Chapter 2

Biophysical Characteristics of Lakes

This chapter deals with some of the most fundamental questions a lake basin manager needs to consider:

- What is a "lake"?

- What characteristics of lakes affect their management?

- What is a "lake basin"?

- What is the appropriate *scope* of management?

What is a "lake"?

It may surprise the reader, but there is no agreed definition for what is a lake. That said, for the most part, you know a lake when you see one. They are generally of large size, the water is not flowing, and it usually has some life such as fish or birds.

Over the years, the JICA trainees in the Integrated Lake Basin Management Course have been asked to provide their own definitions for what a lake is. Their answers usually include words such as:

Aquatic ecosystem, Water, Watershed/Landscape, Resources, Natural or artificial, Biodiversity, Wetlands, Role in development, Capacity for recovery and so on...

One definition that seems to cover most of these points and does not raise too many objections is the following:

"A lake is a relatively permanent and isolated surface water body with multidirectional flow."

The terms "relatively permanent", "isolated", "surface", "multidirectional flow" need to be considered in reference to rivers, wetlands, groundwater and oceans to understand just what it is that makes a lake a lake.

However, the most important thing from a manager's perspective is to not worry about specific definitions, but rather about characteristics that impact the kind of decisions that need to be made. The remainder of the chapter addresses these points.

Three Characteristics of Lakes

The fact that the word "lake" is applied to such diverse waterbodies as Lake Baikal (1,637 m deep, 31,500 km^2 of surface area, and 25 million years old) and Lake Baringo (2.5 m, 108 km^2 of surface area, and a few thousand years old) indicates that, in spite of the tremendous diversity of lakes around the world, they share some common characteristics. These characteristics are examined below with the implications for management noted.

Long Retention Time

Rivers flow-lakes don't. Specifically stated, rivers are lotic (flowing water) whereas lakes are lentic (standing water). Of course, that is an over-simplification-lakes have outlets and their water is flushed, but the period of flushing is quite long, reaching over hundreds of years for some lakes. This flushing period is called the retention time (or hydraulic residence time) and is equal to the volume divided by the outflow. For most lakes, the volume is so massive it dwarfs the flow, leading to long residence times. For example, Lake Malawi contains around 18,400 cubic *kilometers* (km^3) of water, but the flow out of the lake (through rivers and evaporation) is just 66 km^3 per year. With that much water, Lake Malawi, like most other lakes, is a permanent feature of the landscape on the human-time scale.

Long retention time has several important implications. One is that lakes are relatively stable. Even in severe droughts, lakes still have some water in them: their large volumes mask short-term variations. There are exceptions of course, usually of lakes in closed basins like the Aral Sea, which is known to have dried up 3 times in the last 2 millennia. Nevertheless, most lakes hold and can absorb large amounts of water, buffering both floods and droughts. Acting as a "pool" of water, they present a flat surface allowing for easy navigation. Additionally, long-retention time implies a slow rate of flow which allows for more time (than in a river for example) for suspended materials to settle to the bottom-this means that lakes act as sinks for many materials. Also, by simply being around for a long time, they foster civilizations and can become symbols of a culture (like rivers, of course).

Another implication is that long-term stability coupled with relative "isolation" provides sufficient conditions for complex ecosystems to evolve in lakes. Just as islands can be viewed as "islands of land in an ocean of water," lakes can be characterized as "islands of water in an ocean of land." Both situations represent isolated ecosystems within which area-unique biological communities can develop and evolve. Lake Malawi provides an example of what millions of years of relative isolation, coupled with natural selection, can accomplish-over 500 endemic (native) fish species exist in this lake. However, this biodiversity can be rapidly destroyed, as demonstrated by the major loss of fish community structure in Lake Victoria. This illustrates the important point that lake ecosystems are very resilient when faced with stresses that have existed over evolutionary-time scales but they are extremely vulnerable to "new" stresses (usually anthropogenic) that the ecosystem has never faced before.

Finally, and most importantly for management, once a lake is degraded, it takes a very long time-if ever-to put things right. The implication is that before a decision is taken that adversely affects a lake, one must be really sure that is a wise course to take because turning back the clock is very hard, very costly, and often, just plain impossible. The loss of fish species in Lake Victoria is a clear example; the long-term release of toxic chemicals from sediment is another. Thus, the long retention time of lakes leads to lags in response that makes them poorly matched to the human management timescale.

Complex Dynamics

In addition to long retention time, lakes are complex systems: what you put into a lake is not necessarily what you get out. And what you get out depends on how much was put in, when, and in what order. This complex response is termed "hysteresis" and is illustrated in Figure 2.1.

Imagine a relatively pristine (oligotrophic) shallow lake lying at point A in Figure 2.1. Nutrient concentration is quite low, so the concentration of plankton living in the lake (an indicator of trophic state) is also low-there is not enough food to go around. As human population around the lake grows and as incomes increase, nutrient loading to the lake (and therefore concentration in the lake) inevitably increases, but the plankton concentration increases only slightly (to point B), reflecting the ecosystem's natural capacity to absorb external influences and neutralize them. Then, with only a slight additional increase in loading, the lake ecosystem changes dramatically, with a sudden increase in plankton density-often exhibited as an algal bloom (point C). The algal bloom is an easy-to-see sign that something is going wrong in the lake and that uses are being impaired; consequently, local people call on politicians to implement policies to decrease nutrient loading.

Reducing the nutrient load requires changes in human behavior-that requires political will-and like most things political, it only lasts until the next election. The difficulty for a decision maker is that the lake cannot simply go from C back to B. There are likely to have been irreversible changes to the ecosystem (in this case, phytoplankton have replaced macrophytes as the dominant species), so the path is usually from C to something like D. That means sacrifice over a long period without much to show for it, i.e. plankton concentrations are still high; blooms are still occurring. That is a tough road for a decision-maker to walk. The chapter on Information in these materials talks about the role of information and illustrates how science can be used to find where a lake lies on the graph (between A and D). Science can also offer shorter paths from C back to A through things like biomanipulation and in-lake restoration methods.

Figure 2.1. An example of complex dynamics of a lake.
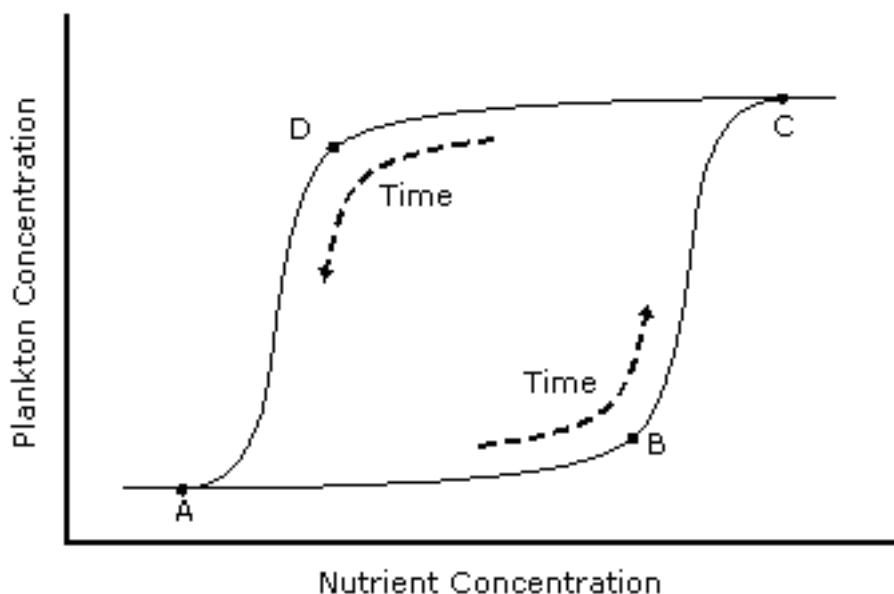
The complex nature of lake ecosystems also gives rise to various indirect effects such as biomagnification. Biomagnification refers to the increase in concentration ("magnification") of certain compounds in organisms ("bio") as one goes up the food chain (i.e., as organisms at lower positions in the food chain are eaten by organisms at higher positions in the chain). Compounds such as PCBs and dioxins are extremely soluble in fat (lipophilic) and therefore remain in the bodies of organisms that consume them. Those organisms may get eaten, indirectly transferring the lipophilic compound to the predator. The Laurentian Great

Lakes provide a good example of this phenomenon (See Table 2.1). As shown in the table, the concentration of PCBs increases up the food chain. This implies that organisms higher up the food chain (including humans) are exposed to higher concentrations and therefore are at higher risk.

Note that for a decision maker and any one eating Lake Trout (or Herring Gull Eggs!), this is a real problem. It is ironic that while the lake's complex food chain makes existence of valuable fish like the Lake Trout possible, the same complexity leads to indirect effects like biomagnification that may make the fish dangerous to eat.

Integrated Nature

Lakes integrate; they are the mixing pots of nature. They receive inputs from their catchments (and beyond), mix the inputs together, transform them and spread them out again. Additionally, fish, water and even pollution are able to move around more or less freely in all directions. This property-integrated nature-is the third key characteristic of lakes.

One important implication of integrated nature is that a problem at a lake is shared by most users. Rivers provide a simple counter-example: pollution at one point in a river immediately flows downstream, often leading to a disconnection between those causing the pollution and those affected by it. This can result in upstream-downstream conflict. The integrated nature of lakes means that one user's effect on another is spatially spread out and shared, including by the original user. This is very similar to global warming: the effects of one person's emission of greenhouse gases are felt by all, including the emitter.

Another implication of integrated nature is that most uses of lakes are "non-excludable"; that is, it is costly to exclude users from accessing a given lake resource. As Chapter 3 describes, when access to resources is costly to control, open access is the default regime. This is not desirable because open access, combined with human behavior, often leads to overuse and destruction of the resource base.

Table 2.1. Biomagnification of PCBs in the Laurentian Great Lakes

Organism	PCB concentration (relative to conc. in phytoplankton)
Humans	?
Herring Gull Eggs	4960
Lake Trout (a large fish)	193
Smelt (a small fish)	47
Zooplankton	5
Phytoplankton	1

(Adapted from USEPA and Government of Canada, 1995)

It is important to note that this physical property of lakes-integrating nature-profoundly affects a social issue-how the use of lake resources is managed.

Overall, these three defining characteristics-long retention time, complex dynamics, and integrating nature-when taken together, make lakes what they are: beautiful, valuable, complex, but also vulnerable and difficult to manage.

Lakes and Their Basins

Water somehow gets into a lake. In some cases, like Lake Victoria-a large, relatively shallow great lake-most of the water enters as direct precipitation. For most lakes, however, the large majority of water enters as precipitation runoff from surrounding land. For decision makers, what is happening on that surrounding land is tremendously important because it has profound effects on the lake itself. Therefore, it is widely recognized today that lake management cannot stop at the lakeshore but must extend to the surrounding land, and even beyond in cases where atmospheric transport is important.

The problem is finding a common term for that surrounding land. Nowadays, several terms are used almost interchangeably. The first is "catchment". The meaning is intuitive-the catchment is the area around a lake that "catches" precipitation, which then drains to the lake (noting of course evaporation, evapotranspiration, seepage to groundwater, etc. that occur along the way). A similar term is "drainage basin", which maintains the intuitive flavor of "catchment"-namely, it is the area from which water "drains" to the lake. "Watershed" used to mean the boundary between two catchments (or drainage basins!) but has become synonymous with the catchment itself, not just the infinitely thin dividing line around the edge of the catchment. "Basin" literally is like a wash basin-the area covered only by water-in this case, the lake itself. However, this use of the term is not common among policy makers and "basin" too has come to be simple shorthand for "drainage basin". Finally, "lake basin" is a drainage basin with a lake in it. Naturally there are catchments, drainage basins and watershed without lakes in them; lake basins must have a lake to live up to their name!

The concept of the linkage between a lake and its surrounding drainage basin is of fundamental importance in lake management. Problems with lakes can originate within the lake itself (such as over-fishing), be transmitted to the lake from its upstream drainage basin (such as agri-chemicals from irrigation areas), or in a few cases come from outside the drainage basin (such as acid rain). Use of the lake's resources can also impact on downstream communities. Thus, recognition of this fundamental interrelation between the lake and its upstream and downstream drainage basin is an essential part of effective lake management efforts.

Basin Types

Because the basin is so important, it is a good idea to consider the various types of basins that are commonly encountered. Categorizing lake basins by their water balance, that is, how water gets into and out of the lake, is one helpful way. Scientists distinguish between open and closed lake basins, or those that have rivers draining the lake and those that do not. The categorization in Figure 2.2 builds on and extends this simple dichotomy to account for the diversity of basin types in the 28 lakes covered in the LBMI project.

Other Features with Implications for Management

In addition to the type of basin a lake is in, there are several other factors that determine the character of the lake being considered. These factors include: the origin and age, the climate of the lake basin, the salinity of the water, and the mixing and stratification in the lake.

Origin/Age

Of the over 5 million lakes currently existing on the earth's surface, about 75 percent of the were formed as a result of the last ice age, which ended around 10,000 years ago.

Figure 2.2 Categorization of Lake Basin Types.

 North American Great Lakes Basin	**Surface Drainage Basin**-An open basin with surface water outlet(s). Water leaves the lake by one or more rivers, allowing ions (components of salinity) to be flushed. Thus, the water remains fresh. Many of the lakes in this report are in open drainage basins, with rivers being the major water outflow. Water also leaves this type of lake via evaporation and groundwater, but those components are relatively minor compared with river outflows. Examples are Lakes Baikal, Biwa, Constance, Dianchi, the North American Great Lakes, Peipsi/Chudskoe, Toba, and Xingkai/Khanka.
 Lake Naivasha Basin	**Subsurface Drainage Basin**-An open basin with a significant subsurface inlet/outlet(s). Many lakes have no surface river discharge, yet remain fresh due to substantial flow of water (and salt) via groundwater. Lake Naivasha in Kenya is an excellent illustration of a lake dominated by groundwater flow. Lake Ohrid is an interesting case where much inflow to the lake comes from groundwater from a different surface lake basin. Examples include Lakes Baringo, Chad, Naivasha, and lakes feeding Lake Ohrid.
 Lake Malawi Basin	**Transitional Drainage Basin**-A basin with some surface or subsurface outflow but with significant evaporation. This type of lake occurs mainly in low latitude, and arid/semi-arid areas where solar radiation-and hence evaporation-is strong. Small changes in climate or human use can switch a transition basin lake between open and closed states. Greater relative dependence on direct precipitation and evaporation makes these lakes more sensitive to atmospheric inputs than other open basins of equal area. The Lake Malawi/Nyasa Basin has a discharge in the south that sometimes fails to flow, sometimes making it a closed basin. Examples include Cocibolca, Malawi, Sevan, Tanganyika, Titicaca, and Victoria.

Figure 2.2 Categorization of Lake Basin Types (Cont'd).

Lake Nakuru Basin	**Closed Drainage Basin**-A terminal basin with neither significant surface nor subsurface outflow. Water leaves the lake only through evaporation, which generally leads to higher salinity (total ionic concentration). Thus, most lakes in closed basins are either saline (total ionic concentration >3 g/L) or are becoming so. Examples of closed basin lakes include the Aral Sea, Issyk-kul, and Nakuru.
Chilika Lagoon Basin	**Coastal Drainage Basin**-A drainage basin with flows to and from the ocean. Freshwater typically enters the lake through rivers draining to it. The lake periodically/seasonally drains to the ocean; sometimes the ocean drains to the lake. This can lead to a complex and seasonally dependent salinity gradient that is important for the biota. Examples include Chilika Lagoon and, to a lesser extent, Laguna de Bay.
Tonle Sap Basin	**Mixed Flow Drainage Basin**-A drainage basin with inflowing rivers that reverse direction depending on the season. In contrast to a coastal lake, the flows come from a freshwater river. This reversal of flow leads to large fluctuations in lake water level and area. These lakes commonly occur in internal deltas. Tonle Sap is a prime example of this type. For this type of basin, the size of the lake's drainage basin is seasonal, since the connecting river inflow is seasonal.
Tucurui Reservoir Basin	**Reservoir Basin**-A drainage basin with a dammed river. In many areas where geology and climate do not favor the formation of natural lakes, reservoirs are constructed, although the reasons for construction are quite diverse and often contentious. Reservoirs tend to have large basin-to-lake area ratios and often have a highly dendritic shape: both of these characteristics are illustrated in the two figures to the left for the Tucurui Reservoir and its extensive basin. The transition from river to lake environments within the reservoir proper is gradual and progresses with proximity to the dam. Examples include the Bhoj Wetland, and the Kariba and Tucurui Reservoirs.

Coastal lakes are even more recent, having been formed when sea levels stabilized around 6,000 years ago. Tectonic lakes range greatly in age, but tend to be very old. The oldest, Lake Baikal which lies in a tectonic rift in Siberia, is thought to be over 20 million years old. The Great Rift Valley of Africa contains similarly old and deep lakes such as Lakes Malawi/Nyasa and Tanganyika. Eight of the world's 15 ancient lakes (greater than two million years old) are included in this study.

A lake's origin has great implications for its characteristics. For example, coastal lagoons are naturally susceptible to siltation, as they usually lie at the end of large riverine catchments. They go through an aging process in which they gradually fill in with silt, become more-and-more closed off from the sea, and lower in salinity. On the other hand, tectonic lakes tend to be deeper and older, and therefore have longer retention times. They are more likely to contain endemic species with significant biodiversity value.

Climate

Solar energy input affects the quantity and seasonality of flows into a lake, the thermal properties of the lake, and biological processes in the lake. Climate is typically classified using the Köppen climate system, which recognizes six major climatic types-polar, cooler humid, warmer humid, dry, tropical humid, and highland-each of which can be further subdivided.

The 28 lake basin covered in the LBMI project displayed a wide range of climate types. Most were in tropical (10) or subtropical (5) climates, which are characterized by abundant rainfall and strong solar radiation. A further six lakes were in arid or semi-arid regions (areas with between 25-200 mm and 200-500 mm annual rainfall respectively). Many of these arid and semi-arid regions are low in latitude and therefore subject to strong solar radiation and high evaporation. The majority of the world's saline lakes occur in closed drainage basins in arid and semi-arid regions (Williams 1998). Lake Titicaca occupies a unique position as a high-elevation, tropical lake. The remaining six lakes are located in temperate regions.

Shallow lakes are particularly sensitive to climatic variation. For example, Lake Nakuru has little buffering capacity to withstand both intra-seasonal and inter-seasonal climate variability because of its shallow depth, high evaporation rates, and seasonal inflowing rivers. The first peak flow occurs in May (a month after peak rainfall), while the second peak coincides with rain in the month of August. The Lake Nakuru basin is a closed basin so only evaporation accounts for water loss from the lake. Consequently, long drought periods, such as 1993 to 1996, have resulted in excessive lake-level decline.

Salinity

A very common but unfortunate assumption is that unless a lake contains freshwater, it is useless to people. As a direct source of drinking water, this may be true, but saline lakes make up approximately half of the lakes in the world (by volume) and have wide-ranging values which often become apparent when they are lost.

Williams (1998) has defined saline waters as those with total ionic concentrations greater than 3 g/L. Waters less saline than this are considered fresh. When water evaporates, most of the ions remain behind. When evaporation is the dominant way for water to leave a lake, there is a gradual increase in the lake's salinity. All three saline lakes in the LBMI survey-the Aral Sea, Lake Nakuru, and Issyk-kul-occur in closed basins (the fourth saline waterbody is the coastal Chilika Lagoon).

The study lakes cover the spectrum of salinity from freshwater to hyper-saline lakes. The salinity of a lake is of utmost importance to the biota, and consequently to human users. The Aral Sea was once a moderately saline water body, but due to upstream diversions of rivers, the lake's water balance has become dominated by evaporation and its salinity has dramatically increased, leading to the complete loss of the fishery. However, increasing salinity can be beneficial. The Chilika Lagoon shows how a reduction in inflow of saline (ocean) water led to a drop in salinity that led to a decline in fish that were attuned to the saline ecosystem. Lake Nakuru, a sodic lake in the Kenyan portion of the Rift Valley, provides an example of where extreme salinity is the basis of the lake's most important and unique values.

Mixing/Stratification

Water movement in lakes is multidirectional and complex. For many lakes, there can be periods when the lake stratifies; this is, the upper water of a lake does not mix with the lower water. Effectively, the lake is separated into two waterbodies, one lying on top of the other. Stratification can be caused by warming of the upper waterbody through solar radiation, or by differences in salinity between upper and lower waters. Strong stratification-that is, large temperature differences between upper and lower waters-occurs particularly in tropical lakes.

The principal consequence of stratification is that the bottom waters become disconnected from the atmosphere and do not receive a regular supply of fresh oxygen. Oxygen levels drop in these waters as various biological processes use up the existing oxygen. Fish and many other biota cannot live in these oxygen-depleted waters. Undesirable chemical reactions can occur that lead to pollutants, such as methane and phosphorus, being released from the bottom sediments.

Stratification and mixing can occur in various patterns including monomictic (mixing once a year), dimictic (twice a year), polymictic (many times a year), and meromictic (continuously stratified). Mono- and dimictic lakes are usually found in temperate regions where the seasonality of solar radiation is most pronounced. Shallow lakes tend to be well-mixed (polymictic) year round, with only brief periods of stratification. Some lakes, such as Lakes Malawi and Tanganyika, are permanently stratified because no force can supply the energy needed to mix the huge volumes of water in these very deep lakes. Any material that sinks into the lower layer of these lakes is virtually gone forever.

Further Reading

1. Aladin on "Biodiversity loss in a saline lake ecosystem: Effects of introduced species and salinization in the Aral Sea" gives a good overview of biodiversity and how exotic species introductions can affect it. The paper also discusses how very far upstream management decisions (to divert water) can affect the biodiversity of a far away lake.

2. Kodarkar on "Implementing the ecosystem approach to preserve the ecological integrity of urban lakes: The case of Lake Hussainsagar, Hyderabad, India" provides a much more detailed look at the "ecosystem approach" which is consistent but slightly different than the ILBM approach discussed in these materials.

3. Magadza on "Eutrophication and Pathogenic Contamination of Lake Chivero: Lessons for Sustaining Technological Interventions in Lake Basin Management" shows just how complex dymanics of a lake can be, and unfortunately how a lake can go through cycles of degradation, improvement, and degradation again.

4. Tapas covers the much smaller but much more common type of lakes seen in Bangladesh called haors, baors, and beels. This provides an interesting contrast to the generally large lakes covered in this chapter and in most of this training material.