PROBLEMS, RESTORATION, AND CONSERVATION OF LAKES AND RIVERS

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Summary

Water is the basis of life and probably the most essential requirement for economic growth and social development. Water shortages are becoming more widespread every year and competition between different uses is increasing. Water quality is deteriorating at an alarming rate and aquatic ecosystems are being irreversibly disturbed due to increased anthropogenic activities. As more water is withdrawn and consumed for human uses, there is growing concern about whether the depleted water supply to lakes, rivers, estuarine ecosystems, and associated wetlands is adequate to maintain healthy functioning of these ecosystems. Water has to be provided in sufficient quantities to guarantee the health and maintenance of ecosystems. It is important to ensure that the actions of humans do not damage the natural functioning of the ecosystems related to lakes and rivers. The threats and their consequences on lake and river ecosystems with possible mitigation and restoration measures are reviewed. Conservation measures for lakes and rivers, carefully using and protecting these resources, is emphasized. Failure to restore or conserve these aquatic ecosystems promptly will result in sharply increased environmental costs and the damage can be irreversible. Achieving better management of these resources requires not only a thorough understanding of the functioning of the ecosystems, but also sufficient planning, financial resources, and community participation.

1. Introduction

Water is the basis of life and probably the most essential requirement for economic growth and social development. Rivers, streams, creeks, springs, lakes, ponds, and related ecosystems have evolved over time to support an enormous variety of plant and animal species. Freshwater ecosystems offer important cultural and recreational resources for human populations around the world.

Over 70% of the earth’s surface is covered with water, but, freshwater resources accessible for direct human use account for less than 1% (Table 1). This is the water found in lakes, reservoirs, rivers and streams, and underground aquifers that are shallow enough to be tapped at an affordable cost. The atmosphere does not hold a large proportion of Earth’s freshwater at any one time, and large quantities of water are continually cycling through the atmospheric reservoir on very rapid timescales. This cycling of water through the atmosphere is essential to renew freshwater resources on which all life depends.

Location	Percentage of total water	Estimated average residence time of water
Oceans	97.2	Thousands of years
Ice caps and glaciers	2.24	Tens of thousands of years and longer
Groundwater	0.61	Hundreds to many thousands of years
Lakes[a]	0.016	Tens or hundreds of years
Atmosphere	0.001	9 days
Rivers and streams	0.0001	2 weeks

[a] About 40% of lake water is contained in Lake Baikal and North American Great Lakes. About half of lake water is brackish.

Table 1. Distribution of water on Earth

Water shortages become more widespread every year and competition between different water uses is increasing. Water quality is deteriorating at an alarming rate and aquatic ecosystems are being irreversibly disturbed because of increased anthropogenic activities. As more water is withdrawn and consumed for human uses, there is growing concern about whether the depleted water supply to lakes, rivers, estuaries and associated wetlands is adequate to ensure healthy functioning of these ecosystems. Scarcity of freshwater results from the unequal distribution of water on Earth and water pollution that makes water unusable. According to the World Resources Institute, global water consumption is rising rapidly, and water availability is likely to become one of the most pressing and contentious resource issues of the twenty-first century. One-third of the world’s population lives in countries already experiencing moderate to high water stress, and this could rise to two-thirds in the next 30 years without serious water conservation measures and coordinated watershed planning.

Freshwater is not always available where or when it is needed the most. Moreover, freshwater resources are very unevenly distributed, ranging from arid regions receiving little rainfall to the most humid regions receiving high rainfall. Most global runoff is in a limited number of rivers with the Amazon carrying 16% of the global runoff, and the Congo-Zaire River carrying one-third of the total river runoff in all of Africa. At least 95% of the Amazon’s river flow is inaccessible and half the Congo-Zaire river is inaccessible. Arid and semiarid zones of the world, which constitute 40% of the landmass, have only 2% of the global runoff. Moreover, the potential availability of water per person varies greatly. For example, Asia’s billions of people share the world’s greatest river flow, but the per capita availability is the lowest.

A number of human activities are changing the flow of water and interact with the hydrological cycle at many levels. Water is withdrawn from rivers, lakes or groundwater, sometimes in unsustainable quantities, causing severe environmental damage. Deforestation and changes in landscape affect the quantity and quality of surface water and groundwater. Building dams on rivers has major effects on aquatic ecosystems, many of them adverse. Changes to the flow regime can cause irreparable changes to biological communities downstream and to the physical characteristics of river channels, flood plains, and coastal deltas.

People have used water, mainly rivers, lakes and lagoons, as a convenient sink into which to dump wastes from either point or nonpoint sources originating mainly from domestic and industrial sectors, and from agricultural runoff. The list of pollutants is endless, and varies from organic pollutants to synthetic and highly toxic chemicals. The amounts and nature of wastes have outstripped nature’s ability to break them down into less harmful substances. An obvious and pervasive problem facing lakes is that of eutrophication, and for rivers the problem is water quality degradation. Eutrophication is the direct result of nutrient enrichment by phosphorus and nitrogen present in water largely caused by human and animal wastes, detergents, and agricultural runoff. Chemical pollutants in water cause harmful effects in humans, animals and plants and may consist of toxic substances, heavy metals and highly persistent compounds, which can accumulate in the food chain.

Surface water resources are used for domestic, industrial, and municipal supply, irrigation, production of energy, navigation, fisheries, and recreation. Ensuring adequate supplies for the healthy functioning of aquatic ecosystems has long been neglected, and the consequent damage to the environment has been immense. Nevertheless, improved understanding of the ecosystems associated with water resources has increasingly acknowledged that they provide various useful services, such as flood control, storm protection, and maintenance of biodiversity and natural resource stocks. Conservation, management, and restoration of water bodies have become a necessity for ethical reasons and for their aesthetic and cultural importance to societies. Although the scientific management of rivers, lakes, and reservoirs is still relatively new, it promises to be of great value to the advancement of societies. With the development of limnology as a multidisciplinary science, great strides have been made in understanding the functioning of aquatic ecosystems and their interrelationships. Also, studies have provided a deeper understanding of the ecology, stability, resilience, and effects of management of freshwaters, integrating information gathered over a long time. Further in-depth understanding of the physics, chemistry, and biology of our lakes and rivers is urgently needed, before these systems are changed irrevocably by increasing anthropogenic activities. Limnologists have an important role to play in this vital matter.

2. Dynamics of Rivers and Streams and Lakes

2.1 Energy Flow and Nutrients in Rivers and Streams

The lotic ecosystem is an essentially open system with respect to energy, in the form of organic matter, under a strong unidirectional flow. Running waters are, however, sustained energetically through a continual energy inflow in the form of solar radiation and through the intimate relationship between streams and the surrounding terrestrial ecosystems. Energy sources in streams and rivers comprise solar radiation, which supports autochthonous primary production, and allochthonous organic matter, including coarse particulate organic matter (CPOM) produced by adjacent riparian ecosystems, fine particulate organic matter (FPOM) coming through wind blow, surface runoff, bank erosion, etc., and dissolved organic matter (DOM). The fragmentation by shredders in headwaters is an important food source of FPOM for organisms downstream, in addition to food produced by several other processes. Organic molecules derived from riparian flora are also an important carbon source for bacterial assemblages downstream. Likewise, headwaters have a close relation with downstream faunal communities.

Allochthonous organic matter, which is passed through a series of consumers in grazing food chains, tends to resist breakdown and is degraded by detritivory and decomposition; some allochthonous organic matter enters the detritus storage pool and remains for a long time or is displaced downstream. Therefore, an energy budget in streams and rivers is constructed for the ecosystem with allochthonous and autochthonous energy budget balances, including imports and exports, and primary production, respiration, and storage change in the detritus pool (Box 1).

A single synthetic framework has been proposed to describe the function of lotic ecosystems and variations among sites related to terrestrial conditions. The relative contribution of autochthonous and allochthonous resources varies with successive stream segments from spring brooks to large rivers. Low-order forested streams have considerable shading and low primary production. However, they experience large inputs of allochthonous coarse organic particulate matter (CPOM) from leaves and other particulate matter providing a major energy source for macroinvertebrates and micro-decomposers. Higher-order wider rivers experience much less influence from the riparian vegetation, but the light climate increases, and with ample sunlight, primary production increases and the direct input of organic matter decreases.

The apparently predictable geomorphological hydrological downstream changes, including energy input and organic matter transport, act as a template upon which biological communities are adopted by the dynamic system. The River Continuum Concept includes a number of predictable changes along the continuum concerning temperature fluctuation amplitude, relative proportion of different functional groups, species diversity, and ratios between primary production and ecosystem respiration (P/R Ratio), and the relationship between CPOM and fine particulate organic matter (FPOM). According to this theory, low-order streams have a low P/R value less than 1, due to coverage by a dense canopy, a large amount of leaf inputs and shredders occupying a large portion of organisms and dominating hetrotrophy. In mid-order streams, improved light conditions in wider channels increase algal and macrophyte production, increasing the P/R ratio to higher than 1, and the abundance of grazers and scrappers. In intermediate stream orders, large temperature variation maximizes the species richness. High turbidity and large depth of high order rivers reduce light and the P/R is reduced to less than 1 and the CPOM/FPOM ratio is the lowest. Phytoplankton contributes to the primary production and collectors dominate because of the lack of coarse organic matter and increasing number of fine particles.

This concept was originally developed from investigations in temperate deciduous forest areas, but it is not readily applicable to a multitude of specific situations, including anthropogenic alterations and changes that are more important. The maximum species diversity in intermediate order streams based on temperature is not always satisfied, especially in taxa other than macroinvertebrates. The hypothesis of largest amount of CPOM in low-order streams is not always applicable to rivers in arid zones where autotrophy, rather than CPOM inputs, dominates. The color of the river water changes the features apart from river continuum concept. Many modifications and supporting works have been, therefore proposed to accommodate these criticisms, such as a necessity to investigate various habitats and biomasses of different functions. However the concept provides useful conceptual frameworks to describe how ecological functioning varies along riverine ecosystems, and has stimulated the conceptual context for a while.

Box 1. River continuum concept

2.1.1 Organic Matter in Rivers

Particulate organic matter is divided into two categories, CPOM (particles larger than 1 mm in size) and FPOM (particles from 1 mm to 0.5 μm in diameter). Coarse organic detritus and autumn-shed leaves are a major CPOM source in temperate and tropical forested streams. Although large woody debris is categorized as CPOM, they have an indirect role in the energy flow in streams because of its poor quality as food. Some FPOM originates directly from adjacent terrestrial forests, but it is mainly generated from CPOM through shredders, microbial processes, physical abrasion, and from feces. Benthic algae detached by various processes and suspended algae from lakes and large rivers are also important sources of FPOM. Flocculation of dissolved organic matter is another source of FPOM. Generalizing the amount of CPOM entering the stream system is difficult and has been estimated at 335 g. of carbon m^{-2} y^{-1} in the eastern United States.

The standing stock of CPOM decreases with increasing stream order, partly due to higher inputs, processing of litter in low-order streams and the storage of material behind debris dams, and has been estimated at 150–250 g. C m^{-2} y^{-1} for the 1st, 100–150 g. C m^{-2} y^{-1} for the 2nd, and 7.5–8.5 g. C m^{-2} y^{-1} for the 6th order tributaries of the Matawek-Moise River in Canada. Open streams, however, receive less CPOM than a forested stream. The amount of FPOM varies from stream to stream and increases with order. The presence of debris dams markedly increases the standing stock of FPOM and varies with season. At microhabitat level, accumulation of organic matter is highest in pools, followed by riffles, and rock substrates have the lowest.

Some filter feeders feed on suspended FPOM, while collectors and grazers feed on benthic FPOM. DOM is defined as organic matter less than 0.5 μm in diameter, ranging from sugars, lipids, amino acids and proteins to humic molecules and colloids. In most cases, a small fraction of DOM consists of simple sugars and low molecular weight compounds, however they play an important role in energy flow. Most DOM originates from terrestrial decomposition and enters streams, and the rest is from instream sources, such as detrital leaching and exudates from algae, higher plants, and heterotrophs.

DOM sometimes aggregates into flocs by mechanical forces to become FPOM, providing opportunities for colonization by microorganisms. DOM is incorporated into food webs mainly as microbial uptake within biofilms and subsequent transfer to higher trophic levels, although some specialized animals are capable of directly assimilating it.

The ratio between dissolved organic carbon (DOC) and particulate organic carbon (POC), DOC:POC, varies from 0.09 to 70 in North American streams, to some extent because of stream size and watershed characteristics. POC concentration is low in undisturbed forests and high in streams flowing through agricultural or multi-use watersheds and lowland rivers.

About half the organic matter entering the channel of streams and rivers is exported downstream, a quarter is stored for a period on stream banks or within channel beds, and the remaining quarter is processed and decomposed, producing carbon dioxide, in biological processes within the channel. An analysis of energy budgets implies the importance of the ratio of gross primary production, P, to community respiration, R. The ratio of P and R equals 1 if an ecosystem respires all the chemical energy fixed by the primary production. If energy is imported from outside the organic system, the P/R value is less than 1, and the P/R value is greater than 1 for exported fixed energy. A P/R

value greater than 0.5 indicate that over half of the respired energy is attributable to autochthonous primary production and this is a more sensible dividing line between streams whose energy base lies primarily with its banks, rather than beyond.

For heterotrophic streams, the $P/R < 1$ (0.5) and the ratio between imports, I, and exports, E, is $I/E > 1$ for low instream primary production and large inflow of organic matter.

For autotrophic streams, the $P/R > 1$ (0.5) and the I/E is small for high primary production that is finally exported.

2.2 Nutrient Dynamics of Rivers

The amount of nutrients is highly variable, especially in streams and small rivers, with location and season, due to local geology and rainfall, position in the river continuum, and the extent of human influences. Large rivers often have their nutrient concentrations modified artificially such as by industrial emissions, sewage and agricultural effluents, and dams.

The role of nutrients is different in streams and lakes. In the lentic system, primary production is usually limited by nutrients, and lotic productivity is often limited by light intensity, especially in low-order streams shaded by dense canopy. Production of periphyton (epiphytic algae) and submerged macrophytes further reduce light availability. This is particularly apparent in high-order streams, due to high turbidity and greater depth. Nutrient availability reduces productivity in intermediate ordered streams when the concentration of soluble reactive phosphorus is below 15 $\mu g\ L^{-1}$ and inorganic nitrogen is below 60 $\mu g\ L^{-1}$. All available nutrients can contribute to primary production in the euphotic zone of lakes, but in the lotic system nutrients are continuously input from upstream.

The internal biotic cycling of nutrients develops streamwise (along the stream) in lotic systems under a strong unidirectional flow, which is termed “spiraling”, in contrast to cycling over time in lentic systems. Nutrients generated at a particular location will be transported some distance before subsequent re-utilization. A given nutrient atom might be re-used many times, however, each cycle is displaced downstream from the previous cycle. Therefore, nutrient spiraling describes the interdependent processes of nutrient cycling and downstream transport. Application of the spiraling concept requires a method to quantify the distance traveled by an atom in completing a cycle. The spiraling distance, S, is therefore, defined as the sum of transport in two compartments: the nutrient uptake length, SW (the distance traveled as inorganic solute, from when it becomes available in the water column until its uptake and incorporation into the biota), and the turnover length, SB (the distance traveled within the biota until its eventual release back into the water column). The atom travels greatest in the water column, and therefore, $SW >> SB$.

The uptake of inorganic nutrients from a stream is primarily by autotrophs and microbes that will reduce SW by incorporating nutrients into benthic biomass. An increasing metabolically active biomass of these organisms removes nutrients more rapidly. With a large amount of coarse particulate organic carbon, the uptake length of phosphate is shorter, and the retention of inorganic nitrogen increases with increasing thickness of periphyton mat, while as the biomass reaches a steady state, its uptake rate is balanced with output, and thus the system stores no more nitrogen. Consumers can stimulate nutrient uptake or release and may increase spiraling distance, either by diminishing benthic populations responsible for uptake, or by fragmenting large into small particles, which are then most likely to be transported downstream. Consumers can also enhance the rate of regeneration of nutrients by excretion and egestion, which contributes significantly to nutrient dynamics in highly productive systems whose nutrients are scarce. Aquatic macrophytes are capable of removing substantial amounts of nutrients from flowing water. Movements and migrations by animal populations can result either in significant inputs or outputs. Spawning runs of fish may input substantial amounts of nutrients to streams, however, emergence of the adult stages of aquatic insects does not contribute much to overall nutrient dynamics. Apart from the influence of the animal community, aquatic macrophytes are capable of modifying the nutrient spiraling by removing substantial amounts of nutrients from flowing water.

The spiraling length (S) is not a function of consequent uptake and release intensities alone; it also depends on sorption to the sediment (especially important for phosphorus), current velocity, and the amount of discharge. Although sorption to the bottom sediment is less influential for nitrates, the physical-chemical process is important in phosphorus cycling. At low levels of dissolved phosphate, organic or inorganic phosphorus compounds are absorbed rapidly by sediments, and a significant adsorption of ammonium to sediment occurs during summer time. The hydrologic regime has a marked influence on nutrient concentration and nutrient uptake. Storms can influence nutrient uptake rate by affecting the standing stock of leaf litter and organic matter. Geomorphological characteristics of river channels influence the storage and transport of nutrients; retention and uptake increase in low flows, with a large periphery length with respect to volume flux, presence of debris dams and permeable substrates increasing retention. Spiraling distance is considered to increase gradually with increasing order of streams. In broad rivers, however, effects of floodplains and side channels are expected. Spiraling distance was 167 m for phosphorus in a Tennessee stream, and the turnover distance was 26 m in a laboratory experiment.

2.3 Physical Processes of Lakes

The boundaries of lakes are well defined with a shoreline, an air–water interface, and a bottom sediment. The external inputs are defined as: atmosphere, stream water, and terrestrial runoff from areas surrounding the lake. Depth is one of the most critical components for lake ecosystems, as it strongly influences biological and chemical processes, including light penetration, temperature profile, amount of mixing, nutrient cycling, and decomposition processes. Distinguishing the dominant processes between lakes and reservoirs is necessary (Box 2) for general understanding of these ecosystems. There are many different types of lakes, classified according to lake formation and origin, the amount of water exchange, hydrochemistry, and so forth. An important distinction is drawn between closed (endorheic) lakes, with no outflow, and exorheic lakes, which are drained by outflowing rivers. Endorheic lakes are very dependent on the balance of inflows and evaporation and are very sensitive to change in either.

Exorheic lakes also may be sensitive to changes in the amount of inflow and the volume of evaporation.

Drainage basins are generally wider and less elongated with lakes than with reservoirs. Many lakes include a considerable part of adjacent drainage areas, while reservoirs usually have the greatest proportion of the drainage basin upstream from them and the drainage basin is nearly identical between the reservoir and the upstream river. Larger drainage basins associated with reservoirs may result in greater annual flows entering reservoirs than lakes. The energy of rainfall determines the rate of erosion and transport of particulate matter from the watershed to the stream, so the process of watershed runoff is similar between lakes and reservoirs. Watershed characteristics, however, affect the quantity and quality of material delivered to the impoundment system. In general, upstream from lakes the stream order is lower and the relative drainage basin size to the impoundment is smaller than for reservoirs. Watershed characteristics influence the sediment delivery ratio to the impoundment system. As watershed size increases, the interception and deposition of transported particulate matter potentially increases, so the sediment delivery to the steam is inversely proportional to the watershed size. The absolute quantity of sediment and its adsorbed constituents continuously increase with increased drainage area, and the relationship between drainage area and sediment delivery ratio is logarithmic.. Land use in the flood plain has a greater impact on stream water quality than land use outside the flood plain.

Lakes are generally located in upper parts of a drainage basin while reservoirs are located near the mouth of the drainage basin. Thus, the stream order above the lake is generally lower than that of reservoirs. The river continuum concept implies differences in the contribution of various forms of organic carbon to lakes and reservoirs. Autotrophic production tends to increase with stream order, at least until the ninth order. Autochthonous autotrophic production is an important contributor to the organic carbon supply in larger streams of forested areas and in open-canopy streams of all sizes. Sediment, particulate organic matter, and adsorbed constituents are transported primarily during storm events or increased flows. For rivers this transport occurs through a series of storm events with intermittent periods of deposition and processing in the stream between storm events. As fine particulate organic matter (FPOM) is preferentially transported compared with coarse organic matter (CPOM) and stream processing increases the amount of FPOM, reservoirs may receive relatively higher proportions of FPOM and dissolved organic matter than lakes. The spatial distribution of sediment loading is different between lakes and reservoirs. In lakes the inflow is generally equitably distributed around the periphery of the stream. Reservoirs in contrast generally receive the majority of their inflow from one or two major tributaries at a considerable distance from the outflow. This promotes the development of pronounced physical and chemical gradients within reservoirs that have important consequences for reservoir biological productivity and water quality. Abiogenetic turbidity and large water-level fluctuations for flood control and hydropower operations often restrict the development of attached algal and rooted macrophyte communities in reservoirs, and so the contribution of planktonic production increases.

Box 2. Differences between lakes and reservoirs

Solar radiation is the major source of energy in lakes as light for photosynthesis and as heat, and also provides the heat that drives the wind patterns that, in turn, induce mixing in the lake water column.

2.3.1 Light Zonation

The amount of light available at a particular depth determines the amount of photosynthesis, which is restricted to the upper layers, the photic or euphotic zone, that extends from the lake surface down to where the available light is about 1% of the light at the surface. The aphotic zone extends from below the photic zone to the bottom of the lake where the light levels are too low for photosynthesis, and causes this zone always to consume oxygen. The boundary between these two zones varies daily and seasonally with varying solar intensity and water transparency.

2.3.2 Thermal Stratification and Wind Action

More heat is absorbed at the surface than at depth, which results in the formation of two layers of water, less dense water at the surface and cooler dense water at the bottom. Energy must be expended to overcome thermal resistance and to induce mixing. The amount of energy needed for mixing increases with increase in temperature differences between the layers.

During early spring, soon after ice melts, the wind action on the lake surface moves surface water downwind, with an upwind movement of the bottom water. The whole lake water circulates and mixes by wind (spring overturn) until the water temperature increases sufficiently as spring progresses to reestablish a thermal stratification. During the summer, the surface water temperature is substantially higher so that the thermal resistance to mixing is too great to be overcome by wind mixing. The lake is thus stratified into three principal regions: the upper circulating warmer water is called the epilimnion, the lower cooler region (stationary) region is called the hypolimnion, and the middle transitional region where the rate of temperature change with depth is greatest is called the metalimnion. This region acts as a barrier to free movement of contents between the upper and the lower layers of water due to density differences. However, the upper layers of the epilimnion may be well stirred owing to wind action and are called the mixed layer, the depth of which depends on the season and the interaction between wind and sun on any given day. In the autumn, the heat income to the lake decreases and great heat losses occur at night causing the epilimnion to sink and erode the metalimnion. Eventually, as the difference in temperature and density is so slight, the resistance to mixing is overcome by wind action, and convection currents, which causes the whole lake to mix and circulate again (fall overturn). If the water surface of the lake freezes during winter, the stratification inverses, with a slight increase in water temperature with depth.

Lakes that have winter ice cover are called dimictic as they mix twice a year- spring overturn (after ice melts) and fall overturn (before ice cover). Monomictic lakes are never completely ice-covered and winter is a single continuous wind-stirred event. Shallow lakes that are exposed to wind, and in which the thermal stratification is easily destroyed, but are reestablished and disrupted repeatedly, are called polymictic lakes. At the time of circulation, most lakes are completely mixed from top to bottom and are called holomictic, but lakes that are too deep and have a permanent stagnant water layer at the bottom because of insufficient energy to overcome thermal stratification are called meromicitc. Another cause of meromixis is a high-density saline water layer (monimolimnion) due to high contents of dissolved salts beneath the overlying freshwater (mixolimnion). Lakes that are always covered with ice and never mix are called amictic.

Wind-induced water circulation: Water movements within lakes produced by wind result in a variety of rhythmic movements (oscillations) on the water surface, such as waves, surface currents and Langmuir circulation or streaks, and internal oscillations within the lake. Waves consist of the rise and fall of water particles, involving some oscillation but no net flow, but the currents consist of a net unidirectional flow. Vertical mixing and horizontal flow are caused by the surface wind. Currents at the lake surface are called surface drift. Lakes are mixed most vigorously by storm winds, which produce surface and internal waves (especially at the thermocline), and strong horizontal currents.

2.3.3 Circulation in Tropical Lakes

Polymixis is frequently found in shallow tropical lakes, particularly if they are in windy climates and at high elevations (where nocturnal heat loss by convection is greater than at low elevations); lake water circulates freely most of the time, with stratification occurring only under unusually calm conditions.

2.3.4 Importance of Water Circulation in Lakes

Water movements have profound consequences for the chemistry and biology of lakes and are critical to the distribution of all forms of energy, momentum, nutrients, dissolved gases, algae, some zooplankton, and sedimentary materials. The lack of water mixing between the epilimnion and the cooler hypolimnion is a major factor determining the productivity of lakes and rapid top-to-bottom mixing and lake overturns are extremely important in recycling nutrients, especially in shallow lakes, which often support high levels of productivity.

2.4 Chemical Processes in Lakes

Coinciding with the thermal stratification, nutrients are often depleted in the epilimnion or the photic zone, while the concentrations remain constant or even accumulate in the hypolimnion. By analogy with the temperature, the depth at which rapid change in a substance occurs is called the chemocline. Horizontal zonation of chemicals may also occur, with highest concentrations near the shore (i.e. at the littoral zones).

The major nutritional components of lake biota are carbon, nitrogen and phosphorus, which exist dissolved in water, bound to organic matter, or in the sediments. Complex mechanisms govern their availability in water, solubility, and biogeochemical cycling. The ionic composition of the lake is dominated by four major cations (calcium, magnesium, sodium, and potassium) and by three anions (carbonate, sulfide, and chloride).

Phosphorus and, to a lesser extent, nitrogen are often limiting nutrients to algae and higher plant growth in lakes, and overall nutrient levels indicate the trophic status of the lake ranging from eutrophy (high nutrients) to oligotrophy (low nutrients). Although phosphorus inputs and recycling establish the potential productivity of lakes, predation controls the allocation of phosphorus for fish production, algal blooms, or other components of the pelagic food web. In the normal dynamics of many lakes, large piscivorous fishes are keystone predators that structure the food web below them, and such lakes have large-bodied zooplankton grazers that effectively control phytoplankton. When pulses of phosphorus enter these lakes, the nutrient is transferred effectively to higher trophic levels and does not accumulate as algal biomass. Oxygenated conditions decrease the rate of phosphorus recycling from sediments in many lakes. If production in the overlying water increases, deep waters can be deoxygenated and phosphorus recycling can increase, thereby further increasing algal production. Oxygenation of bottom waters prevents this positive feedback and confers resilience in moderately productive and unproductive lakes.

Oxygen profiles in lakes are strongly dependent on thermal stratification and light penetration. Diurnal cycles in oxygen concentrations are associated with high densities of macrophytes, attached algae and phytoplankton, with oxygen levels increasing during the day because of photosynthesis and depleting at night because of respiration. Extremely high oxygen demands during increased decomposition can reduce the lakes to almost fully anoxic conditions with resulting massive animal deaths. The lake mixing and overturning events can also bring the anoxic bottom layers to the surface, which also can be detrimental to biological life.

Submerged macrophytes play an important role in stabilizing a clear water state in shallow lakes by various mechanisms (Box 3). Submerged macrophytes of the littoral zone provide a crucial habitat for epiphytic algae, invertebrates, and fish. They also modify inputs to lakes from riparian or upstream ecosystems, store substantial amounts of nutrients, and are a source of dissolved organic compounds. Oxygen production by macrophytes and attached algae can decrease the rate of phosphorus release from sediments, and high denitrification rates in littoral vegetation can decrease nitrogen availability.

The dynamics of shallow lakes provide the best limnological example of alternative states. Shallow eutrophic lakes exist in two states: turbid and dominated by phytoplankton, or clear and dominated by macrophytes (usually rooted aquatic plants, but sometimes attached macroalgae). The turbid state involves dense phytoplankton growth driven by nutrient recycling from sediments. Shading by phytoplankton blocks growth of attached plants. The plant-dominated state involves dense growths of attached plants that stabilize sediments (thereby slowing nutrient recycling) and shelter phytoplankton grazers. The change to the plant-dominated state can be triggered by a trophic cascade: piscivore stocking or planktivore removal, or both, to increase grazing and reduce phytoplankton. The change to the turbid state can be triggered by water-level fluctuations or grazing of macrophytes by fish or birds. Some lakes have changed states several times, with intervals of years to decades passing between transition events.

Box 3. Alternative stable states in lakes

2.5 Biological Processes in Lakes

Phytoplankton mainly occupy the photic zone of the lake and absorb nutrients directly from water. Their populations show clear patterns of seasonality and periodicity. A typical seasonal cycle of a temperate lake can consist of a large spring diatom bloom, smaller irregular summer peaks of various flagellates, and the large autumnal bloom of diatoms, blue-green algae, and dinoflagellates. Almost all phytoplankton show vertical variation in abundance through the photic zone (more densities in the surface layers), despite mixing by winds and waves.

The major consumers of phytoplankton are herbivorous filter-feeding zooplankton, and therefore their populations are highly dependent on phytoplankton productivity. Zooplankton populations also show patterns of seasonal succession that vary between species and within species among lakes. Cyclomorphosis is conspicuous among zooplankton, especially in cladoceran species due to high predation (size-selective) pressure mainly from phantom midge larvae. Lake zooplankton show patterns of diurnal vertical migration, which is believed to be a strategy to avoid visual feeding predators.

Fish are the most important predators in the lake ecosystem because each fish is planktivorous at least in the juvenile stages. They have a large feeding capacity and their broad spectra of food size selectivity endangers almost all zooplankton species because fish can easily switch from one prey type to another. Intense selective predation on zooplankton can eliminate large forms of zooplankton, thus releasing browsing pressure on phytoplankton, and thus increasing the algal biomass of the lake.

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Dr. Tilak Priyadarshana is a researcher at the Department of Environmental Sciences and Human Engineering, Saitama University, Japan. He graduated from the University of Ruhuna in Sri Lanka and afterwards he continued his research for a Ph.D. at the Department of Civil and Environmental Engineering at Saitama University, Japan. His major interests include community ecology with major emphasis on aquatic ecosystems and how major ecological processes, such as competition (i.e., bottom-up forces), predation (i.e., top-down forces), and keystone species (i.e., intermediate, strong regulators, often in the middle of the food web) structure freshwater communities and in turn how these findings can be utilized to manage aquatic ecosystems. He is the author of several research publications on ecological restoration of lakes and reservoirs.

Bae Kyung Park is currently a Ph.D. student at the Department of Environmental Science and Human Engineering, Saitama University. His major field of study is aquatic ecology, especially focusing on characteristics and role of planktivorous fish in aquatic food webs. He is also studying the energy budget of planktivorous fish and characteristics of interaction between predator and prey. He completed his Master of Science degree majoring in water quality management at Kangwon National University, Republic of Korea. He has participated in several projects including water quality and pollutant influx of rivers, lakes, and sea. He was at Rutgers, The State University of New Jersey, USA, as a visiting researcher from March 1994 to February 1995. He participated in three projects, which focused on water quality management and toxicology. From 1996 to 1998, he worked as a researcher in the Seoul Development Institute, Republic of Korea. He duties covered areas such as water environment and solid waste management. He has participated in research on wastewater treatment systems and sludge disposal and has been involved in research on water resource management through storm water retention/infiltration.