding and stunting such as bluegills. The increased mortality reduces crowding and results in better growth and larger sizes among surviving individuals when the lake refills. Drawdown also increases growth in large **piscivorous** (fish-eating) sport fish, such as bass. Drawdown forces small fish out of weedy shallows so they are more easily preyed upon by the large fish. Drawdown has only a short term effect (1-4 years), and must be done on a regular basis to provide long term benefits. However, water runs downhill free of charge, and annual drawdowns are cheap and convenient when a dam and gate are available or can be built on a lake outlet. Drawdowns must be planned carefully to insure adequate refill rate, residual habitat during drawdown, etc. Various drawdown approaches have widely varying effects upon different aquatic plant species, and the "target species" must be carefully identified.

The amount of residual water needed to preserve a healthy fishery during drawdown varies with season and the desired outcome. Fall and winter drawdowns apparently require less residual lake volume and should be of longer duration than summer drawdowns. Maximum depth of residual water should not be less than 6 feet in autumn and 14 feet in winter. A conservative guideline for drawdown is to achieve 50-60% of the lake or pond's littoral surface area, with the lake being partially refilled before total ice cover is expected.

Potential disadvantages of drawdown in southern New England include: (a) replacing an existing weed problem with another as bad or worse, (b) limiting warm-water sport fish species by reducing aquatic plants and the habitat they create, (c) exposing fish to severe climatic events (heat, freezing, etc.), and (d) creating a potential for disease through crowding the fish community. Possibility of the latter two problems (exposure and disease) are minimized during a late summer to late fall drawdown. The possibility of replacing one nuisance weed with another requires accurate identification of the plants involved and expert

advice on aquatic plant ecology and physiology. Some species are more susceptible to drying, freezing, etc., and have different life histories.

Weed Control: Dredging (depth of substrate)

Removal of lake or pond sediments is expensive, but may pay for itself in long term weed control. The method is most effective when uninhabitable bottom is exposed and when total depth exceeds about 10 feet. Control is achieved by (a) eliminating bottom material (organic muck, silt, etc.) suitable for weed growth and/or by (b) reducing light intensity at the bottom by increasing the depth of overlying water. Again, changing the bottom environment by sediment removal may eradicate one species and encourage another. Ten feet or more of overlying water usually blocks enough light to control growth of nuisance plants. When aquatic plants have been brought under control, increased competition for light and nutrients by algae often limits weeds in even shallower water.

Sediment removal is accomplished by two methods. First, if the lake can be drawndown sufficiently, sediments may be allowed to dry in place and then be excavated by conventional means (bulldozer, power shovel, frontend loader, etc.). A "dry dredging" project must be licensed under the Inland Wetland Act of Connecticut, and must be carefully planned to avoid potentially serious side-effects. A dry dredging project may mean loss of the fishery during implementation. Plans for rescuing fish populations and establishing the future fish community must be made prior to dredging. The excavation sequence and de-watering process must have good controls to avoid downstream impacts. Disposal of dredge spoils also requires careful planning. If the lake from which the sediments are being removed has been treated repeatedly with chemicals, the sediments should be analyzed for potentially dangerous residues. Sediments often are an excellent source of fertile and weed-free soil. However, potentially harmful concentrations of chemicals (such as copper and herbicides) may limit its usefulness.

Disposal of dredged materials, if it is to occur in **Regulated Wetland** areas, must be licensed under the Inland Wetland Act in Connecticut, and should be avoided. In shallow impoundments and lakes which have been treated heavily with copper, "lake bottom landscaping" may offer an attractive and cost-effective alternative to sediment removal. Use of conventional excavation equipment makes possible the construction of islands made from bottom material (becoming in-lake disposal sites) in some lakes. A landscape plan of final lake bathymetry can be designed to create a balanced **littoral zone** in which aquatic plants will establish a healthy biological community in balance with phytoplankton, zooplankton, and fish.

The second method of removing lake sediments is "wet dredging" which must be used when sediments cannot be exposed and dried in place. In wet dredging a large, rotating, corkscrew blade pushes organic sediment through a pipeline to shore. The "slurry" of sediment has a high water content (often 90%) to facilitate pumping. Therefore, large de-watering systems must be constructed on land near the lake. De-watering systems allow the dredged sediments to settle out of the slurry, and then dispose of the water. The water from wet sediments is extremely nutrient rich and should not be allowed to flow untreated back into the lake or into other surface waters.

Sediment suspended in the lake but not removed during dredging creates two water quality problems: increased nutrient concentrations and increased oxygen demand. Hence dredging may lead to algal growth and anoxia. Fortunately, those problems have been reduced by improvements in dredging equipment in recent years. A problem with wet dredging which does not occur in dry dredging is incomplete removal of surface sediments. Several documented cases exist in which narrow strips of sediment remained between passes by the dredge. The strips were largely "new" areas of exposed sediment surface high in phosphorus, and caused increased algae grwoth in the lake water and rapid recolonization of the bottom by plants.

Weed Control: Liners and Screening

Control of aquatic weeds in relatively small areas, such as boat slips and swimming areas, may be achieved by covering the bottom with liners or screens. Impervious liners such as plastic sheets also inhibit the release of phosphorus from the bottom. However, most sediments also release gases such as nitrogen and methane, the accumulation of which makes impervious liners impractical. Plastic liners must be securely anchored, for instance with clean sand.

A second kind of cover, fiberglas screening, is tightly anchored over aquatic weeds and compresses them against the bottom. The weeds are not eliminated, but a suitable bottom is provided for swimming and boat slips. Screening of appropriate mesh size allows continued access to the bottom for small animals and helps maintain a healthy biological flora and fauna. Aquatic weeds under screening also continue to compete for nutrients with algae in the water column. Fishing (except with surface lures) in areas covered with screening should be prohibited.

Screening generally is cost-effective only for small areas, but it reduces nuisance weed growth for many years. A relatively new nylon material called "Dartex" is vented for gas release, negatively buoyant, relatively easy to install, and relatively durable. Dartex and similar materials may be a cost-effective

solution for high-use areas of lakes.

Weed Control: Light Limitation

As discussed previously, the amount of light reaching lake bottom is an important factor in weed growth. A material now on the market reduces light penetation while imparting an aqua color to lake water. Essentially, the material mimics the effect of tea-colored humic materials in bog lakes in which aquatic plants rarely grow beyond a depth of one meter. Light limitation induced by the dye generally is effective only during the year of treatment, and is limited to small lakes with low hydrologic turnover. The method is not appropriate when a water supply (for domestic consumption) exists anywhere downstream, and discharge permits must be obtained prior to treatment. Dye is most effective in early spring during plant germination. The method is particularly efficient when a spring bloom of algae may already limit light penetration significantly. After dye application, light (and heat) is absorbed in a very thin surface layer. Intense thermal stratification, anoxia, and sediment nutrient release can result. Light limiting dyes should be assessed carefully to avoid potentially serious side effects.

Application of a limited amount of dye to supplement light absorption of an algal bloom also may prevent reestablishment of nuisance weed growth following other restoration techniques. Algal abundance often increases following dredging, waterlevel management, herbicide applications, etc. because of increased availability of nutrients and light. **Green algae** generally are not a nuisance, but **blue-green algae** may be more of a problem than the aquatic weeds. Blue-green algae convert inert atmospheric nitrogen gas to nitrogen compounds required for plant growth. That advantage favors blue-green algae over green algae when environmental nitrogen:phosphorus ratios are low. Experimental evidence indicates the advantage of blue-greens over greens is reversed by applying nitrogen salts and raising the environmental N:P ratio.

Control of Eutrophication: Algal Blooms

Over-abundance of algae (microscopic, free-floating plants) results from high nutrient availability in the presence of other suitable environmental conditions. Control of algal blooms is achieved either by killing the algae or reducing nutrient enrichment. Success depends upon controlling causes rather than symptoms. Treating symptoms, for instance using **algicides**, is temporary, has dangerous side-effects, and becomes expensive in the long term. Treating causes, for instance reducing nutrient inputs by systematic watershed management and planning, is more permanent, has fewer side-effects, and becomes cost-effective in

the long term.

Algae Control: Chemical Treatment

Contact algicides (such as copper sulfate) are the only effective chemical control of algae. Copper sulfate generally is more effective when treatment is performed before the algae become dense enough to be a problem. Copper sulfate is less effective and must be used in higher concentrations in hard water because copper combines with carbonates and precipitates out of solution. Copper sulfate should not be used when trout are present.

Application of copper sulfate is limited by law in Connecticut to a maximum concentration of 0.25 parts per million. A concentration of 0.5 ppm is more effective, but has adverse effects on other organisms. Long term control of algae by copper sulfate and other contact algicides generally requires repeated applications. The resulting accumulation of chemicals on the lake bottom may foreclose sediment removal and disposal in the future.

The decay of poisoned algae may exhaust dissolved oxygen, increase nutrient concentrations and regeneration, and kill fish. Regrowth of algae following treatment may be denser than that which was treated, and may consist of less desirable species. Chemical treatment of algal blooms is appropriate primarily as a maintenance procedure when control of nutrient loading is impossible.

Algae Control: Aeration

Much less phosphorus is released from sediments when water overlying the sediments is oxygenated than when overlying water is anoxic. When a large proportion of lake bottom becomes anoxic during summer stratification, large amounts of phosphorus may diffuse into a lake, creating bloom conditions. Aeration is an appropriate method for controlling sediment release of phosphorus in some lakes. Two types of aeration are available: one method mixes the entire water column, the other maintains or manipulates thermal stratification.

"Destratification aeration" uses bubblers or mechanical mixing devices to expose all the water in a lake to the atmosphere. Destratification is the most effective way to aerate an entire lake, but a destratified lake generally will not support a cold water fishery in southern New England. Currents induced over the bottom by mixing actually may increase the transport of phosphorus from sediments to water. The increased transport of phosphorus will increase total algal abundance, although the concentration of algal cells may be less at the surface because the cells are diluted throughout the entire water column by the mixing.

Careless installation and use of bubblers may increase turbidity by resuspending bottom sediment.

"**Hypolimnetic aeration**" aerates only the bottom layer of lake water and does not destroy thermal stratification. Maintaining thermal stratification while aerating is less efficient than methods involving destratification. Therefore, hypolimnetic aeration is most cost-effective in lakes with relatively small volumes of cold water.

Maintenance of an aerobic hypolimnion improves cold water fishery habitat, preserves an oxygenated dark layer in which zooplankton can escape fish predation during daylight hours, and limits both release and transport of phosphorus from sediments. When in-lake phosphorus loading contributes significantly to algal abundance in a small lake, hypolimnetic aeration may be an effective and convenient restoration alternative.

A newly developed modification of hypolimnetic aeration takes advantage of the natural stratification of temperature and dissolved oxygen in lakes. The technique uses selective mixing and aeration to create aerobic layers within the vertical profile. "Layer aeration/circulation" may be particularly cost effective because it redistributes oxygen already available in a lake. Hence, compressor capacity and costs of capital equipment and operation are reduced.

Algae Control: Selective Withdrawal

Selective withdrawal of nutrient-rich bottom water is another method appropriate for lakes with in-lake nutrient loading. Removal of bottom water intercepts phosphorus diffusing from the bottom, decreasing nutrient accumulation below the thermocline and transport to the epilimnion. Water taken from the bottom may be treated to improve its quality and either discharged downstream or returned to the lake. When withdrawn water is discharged downstream, all the phosphorus removed from the lake bottom is removed from the lake permanently. Hypolimnetic withdrawal and discharge treatment must be carefully designed and implemented to prevent adverse effects downstream. Only a part of natural surface outflow should be displaced by removal of bottom water so that lake level is not altered.

Hypolimnetic withdrawal has been used in several European lakes and recently has been employed at Lake Wononscopomuc in Salisbury, Connecticut. At Wononscopomuc the combination of watershed management, control of overwintering geese, and hypolimnetic withdrawal have improved lake water quality noticeably. Phosphorus accumulation and vertical transport have been reduced, onset of hypolimnetic anoxia has been delayed, hypolimnetic accumulations of reduced substances such as hydrogen sulfide have

been reduced, and light penetrates deeper into the lake.

An experimental method of hypolimnetic withdrawal is in progress at Lake Waramaug, Connecticut. In addition to hypolimnetic withdrawal and discharge, a second withdrawal system treats withdrawn bottom water and returns it to the middle depths of the lake. The second system has the effect of hypolimnetic withdrawal at the inlet end and the effect of hypolimnetic aeration at the outlet end. The water withdrawn is treated to remove some of the phosphorus, to increase dissolved oxygen content, and to oxidize chemically reduced substances, specifically ferrous iron. The oxidized (ferric) iron precipitates, removing phosphorus from the water both in the treatment system and after its return to the lake. Removal of phosphorus by reaction with iron is similar to (and more rapid than) precipitation of phosphorus by alum. The hypolimnetic treatment systems at Lake Waramaug do not aerate the entire hypolimnion, but increase the depth to the anoxic boundary and reduce phosphorus transported to the epilimnion. Deepening the anoxic boundary also may improve survival of the cold water fishery and zooplankton. Essentially, the systems at Lake Waramaug are "hypolimnion skimmers" which help to isolate bottom water (hypolimnion) from surface water (epilimnion).

Algae Control: Nutrient Precipitation/Inactivation

The "**alum treatment**" is the application of aluminum sulfate to a lake for the purpose of precipitating phosphorus from the water column and making it chemically unavailable in the sediments. Criteria for selecting lakes for phosphorus inactivation by alum follow.

1. Lakes should be eutrophic or mesotrophic so that improvement in lake water quality will be significant.

2. Water retention time should be long enough to produce observable and persistent improvement. Generally, that means the watershed/lake area ratio should be small.

3. Phosphorus should be the limiting nutrient for planktonic algae, and should remain so (or become so) after treatment.

4. A substantial proportion of phosphorus in a lake should be in forms susceptible to inactivation at the time of treatment.

5. Phosphorus inputs from a lake watershed should not be large enough to negate the effects of treatment. That means phosphorus present in the lake and supplied from internal sources (such as from the sediments) should be a substantial proportion of the total annual supply.

6. Lake depth should be great enough to allow adequate settling

and to prevent resuspension of precipitated phosphorus.

7. Lake surface area should be small enough to permit treatment at acceptable cost, but large enough to behave like other lakes which have been treated.

8. A lake should have sufficient recreational or other value to justify the expense of the treatment.

9. Background data (natural resource data base) should be available or be obtained on physical, chemical, and biological characteristics of the lake and watershed.

"Surrogates" for alum are currently under study, which could provide similar nutrient inactivation benefits without the related short- and long-term impact potential.

Algae Control: Other Methods

A number of other methods, still experimental or theoretical, may become useful in the future and under special circumstances.

Addition of nitrate to lake hypolimnia has had some success in Europe. Nitrate behaves like oxygen in decomposition processes, and may reduce sediment phosphorus release.

An "Automatic Discharge Control Assembly" (U.S. patent) can be installed in most lakes to automatically remove a selected ratio of surface and deep water (any depth) without affecting lake level or involving annual energy costs. In lakes where over-bottom water contains adequate oxygen, but slightly higher nutrient concentrations than surface water, downstream effects are not problematic. If anoxia develops, carefully planned treatment of the withdrawn water is necessary and a permit is required from the State.

"Enhanced Interflow" can be designed to deliver watershed inflow to specific and optimum depths in the lake's thermal structure.

Experiments are in progress with a new algicide (not available at this time) which kills algae while reducing adverse effects of the decaying biomass.

Finally, it must be emphasized that watershed management is the first step in restoration and preservation programs. It should be noted, also, that no "cure-all" exists for lake problems. Every lake is a unique individual which must be studied and carefully diagnosed before treatment is prescribed. Perhaps a new, inexpensive technique will work in your lake, more likely not.

Table 4. Summary of Management Methods

"Watershed" Methods

A. Erosion and Sedimentation Controls:

Source Controls: mulch, seeded barriers, miramat, rip-rap, outlet protection, etc.

Recovery Methods: sedimentation basins, wetland/floodplain management, water velocity reduction, check dams, etc.

B. Detention and Diversion:

Agricultural Management: best management practices (BMP's) for animal waste, cover crops, buffer strips, fencing, agricultural land use, etc..

Urban Runoff Controls: "first flush techniques", fertilizer use, waste- and stormwater management.

Wastewater Management: sewering, septic system management, land-use, potential spill containment.

Wetland Function Enhancement: runoff renovation, sediment, nutrient, and contaminant removal, groundwater recharge.

Enhanced Interflow: injection of streamflow below photic zone of lakes, sediment and turbidity containment and management.

"In-Lake" Methods

A. Nutrient Control Methods:

Chemical Methods:
- Nutrient Inactivitation (see #1. below)
- Sediment Oxidation (see #2. below)

Physical Methods:
- Depth-Selective Discharge (see #3. below)
- Dredging: "wet" and "dry" (see #4. below)

B. Biomass Control Methods:

Chemical Methods: (see #5. below)
- Algicides
- Herbicides
- pH/Alkalinity Control Methods
- Dyes/Light Limitation

Physical Methods: (see #6. below)
- Harvesting: weeds, fish, etc.
- Lake Level Manipulation: seasonal elevation, outlet configuration
- Sediment Covers
- Aeration:
  - Destratification
  - Hypolimnion Aeration
  - Layer Aeration/Circulation

Biological Methods: (see #7. below)
- Plant Pathogens: viruses affecting plants and blue-green algae (cyanophages).
- Plant Predators: zooplankton upon phytoplankton, phytophagous (plant eating) insects and fish.
- Trophic Level Management: phytoplankton, zooplankton, and fish.

Table 4. Summary of Management Methods (cont.)

Specific "In-Lake" Techniques

#1. Nutrient Inactivation -

Principle:

Phosphorus is chemically bound to aluminum hydroxide; P stripped from water column and trapped in sediments as insoluble compound.

Advantages:

* Aluminum-phosphorus complex insensitive to redox changes.
* Effective in deep lakes with large internal phosphorus loads.
* Aluminum hydroxide stable at pH's commonly found in lakes (pH 6-8).

Disadvantages:

* pH dependent: toxicity from Al (III) and reduced phosphorus binding capacity may occur below pH 6 (acid conditions).
* Phosphorus must be in inorganic compounds for best results (humic materials in bog lakes may interfere).
* A large "dose" often is needed for long term results.
* Watershed inputs of phosphorus must be controlled for treatment longevity.

#2. Sediment Oxidation -

Principle:

Treatment oxidizes the upper anaerobic sediments, reduced internal load where iron dominates redox, enhances denitrification (nitrate acts as alternate electron acceptor). Addition of ferric chloride will remove hydrogen sulfide and form ferric hydroxide to bind phosphorus. Addition of lime (calcium hydroxide) will raise pH and stimulate denitrifying bacteria.

Advantages:

* Nontoxic alternative to aluminum (alum treatment).
* Treatment longevity may be better than alum.
* May favor green over blue-green algae.

Similar Techniques:

* Nitrate treatment of hypolimnion.
* Application of advanced wastewater treatment effluent at sediment interface.

* Injection of nitrate-rich agricultural runoff

Disadvantages:

* External load must be controlled.
* If internal phosphorus load already co-exists with high pH and high temperature (as in shallow system), treatment may be ineffective.

#3. Depth-Selective Withdrawal -

Principle:

Changes the depth at which water leaves a lake for a variety of reasons including:

Removal of nutrient-rich water
Removal of anoxic, chemically reduced water
Removal of water at a particular temperature
Removal of water at a particular light level.

Although used primarily in deep, thermally stratified lakes, can be effective in shallow lakes when temperature/density gradients are ephemeral or poorly defined.

Advantages:

* May be gravity driven in many systems
* Net reduction of phosphorus budget
* Reduced algal bloom intensity
* Reduced intensity of anoxia.

Disadvantages:

* Adverse effects downstream from discharge
* Operation costs if not gravity-operated
* Depends upon existing thermal stratification
* Limited by water budget (hydraulic turnover)

#4. Sediment Removal: "wet" or "dry" dredging -

Principle:

Removal of sediment for:

Deepening
Nutrient control
Removal of toxic substances
Removal of aquatic macrophytes (= aquatic weed)

Effectiveness depends upon:

Depth of light penetration
Composition of remaining sediments

"Dry" dredging by conventional excavation after lowering of lake. "Wet" dredging by grab bucket/dragline, hydraulic dredge, or "siphon" dredge.

Advantages:

* Long-term reversal of succession.

Disadvantages:

* In-Lake Effects of Excavation: resuspension, toxins, etc.
* Adverse Effects on phosphorus diffusion from sediments due to changed surface area to water volume ratio.
* Adverse effects on benthic fauna (possible 2-3 year recovery)
* Dewatering and disposal of spoils.

#5. Chemical Methods of Biomass Control -

Algicides: e.g. copper sulfate/"Cutrine", Aquazine, Endothall, Diquat, etc.

Herbicides: e.g. Diquat, Floridone (Sonar), 2,4-D Ester, Endothall, Dichlobenil, Rodeo, Amitrol, etc.

Principle:

Kill by direct contact, interferes with photosynthesis, or disrupts normal growth and cell division.

Advantages:

* "Target organism" control
* Immediate or rapid effects
* Short term cost.

Disadvantages:

* Toxic effects on other organisms
* Does not treat underlying causes
* Repeated use necessary and expensive
* Direct and indirect consequences; e.g. algal blooms following weed kill, oxygen loss, habitat loss, etc.
* Use restrictions.

Aquashade:

Principle:

Dyes water to reduce light penetration and plant growth.

Advantages:

* Non-toxic
* Relatively inexpensive.

Disadvantages:

* Intensified light/heat absorption and stratification
* Oxygen loss at depth.

pH/Alkalinity Control - "Liming":

Principle:

Increases alkalinity of water and counters acidification. Increases and stabilizes pH.

Advantages:

* Non-toxic
* Lowers solubility/mobilization and toxicity of metals

Disadvantages:

* Toxicity of metals may increase briefly during pH shift due to hydrolysis.
* Decreases effectiveness of copper sulfate if pH and alkalinity too high.

#6. Physical Methods of Biomass Control -

Harvesting:

Principle:

Physical removal of unwanted plants by manual removal, mechanical mowing, "tillage" suction dredging, and diver-operated dredging.

Advantages:

* Non-toxic
* Area-selective
* Immediate removal of nuisance

* Multiple-uses not affected
* Harvested plants may have use

Disadvantages:

* Capital, operation, energy, and labor costs high
* Seasonal
* Relatively limited areas, little nutrient removal
* Fragmentation, regrowth, species composition
* Fishery effects
* Limited operating depth
* Weather dependent operation
* Damage by or to physical obstructions.

Lake Level Manipulation:

Principle:

"Drawdown" of a lake or pond is a multipurpose method for control of certain plants, fishery management, structural repairs, "dry" dredging, installation of sediment covers, etc. Weed control results from the dessication (heat or freezing) of plants and perenniating organs (seeds, rhizomes, etc.).

Advantages:

* Low cost
* Species selective (with good planning)
* Oxidizes sediments
* Consolidates sediments
* Combines wtih other techniques (e.g. dredging)

Disadvantages:

* Requires outlet structures
* Depends on water budget and light penetration
* Effects variable on plant species
* Algal blooms may follow reflooding
* Needs further study
* Residual volumes of water and oxygen needed for fish.

Sediment Covers:

Principle:

Covering of bottom sediments with screening or sheeting to control rooted macrophytes. Floating covers may be used for swimming areas for 15-35 days in spring.

Advantages:

* Non-toxic
* Selective treatment area
* Bottom obstacles less problem
* Ease of installation and licensing

Disadvantages:

* Costs
* Difficult over large areas
* May float or slip on steep slopes
* Does not correct cause of problem (nutrients & light)
* May be damaged
* Material may degrade in sunlight
* Sediment accumulation on cover.

Destratification Aeration:

Principle:

Complete circulation, eliminating thermal stratification, to maintain aerobic conditions. Raising oxygen content decreases solubility of phosphorus.

Advantages:

* Increased habitat.
* Reduces phosphorus and metal load in some cases.
* Relatively low cost.
* May reduce spring diatom bloom by increasing "critical depth" and decreasing growth rate.
* Stimulates zoolankton.
* Increases nitrification.
* Favors green/diatom algae over blue-green algae.

Disadvantages:

* Eliminates thermal stratification.
* May increase internal phosphorus.
* May increase phosphorus in photic zone.
* Rapid mixing necessary for best effects.
* Transparency worsens more often than not.
* Phytoplankton decrease in less than 1/2 cases.
* Operating cost.

Hypolimnetic Aeration:

Principle:

Increase oxygen content of hypolimnion without destroying thermal stratification.

Advantages:

* Improved habitat
* Decreased phosphorus load
* Decreased ammonium, manganese, iron, and hydrogen sulfide
* Potential for depth-selective withdrawal remains.

Disadvantages:

* Nitrogen supersaturation (rarely troublesome)
* Increased mixing
* Metalimnetic oxygen deficits remain
* Capital and operating costs.

Layer Aeration:

Principle:

Manipulation of natural heat and oxygen distribution to create aerated isothermal layer(s) and multiple "thermoclines".

Advantages:

* Smaller compressors and shorter operation season
* Improved habitat
* Density/viscosity gradients altered
* Decreased internal phosphorus and transport
* Depth-selective withdrawal enhancement
* Can be used to prolong spring circulation and to increase critical depth of mixing.

Disadvantages:

* Nitrogen supersaturation (rarely troublesome).
* Capital costs.

#7. Biological Control -

Principle:

Obtain a more acceptable balance of plant biomass by manipulating existing flora and fauna or by introducing certain species.

Advantages:

* Non-toxic, non-mechanical
* Costs
* Potential effectiveness
* Potential positive side effects.

Disadvantages:

* Unknown ecological effects and consequences
* Undesirable migrations to neighboring systems.

Appendix I.

Sources of Information and Assistance

A. Local: use "Town and City" Blue Pages in telephone book

Inland Wetland Agency
Conservation Commission
Planning and Zoning Commission
Health Department
Regional Planning Agency
Soil Conservation Service

B. State: use "Connecticut State Of ..." in Blue Pages

State Department of Environmental Protection (566-5599)
  Water Compliance Unit
  Inland Wetland Division
  Fish and Wildlife
  Pesticide Control Unit
Connecticut Agricultural Experiment Station (789-7214)
The University of Connecticut (486-2000)
  P. H. Rich, Ph.D, Dept. of Ecology & Evolutionary Biology (486-5705)
State Universities and other colleges and universities
The Institute of Water Resources (486-4523)

C. National:

U. S. Environmental Protection Agency (Boston)
U. S. Geological Survey (Hartford) (244-2528)
North American Lakes Management Society

D. Private Consultants:

Look in "Business to Business Directory" and "Yellow Pages" under "Environmental" and "Ecological", e.g.

R. W. Kortmann, Ph.D., Ecosystem Consulting Service, Inc. (742-0744)

Glossary

absorbed: to be engulfed or incorporated; in contrast to "adsorbed": to be deposited on the surface.

acid rain: strong mineral acids in precipitation (wet and dry), originating as oxidized sulfur and nitrogen compounds created by the combustion of fossil fuels.

adsorbed: to be deposited on the surface; in contrast to "absorbed": to be engulfed or incorporated.

aerate, aeration: to charge with or expose to air or oxygen.

aerobic respiration: biological oxidation of organic matter to carbon dioxide and reduction of oxygen to water.

algicide: a substance which kills algae.

algae (singular: alga) one-celled, filamentous, or colonial plants; freshwater species mostly microscopic; collectively called "phytoplankton" when suspended and drifting in water (planktonic).

algae bloom: episodes of over-abundant growth of (usually) planktonic algae; generally refers to conditions obvious to a lay observer.

allowable phosphorus: maximum phosphorus loading which will not destroy lake water quality with intense algal blooms or nuisance weed growth; calculated from phosphorus models.

alum treatment: application of aluminum sulfate in lakes to precipitate phosphorus from the water column and make phosphorus in the sediments chemically unavailable.

anaerobic respiration: biological oxidation of organic matter to carbon dioxide without reduction of oxygen to water; instead produces chemically reduced inorganic by-products such as ferrous iron and hydrogen sulfide; distinct from "fermentation": anaerobic oxidation of organic matter to carbon dioxide producing chemically reduced organic by-products such as alcohol and methane.

anoxia, anoxic: devoid of oxgyen; in contrast to "oxic": oxygen present.

autotroph: "makes its own food"; generally refers to photosynthetic plants, algae, and bacteria; primary producers.

base flow: groundwater discharge by streams between episodes of storm runoff; calculated using a unit hydrograph.

bathymetric map: a map showing the depth contours of a body of water; an underwater topographic map.

biomass: the total weight of living material, generally calculated on an areal basis; refers to both roots and shoots of plants.

blue-green algae: a group of bacteria also classified as a phylum of algae; many species capable of converting nitrogen gas from the atmosphere into nitrogen compounds needed for plant growth; generally abundant in lakes having excess phosphorus; four genera most often involved in algae blooms: "Annie, Fanny, and Mike" (= Anabaena, Aphanizomenon, and Microcystis).

carbon: the "building-block" element used in photosynthesis to create organic matter; exists in air as carbon dioxide, dissolved in water as a variety of compounds called DIC (Dissolved Inorganic Carbon), and in innumerable organic compounds derived from living processes.

chemical reduction: a chemical process which adds electrons to atoms; generally accompanied by the removal of electrons (oxidation) from other atoms; photosynthesis and respiration are oxidation-reduction reactions; photosynthesis reduces carbon dioxide to organic matter and oxidizes water to oxygen; respiration oxidizes organic matter to carbon dioxide and reduces oxygen to water; in the absence of oxygen anaerobic respiration reduces other substances such as ferric iron to ferrous iron and sulfate to sulfide.

chemolithotrophy: a special case of respiration in which chemically reduced inorganic matter is oxidized by bacteria; in the sulfur cycle of lakes, for instance, chemolithotrophic bacteria grow by oxidizing hydrogen sulfide (produced by anaerobic respiration) to sulfur and sulfur to sulfate; chemolithotrophic bacteria and blue-green algae often produce dense layers of pigment and organic matter deep in thermally stratified lakes.

clay content: the proportion of soil particles (small) classified as clay; clay content increases renovation capacity, but decreases percolation and drainage.

clinolimnion: approximately equivalent to the metalimnion; the stratum of a lake in which temperature change decreases exponentially with depth during the onset of summer stratification.

coefficient of eddy diffusion: a measure of the intensity of mixing across the clinolimnion; the slope of a semi-log plot of temperature change per depth in the clinolimnion.

contour interval: the difference between elevations of the contours drawn on topographic and bathymetric maps.

depth to bedrock: the depth of surficial deposits overlying bedrock; approximately the same as "depth of refusal".

destratification aeration: aeration designed to destroy thermal stratification and mix a lake from top to bottom.

detritus: dead organic matter (mostly plant material) subject to decay and ingestion by detritus feeders (detritivores).

diffusion: molecular diffusion (mixing on a microscopic scale produced by molecular thermal motion) plus eddy diffusion (random molecular motion induced in lake water by wind); produces mixing which transports heat and substances through the clinolimnion (metalimnion).

dimictic: mixing twice a year, as in a temperate dimictic lake; in contrast to monomictic: mixing once a year, and meromitic: never mixing completely.

drainage: a property which affects flow of water through soils.

drainage basin: the area surrounding a lake which provides groundwater and surface runoff water to a lake; also called the "watershed" and "paralimnion".

dystrophic: a class of lakes in which decomposition of organic matter is deficient (generally nutrient limited); a bog lake.

ecological pyramid: refers to the progressive loss of numbers of individual organisms and biomass observed in food chains/webs between the plants (primary producers), herbivores (primary consumers), and carnivores (secondary consumers) in an ecosystem.

ecosystem: the unit of natural organization in which living organisms interact collectively with physical and chemical processes in the environment; a habitat in which the organisms derive their energy and nutrients from the same source(s).

effective precipitation: the proportion of precipitation falling on the drainage basin which enters a stream as surface and groundwater runoff.

epilimnion: the warm, well-mixed, well-illuminated surface

stratum of a lake during summer stratification.

equilibrium: when forces which counteract each other are in balance; in chemistry: when the rate of the forward reaction equals that of the back reaction (note that reactions do not stop, their rates simply come into balance with no net changes observed in products and reactants).

erosion: mobilization of soil particles by water and wind.

eutrophic: the status of a lake in which the concentration of phosophorus exceeds 30 mg/cubic meter; eutrophic lakes commonly have anoxic hypolimnia and periodic algae blooms.

eutrophication: the biological response of a lake to increased phosphorus inputs; not to be confused with lake "succession": the filling-in of a lake basin by geological processes.

evapo-transpiration: the loss of water vapor through the leaves of living plants; amounts to about half the annual volume of water passing through a southern New England drainage basin.

exponential: pertaining to exponents; changing by powers greater than one.

fall overturn: the period of top to bottom mixing in a temperate, dimictic lake following summer thermal stratification.

fermentation: a special case of anaerobic respiration in which organic (as opposed to inorganic) substances are reduced during the oxidation of organic matter.

filter feeders: specialized consumers which prey on small organisms suspended in water by straining the water through various kinds of filters; for instance most zooplankton sweep the water with comb-like appendages to capture phytoplankton.

food-chain, food-web: pathways of material and energy through the prey and predator network of an ecosystem; a simple system of one kind of producer, first, second, and tertiary consumer, etc. is called a food-chain; a more complicated system with more than a one kind of organism at each level and with organisms feeding on more than one level is called a food-web.

grazer: predator on living prey; in contrast to a detritus feeder which eats organic matter already dead and decaying.

green algae: a phylum of algae commonly growing in lakes and

indicative of balanced nutrient inputs.

groundwater: water saturating soil; water contained in soil when all soil intersticies (spaces) are filled.

hard water: water having high concentrations of dissolved alkaline earth elements, such as calcium and magnesium; typical of limestone areas.

herbivore: a predator upon plants; "plant-eater".

heterotroph: "feeding upon others", incapable of creating its own food, animals; in contrast to "autotroph": "makes its own food", plants.

humic material: common organic compounds produced in terrestrial vegetation and found dissolved in natural waters; makes water "tea-colored" and reduces transparency in many soft water lakes in New England (abundant calcium in hard water precipitates humic materials).

hydrogen: a constituent element of water and organic matter.

hydrogen bond: a strong inter-molecular bond forming between hydrogen and oxygen atoms in neighboring water molecules; dramatically affects the properties of water.

hypolimnetic aeration: aeration designed to increase oxygen concentration at the bottom of a lake without destroying thermal stratification.

hypolimnion: the bottom stratum of a lake during summer stratification; cold, dark, and isolated from re-aeration from the atmosphere.

hypsographic curve: the plot of lake area against depth; used to obtain the volume of a lake at specific depths for the calculation of mass balances.

impoundment: a lake or pond created by damming a stream or river.

infra-red radiation: part of the solar radiation spectrum just below the frequency of visible light; quickly absorbed by hydrogen bonds in the first few molecular layers of lake water.

inorganic: not made of carbon or, if containing carbon, not having organization characteristic of living material.

internal loading: the regeneration and release of nutrients, particularly phosphorus, from lake sediments.

iron: exists in lake hypolimnia as insoluble, oxidized ferric iron in the presence of oxygen, or as soluble, reduced ferrous iron in the absence of oxygen; ferric iron combines with and precipitates phosphorus, but releases that phosphorus when reduced to ferrous iron.

lake succession: (see "succession")

latent heat: heat (released by the formation of hydrogen bonds) which must be removed from water at 32 F (0 C) to form ice, and added to water at 212 F (100 C) (to break hydrogen bonds) to form water vapor.

leaching field: the part of a septic system which returns wastewater to the ground.

light: the visible part of the solar spectrum between infra-red and ultra-violet which provides the energy to drive photosynthesis, the conversion of carbon dioxide and water to organic matter and oxygen.

limnology: the study of lakes.

littoral zone: the shallow part of lakes in which large aquatic plants grow.

loading: the amount of nutrients annually available on an areal basis.

mass-balance: calculation and comparison of the amount of a substance present in a lake at different times.

mesotrophic: the status of a lake intermediate between oligotrophic (total phosphorus less than 15 mg/cubic meter) and eutrophic (total phosphorus greater than 30 mg/cubic meter); mesotrophic lakes generally show hypolimnetic anoxia by the end of summer stratification and have occasional algal blooms.

metalimnion: the stratum of water between the warm "epilimnion" above and the cold "hypolimnion" below during summer thermal stratification; where the temperature of the water changes at least one degree C per meter depth.

non-point source: a diffuse input from a watershed, for instance surface runoff; not coming out of pipe.

non-polar compound: a compound without partial charges induced on the molecule by asymmetries, generally somewhat soluble but immiscible in (won't mix with) water.

non-volatile: very low vapor pressure, slow to evaporate.

nutrient: an element or compound needed for growth in plants, animals, and bacteria; major (macro-)nutrients needed for the production of organic matter are "CHONPS": Carbon, Hydrogen, Oxygen, Nitrogen, Phosphorus, and Sulfur.

nutrient budget: annual gains and losses of nutrients in an ecosystem.

nutrient sink: a destination for nutrients from which there is no escape except in a geological timescale; for instance, permanent lake sediments.

oligotrophic: "poorly nourished", the status of a lake with little phosphorus loading (total phosphorus concentration less than 15 mg/cubic meter); generally having a well oxygenated hypolimnion and few periodic algae blooms.

omnivore: eats anything, plant or animal.

organic: made of carbon and having organization characteristic of living materials.

oxic: oxygen present; in contrast to "anoxic": devoid of oxygen.

oxidized microzone: a thin (less than a tenth of an inch to a few inches) layer of oxidized sediments overlying deeper, chemically reduced sediments; suppresses the release of phosphorus from sediments; disappears when overlying water becomes anoxic.

oxygen: a colorless, odorless gas; one fifth of the volume of the atmosphere; produced by chemical oxidation of water in photosynthesis; supports combustion and aerobic biological respiration, both of which chemically reduce oxygen to water; not very soluble in water, under atmospheric pressure water generally contains less than 10 ppm (parts per million = milligrams per liter).

paralimnion: lake drainage basin; informally called "watershed".

percolation: a measure of the rate at which water flows through soil; in contrast to "renovation capacity": the ability of soil to remove contaminants from water flowing through it.

periphyton: catchall term for algae and bacteria growing attached to surfaces in lakes; a more accurate classification of attached algae: "epiphytic" (attached to other plants), "epipelic" (growing on mud), and "epilithic" (attached to non-living surfaces).

phosphorus: rarely found in elemental form in nature; the nutrient element most commonly limiting growth of

organisms in lakes; exists in lake water in parts per billion concentrations (= milligrams/cubic meter).

phosphorus tolerance: the amount of phosphorus a lake can receive without destruction of water quality from excess growth of algae; like "allowable phosphorus", calculated from phosphorus models.

photolithotrophy: a primitive, bacterial type of "photosynthesis" in which water is not oxidized to oxygen (instead oxidizes chemically reduced by-products of anaerobic respiration and fermentation); produces deep pigment layers in anaerobic waters of thermally stratified lakes.

Photosynthesis: the simultaneous oxidation of water to oxygen and reduction of carbon dioxide to organic matter driven by sunlight; the ultimate source of organic matter on Earth; occurs in lakes above the "compensation depth" (= approximately 1% of surface light).

PAR (Photosynthetically Active Radiation): the specific wavelengths of visible light used in photosynthesis; the part of the solar radiation spectrum which should be measured in lakes.

phytoplankton: algae suspended and drifting in water; prey upon by zooplankton.

piscivorous: fish-eating.

plant: technically, both large plants and algae, but generally used by limnologists to mean a large, rooted plant growing in the littoral zone; a more precise term is "macrophyte": Greek for "large plant".

point source: a well-defined input from a lake watershed; coming out of a pipe, etc.

polar compound: a compound having partial charges induced on the molecule by asymmetrical arrangement of constituent atoms; the partial charges interact with the same type of charges induced on the asymmetrical water molecule; polar compounds are both extremely soluble and miscible in water.

postpeak flow: the period of return from peak storm discharge to baseflow in a hydrograph.

precipitation: wet precipitation = rain or snow; dry atmospheric precipitation includes phosphorus and the substances which represent "acid rain".

prepeak flow: the onset of storm discharge in a unit hydrograph.

primary consumer: a herbivore; preyed upon by secondary consumers (carnivores).

primary producer: a photosynthetic autotroph; a green plant.

productivity: the rate of production of organic matter by a trophic level; e.g. primary productivity of plants; includes dead as well as living (biomass) material.

regulated wetland: in Connecticut, any area consisting of poorly drained, very poorly drained, or floodplain soils; subject to Inland Wetland and Watercourses Act jurisdiction.

renovation capacity: the ability of soil to remove contaminants (including nutrients) from water passing through it; in contrast to "percolation": the rate at which water travels through soil.

respiration: the reverse of photosynthesis and source of energy for animals including ourselves; the simultaneous oxidation of organic matter to carbon dioxide and reduction of oxygen to water; in anaerobic respiration something other than oxygen is reduced.

runoff: technically, both groundwater and surface runoff from a drainage basin; informally, surface runoff (storm runoff) as distinct from groundwater baseflow.

sediment, sedimentation: particulate matter which accumulates on the bottom of lakes and streams; informally used as a verb to mean "sink", "settle",or "precipitate"

septic plume: the volume of soil affected by septic seepage containing high concentrations of nutrients.

septic seepage: the liquid produced by a leaching field, septic leachate.

septic tank: the part of a septic system in which solid materials which sink or float are separated from liquids.

soft water: water having low concentrations of alkaline earth elements such as calcium and magnesium; typical of granitic watersheds.

soil map: map designating the types and properties of soils contained in an area.

solute: the substance dissolved in a solvent to produce a solution (e.g. phosphorus dissolved in water).

solvent: the (usually liquid) substance in which a solute is dissolved (e.g. water containing phosphorus).

specific heat: the amount of heat required to raise the temperature of a gram of substance one degree C; extraordinarily high for water due to hydrogen bonds.

spring overturn: the period of top to bottom mixing in a temperate dimictic lake between ice-out and the onset of summer thermal stratification.

standing crop: the amount of organic matter present at a given moment.

stratum (plural: strata): a layer of material distinct from that above and below it.

succession: long term filling of lakes by geological processes which may or may not be accompanied by changes in nutrient availability; in contrast to "eutrophication": a biological response to increased availability of phosphorus.

summer stratification: the appearence in summer of three thermal layers in lakes: epilimnion (warm, well-mixed surface water), metalimnion (the gradient zone between warm water above and cold water below), and hypolimnion (cold, stagnant bottom water).

synoptic field sampling: a condensed, "quick and dirty" sampling schedule to find specific means and extremes of environmental variables; best employed after the results of a more systematic sampling schedule have been studied.

thermal motion: vibration of atoms and molecules by heat energy; produces diffusion; augmented with mixing momentum in lake water induced by wind to produce eddy diffusion.

thermocline: the depth of maximum temperature change in a metalimnion; approximately equivalent to metalimnion in older usage.

topographic map: a map upon which contours of surface elevation are drawn; useful for determining boundaries of lake drainage basins.

transparency: a property of water which determines the depth to light penetrates and photosynthesis provides oxygen in lakes; measured with a Secchi disk or with an underwater light meter.

ultra-violet radiation: part of the spectrum of solar radiation

just above visible light; quickly absorbed at the surface of lakes; destroys dissolved organic matter in lakes (including humic substances), inhibits algal photosynthesis near the surface, and causes sunburn.

unit hydrograph: an graphical analysis of stream discharge data before, during, and after a unit rainstorm (e.g. 1 inch or 1 cm. effective precipitation) which provides extremely useful information about watershed hydrology and nutrient inputs.

universal soil loss equations: a method of estimating the mobilization of soil by water movement based on soil type, slope, etc.

visible radiation: part of the spectrum of solar radiation observed by the human eye; between the infra-red and ultra-violet; includes PAR.

volatile: high vapor pressure; strong propensity to become vapor; easily evaporated.

water budget: annual inputs and losses of water through a drainage basin-lake system; the amount of water passing through a lake in a year.

watershed: technically, the divide separating drainage basins; informally, the drainage basin of lake.

zooplankton: small to microscopic animals suspended and drifting in water; includes mostly crustaceans and rotifers; preys upon phytoplankton and itself, is preyed upon by small fish.