Environmental Studies 30 -- The Global Ecosystems

LECTURE 19 and 20: Lakes and Streams

I. Lakes

A. Formation

Lakes are somewhat like estuaries. A large fraction of the earth's lakes were formed by the Pleistocene glaciers and will fill with sediment in a short of period time, geologically speaking. Lakes in arid areas also fluctuate in level and even disappear as climate change alters their water budgets. Only a few big, deep lakes in zones outside the areas of glaciation have existed continuously for a million years or more (e.g. Lake Baikal in Siberia and Lake Tanganyika in Africa). Some common modes of lake formation include:

1. **Glacial action:**

   a. **Uneven scraping of the bedrock due to different rock composition.** The lake districts of the northeastern U.S. and Canada are covered with lakes of this type. These lakes are usually relatively small and shallow, but in some areas as much as 50% of the land area may be water covered. The chains of little lakes at the bottoms of glacial valleys in the mountains are often similarly formed.
   b. **Cirque lakes.** These lakes are common in the mountains. An isolated glacier carves a little niche in the side of a mountain, leaving a lake when it melts (See Figure 19.1).
   c. **Moraine dammed lakes.** Moraines are the debris piles made by glaciers. These often dam a glacial valley and pond a lake behind the glaciers. The Canadian-American Great Lakes are behind the terminal moraine of the last continental ice sheet. The moraines plugged a series of the upper drainages of the Mississippi system, and the ponded water rose until it flowed to the sea via the St. Lawrence River instead.

Often glacial lakes are partly formed by several of these processes simultaneously (e.g. cirques with a moraine dam).

2. **Tectonic activity.** Earth movements sometimes create depressions that fill with water. The world's very deep lakes are often formed, for example, in grabens, where a block of rock drops between two faults, leaving a basin between two ranges of hills or mountains. Lakes Baikal and Tahoe are good examples. The system of lakes in the Rift Valley of Africa are mostly in a crack in the earth's crust where continental drift is ripping the continent in two. Lake Victoria is the exception. It is between two branches of the rift where an old system of river valleys has been tilted backwards to flood the headwaters valleys. Several other kinds of tectonic movements also produce lakes.

3. **Volcanic activity.** Lava flows can dam river valleys to form lakes. Clear Lake is an example. Also lakes very often form in the crater or caldera at the top of a volcano. Crater Lake, Oregon is a particularly spectacular example. Lakes also form in volcanic explosion craters and meteor impact craters.

4. **Landslides.** Landslides can dam river valleys, as with the recently formed Quake Lake in Yellowstone National Park. These lakes are prone to erode away the landslide catastrophically and cause severe floods. Glacial ice sometimes dams water with similar consequences. Also, small lakes sometimes form in a depression on the uphill side of a landslide. There are a couple of lakes of this type at Point Reyes.

5. **Solution lakes.** Small, deep lakes often form in limestone country when solution holes enlarge or caves collapse. The Mayans in Yucatan often built their towns around these (Chichen-Itza).

A series of other less common natural processes also form lakes. G. Evelyn Hutchinson listed a total of over 70 types in 1957 and several others have been added since.

6. **Reservoirs.** Humans are large scale makers of lakes to store water. Generally, these lakes are unusual in the extent of their annual fluctuation of water level, a necessary consequence of their purpose as water storage systems.

B. Hydroclimate

The hydroclimate of a lake is primarily a function of its mixing regime, the nature of its drainage basin, and the nature of the lake basin itself.

1. **Mixing regime.** The mixing regime of a lake is determined partly by its heat budget (and hence by terrestrial climate) and partly by its depth and size. The size of lakes limits the amount of mixing energy delivered by the wind. This, combined with the lack of significant tides means that even the very largest lakes are subjected to considerably less turbulent mixing than the ocean or estuaries. Small lakes in forested basins have such weak currents that turbulent mixing through the thermocline is zero. On the other hand, if a lake is shallow enough it will not stratify at all. Clear Lake, California is an example. It is mostly less than 10 m deep and does not stratify. Neglecting some of the less common patterns, lakes that do stratify can be divided into the following types:

    a. **Dimictic** - Lakes that mix twice a year, in the spring and in the fall. The winter stagnation period occurs because of ice cover, while the summer stratification occurs because of thermocline formation. These lakes usually have bottom temperatures around 4°C year-round, and are the most common type in the cool and cold temperature regions and in subtropical alpine areas.

    b. **Warm Monomictic lakes.** These lakes do not freeze in the winter, but rather are isothermal (usually above 4°C) for a few months in the winter. They stratify in the spring and usually remain stratified until late fall or early winter. These lakes are the dominant type in the tropics and lowland subtropics. Lake Tahoe is an interesting outlier of this type. The smaller lakes of the Sierra (above about 1,200 m) are all dimictic. Tahoe cools to just about 4°C, but its large volume and large area does not permit it to reach 0°C at the surface to initiate ice formation, at least under present climatic conditions. Most of California's lower elevation reservoirs exhibit the warm monomictic pattern.

    c. **Oligomictic lakes.** Very deep tropical lakes do not freely circulate below about 200 m. Lakes Tanganyika and Malawi are the best known examples of lakes of this type. These lakes have only a very small thermocline during the dry season, but apparently do not lose enough heat or receive enough wind to mix them to the bottom. The bottom water of such lakes may be renewed by occasional catastrophic mixing in an especially cold or windy year, or perhaps small parcels of water cool in shallow regions and sink into the hypolimnion every year. This last alternative would make their deep circulation something like that of the ocean. The physics of the mixing of these lakes is rather poorly understood as yet.

2. **Nature of the drainage basin.** Lakes are described as being oligotrophic, mesotrophic or eutrophic, depending upon whether the nutrient supply available for the plankton is small, medium or large. The size and character of the drainage basin is the most important single determinant of nutrient supply. Lakes with big basins, relative to lake size, usually have a large input of nutrients; they have a large surface of weathering land to supply them. California's lowland reservoirs are generally eutrophic for this reason. Lake Tahoe and Crater Lake are two of the world's clearest lakes because they have very small drainage basins. Also, granitic basins at high elevations (cold temperatures) tend to have slow weathering rates and hence a small supply of nutrients in streams. Other rock types and warmer lowlands tend to produce mesotrophic or eutrophic lakes. Human disturbances or pollution producing activities can very substantially increase nutrient loading from the basin, of course.

3. **Shape of the lake basins.** Deep, steep sided lake basins with a small exposure of littoral sediments to the epilimnion tend to produce oligotrophic lakes. During the stratified period, nutrients tend to settle into the hypolimnion and only return to the euphotic zone during the mixing period. At the opposite extreme, shallow unstratified lakes tend to have highly efficient recycling of nutrients and hence relative eutrophy.

In summary, lakes vary greatly in the loading of nutrients from the basin, including human inputs in the frequency of return of nutrients to the epilimnion by mixing, and the degree of euphotic zone exposure to the sediments, which links the primary producer and decomposer communities directly.

C. Lake Biota:

1. **Littoral zone.** The littoral zone of lakes is often large relative to the volume of the lake, by comparison with the ocean at least. When bottom sediments are soft and the lake reasonably clear, the littoral is often dominated by aquatic macrophytes. The structure of the community resembles that of the subtidal algal macrophyte community of the seas, but most of the plants involved are seed plants, not algae. Filamentous algae and chara (a large, branched algae with whorls of needle-like leaves that looks as if it is a higher plant) are important in many littoral communities, however. The interaction between the littoral and pelagic communities is complex and poorly understood. In some cases the macrophytes seem to accelerate nutrient outflow from the sediments and increase plankton production. In other cases they seem to compete for dissolved nutrients. A diverse assemblage of crustacean and insect herbivores live in the littoral and fish production is often disproportionately high there.

2. **Plankton and Nekton.** This community bears a general resemblance to that of the sea. The primary producers are all small to very small algae. The variety of groups involved is greater than in the sea. In addition to diatoms and dinoflagellates, green algae, bluegreen algae and several smaller groups are important. The diversity in any given lake is similar to the sea, but the nutrient regimes of lakes vary over a much wider range than the sea, giving a considerably longer total list of freshwater species. The bluegreen group is particularly noteworthy because some bluegreens (really large photosynthetic bacteria) fix atmospheric nitrogen. Particularly in warm, phosphorus-rich lakes, often polluted ones because sewage has a low N:P ratio, these algae dominate. Some are very large for plankters, forming conspicuous macroscopic colonies of a millimeter or so long, and float. When they die in large numbers, they form an obnoxious scum.

   The zooplankton of any one lake is much less diverse than that of the sea and many fewer invertebrate phyla and classes are represented in it. Copepods are similarly important, but the other major groups in the sea are rare. Caldocera, Daphnia and its relatives, are a crustacean group of about equal importance to the copepods. The third major group are the rotifers, a curious group of ciliated microscopic invertebrates that are common in freshwater habitats including lake plankton. Many other groups contribute a rare plankter here or there. (There is one species of freshwater jellyfish in North America, for example. It is rare, but is recorded from Lake Berryessa.)

   The nekton community of lakes is almost entirely composed of fish. Its structure is highly variable, for reasons discussed below. In some cases, a multi-trophic level community of fish preys on the zooplankton, much like the sea, while in other cases the open water is little exploited by fish. In the latter case, invertebrates like the insect Chaoborus (a highly specialized, non-biting mosquito, the famous Clear Lake Gnat is one of these) become the top carnivore of the plankton.

3. **Benthos.** As in the sea, bacteria and fungi form the base of benthic food webs. The dominant benthic organisms of lakes are deposit feeding insects and oligochaetes (related to terrestrial earthworms). Some suspension feeders like freshwater clams occur, but they are more frequently found in rivers. Probably the lower energy environment of freshwater does not

keep the deeper water well enough mixed to favor suspension feeders. Benthic fish occur in lakes (e.g. Catfish, Carp) but they are less elaborately specialized than in the sea.

D. Lake Biogeography (in the sense of species distributions).

Lakes have much the character of islands, with major dispersal barriers between them. They are also generally very temporary habitats on the time scale of evolution and geology. Some elements of the lake biota have quite successfully coped with these barriers, others not. The phytoplankton, for example, are generally cosmopolitan; the species occur around the world in suitable habitats. Lake Titicaca in Peru has several species of phytoplankton in common with Lake Tahoe. Some of the zooplankton of these two lakes are similar -- the rotifers and caldocera. The copepods are more restricted. Most species and some genera occur only on a given continent, or a large fraction of the continent. Exactly how this large scale dispersal occurs is a bit of a mystery. Some of the species involved, by no means all, have tough resting stages. Darwin suggested that the feet of water birds were a good guess, and that is still the conventional story, although no one has taken much of an interest in the problem.

The fish are quite a different matter. They seem to be extraordinarily limited in their capacities to move from one lake to another. Coupled with the fact that lakes are geologically youthful and prone to severe disturbances with changing climate, the barriers mean that most lakes probably have far fewer fish species than they could support, and rather unspecialized ones in general. Introductions of fish by humans, either accidentally or deliberately, are very often undertaken and are often successful. They often also cause wholesale reorganization of the native fish community. California, for example, has very few native warmwater predatory fish, and species from the richer eastern U.S. have been very widely and successfully introduced as sportfish. On the other hand, the native Sacramento Perch is now fairly rare because of these introductions. Similarly, North American and European Salmonoids, especially Rainbow Trout, Brook Trout and Brown Trout, have been introduced to alpine streams and lakes all over the world.

Given sufficient time, lakes can apparently evolve a very elaborate series of highly specialized fish in situ. The large lakes (Victoria, Tanganyika, Malawi) of the African Rift have at least 200-300 species of (mostly) endemic, highly specialized fishes. One suspects that temperate lakes, if left undisturbed long enough, would do the same, although a latitudinal gradient of diversity might remain. As yet, however, we do not know what "sufficient time" means in this context. The age of the African Great Lakes is a matter of some uncertainty. They may have been continuously filled with water for a million years or more. On the other hand, Tanganyika may have dried up about 400,000 years ago and Victoria may have filled only about 200,000 years ago. Glacial lakes generally date from the last 10,000 years, since that is when the Pleistocene ice retreated. Temperate-zone lakes, mainly glacial, do not have the large flocks of endemic species characteristic of the older tropical systems. On this, admittedly thin, comparative data, it seems that a few tens of thousands to a few hundred thousands of years are required to evolve something like an equilibrium number of lake fishes beginning with a few stream-fish ancestors. One of the most interesting problems in the estimation of maximum rates of evolution in the face of many empty niches remains to be solved here.

II. Streams

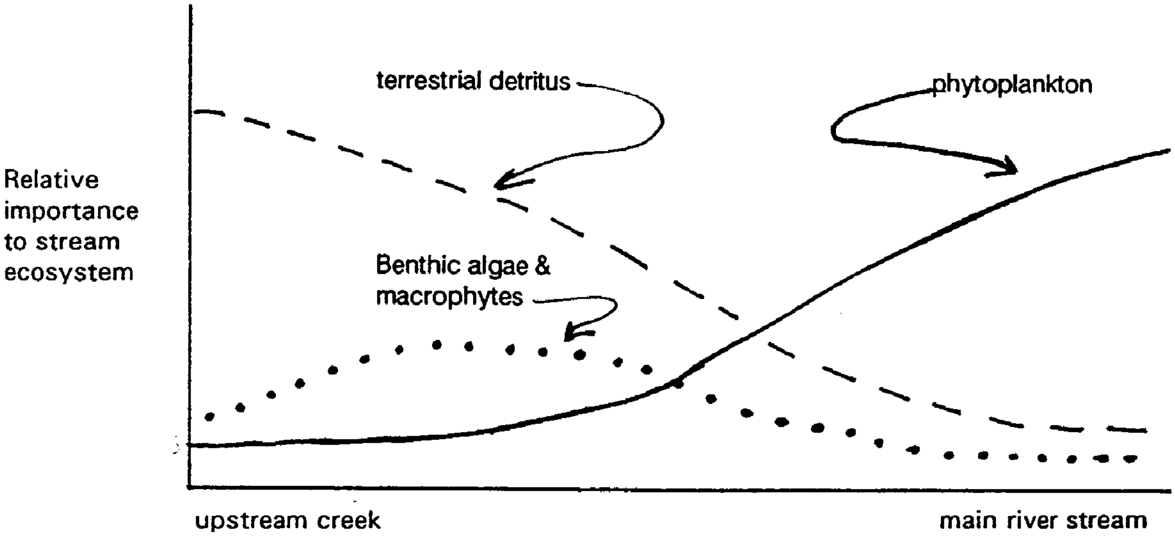
Streams are very different environments from lakes. The one way flow of water in them causes considerable mixing and a longitudinal pattern of development. The volume of water is small compared to most lakes, and contact with the bottom sediments relatively more important. Streams are rather strongly influenced by the terrestrial environment and are usually quite variable because the flow regime changes so much during the course of the seasons (and between years due to floods and droughts). On the other hand, river systems are usually geologically much more long lived than lakes. As the contours of the land change due to mountain building, sea level changes, and erosion, river systems change their shapes but do not disappear. The world's major river systems, the Amazon, Congo, Mississippi, Hwang-Ho, and so forth, have geological histories reaching back millions of years.

A. Geomorphology and Hydroclimate

River systems can be divided into two regions, the erosional headwaters and the depositional downstream regions. The smaller headwater streams are removing sediment from the land, whereas the larger depositional downstream reaches drop part of their sediment load, filling and raising the level of valleys.

The hydroclimatic (and other basic structural features of the ecosystem) changes from headwaters to the sea are fairly continuous. In fact, the River Continuum Concept has recently been introduced to organize thinking about stream ecosystems. The continuum concept is described by the contrasts in the following table and graph:

Headwater Streams	Lowland Rivers
small	large
clear	turbid
low salt & nutrient content	high salt & nutrient content
cool	warm
Food chains based on benthic algae or terrestrial (allochthonous) detritus	Food chains based on export from upstream and plankton



The clear, shallow upstreams systems are spread out on the landscape. Terrestrial vegetation can drop leaves and twigs right into the middle of a small creek, and shading may inhibit algal growth. As small streams flow together and create rivers, the width of the stream creates a light gap, while the number of trees per unit area of stream goes down. Benthic algae attached to rocks become important. These are usually intensely grazed by insects, so only a film of microscopic algae covers the rocks. As the water gets deeper and more turbid in still larger rivers, the benthic algae disappear due to low light conditions. If the turbidity to inorganic sediment is not too high, phytoplankton become important.

B. Organisms

The phytoplankton, benthic algae, and macrophytes of rivers span the same main groups as for lakes. The benthic algae, as one might expect, are mostly filamentous attached forms (including green, bluegreens, and diatoms) or sticky film forms (mostly diatoms). The plankton are presumably accidental forms on a suicide mission due to the unidirectional flow of the stream.

The dominant herbivores and small predators of streams are insects. Some crustaceans, oligochaetes, clams and so forth are important, but the insects have been surprisingly successful at re-invading this aquatic habitat from land. Several of the major orders of insects are exclusively aquatic and mostly stream dwelling, including Dragonflies, Stoneflies, Mayflies, and Caddisflies. Many other orders have aquatic families, including the huge beetle, true bug and true fly orders. One can gain some ideas of the diversity of stream insects by looking at the fly fisherman's imitations at a large sporting goods store. Picking up a few rocks in a stream is an even better way. Several feeding strategies are exhibited by the herbivores -- shredders of coarse particles like leaves, collectors of fine detritus, and grazers of benthic algae. The whole system is often quite diverse and at present is poorly understood.

The fish of streams, particularly the active fish of areas with high currents, resemble the open water nekton of the sea. Not surprisingly, many fish groups important in this habitat are anadramous species which breed in streams but spend most of their adult life in the sea (Salmons, Striped Bass). Some species can live in either streams, lakes, or be anadramous, for example Rainbow Trout/Steelhead. In temperate areas, the fish faunas of the lower reaches of streams are largely fairly generalized. Many species occur in both the quieter parts of lakes and in streams. The fish of tropical river systems are very much more diverse and more highly specialized than in temperate ones. The Mississippi System has about 200 species of fish compared to over 1000 (and still counting) for the Amazon. Among the extreme adaptation characteristic of tropical fish is an Amazonian species that specializes on fruit that drops from streamside trees into the water. It apparently locates the fruit by the sound of it falling, at least Amazonian fishermen are reputed to lure it by throwing stones in the water near their fruit-baited hooks.

III. Human Uses of Freshwater

The uses of fresh water include all those mentioned for estuaries plus direct consumptive uses such as irrigation, municipal, and industrial applications. Freshwaters, because of their relatively small size and, in the case of lakes, relatively weak mixing, are not so effective at diluting and absorbing pollutants as even estuaries. Use conflicts and major degradation of water quality for many purposes are extremely common. Solving one problem has often led to new ones. The classic example is the invention of sanitary sewers in the 19th Century to solve public health problems. Dumping human wastes in rivers or lakes largely gets rid of typhoid and intestinal parasites, but it commonly makes long stretches of rivers useless for most other purposes. Even the treatment of sewage by the common treatment systems, which use bacteria and fungi to digest most of the easily degraded forms of organic matter in the sewage stream, solves only part of the problem. The tendency of the sewage to make the river anoxic (because bacteria and fungi metabolize the waste organic matter in the river) is reduced, but most of the nitrogen and phosphorus pass through the plant. The nutrients then cause excessive algal growth in the lake or stream, almost as if the sewage was recreated by plant growth in the recipient water body. This process is called eutrophication. Lakes as large as Lake Erie have been extensively altered by eutrophication.

The sheer scarcity of water can be an extreme problem in arid areas. The Colorado River, for example, is over-allocated. A series of court decisions have promised more water to users than the river carries in a normal year! It is said that in California, lawyers make more money from disputes over water than any other kind of litigation.