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INTRODUCTION

The subject of waste-water effects on ecological systems encompasses great breadth and variability. Dissecting ecological systems into easily studied physical units or individual populations and isolating the effects of myriad wastes, one at a time, results in few generalizations about all wastes in all aquatic ecosystems. A better method is to examine each type of waste individually in relation to representative groups of organisms in a shopping-list approach. A still better way is to study the functioning of ecological groupings of aquatic populations within the abiotic environment and then to study each group's functioning with respect to a limited variety of wastes. The last approach is used in this book because it emphasizes consideration, first, of the natural function of the particular biotic component, and then of the effect of the waste(s) most pertinent to that group. The ecological groups discussed include the phytoplankton, zooplankton, periphyton, macrophytic rooted plants, benthic macroinvertebrates, and fish (the last mostly as a bioassay animal and as a target for standards of water quality).

Obviously, if all these groups are to be considered, the limitation must be on the variety of wastes discussed. The limitation is handled to some extent by considering the effects of wastes most important to each group and those waste constituents most closely associated with the natural processes and their control. For example, nutrient elements are extensively discussed with respect to the algae, both planktonic and periphytic, because these groups react first to an increased supply of limiting nutrient. On the other hand, a lowered concentration of dissolved oxygen does not greatly affect the algae because of their

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More information

autotrophic nature and is not discussed in relation to them. However, the dissolved oxygen level is an important factor in regulating the response of macroinvertebrates and fish to oxygen-demanding wastes and is, therefore, considered in relation to these animals.

Selecting the most pertinent (in my opinion) wastes with respect to each functional group has necessitated slighting certain wastes. Nutrients, heat, and organic waste are discussed in considerable detail; toxicants are given less attention. The toxicity limits of specific compounds are considered in some detail with respect to fish, and the relative effect of "toxicity" in general is stressed in connection with benthic community composition.

This approach dwells on the concepts relating to the effects of particular wastes on community structure and processes, with only minor emphasis on any given species. Admittedly, information is lost when individual species populations are not considered, and not all species in a genus or family react similarly to a waste. However, available information is not adequate to allow analysis of the effects of wastes on individual species (except in the case of some fish). Further, information on community structure and processes is usually adequate to permit description of the ecological effects of a waste and is more meaningful to persons charged with the management of water resources than are lists of species and their quantitative changes. The most useful goal from the standpoint of management is to describe changes through measurements of structure (e.g., species diversity and biomass, noting any changes in dominant species) and of processes (e.g., productivity, respiration rate, growth rate, and reproductive rate). Of course, not all measurements are equally appropriate to all groups of organisms, and that is a principal point that is discussed.

A significant goal of this book is to convey an understanding of how the functional groups of organisms respond, first to natural factors and then to the superimposition of representative wastes. But more importantly, given that information, the next step is to sort out the important controlling factors and to predict the direction and in some cases the relative magnitude of change.

Chapters 1 through 6 present some general concepts of ecology and explain how they are related to the management of ecosystems. These concepts represent a working philosophy about aquatic systems that is a necessary background for the discussion in Chapters 7 through 12 of specific wastes and their effects.

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PART ONE

GENERAL CONCEPTS OF AQUATIC ECOLOGY

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1

AQUATIC ECOSYSTEMS AND MANAGEMENT

An *ecosystem* can be described as some unit of the biosphere, or the entire biosphere itself, within which chemical substances are cycled and recycled while the energy transported as part of those substances continually passes through the system. Although every ecosystem must ultimately obey the laws of thermodynamics and degrade to complete randomness (*wind down*), consistent with the universe, energy may be accumulated momentarily in an ecosystem. However, without a continuously renewed input of energy, the accumulation would be exhausted and the system would wind down.

The single continuous input to the world's ecosystems is from solar energy, and the conversion of that electromagnetic energy into chemical energy and then into work is what allows an ecosystem and the organisms that make up that system to function.

Because the processes of energy flow and nutrient cycling are quite variable, the assignment of clear boundaries between what might otherwise seem like clearly separate systems is not easy. However, for the sake of practicality and manageability, boundaries are cast that allow ease of study and process measurement. Thus, a stream and its immediate watershed as well as a lake and its watershed inputs are considered ecosystems. The system could be considered closed under some conditions if one is describing chemical nutrients, but never if one is referring to energy, because there is always an input to and a loss from the system. Because an ecosystem responds to inputs as an integrated system, the study of whole systems is useful for management.

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Ecosystem composition and energy sources

Each ecosystem has a structure that determines how it functions in the transfer of energy and the cycling of nutrients. This structure can be thought of as the organization of the internal groupings of chemical nutrients and energy through which the functioning occurs. This matter is living and dead, the living being represented best by the trophic levels of organisms leading from algae and/or rooted plants to fourth-level carnivores, for instance, in some grazing food webs. Outside organic matter is processed and decomposed by insects, fungi, and bacteria through the carnivores in detritus-based food webs.

The watershed has come to be regarded as an integral and inseparable part of the ecosystem (Borman and Likens 1967; Likens and Borman 1974). The character of the watershed determines whether the stream's energy source is mostly *autochthonous* (produced within) or *allochthonous* (produced outside). In a comparative study of the Northeast area, Likens (personal communication) has shown that an autochthonous-producing forest results in the domination of the drainage stream by allochthonous inputs, whereas the watershed lake is autochthonous. Wissmar found a high mountain lake in a coniferous forest dominated by allochthonous inputs (Table 1). Lakes and streams in poorly vegetated watersheds and relatively large lakes tend to be dominated by autochthonous sources, as do also lower stretches of streams and large rivers (if not turbid).

It is necessary to know the proportions of allochthonous to authochthonous energy sources in ecosystems because of the management decisions affecting aquatic ecosystems that must be made. To effectively protect and use aquatic systems, man must know how systems use and respond to different amounts and varying compositions of natural energy.

Table 1. *Comparison of energy sources in two ecosystems, in grams of carbon per square meter per year*

	Deciduous forest			
Energy source	Forest	Streams	Lake	Coniferous forest - lake
Autochthonous	941	1	88	4.8
Allochthonous	3	615	18	9.4

Source: Data on deciduous forest from G. E. Likens, personal communication; data on coniferous forest from Wissmar et al. (1977).

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More information

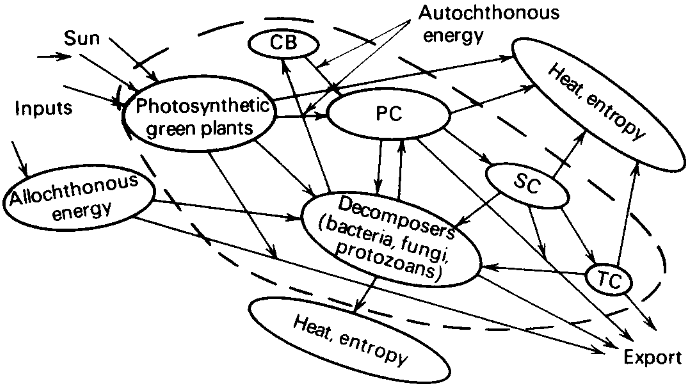
Energy flow and nutrient cycling

If one could measure all the organisms and their main processes in an ecosystem and if their energy-consuming and energy-processing characteristics fell neatly into separate levels, one would be able to arrange a flow diagram as shown in Figure 1. Such a diagram shows several important points: (1) energy flows through the system and does not return, because by the second law of thermodynamics matter moves toward randomness, from states of high concentration to states of low concentration, and when that happens the energy contained becomes less (note entropic heat loss); (2) loss in energy as heat occurs at each step in the transfer process; and (3) allochthonous energy moves through the heterotrophic microorganisms or decomposers. A significant role of net production of usable energy for consumers is attributed to these microorganisms (note arrow from decomposers to consumers) in addition to decomposition (Pomeroy 1974).

Even for allochthonous sources from surrounding forests or from man's input of organic waste, the ultimate source must be either photosynthesis or to a lesser extent chemosynthesis.

The process of *photosynthesis* includes two phases: (1) a light reaction that traps solar energy and releases molecular O_2 and (2) a dark reaction (light not needed) that utilizes the trapped energy as ATP (adenosine triphosphate) and fixes CO_2 or HCO_3 into cell material. The process yields energy and synthesizes new cells and can be summarized by:

Figure 1. Energy flow and nutrient cycling in an aquatic ecosystem (boundary indicated by dashed line). CB, chemosynthetic bacteria; PC, primary consumers; SC, secondary consumers; TC, tertiary consumers.



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$$6\ CO_2 + 12\ H_2O + \text{light} + \text{chl } a \text{ and accessory pigments} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

The organic compound is glucose – the compound that holds the sun's energy trapped by photosynthetic organisms and allows the maintenance of our biosphere (that thin film of atmosphere, water, and land around the planet Earth that supports life). The process is performed by green plants and a few pigmented bacteria. Only the green plants release O_2 as a by-product.

Chemosynthesis is the other process through which organisms are totally self-sufficient in trapping energy and building cell material. This process yields energy through the oxidation of reduced inorganic compounds and thus requires no previous biological mediation by the various bacteria utilizing this process. The primitive earth was rich in reduced inorganic compounds that are currently used by some bacteria for energy. An example is nitrification:

$$2\ NH_3 + 3\ O_2 \rightarrow 2\ HNO_2 + 2\ H_2O + \text{energy}$$

This process is less important to ecosystems as an energy yielder and more important as a material recycler, because chemosynthetic processes by bacteria are heavily involved in the cycling of such nutrients as nitrogen and sulfur.

Nutrients, such as N, C, P, and S, follow the same pathways as energy in the system; they are consumed by autotrophs (green plants and chemosynthetic bacteria) from inorganic pools and fixed into organic compounds. These nutrients are then transferred through trophic levels just as energy is, because the reduced organic compounds are the carrier of the entrapped chemical energy. For example, CO_2 is the most oxidized state of C, but when fixed into glucose through photosynthesis, 1 mole ($C_6H_{12}O_6$) contains 674 kilocalories (kcal) of energy releasable through respiration by plants, animals, or decomposer microorganisms by the same biochemical pathways. The energy content of whole organisms in the various trophic levels ranges from 4 to 6 kcal gm^{-1} dry weight.

The principal difference between energy and nutrient transport is that once organisms have utilized the energy from complex compounds and oxidized them completely (e.g., glucose to CO_2 and H_2O), the compounds are recycled through the inorganic pool(s) and are almost totally reusable by the community. There is no permanent loss, but, practically, a certain fraction may be lost to the sediments and require tectonic uplift for recycling. The recycling process is shown in Figure 2 (note heavy arrow from decomposers to inorganic pool).

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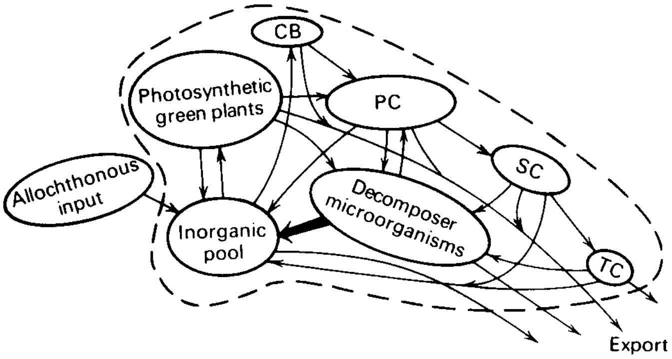
Efficiency of energy and nutrient use

The efficiency of the transfer of energy and/or nutrients is usually measured by the ratio of net productivity of a trophic level to the net productivity available for its consumption (Russell-Hunter 1970, pp. 25, 191). These values usually range between 10% and 20%. The level of this efficiency depends greatly upon the structure of the food web through which the materials are moving.

Structure in ecosystems can be thought of as the organization of species populations into appropriate trophic levels. However, trophic level is rather artificial and few organisms conform to a single trophic level throughout their entire life cycle. Nevertheless, populations organize, in time, in such a way that energy usage is optimized. Ecosystems that are physically stable, such as tropical rain forests and coral reefs, maximize organization and complexity and remain rather constant in biomass, productivity, species diversity, and, consequently, efficiency. Very simply, the greater the variety of energy users in an ecosystem (alternate pathways), the greater the chance that a quantity of energy packaged in a particular way will be intercepted and used before it leaves the system. Instability in ecosystem structure brought about by natural or man-caused variability in the physical-chemical environment results in decreased efficiency and instability in energy and nutrient usage, and nutrient recycling is, therefore, the "looser." Where systems approach steady state, that is, inputs equaling outputs, nutrient recycling tends to be "tighter" and "more complete" (Borman and Likens 1967; Bahr et al. 1972).

Figure 2. Transport and recycling of nutrients through an ecosystem (boundaries indicated by dashed line). CB, chemosynthetic bacteria; PC, primary consumers; SC, secondary consumers; TC, tertiary consumers.



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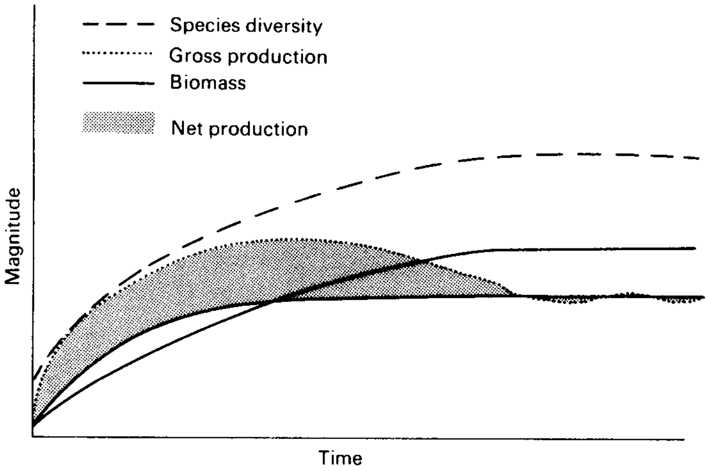
Odum (1969) has illustrated the effect of maturity on the characteristics and processes of ecosystems (Table 2 and Figure 3). He contends that diversity tends to be low in immature systems and high in mature systems. Correlated with diversity is relative stability, although how to define and measure stability is still a matter of controversy. However, net production tends to be inversely related to diversity, and Margalef (1969) has suggested that at low diversity, fluctuations in production per unit biomass are quite large and diversity changes are small, suggesting instability, whereas at high diversity, fluctuations in production per unit biomass tend to be small with considerable changes in diversity, indicating stability. One can see from Figure 3 that with time ecosystems tend to develop into a rather steady-state condition, with little net productivity and maximized structure. If production is low and associated fluctuations are small in a mature ecosystem, it follows that nutrients are conserved and cycled more slowly and energy thus moves through the system at a slower rate and entropy is less - the system is more efficient in its functioning.

Examples of efficiency in ecosystems give some idea of their maturity. Fisher and Likens (1972) showed that Bear Brook, a northeastern forest stream, was only 34% efficient (total respiratory loss/total energy input). Thus, 66% of the energy left the system downstream unused, indicative of immaturity. Lindeman's (1942) study of Cedar Bog Lake

Figure 3. Conceptual plot demonstrating successional changes in species diversity, gross production, and biomass. The shaded area representing net production approaches zero as the ecosystem matures. (Bahr et al. 1972, modified from Odum 1969)



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showed it to be 54.5% efficient with 45.5% lost to sediments. Odum's (1956) results from Silver Springs in Florida showed only 7.5% lost from the system downstream with 92.5% being utilized.

Management of ecosystems

What does man want from aquatic ecosystems? Obviously he does not want to destroy them, but he is highly inclined to manipulate them to his purpose whether it be to increase or decrease their productivity, keep them natural, or have them accept (assimilate) wastes with a minimum adverse effect on other uses. The problem is that these uses are conflicting. For example, to produce more and bigger sport fish could require stimulation of primary production, which, in turn, will result in decreased structure (species diversity) and less stability. The yield of particular game-fish populations may increase, but at the expense of the overall stability and efficiency of energy-handling and nutrient-recycling capabilities of the system. In the same light, ecosystems cannot assimilate wastes without some cost to their structure and stability, with consequent reduced efficiencies in nutrient cycling and energy utilization. Instability may produce a more variable oxygen content, which could reach lethal limits at times.

Stable communities are probably not more able to resist change from waste input than unstable ones. Bahr et al. (1972) argue that if this were true, species diversity would decrease with waste input (abiotic change) at an increasing rate (curve B in Figure 4), rather than at a decreasing rate as is usually observed (curve A). Highly diverse com-

Table 2. *Characteristic properties of ecosystems*

	Type of ecosystem	
Property	Immature	Mature
Net production (yield)	High	Low
Food chains	Linear	Weblike
Nutrient exchange	Rapid	Slow
Nutrient conservation	Poor	Good
Species diversity	Low	High
Stability-resistance to perturbations	Low	High
Entropy	High	Low

Source: (Odum 1969), with permission of the American Association for the Advancement of Science.

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