UNIT ONE

INTRODUCTION TO THE AQUATIC ENVIRONMENT

Distribution and Availability

The salty oceans (situated between continents), & other inland water bodies, (situated within continents) together with atmospheric and geospheric water, constitute the water system of the earth. The distinction between oceans & continental water bodies leads to the 2 main disciplines of aquatic ecology – *oceanography* and *limnology*.

Thus, *oceanography* is the scientific study of aquatic systems between continents while *limnology* is the scientific study of aquatic systems within continental boundaries (both fresh & salt water). So, *aquatic ecology* is the scientific study of the physico-chemical, geological, & biological factors that affect aquatic organisms in oceans & inland waters.

Although the global ocean forms a single continuous water body, it has been divided into 3 major types by international agreement viz, *Atlantic*, *Pacific*, and *Indian* oceans. Others provide more divisions for the oceans. Inland waters are many & of varied types, origin, & located in the various continents. It includes *lakes* (fresh & saline), *pools*, *ponds*, *reservoirs*, *streams*, *rivers*, *palustrine wetlands* (marshes, swamps**,** bogs, fens, etc), *estuaries* (of variable salinity), *underground water*, etc. But they are often broadly be divided into 2 namely, lentic (standing) & lotic (running) waters.

Lentic water refers to standing waters such as lakes, marshes, & other enclosed water bodies that are not oceanic & in which the flow is primarily imposed or caused by wind & heat & is not unidirectional. Shallow lentic water bodies, the bottom of which may be everywhere colonized by plants, are called *pools* or – if they have an artificial outlet – *ponds*. In addition, cavities in plants can sometimes become filled with water albeit on a temporary or seasonal basis & are called *phytotelmata*.

Lotic water on the other hand, refers to running waters or primarily unidirectional flowing water systems e.g. streams, rivers, estuaries, etc imposed by gravity that are also not oceanic in nature i.e. the flow of water is directed. Unlike a lentic water body, it is organized horizontally & all the factors in it change from the source downstream. Globally, rivers constitute less than 2 % of the water held in freshwater lakes (& lentic systems are estimated to contain about 100 times more water than lotic ones). Rivers plus their bothering wetlands & linked aquifers, are home to extensive biota & are also major source of water for irrigation, agriculture, industry, human consumption, & water purification.

The ocean contain over 97 % of the earth's water. The remaining is mostly fresh water (Table 1.1).

Table 1.1: Water Distribution on Earth

Site	Contribution (%)
Ocean	97.1
Glaciers & ice caps	2.24
Groundwater	0.61
All lakes	0.016
Atmospheric moisture	0.001
Rivers	0.0001

Below are some physical features of the oceans:

- Of the earth's surface, 71 % is covered by the oceans (361 x 10^6 km^2);
- The deepest oceanic trench is 11,022 m (Mariana); the highest mountain is 8848 m (Mountain Everest);
- The southern hemisphere has the largest % of water (80.9 %) in the oceans;
- The world's oceans are made up of 50% Pacific, 29% Atlantic, & 21% Indian oceans by volume;
- The major depth zones of the ocean (78%) lies between 3 & 6 km;
- Of ocean waters, 50% have a temperature range between 1.3 – 3.8, salinity (grammes of salt in 1 kg seawater) between 34.6 & 34.8 $^{o}/_{oo}$;
- The mean depth of the oceans is 3.7 km; the mean temperature is 3.5˚C and the mean salinity is 34.7 $^{o}/_{oo}$ (often approximated to 35 $^{o}/_{oo}$)

Though only about 3% of the earth's continental land surface is covered by water, this aqueous component is clearly vital to aquatic & terrestrial life including humans. The salinity of inland water systems range from about 0.5 $^{o}/_{oo}$ (freshwaters) or more (some even greater than 340 $^{o}/_{oo}$). Of these inland waters, freshwater bodies are even more important because the salty ocean waters & its inland water equivalents are unsuitable not only for humans but many other organisms. It is also not suitable for irrigation as well as most industrial purposes. Besides, most of this fresh water is locked up in the great polar ice caps or glaciers or in groundwater too deep or salty to be used (Table 1.1). It should also be noted that some inland waters especially some lakes are salty & not fresh. For instance, the Great Salt Lake in Utah (salinity range from 50 - 270 $^{o}/_{oo}$) & the Dead Sea in Israel (salinity greater than 340 $^{o}/_{oo}$) have very high salinities. However, with a salinity of over 400 $^{o}/_{oo}$, Don Juan pond, situated in Antarctic, is significantly saltier than most other hypersaline lakes around the world & its saltiness keeps it from freezing even in Antarctic winter. In fact, saline lakes contribute half of the water volume of inland lakes while freshwater lakes also contribute the remaining half.

Note on saline lakes:

There are 2 types of salt lakes – those that do not originate from the sea & have a chemistry dominated by salts derived from Ca, Mg, & sulphate are referred to as *athalassohaline lakes* & those that are relics of the sea e.g. the Caspian Sea have Na & chloride as major ions – and are referred to as *thalassohaline lakes*. The economic importance of saline lakes is relatively small because the water is too salty for drinking, or irrigation, but their precipitated salts are sometimes extracted. In addition saline lakes are scientifically important not only because they contain unusual species but also because they form one end of a salinity spectrum important to resolving how community structure & functioning changes systematically along salinity gradients. They further serve as models for predicting the effects of increasing salinization in rivers draining vast areas of poorly irrigated semi-arid land & projected impacts of increased evaporation during global warming.

The concept of salinity is so important that aquatic ecologists have develop a nomenclature for water bodies based on it (Table 1.2).

Table 1.2 Nomenclature of water bodies of different salinities

	Salinity (ppt)	Nomenclature
1	0.0 – 0.5	Freshwater
2	0.5 – 3.0	Oligohaline brackish water
3	3.0 – 10.0	Mesohaline brackish water
4	10.0 – 17.0	Polyhaline brackish water
5	17.0 – 30.0	Oligohaline sea water
6	30.0 – 34.0	Mesohaline sea water
7	34.0 – 38	Polyhaline sea water
8	> 38.0	Brine

While Lake Superior (USA) has by far the largest surface area among freshwater lakes, the depth of the 2nd largest lake in terms of surface area (Lake Baikal, Russia) is so much greater that it holds much larger volume of water. Lake Baikal contributes about 20% of all the surface freshwater world-wide. Together, lakes Baikal, Superior, & Tanganyika (East Africa) contain nearly half (44%) of the entire surface freshwater in the world.

Additionally, about half of lake water is *brackish* (i.e. of variable salinity) & cannot be drunk by most animals. It has salinity values that lie between that of ocean & freshwater.

Moreover, though rivers & lakes constitute a small proportion of the world's fresh water (Table 1.1), they are the major sites of irresponsible waste disposal & fishing activities. They are also used for irrigation as well as a source of drinking water supply, etc. It is assumed that if the world's water supply were only about 100 litres (26 gallons), our usable supply of freshwater would be only about 0.014 litres (2.5 teaspoons). Because of the small % of fresh water, the increasing human population, & overconsumption as well as increased pollution, many people in many parts of the world experience *water stress* i.e. episodic lack of renewable fresh water supply or the more serious condition of *water scarcity* i.e. the chronic lack of renewable freshwater supply every year.

Four causes of water scarcity are noted:

1. A *dry climate* – have 10-30 cm of rain per annum (arid climates) and enough to support extensive grasslands;
2. *Drought* – a period of 21 days or longer in which precipitation is at least 70 % lower & evaporation is higher than normal;
3. *Desiccation* – drying of the soil because of activities like deforestation & overgrazing by livestock; &
4. *Water stress* – low per capita availability of water caused by increasing number of people relying on limited runoff levels.

NB: Social scientists have also introduced the term *water deprivation* – the inability to reliably obtain water of adequate quantity & quality to sustain life & livelihood – as a basic index of poverty.

Furthermore, freshwaters are not evenly distributed globally & differences in the average annual precipitation divide the world's countries into *water haves* & *water have-nots* e.g., Canada with only about 0.5 % of the world's population has 20 % of the world's freshwater, whereas China with over 21 % of world's population has only 7 %.

Life zones

Aquatic life zones are the ocean water & inland water (fresh & saline) portions of the earth's hydrosphere that can support life (its ecosphere). They are the aquatic equivalents of terrestrial biomes.

Life in the aquatic environment has numerous potential advantages over terrestrial existence. These *advantages* include:

- Physical support (buoyancy) compared to air in the terrestrial environment
- Accessibility of three-dimensional space
- Passive movement by water currents
- Dispersal of motile gametes in a liquid medium
- Minimal loss of water (freshwaters)
- Lower extremes of temperature & solar radiation
- Ready availability of soluble organic and inorganic nutrients, etc

But there are also potential *disadvantages* in aquatic environments such as:

- Osmotic differences between the organism & the surrounding medium (leading to endosmosis or exosmosis)
- High degree of physical disturbance in many aquatic systems
- In undisturbed aquatic systems like lakes, photosynthetic organisms have to maintain their position at the top of the water column for light availability
- In many water bodies (e.g. lake water column, etc), physical & chemical parameters show a continuum – with few microhabitats leading to species competition in relation to different reproductive & growth strategies, etc.

It should be noted however, that in aquatic environments, distribution of organisms is largely dependent on the water's salinity i.e. the amount of salts dissolved in a given volume of it. Hence, aquatic life zones are classified into 2 major types as have been noted based on salinity viz;

- Salt/ocean water life zones also called marine life zone –
  - Shallow ocean waters (coastlines),
  - Open ocean waters,
  - Deep ocean waters,
  - Estuaries,
  - Coastal wetlands,
  - Coral reefs,
  - Mangrove swamps,
  - Barrier islands, etc
- Inland water life zones of;
  - Freshwaters
    - Lakes
      - Fresh
      - Salty (thahassohaline and athahassohaline

- Rivers and Streams
- Reservoirs

○ Inland wetlands, etc

These life zones have distinct geological & morphological structures & with several types of organisms (Fig. 1.1 & 1.2). These major organisms include:

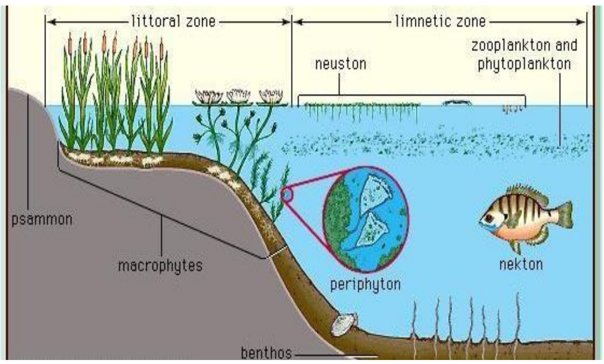


Fig. 1.1 Lake water life zone structure & associated organisms

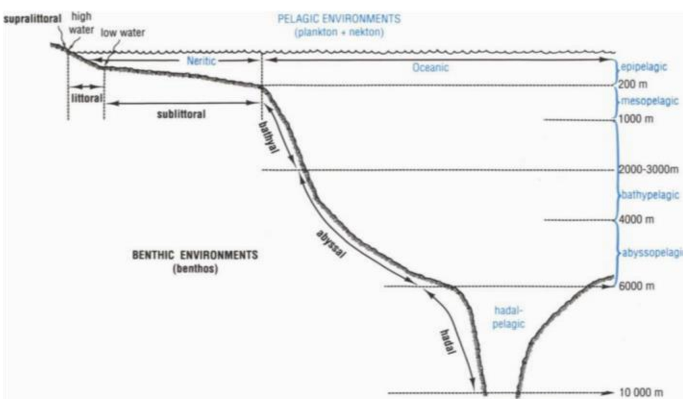


Fig. 1.2Life zones of the ocean environment

1. *Plankton*: free-floating, weakly swimming microscopic organisms whose natural rate of movement is usually smaller than the strength of the current in a water body. Their movement is at the mercy of the water body. They range in cellular complexity from prokaryotes to eukaryotes. They also occur in different size categories:

- < 0.2 µm (femtoplankton)
- 0.2-2 µm (picoplankton)
- 2-20 µm (nanoplankton)
- 20-200 µm (microplankton)
- >200 µm (macroplankton)

Specifically, plankton includes:

- Virioplankton (viral plankton)
- Bacterioplankton (bacterial plankton)
- Phytoplankton (algal plankton)
- Zooplankton (animal plankton)
- Mycoplankton (fungal plankton)

<u>**NB**</u>: *Saproplankton* is the bacterial & fungal portions of plankton.

2. *Nekton*: These are strongly swimming macroscopic organisms whose natural rate of movement is normally greater than the current strength in the water body e.g. fish, turtles, whales, etc. They can swim against currents.

3. *Benthos*: These consist of bottomdwellers such as oysters & sea stars which anchor themselves to ocean bottom structures e.g., lobsters & crabs which walkabout on the sea floor (*epifuana*); & clams & worms which burrow into the sand or mud (*infauna*).

4. *Decomposers*: These consist of organisms (especially bacteria) which break down organic compounds in the dead bodies & wastes or aquatic organisms into nutrients that aquatic primary producers can use. They are not restricted to particular depth or water zone.

Benefits of Aquatic Ecosystems

Aquatic systems provide many ecological & economic services that serve the needs of human societies directly or indirectly.

Ecological services provided include:

- Climate moderation
- CO_2 absorption
- Nutrient cycling

- Waste treatment
- Reduced storm impact (mangroves, barrier islands, coastal wetlands)
- Habitats & nursery areas
- Genetic resources & biodiversity
- Scientific information,
- Flood control,
- Ground water recharge, etc

Some of the *economic services* provided include:

- Food
- Animal & pet feed
- Pharmaceutical products
- Harbours & transportation routes
- Coastal habitats for humans
- Recreation
- Employment
- Oil and gas resources
- Mineral resources
- Building materials,
- Drinking water,
- Water for irrigation,
- Hydroelectricity production, etc

However, human activities are seriously affecting aquatic systems due mostly to population growth, overconsumption of resources, & technologies that directly increases per capita production & consumption & indirectly by encouraging the growth of population & urbanization with its attendant pollution problems. The concept of economic growth involving the combine effects of population growth overconsumption of water resources, per capita water resources overconsumption in affluent societies, & the development of technologies for production that increase the adverse effects on water resources & other finite resources has been termed *demophora*.

Specific major threats to the ecological & economic services provided by *oceans* include:

- Coastal development which destroys & pollutes coastal habitats;
- Runoff of non-point sources of pollutants like silt, fertilizers, pesticides, heavy metals, & livestock wastes;
- Point source pollution such as sewage from cruise ships & spills from oil tankers, heavy metals from surface mining;
- Pollution & degradation of coastal wetlands & estuaries;
- Overfishing which depletes populations of commercial fishes;
- Use of fishing trawlers, which drag weighted nets across the ocean bottom, degrading & destroying these habitats;
- Invasive species, introduced by humans, that can decrease populations of native aquatic species & cause economic damage;
- Climate change, enhanced by human activities, which is warming the oceans & making them more acidic. This can cause a rise in sea levels that would destroy coral reefs & flood coastal marshes & cities, etc.

Specific major threats to the ecological & economic services provided by *freshwaters* include:

- Dams & canals fragment huge portions of the world's largest rivers & destroy terrestrial & aquatic wildlife habitats along these rivers and in their coastal *deltas* & estuaries by reducing water flow & increasing damage from coastal storms;

- Flood control levees & dikes built along rivers disconnect the rivers from their *flood plains*, destroy aquatic habitats, & alter or reduce the functions of nearby wetlands;
- Cities and farms add pollutants & excess plant nutrients to nearby streams, rivers & lakes. For instance, runoff of nutrients into lakes – a process call *cultural eutrophication* – causes explosions in the populations of algae & cyanobacteria, which depletes the lakes oxygen. When these organisms die and sink to the lake bottom, decomposers work on them & further decrease the oxygen in deeper waters. Fishes & other species may then die off which causes a major biodiversity & economic loss;
- Many inland wetlands have been drained or filled to grow crops or have been covered with concrete, asphalt, & buildings, etc. Many wetlands are lost due to crop production & others are lost to mining, logging, oil & gas extraction, highway construction, & urban development.

Some Properties of Water – the Medium of Aquatic Systems

Water is the most common substances on earth & yet it is uncommon in many of its properties. It is a unique liquid. It makes life possible & to a very large extent, its properties determine the characteristics of the oceans & other inland water bodies, the atmosphere, & the land (geosphere). Many of the aquatic system's major features are due to the unique set of physical & chemical properties of water, including its dissolving power, high specific heat capacity, transparency, & heat of vaporization, etc. In order to understand these aquatic systems, it is necessary to examine water as a substance & to learn something of its physical & chemical characteristics.

Compared with other compounds of similar shape & molecular weight such as H_2S, NH_3, or HF, etc water exhibits anomalous behaviour. If water behaved at normal environmental temperatures as do similar compounds, it would be present only as vapour. But it is one of the two inorganic liquids (together with Hg) that can exist at the Earth's surface under ambient temperature & pressure as a liquid.

Water's Dissolving Power & its Crystal Lattice Structure

Many of water's unique properties stems from its molecular structure. Oxygen is highly electronegative & in water shares its outer shell valence electrons with its two associated hydrogen atoms. This polar covalent chemical bonding has electrons skewed in the direction of the strongly negative oxygen atom resulting in a slight negative charge on the oxygen atom & slight positive charge on the hydrogen atoms i.e. water molecule is dipolar (Fig. 1.3).

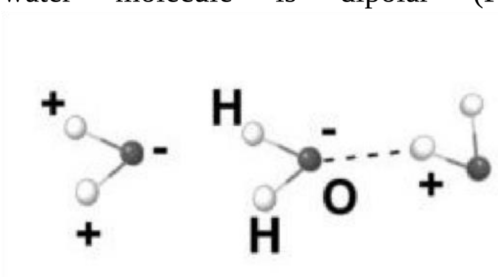


Fig. 1.3 The polarity of water molecule

The dipolar nature of water makes it an excellent solvent for the dissolution & transport of all kinds of substances like solids (e.g., salt crystals, etc), liquids & gases from land catchments & the atmosphere to aquatic systems & so the aquatic systems contain a diversity of dissolved substances. That is why water is called a *universal solvent*.

Water molecules in contact with a salt crystal orient themselves to neutralize or reduce the attractive forces between the positively & negatively charged ions in the crystal structure of the salt. The liberated ions are then hydrated by the water molecules, preventing their recombination & recrystallization. Were it not for this solubility of essential nutrient salts in water, plants would not be able to take up nutrients, & animals would not be able to take up dissolved compounds & their tissues would be unable to release wastes.

The charge asymmetry in water molecules allows the oxygen molecule to form a weak H-bond with the oppositely charged hydrogen atom of the adjacent water molecule (Fig. 1.4).

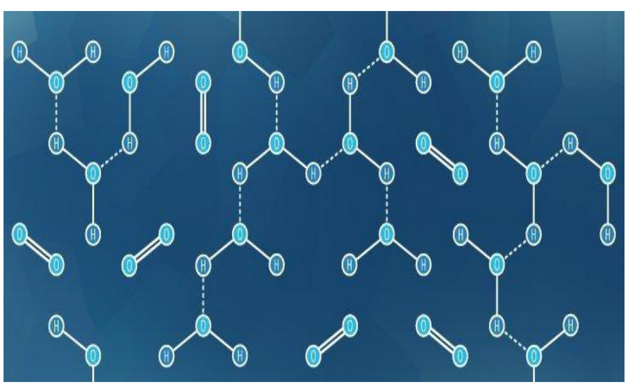


Fig. 1.4 H-bonding between water molecules

Each water molecule can establish H-bonding with 4 other water molecules. The H-bond is weak & contains just over 6 % the energy of a normal covalent bond but is more flexible because as one H-bond is broken, another is formed. As a result, the water molecules cling together.

In a true fluid, individual molecules move freely. This is not true for water which consists of a continuous network of randomly connected H-bonds that form a *liquid crystal*. The liquid crystal structure of water provides a continuous network of H-bonds running in all directions throughout its volume. Thus because of H-bonding between the water molecules, it takes a great deal of energy to separate water molecules from the water surface to form vapour or to separate water molecules from rigid ice, melting it to water. This interlinking of water molecules is responsible for many of the unique properties of water such as a *high melting* & *boiling points* relative to similar compounds.

Thermal conductivity & Heat Capacity

Water has low *thermal conductivity* which results in a relatively slow response to changes in air temperature. Again, water has a high *specific heat capacity* i.e. the amount of heat needed to raise or lower the temperature of 1 g of a particular substance by 1°C. The specific heat capacity of water is defined as unity because it takes 1 cal to heat 1 g of water by 1 °C (Table 1.2).

Table 1.2 Heat Capacities of selected materials

Material	**Heat capacity (cal/g/°C)**
Water	1.00
Mercury	0.03
Acetone	0.51
Wood	0.42
Sand	0.18

Thus, relative to most other liquids and solids such as soils, it takes a great deal of heat to change the temperature of water bodies especially the oceans. Ocean water can store large amounts of heat, and moving currents can transport large amounts of heat, along with the water itself. The high specific heat capacity & low thermal conductivity of water allows it to absorb large amounts of heat with only a small temperature increase i.e. it buffers or moderates temperature extremes. This enables aquatic organisms to survive even the intense solar radiation at the equator, which results in only a small increase in ocean water temperature. This also results in localized surface heating and stratification in standing waters. Also, because water stores a lot of heat per unit volume, large volumes of water in oceans can alter the surrounding coastline climate of a water body that receives oceanic breezes.

Density of Water

Another property of water is its density i.e. its mass per unit volume often measured in g/cm^3. The density of water is affected by temperature, salt concentration, & pressure.

The rate of change of water density is not constant with changes in temperature (Fig. 1.5).

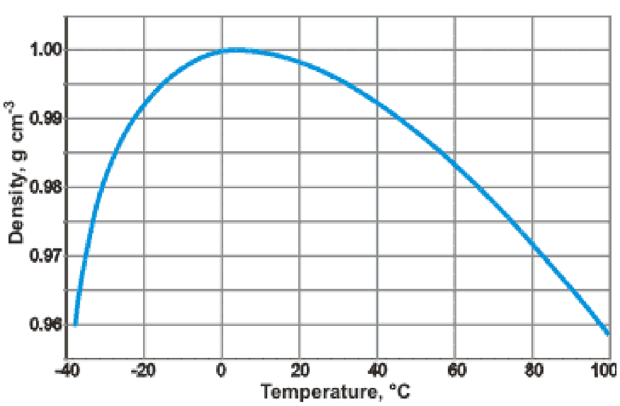


Fig. 1.5 Water density and temperature

Density decreases more rapidly at higher water temperatures (Fig. 1.5).

The relationship between temperature, T (°C) & density, D (g/ml) can be estimated from the equation;

$$D = 1\text{-}6.63 \times 10^{-6} (T\text{-}4)^2$$

Dissolved salts also influence water density i.e. the higher the dissolved salt concentration, the higher the density of water. Thus, we have *salinity-induced density* & *temperature-induced density* effects respectively. But, salinity-induced density effects, dominate over temperature-induced density effects in estuaries & oceans. But often, water density is affected by a combination of both factors.

For instance, the density of pure water at 4 °C is 1.000 mg cm^{-3} or 1 mg ml^{-1}. But, when the salinity changes to that of normal ocean water at 35 ‰, the density increases to 1.028 mg cm^{-3}. This decreases ocean water temperature of maximum density to -3.5 °C. Thus, <u>water's freezing point is lowered as its salinity increases</u>.

Density is also affected by pressure e.g., increasing pressure increases the density of water by reducing the volume occupied by a fixed mass of ocean water.

Density, Anomalous Expansion of Water & its Implication for Aquatic Organisms

Also, unlike most substances, water has an unusual behaviour when it freezes or melts. When water freezes it expands, so that the ice formed requires more volume than liquid water. On the other hand, when ice melts, the molecules are allowed to pack more tightly together. Hence the density of water increases between 0 & 4 °C with the maximum density occurring at 4 °C rather than at the freezing point of 0 °C. Thus, once a water body reaches 4 °C for instance, further cooling at the surface produces lighter water & eventually ice, leaving warmer, denser, water below.

The ice formed insulates the liquid water & prevents deeper lakes from freezing solid. This has important implications for the survival aquatic organisms in both oceans & inland waters.

Viscosity & Surface Tension

Other properties of water important in the study of aquatic systems include viscosity & surface tension.

Viscosity also called *dynamic viscosity* is a measure of a liquid's resistance to flow. It produces frictional resistance or viscous drag on organisms moving through water & tends to slow down the rate of sinking of plankton. It plays an important role in the shape of some aquatic organisms such as fish & insect larvae in streams. High viscosity also limits mixing of water in water bodies; sedimentation of particulate matter; and velocity of circulation.

Viscosity is higher at lower compared to higher temperatures. For instance, surface water at the equator is warmer & therefore less viscous than surface water in the Arctic.

Viscosity is also affected by salt concentration or salinity of the water. High salt concentrations increase viscosity & vice versa.

The ratio of dynamic viscosity to density is called *kinematic viscosity*. This determines how readily fluids flow, steepness of the velocity gradient around an object, & how easily adjacent water layers with different temperatures become turbulent.

Another property of water is *surface tension* – the property of liquids that gives their surfaces a slightly elastic quality or a measure of how difficult it is to break the surface of a liquid. Like viscosity, it results from cohesive H-bonding in water. It enables certain animals & plants to maintain their position in the water surface e.g., the water strider (an insect with long legs that walks on water with long legs and feeds on dead insects). Again, it helps in the accumulation of fine particulate or light-weight debris or material such as pollen at the water surface of lakes & the sea. Surface tension is affected by both temperature & salt concentration of water.

Dissolved salts in addition to increasing water density & viscosity, also increases surface tension. But, organic surfactants i.e. foaming or wetting agents produced by some aquatic plants & animals – act to reduce surface tension.

Pure water is also nearly incompressible & so are other water bodies. For instance, pressure in the oceans increases with depth e.g., every 10 m of depth pressure increases by about 1 atmosphere. Pressure in the deepest trenches such as the Mariana Trench, which is over 11,000 m, is about 1100 atmospheres. It is estimated that if water was truly incompressible, ocean water level would stand about 37 m higher than it does at present.

UNIT TWO

THE PHYSICAL STRUCTURE OF AQUATIC ECOSYSTEMS

Morphology & morphometric parameters

The structure of an aquatic system determines very important features of it. The *morphology* of an aquatic system refers to the study of its structure & form or the overall shape. The processes involved in measuring the morphology of an aquatic basin is called *morphometry*.

Early studies of some morphometric features of water bodies was quite challenging. For instance, depth measurements were initially done using a rope tied to a stone e.g. in an ocean or a deep lake. This was tedious because it could most of a day to lower & raise a weighted line. In modern times, the depth of the ocean is usually measured two ways: 1) using acoustic echo sounders on ships which bounce off the ocean floor to measure ocean depth or 2) using data from satellite altimeters which can take many bottom readings in a day.

a). *Echo Sounders*: Most maps of the ocean are based on measurements made by echo sounders. The instrument transmits a burst of sound & listens for the echo from the sea floor (Fig. 2.1). The time interval between transmission of the pulse & reception of the echo, when multiplied by the velocity of sound in water, gives twice the depth of the ocean. Depths measured by ship-based echo sounders have been used to produce maps of the sea floor.

Echo sounders make the most accurate (± 1%) measurements of ocean depth.

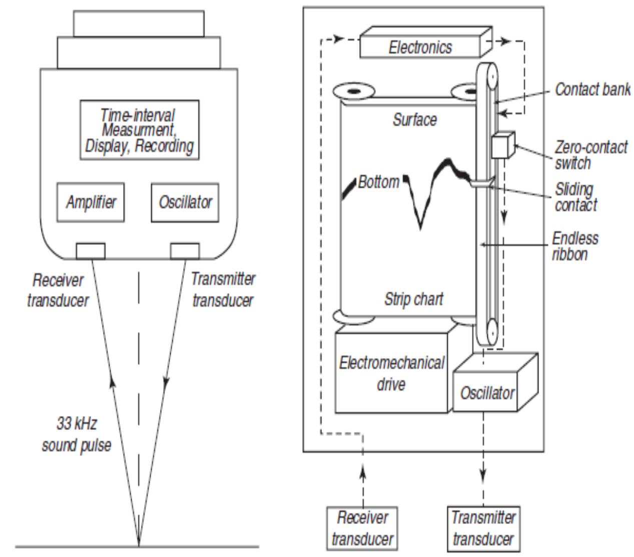


Fig. 2.1 Left: echo sounders measure depth of the ocean by transmitting the pulses of sound & observing the time required to receive the echo from the bottom. **Right**: The time is recorded by a spark burning a mark on a slowly moving role of paper.

b) *Satellite Altimetry*: The depths of the aquatic systems are also measured by satellite altimeter systems which profile the shape of these aquatic systems. The local shape of the surface is influenced by changes in gravity due to subsurface features. For e.g. recent maps based on satellite altimeter measurements of the shape of the sea surface combined with ship data have depth accuracy of ± 100 m.

Morphology of an aquatic system affects its *hydrology* which is the study of the properties, distribution, & circulation of water on, over, or through it. It includes the flow characteristics of the water in the aquatic basin itself.

Ocean Ecosystems

Oceanic & Continental Lithospheres

Studies have shown that the earth's surface is not a static arrangement of continents & ocean but a dynamic variety of jostling rocky or lithospheric plates (Fig. 2.2) divided into 2 types: *oceanic plate*, with a thin dense crust (density of 2.9 g/cm^3, made of basalt (Mafic dark-coloured rock type) with less silicon (< 55 %) & rich in Ca, Mg, Fe) about 10 km thick, & *continental plate*, with a thick light crust (density of 2.7 g/cm^3, made of granite (Acidic light-coloured rock type) with silicon > 65 %, richer in Na, K, Al) about 40 km thick.

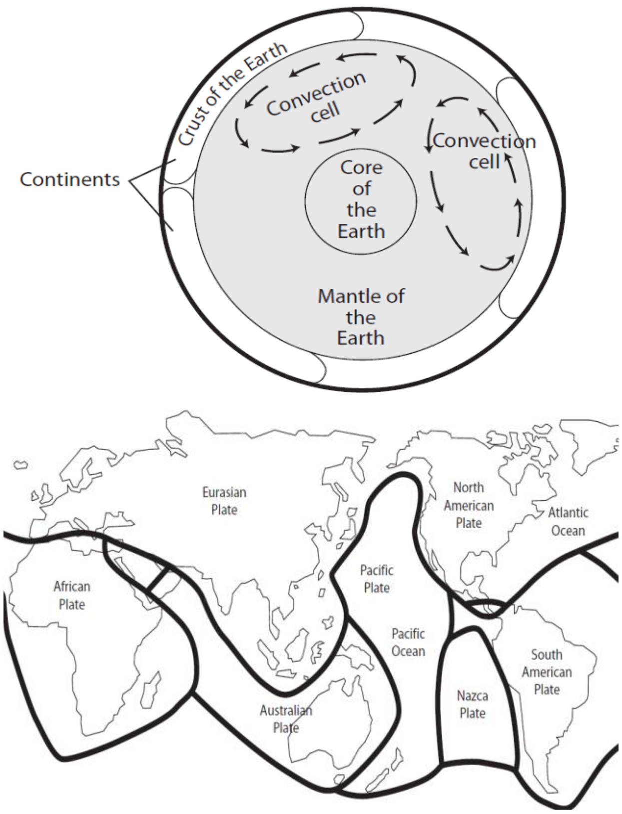


Fig. 2.2 Lithospheric plates of the Earth

Hence, the lighter continental lithospheric crust containing the continents, floats on top of the relatively denser oceanic lithospheric crust containing the ocean basins (Fig 2.3).

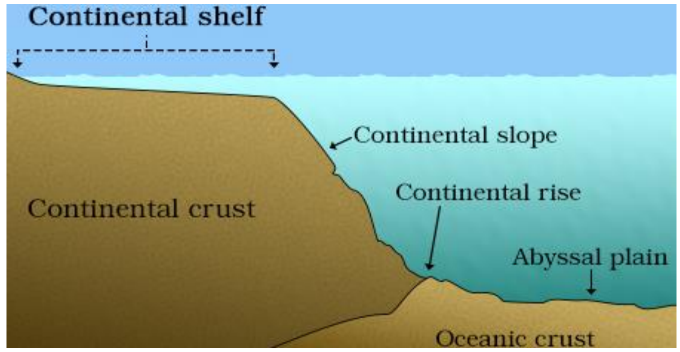


Fig 2.3 Crust density & altitude differences between continental & oceanic plates at a passive continental margin

Provinces of the Ocean Floor

Near the ocean shore, the features of the ocean floor are similar to those of the adjacent continents because they share the same granitic basement. The transition to basalt marks the true edge of the continent and divides ocean floors into 2 major provinces. The submerged outer edge of a continent is called the *continental margin*. The deep-ocean floor beyond the continental margin is properly called the *deep ocean basin* (Fig 2.3).

Types of Continental Margins

Continental margins may be active or passive. Moving lithospheric plates can converge, diverge, or slip past one another. The submerged edges of continents i.e. the continental margins, are greatly influenced by these tectonic activities (i.e. large-scale movements of the earth's lithospheric plates; Fig 2.4).

Continental margins facing the edges of diverging plates are called **passive margins** because relatively little earthquakes or volcanic activity is associated with them (Fig 2.4). Because they surround mostly the Atlantic Ocean, passive margins are sometimes referred to as **Atlantic-type** margins.

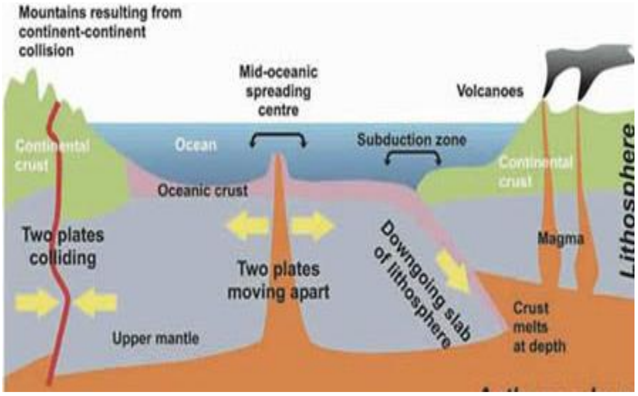


Fig 2.4 Mid-ocean spreading centre, colliding lithospheric plates and subduction zones

Continental margins near the edges of converging plates or near places where plates are slipping past one another are called *active margins* because of their earthquake and volcanic activity (Fig 2.4 & 2.5).

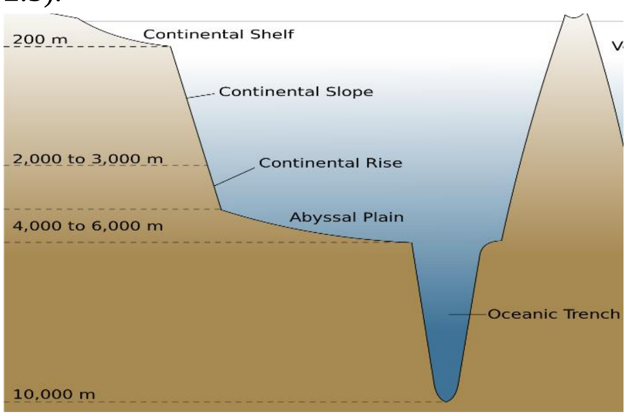


Fig 2.5 Cross section of a typical active continental margin ocean basin

Because of their prevalence in the Pacific Ocean, active margins are sometimes referred to as *Pacific-type margins*.

Active margins coincide with plate boundaries but passive margins do not. Passive margins are also found outside the Atlantic but active margins are confined mostly to the Pacific.

As a general rule, the shelf is narrowest where the continental margin is tectonically active & widest where the continental margin is passive (compare Fig 2.3 & 2.5). Thus, active continental margins have narrow shelves, steep slopes, & little or no continental rise while passive continental shelves have wide shelves, relatively gentle slopes, and a well-developed rise.

Divisions of the Continental Margins

Continental margins have three main divisions: a shallow, nearly flat continental *shelf* close to shore; a more steeply sloped continental *slope* seaward; and an apron of sediment – the continental *rise* – that blends the continental margins into the deep-ocean basins (Fig 2.1).

1. Continental or island shelves are seaward extensions of the continents. They extend to a depth of about 120 m (Fig 2.3 & 2.5). In other words, it is the shallow submerged extension of a continent. They are underlain by granitic continental crust and are much more like the continent than like the deep ocean floor, and they may have hills, depressions, sedimentary rocks, and mineral and oil deposits similar to those on the dry land nearby.

Taken together, the area of the continental shelves is 7.4 % of Earth's ocean area. Most of the material composing a shelf comes from the erosion of the adjacent continental mass. Rivers assist in passive shelf building by transporting huge amounts of sediments to the shore from far inland. Because of their gentle slope, continental shelves are greatly influenced by changes in sea level. Shelves at passive margins are usually wider/broader and flatter than that of active margins. Also, passive-margin shelves have less varied topography than active-margin shelves; the character of continental shelves at a passive-margin may be determined less by faulting, volcanism, and tectonic deformation than by sedimentation. Continental shelves have been the focus of intense explorations for natural resources. Because shelves are the submerged margins of continents, any deposits of oil or minerals along a coast are likely to continue offshore. Water depth over shelves averages only about 75 m, so large areas of the shelves are accessible to mining and drilling activities. Many of the techniques used to find and exploit natural resources on land can also be used on the continental shelves.

2. Continental or island slope is the transition between the gently descending continental shelf and the deep-ocean floor. In other words, it connects continental shelves to the deep ocean floor. The *shelf break* marks the abrupt transition from the continental shelf to continental slope. In general, continental slopes at active margins are steeper than those at passive margins. Continental slope averages about 12 miles wide and end at the continental rise, usually at a depth of about 3700 m. The bottom of the continental slope is the true edge of a continent.

Submarine canyons are relatively narrow, deep V-shaped furrows with steep slopes that cut into the continental shelf and slope, often terminating on the deep sea floor in a fan-shaped wedge of sediment. They are formed when turbulence mixes sediments into water above a sloping bottom – such mass movements of sediment called are called *turbidity currents*.

3. Continental rises form as sediments accumulate at the base of the continental slope. Along passive margins, the oceanic crust at the base of the continental slope is covered by an apron of accumulated sediments called *continental rise*. Sediments from the shelf slowly descend to the ocean floor along the whole continental slope, but most of the sediments that form the continental rise are transported to the area by turbidity currents.

Deep-Ocean Basins

As have been noted, the Earth crust is broken into large plates that move relative to each other. New crust is created at mid-ocean ridges, and old crust is lost at trenches. The relative motion of crust, due to plate tectonics, produces the distinctive features of the deep ocean floor including mid-ocean ridges, trenches, island arcs, and basins (Fig 2.6).

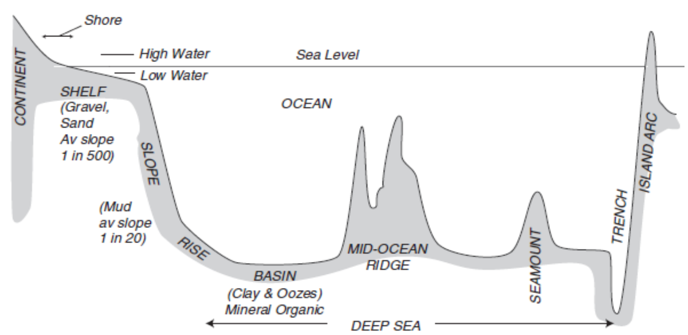


Fig 2.6 Typical features of deep ocean floor

The structure of the ocean floor is quite different from that of the continental margins. It consists of a blanket of sediments up to 3 miles thick overlying basaltic rocks. *Basins* are deep depressions of the ocean floor of more or less circular or oval form. Deep ocean basins constitute more than half of the of earth's surface.

Most of the deep ocean floor lies at a depth of 3000-5000 m.

The *abyssal plain* which lies at the periphery of all ocean basins is almost a flat, featureless expanse of sediment-covered ocean floor. The abyssal plain is not perfectly flat, however, and rises toward the mid-ocean ridges at a very gentle slope. Abyssal plains are most common in the Atlantic and relatively rare in the Pacific, where peripheral trenches trap most of the sediments from the continents. It is dotted with submarine volcanoes called *seamounts*, which do not rise above the ocean surface. Distinct flat-topped seamounts called *guyots* are also found.

The most prominent features of the ocean basins i.e. trenches and their associated volcanic island arcs as well as mid-ocean ridge systems, are products of tectonic processes. *Trenches* are long, narrow, and deep depressions of the ocean floor, with relatively steep sides found where a converging oceanic crust is subducted (Fig 2.6). At trenches, where the plates descend into the mantle, the ocean floor slopes steeply downward. Trenches are the deepest parts of not just the world ocean but also the earth. The Mariana Trench in the western pacific for instance, is the deepest part of the ocean, measuring 11,022 m deep. Little or no continental rise occurs along coasts with trenches because the sediment that would form the rise ends up at the bottom of the trench (Fig 2.6 & 2.7).

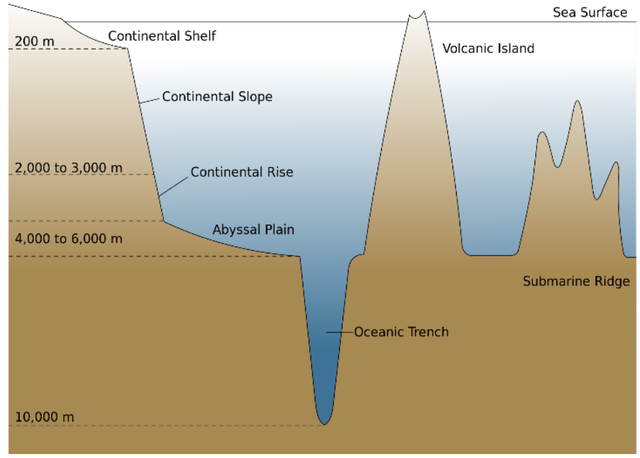


Fig 2.7 Cross section of a typical active continental margin ocean basin showing an oceanic island

Just like trenches, *volcanic island arcs* are formed by tectonic and volcanic activity associated with subduction (Fig 2.6 & 2.7). The descending basaltic lithospheric plate contains materials that melt as the plate sinks into the earth's mantle. These materials rise to the surface as magmas and lavas that form the chain of islands behind the trench. The Aleutian Islands, most Caribbean islands, and the Mariana Islands are island arcs.
The *mid-ocean ridges* are long, narrow elevations of the ocean floor with steep sides and rough topography formed when material rising from the earth's mantle pushes up the oceanic crust (Fig 2.8).

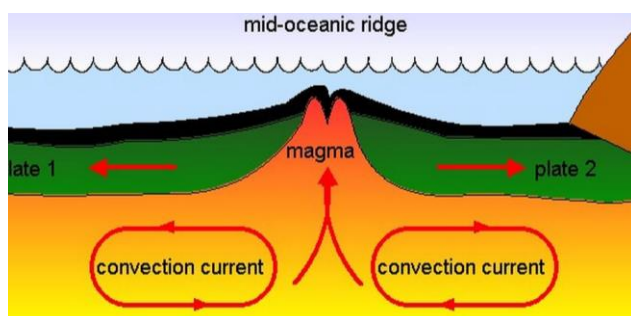


Fig 2.8 Formation of the mid-ocean ridge through sea floor spreading

The ridges, which often are devoid of sediment, rise about 2000 m above the ocean floor. In some places, they project above the surface to form islands such as Iceland, the Azores, and Easter Island, etc. Right at the centre, the ridge is pulling apart (i.e. diverging). This leaves a great gap or depression known as the ***central rift valley***, also referred to as "a wound in the earth's crust." *Sills* are the low parts of the ridges separating ocean basins from one another or from the adjacent sea floor.

NB: As a plate carrying a continent move away or diverge from the spreading centre, the continental margin closest to the mid-ocean ridge is called the ***trailing margin*** or ***edge***. The edge of the continent that is moving towards a deep-sea trench or subduction zone is called the ***leading margin*** or ***edge***.

The floor and sides of the mid-ocean ridge valley are riddled with crevices and fractures. Ocean water seeps down through these cracks until it gets heated to very high temperatures by the hot mantle material. The heated water then forces its way back up through the crust & emerge in *hydrothermal vents*, or *deep-sea hot springs*.

The water from hydrothermal vents is warmer than the surrounding water. At some vents, the water is blistering hot up to 350 ºC. As the hot water seeps through cracks in the earth's crust, it dissolves a variety of minerals, mainly those known as sulfides. When the mineral-laden hot water emerges at the vent it mixes with the surrounding cold water and is rapidly cooled. This causes many of the minerals to solidify, forming mineral deposits around the vents. *Black smokers* – chimney-like accumulation of mineral deposits that is founds at hydrothermal vents – are one type of mineral deposit found at hydrothermal vents. Black smokers progressively build up around a vent as the minerals solidify. The "smoke" is actually a dense cloud of mineral particles.

Deep-ocean hot springs are of great interest not only to geologist, but biologists as well especially with the discovery of an unexpectedly rich marine life around hydrothermal vents.

Inland Water Ecosystems

Lentic Systems

Lake morphology & morphometric parameters

Lakes have different types of shapes e.g. circular, sub-circular, lunate, dendritic, etc. Its morphology is a function of underwater contour lines, its shape, & its geologic origin. Lake morphology is important in terms of water flow, nutrient accumulation, light penetration (lake depth), mixing of the water column, & the separation of the lake into two main horizontal regions i.e. a littoral zone (edge of the lake) & a pelagic (central) zone.

The *drainage basin* of a lake is the area of land or *catchment* that drains water into the lake. But a *lake basin* is the portion that holds the water. The topography of the surrounding area may provide clues to a lake's basin morphology, but details such as depth & contour of the bottom must be measured with a weighted line or an echo sounder.

The most frequently used morphometric descriptors of lakes include the following:

(a) *Bathymetric map* – This is a map or chart showing the submerged equivalent of an above-water topographic map (Fig 2.9).

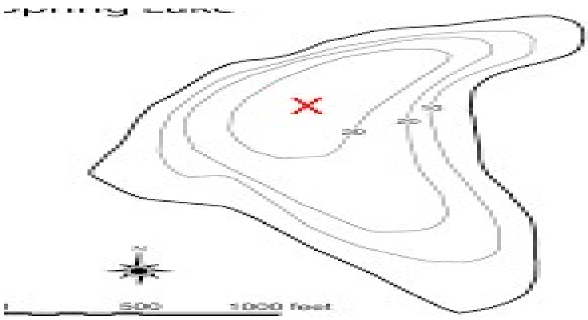


Fig 2.9 Bathymetric map of a lake

They are designed to present accurate, measurable description & visual presentation of the submerged aquatic terrain. In other words, they are topographic *maps* of the aquatic basin floor.

(b) *Shoreline* is the length of the shore line or the area where a body of water meets the land. On a *bathymetric map*, it is represented by the outermost contour line. A lake's shoreline is important because it defines the area where a water body interfaces with the land**.** Changes in a lake shoreline can be significant to aquatic plant management. For instance, at high water levels, & depending on the slope of the land, a lake may have small amounts of aquatic vegetation along its shoreline. But, if water levels were to fall, the reduction in water depth along the lake's shoreline could result in a dramatic increase in aquatic plant growth. Because when the water becomes shallow, sunlight may be able to reach larger areas of the lake bottom, providing the necessary energy for plants to grow.

(c) *Shoreline development* **(**D_L**)** is the length of a lake's shoreline relative to the length of a circle of the same area or the ratio of the shoreline length to the circumference of a circle with area equal to the area of the lake. In other words, the lake shape is compared with an idealized shape (i.e. a circle). A perfectly circular lake would have a DL of 1. Lakes with large DL might be expected to have large littoral or nearshore areas where rooted aquatic plants could grow, providing extensive nursery habitat for fish and other aquatic organisms.

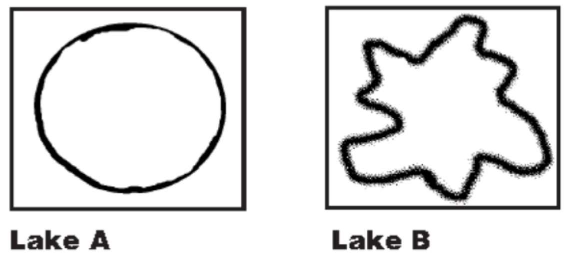


Fig. 2.10 Littoral and pelagic zones of lakes

Consider Lakes A & B above (Fig 2.10). Both lakes have the same surface area. Notice how Lake B has an irregularly shaped shoreline & Lake A is more circular in shape.

If you were to trace the entire perimeter of each lake with a piece of string, you would find that the string used to trace Lake B would be longer than that of Lake A.

Determining a lake's D_L is important because it helps us assess the amount of potential wildlife habitat available for a lake. For e.g. for Lake B with a greater amount of D_L, there is more of an interface between the water & surrounding land & this often translates into more habitats for fish, birds, & other wildlife to raise their young.

The mathematical equation provided below can be used to calculate a lake's D_L:

Shoreline development (D_L) = $L/2\sqrt{(\pi * A)}$

Where ***L*** = *Shoreline length* and ***A*** = *surface area of the lake.*

Note*: a lake in the shape of a perfect circle will always have a* D_L *value of 1.* In other words, lakes with longer, irregularly shaped shorelines are considered to have more D_L, while circular lakes are considered to have less D_L.

(d) *Maximum Length* (L_{max}) – is the shortest distance between the two most distant points on the lake shore i.e. the distance, in a straight line, between the 2 farthest points on a lake measured without intersecting a land mass. It is important because it can influence the depth at which waves can mix water &/or bottom sediments in a lake. As a general rule, the larger the L_{max}, the larger the waves, & the greater potential there is for mixing or disruption of bottom sediments. But a lake's orientation to prevailing winds is another consideration.

(e) *Width* (W) – this is the length of a line from shore to shore at right angles to the L_{max}.

(f) *Maximum depth* **(Z_{max})** – is the deepest depth of the lake. It is sometimes (but not always) indicated in bathymetric maps with an "X – (Fig 2.3)." It cannot be estimated, & can only be obtained by locating & actually measuring the deepest point in a lake. It is important because it influences the movement of fine organic sediments found on the bottom of a lake.

(g) *Mean depth* **(Z_{ave})** - is the average water depth of a lake estimated by dividing the volume by the area (i.e. Z_{ave}=V/A). It is probably the single most useful morphometric feature available because early studies of algae, aquatic invertebrates, & fish populations have shown that shallow lakes are generally more productive than deep lakes. It also has much to do with the potential for waves to disrupt bottom sediments e.g., lakes with greater mean depths usually don't experience as much mixing of bottom sediments, as wave action is less likely to reach the bottom.

(h) *Surface area* **(A)** – is the area occupied by a lake's surface. It is one of the most important morphometric parameters of a lake. It describes the size of a lake & also plays a major role in a lake system such as:

- It can be used to help predict the potential effects of wind on a lake;
- It influences the dilution capacity a lake may have;
- It is useful when trying to choose the appropriate type of boat to use on a lake.

(i) *Hypsographic curve* is a plot of depth along the vertical axis & area along the horizontal axis. Thus, they are graphs used to provide a visual representation of the relationship between the surface area of a lake basin & its depth.

With these graphs, we can be more accurate in predicting how a lake's surface area could change based on changes in water depth. They are often a useful way to depict shape relationships of a lake basin.

Why are hypsographic curves important?

1. They are used for predicting the best time to implement various lake management strategies such as aquatic plant management, habitat restoration, etc.

2. They are also useful for comparing lakes & explaining why some lakes are more susceptible to changes in lake surface area while others of similar size (i.e., surface area) may show very little change.

3. Furthermore, scientists use them for predicting two lake dynamics in particular:

(a) a lake's ability to dilute incoming materials,

(b) the potential for lake water mixing

Both of these dynamics are particularly important because they have much to do with the concentration of nutrients in a lake and a lake's ability to support life — its biological productivity. For instance, it's been found that, in many areas shallow lakes tend to be more productive than deep lakes, meaning that shallow lakes often have greater nutrient concentrations and also produce more fish and wildlife.

(j) *Volume* (V) – this is the total volume of a lake. It can be calculated from the bathymetric map as:

$$V = \sum [A_1+A_2 + \sqrt{(A_1*A_2)}]*h/3 \text{ where}$$

A_1 = area of one contour line,

A_2 = area of the next contour line, etc

h = the thickness of the layer between the two contours.

Lake volume can fluctuate dramatically depending on rainfall & is an important consideration to lake management because;

1. It can influence a lake's *dilution capacity* i.e. the ability of a lake to dilute materials, whether they are naturally occurring from the watershed or from human activity.
2. Scientists also consider lake volume when *estimating nutrient loads* or *flushing rates*, as both can impact algal populations in a lake.

Several ways are used to measure lake volume:

i. In the graphs of fig 2.11, the area between the x-axis, the y-axis & the curve itself is proportional to the lake's volume.

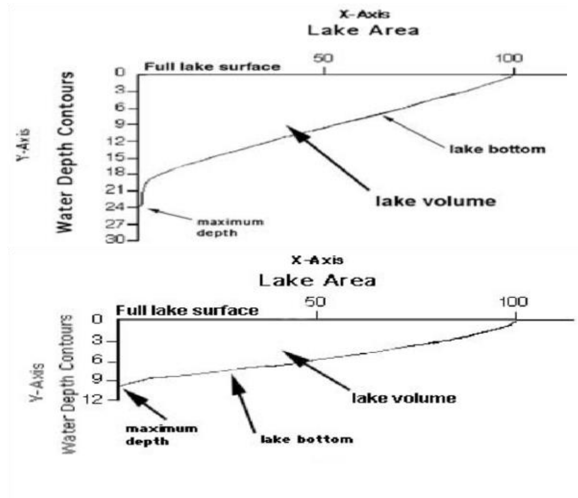


Fig 2.11 Deep and shallow lakes with same surface area

ii. The 2nd way to measure lake volume is by multiplying the mean depth of a lake & its surface area, volume can be found by multiplying the two:

$$(\mathbf{V}) = \text{mean depth } (\mathbf{z}) * \text{surface area } (\mathbf{A})$$

(k) *Volume development* (D_V) is the ratio of the volume of the lake to the volume of a cone of basal area equal to the surface area of the lake & height equal to the maximum depth or a measure of departure of the shape of the *lake* basin from that of a cone.

$$D_V = 3*(Z_{ave}/Z_{max})$$

For the majority of lakes, D_v will be greater than 1 (i.e., a conical depression). D_v is greatest in shallow lakes with flat bottoms. Among deep lakes, etc D_v will be much greater than 1.5 (also in many rock basins).

Extremely small values are found in only a few lakes with highly localized deep holes. Extensive action of shore processes is apt to reduce the ratio.

NB: Lakes with large volume relative to their surface area (high mean depths), would be more cone-shaped lakes and might be expected to have an increased potential for cold-water fishery given their larger hypolimnion relative to their epilimnion. Lakes with shallower depths would be more elliptically shaped and might be expected to be more productive (due to high light penetration and water/sediment contact) and might be expected to have increased potential for warm-water fishery.

Concept of Hydraulic Residence Time

The hydraulic residence time (HRT) is the time required to refill a lake with its natural inflow or the average time taken to refill a lake basin with water if it were emptied. It provides a measure of the circulation of water within the aquatic system. HRT is also called *water flushing time* (WFT) or *water residence time* (WRT) and can be calculated using the formula

$$HRT = \frac{\text{Volume } (m^3)}{\text{Average annual water outflow } (m^3\ yr^{-1})}$$

For instance, the volume of a lake is known to be 8400 km^3 whiles its mean HRT is estimated to be 1225 years, then the average annual water outflow is calculates as follows;

Solution

$$HRT = \frac{\text{Volume } (m^3)}{\text{Average annual water outflow } (m^3\ yr^{-1})}$$

$$\text{Av annual } H_2O \text{ outflow} = \frac{\text{Volume } (m^3)}{\text{HRT (yr)}}$$

$$\text{Av annual } H_2O \text{ outflow} = \frac{8400{,}000\ (m^3)}{1225\ (yr)}$$

$$\text{Av annual } H_2O \text{ outflow} = 6857.14\ m^3\ yr^{-1}$$

Some lakes have inflow but no outflow (*closed basin lakes*). These lose water entirely by evaporation, leading to salt accumulation and the development of high saline environment e.g. Lake Bosomtwe (Ghana), Caspian Sea, etc. Other lakes lack both inflow and outflow and are called *seepage lakes*. In other words, seepage lakes receive water by seepage through the walls and floors of their basin. The principal source of water is precipitation or runoff supplemented by groundwater from the immediate drainage area.

Physical Structure of a Lake

A lake is divided into 2 main regions – a *littoral zone* (edge of the lake) & a *pelagic* (central) *zone* (Fig 2.12 & 2.13). Most lakes show clear separation between littoral & pelagic regions, each with their own distinctive communities.

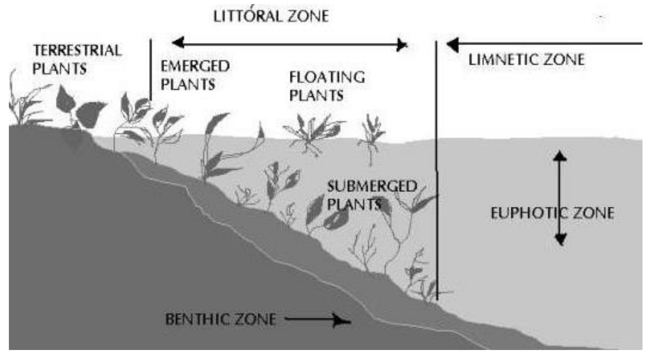


Fig. 2.12 Littoral & pelagic zones showing distribution of aquatic macrophytes

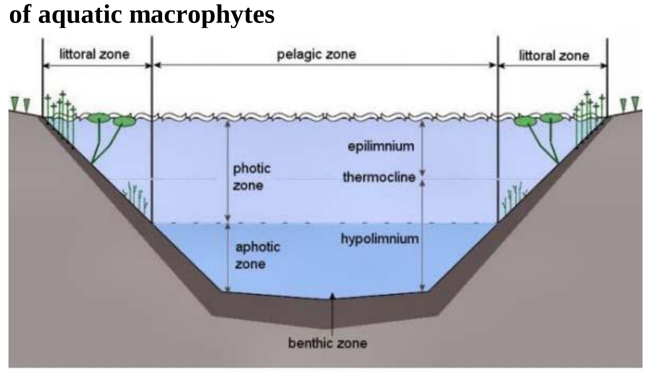


Fig. 2.13 Zonations in lentic systems showing thermal & light zones

a) Littoral zone: This is the shallow edge of the lake characterized by rooted vegetation. It has distinct physical (high light penetration, wave action), chemical (influx of materials from outside), & biological characteristics.

The development of higher plant or *macrophyte* communities (Fig 2.12 & 2.13) as part of the littoral flora is typical of *eutrophic* & *mesotrophic* water bodies but not *oligotrophic* ones.

The shallow water in the littoral zone allows light penetration to the sediments, which provide the base or substratum for rooting macrophytes (mainly higher plants), which are able to survive strong wave action & tend to dominate mesotrophic to eutrophic littoral communities.
In many lakes, the littoral zone also has a rich microbial community, many of which live a life attached to a substrate & are collectively called *periphyton* of which the algae are quite prominent (Fig 2.14; Table 2.1).

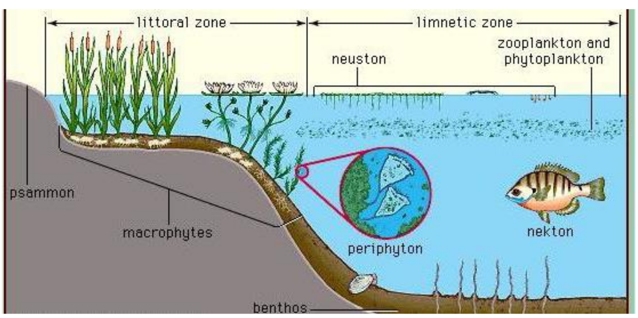


Fig. 2.14 Plankton communities of lakes

Table 2.1 Types of Periphyton

Type of periphyton	**Substrate**
Epiphyton	Plants
Epilithon	Rocks
Episammon	Sand grains
Epipelon	Sediments
Epixylic/epidendron	Dead wood

These periphytons are typically characterized using the substrate they are attached to & on that basis several types can be distinguished (Table 2.1).

Some algae also occur as free floating masses (*metaphyton*) which were originally part of the periphyton. Bacteria, fungi, & protozoa are also well represented in this part of the lake as part of the periphyton community and also as free living forms in the littoral waters.
The microbial community of the littoral zone differ from that of the pelagic in terms of the taxonomic composition, domination of benthic organisms (*epibenthos* i.e. bottom-living organisms), & heterotrophic consumption of mainly *allocthonous* dissolved organic carbon (DOC).
The littoral region is also a major site of recruitment of benthic algae to form planktonic populations.

b) <u>Pelagic (lacustrine) zone</u>: This is the portion of the main lake body with limited light penetration especially in deep lakes. It consists of a vertical water column with an air-water interface at the top & lake sediments at the base.
The first part of the pelagic zone called the *limnetic zone* is the open water zone to the depth of effective light penetration i.e. it lies above the *compensation level* or *point* & together with the littoral zone comprise the *euphotic* or *photic* (*trophogenic*) zone – well-illuminated zone.
Below the limnetic zone is the *profundal* (*trophylytic/aphotic*) zone into which light does not penetrate enough to allow photosynthesis to occur i.e. it lies beyond the depth of effective light penetration or compensation level. In shallow lentic systems, this part may be absent.
The pelagic zone is dominated by free-floating microscopic organisms or *plankton* (Fig 2.14). A number of specialized organisms called *neuston* are adapted to the air-water interface. They are

separated into those organisms adapted to living at the upper surface of the interface (*epineuston*) & those living on the underside of the surface film (*hyponeuston*). *Pleuston* refers to organisms that live in the thin surface layer existing at the air-water interface.
The major community within the lake in terms of area cover & total biomass is the pelagic community. Within this part of the lake, actively swimming animals e.g. fish & some mammals are able to locate themselves at any depth by their own activity & are referred to as *nekton* (Fig 2.14) in contrast to the plankton which are less actively motile.

The lowermost region of the lake water body below the profundal zone is called the *benthic zone*. This zone is the interface between the lake water & the lake sediment surface. The sediment of lakes is inhabited by benthic organisms collectively called *benthos* (Fig 2.8), with bacteria being particularly important in sediments with no light (*aphotic zone*) or oxygen (*anoxic zone*). The benthic zone is common to both the littoral & pelagic zones.

The water column of a lake is linked to the sediments in terms of nutrient cycling & interchange of aquatic populations.

Lake Hydrology & the Catchment Area
Lake Hydrology refers to the study of the properties, distribution, & circulation of water within the lake as well as the manner in which water flow in & out of it. Although interest in lakes tends to focus on the main water body, they are clearly part of a wider catchment area & have important interactions with it. For instance, much of the water contained in lakes is derived from the surrounding land mass, & the chemistry of the lake is largely determined by the chemistry of the inflow water. Entry of inorganic nutrients (particularly phosphates & nitrates), dissolved organic material, dissolved cations, & suspended solids determines the *trophic/nutrient status* of the lake & has a major influence on the development & growth of lake microorganisms.

Classification of Lentic Systems Based on Surface Area
Lentic systems can be classified using several criteria such as salinity, origin, location, trophic status, etc. One other major criterion for classifying lentic ecosystems is surface area. Using this criterion, lentic systems can be characterized as shown in table 2.2.

Table 2.2 Classification of lakes & ponds based on surface area

Type	Surface area (km^2)	# of lakes	Total surface area (km^2)
Great lakes	>10,000	19	997,000
Large lakes	10,000 - 100	1504	686,000
Medium lakes	100 - 1	139,000	642,000
Small lakes	1 – 0.1	1,110,000	288,000
Large ponds	0.1 – 0.01	7,200	190,000
Small ponds	<0.01	ND	ND

Lotic Systems

Streams and Rivers

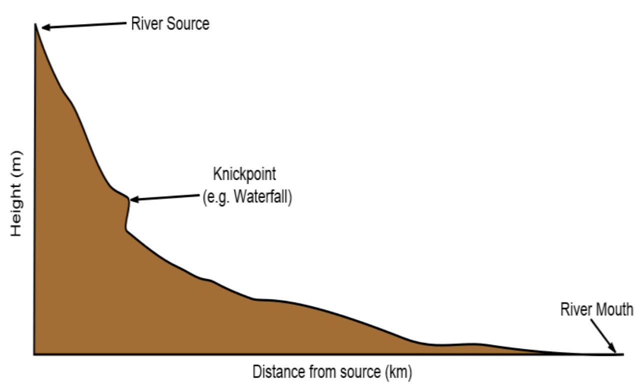
The lotic or running water environment comprises 2 zones: the cool, shallow, & often stony-bottomed *stream* & the warmer, deeper, silty-bedded *river*. The aquatic environment of both streams & rivers are dominated by continuous unidirectional flow that cut channels or beds through the land surface.

Every river arises from a *spring* i.e. groundwater escaping from the Earth or a source of water that flows out of the ground. Rivers differ from streams in being usually considered as larger, faster moving, & often warmer water bodies.

NB: The speed of the river or stream current influences both the composition of the channel (e.g. rocks, sand, gravel, or mud), the oxygen concentration & hence, the composition of organisms found there. In general, the oxygen content of fast moving lotic systems is higher than that of slow-moving ones.

Horizontal Zonation of Rivers

The lotic environment consists of a running water column lying over a bed or substratum. It is basically divided into the *upstream* (source), *midstream*, & *downstream* (delta) portions along which there is a continuous unidirectional flow of water as a result of gravity (Fig. 2.15).



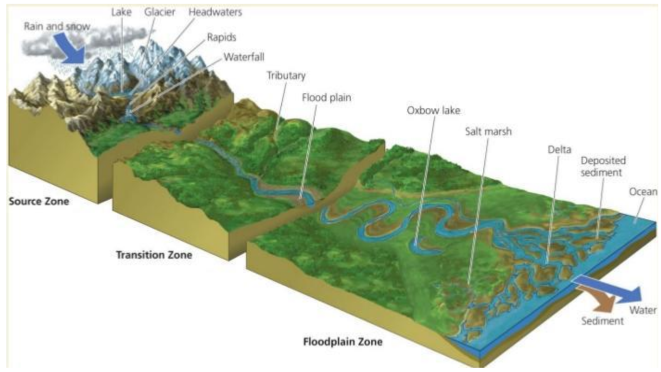


Fig 2.15 Lengthwise zoning of a river

Horizontal zonation is something of a continuum, but one characterized by a number of discontinuities. All rivers, regardless of their type, have the same stages of structural changes from source to delta.

The horizontal profile of every river can be divided into three zones (Fig. 2.15):

• <u>Source zone (headwaters)</u> – mountain streams that slope steeply & rapidly downhill & form V-shaped river valleys, often forming waterfalls & rapids. These rapids shape & carry large-size sediments downstream. It is also referred to as *crenon* or *spring zone*. It represents the places where the groundwater reaches the surface emerging from the soil. Because of their underground origin, spring waters are characterized by a quite stable temperature, a low oxygen concentration & low organic matter content. These stable environmental conditions allow for the life of organisms with strict ecological requirements. The springs are the interface between groundwater & surface water & they host the interstitial fauna, consisting of small animals living in groundwater & in subsurface cavities.

Springs can generally be divided into 2 zones viz;

 spring region called *eucrenon* – where water flows naturally from the water table in rocks onto land surface, spring brook or *hypocrenon*- part of the lotic system consisting of a small stream just after the spring region,

• <u>Transfer zone</u> – characterized by a lower altitude. The flow velocity is slower, the river bed becomes wider, & meanders form. Some of the larger sediments settle at the interim area between the source zone & the transfer zone, thus forming the so-called *sediment cones*. Other sediments are carried further downstream. Here, erosion & deposition processes are in equilibrium in the transfer zone. This region is also called rithron. It is characterized by on average a relatively low temperature, high oxygen concentration & very turbulent waters i.e. the water is typically fast-moving, broken-surfaced, shallow, & relatively cold. The river bed is composed of boulders, pebbles & gravel sometime alternating with sand or mud. It favours *rheophilous*, cold water *stenotherms* (i.e. with a preference for cold waters) - organisms with a high demand for oxygen with specific morphological adaptations to life in very turbulent waters. Plankton is rare or more often absent.

• <u>Deposition zone</u> (flood plains) has a rather low slope; flow velocities are slow, forming wide meanders. Most of the sediments, including the finest ones, settle in this area. The river mouth often opens into a wide delta bottomed by fine sediments, & the river splits into many arms. This region is also called <u>potamon</u>. It is characterized by on average relatively high average temperatures & occasionally suffers an oxygen deficiency. The current is very slow & have a typically slow-moving, still-surfaced, deep & relatively warm. The bottom is mainly sandy & muddy. It favours *limnophilous*, stenotherms – organisms that are thrifty in their use of dissolved oxygen i.e. they prefer fairly warm & calm waters & can also tolerate low oxygen concentrations. The plankton can be abundant.

NB: Rhitron & potamon correspond to salmonid or cyprinid zones respectively (Fig 2.16).

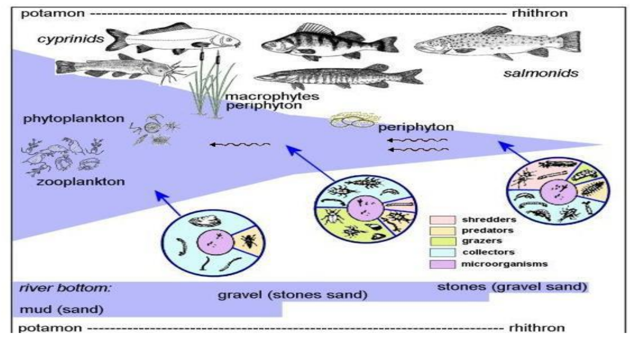


Fig 2.16 Zonation of river & ecological changes occurring along the watercourse.

Characterizing Lotic Systems using Stream Order or Geomorphology

A simple geomorphological classification of rivers is based on the changes of flow at the confluence of the rivers. *Stream order* is the relative position or rank of a stream segment in a drainage network (Fig. 2.17).

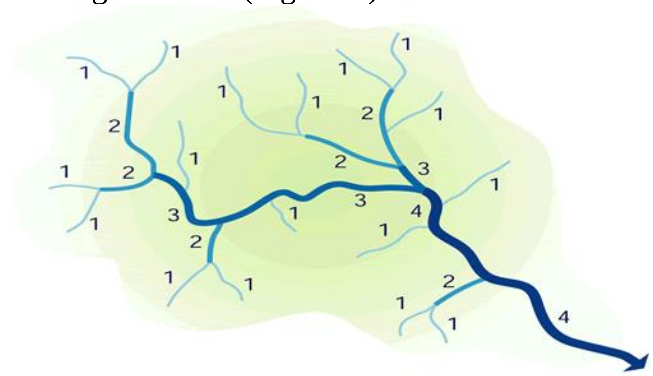


Fig 2.17 Stream ordering in a drainage network

It is assumed that the confluence of 2 rivers in the same category leads to the formation of a water course of a higher category. Thus, 2 rivers without tributaries (order 1) at the point of their confluence form a stream of higher order (order 2). The confluence of two streams of order 2 leads to a stream of order 3. Finally, a river originating when streams of order 1 and 2 merge together is always of order 2 i.e. the order of the stream is not changed by the addition of a stream of lower order. Only when tributaries of equal order are joined is the order increased.

Thus, small, branched, upper tributaries of a permanently flowing river system or “finger-tip” tributary are classified as *first-order* while the largest river in the world, the Amazon, is a 12th-order waterway. First through 3rd-order streams are usually called *headwater streams*.

NB: A *river system* consists of a group of rivers so interlinked that the water carried by the minor component streams and creeks finally unit in one body of flowing water usually designated as the “master” or “trunk” river.

Differences between Lotic & Lentic systems

1. Lotic water bodies are transient i.e. have low water retention times at any particular site.
2. They are typically highly turbulent.
3. They typically little or no thermal or chemical stratification.
4. High turbulence & little thermal or chemical stratification combine to limit the growth of a planktonic community.
5. The substratum or bed of streams is typically well aerated & exposed to light & is the major site of algae & associated biota.
6. Inflow from the catchment area is typically periodic, giving rise to marked fluctuations in water level & flow velocity (high-flow & low-flow periods).
7. Concentrations of dissolved & particulate matter, which are mainly derived from the catchment area, typically follow this periodicity of inflow water from the catchment area.

Microbial Communities of Lotic Systems

Lotic systems are dominated by benthic organisms at the microbial level. Benthic algae or *periphyton* such as single-celled diatoms, colonial filamentous green algae, & cyanobacteria are the most successful photosynthetic organisms in streams. Benthic environments are ecologically important in primary production, nutrient transformation, sediment stabilization, & habitat provision for other benthic organisms. Benthic algae can also proliferate in nutrient-enriched, stable-flowing streams, causing water management problems. Suspended algae of lotic systems are commonly referred to as *potamoplankton* but the true potamoplanktons are those that reproduce within the water column.

Wetlands

Generally, a wetland is an area of land covered with, or saturated by water for at least part of the year. It is thus transitional between terrestrial & aquatic ecosystems. But the *Ramsar Convention on Wetlands* defined wetlands as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static, flowing, fresh, brackish, or salt, including areas of marine water the depth of which at low tide does not exceed six metres”

Many wetlands differ from shallow lakes in showing greater extremes of seasonal change (with periodic desiccation & flooding) & are particularly liable to more permanent alterations & loss of habitat due to human interference. Problems of maintenance & sustainability are key aspects of wetland management.

Characteristics of Wetlands

Wetlands vary widely because of regional and local differences in soils, topography, climate, hydrology, water chemistry, vegetation & other factors, including human disturbance. All wetlands, however, have the following three things in common:

1. Presence of standing water;
2. Wetland soils (which have low levels of oxygen or none at all (i.e. are anoxic), because they are intermittently or permanently saturated) causing waterlogging; and

3. Presence of wetland plants (which have adapted to growing in wet soil).

Using Aquatic Macrophytes to Classify Wetlands

The importance of macrophyte vegetation in wetlands is emphasized by the characterization of wetlands according to the different plant types that dominate. This is referred to as ***structural classification of wetlands***:

i) *Marshes*, low-lying wetland habitats often close to a river/lake that is frequently flooded to a shallow depth. It is usually dominated by emergent aquatic macrophytes & has submerged or floating macrophytes also, etc. A major distinguishing feature is the absence of trees & shrubs. They are often fed by external water source such as ground and river waters, which can either be rich or poor in nutrients & are usually underlain by peat deposits. Marshes are the most productive of these four wetlands. Examples of marshes include tidal, non-tidal, wet meadows, prairie potholes, vernal pools, & playa lakes.

ii) *Swamps*, low-lying area of wetland that is usually at least partly flooded, is covered with grasses and shrubs, but large trees are dominant, has better drainage than a bog, has more woody plants than a marsh and does not accumulate deposits of peat like a bog and is usually dominated by trees. In essence, they are wooded wetlands. Like marshes, swamps are also fed by external water source such as ground and river waters, which can either be rich or poor in nutrients. Swamps are the second most productive wetlands. Examples of marshes include forested swamps, bottomland hardwoods, shrub swamps, and mangrove swamps.

iii) *Bogs* are acidic, poorly drained wetlands with high water table and high organic remains. It usually develops where drainage is blocked. Bogs are characterized by low species diversity and have few or no trees or aquatic macrophytes but an abundance of the acidophilic peat-building *Sphagnum* moss and sedges which dominates it. They have little or no external water inflow and are dependent on a high water table replenished by rainwater. Bogs are the least productive wetlands. Examples of bogs include northern bogs and pocosins, etc.

iv) *Fens***,** have some characteristic of both bogs and marshes. They are distinguished by a mineral-rich groundwater source and a more alkaline pH than bogs. They are often species-rich containing both mosses and aquatic macrophytes and are usually underlain by peat deposits just like marshes and bogs. Fens are the third most productive wetlands.

Functional Categories of Wetlands

The presence or absence of dry periods separate wetlands into seasonal and permanent wetlands.

i) *Seasonal wetlands* are characterized by a dry period when all or most of the area revert to terrestrial status. The wet-dry cycle releases nutrients from soils, and during the wet period, productivity can be very high. Most of the organic matter produced in the flooded period is decomposed in the well-oxygenated dry season so organic deposition is low. Algae, aquatic grasses, and few other plants, insect larvae, and other small organisms that can survive the vigorous environmental fluctuations often become superabundant. Migratory birds, fish, and amphibians that breed in seasonal wetlands feed on the dense but short-lived explosion of the insect population. Examples may include marshes and swamps.

ii) *Permanent wetlands* are characterized by large, long-lived trees and tall reeds that tolerate the permanently waterlogged soils. They are usually found in river deltas, the margin of ponds and lakes, tidal estuaries, and flat areas in the mountains. These wetlands also provide cover and breeding grounds for birds, fishes, reptiles, and mammals. Permanent wetlands are usually less productive than seasonal wetlands but are net accumulators of organic matter, since decomposition is slow under conditions of permanent anoxia. Examples may include bogs and fens.

Natural and Artificial Types of Wetlands

1. *Natural wetlands* are wetlands that are formed naturally e.g. include;

i) *Marine wetlands* - are saltwater wetlands exposed to waves, currents and tides in an oceanic setting. They include coral reefs, and aquatic subtidal beds with sea grass and kelps. Coastal & marine wetlands are important nursery & feeding areas for animals such as fish, dugongs, & marine turtles.

ii) *Estuarine wetlands* - are tidal wetlands that are usually semi-enclosed by land but have open, partly obstructed or sporadic access to the open ocean, & in which ocean water is at least occasionally diluted by freshwater runoff from the land. The most common example is where a river flows into the ocean."

iii) *Lacustrine wetlands* - are large, open, water-dominated systems (e.g. lakes).

iv) *Riverine wetlands* - are wetlands connected by rivers. They are found along the edges of rivers, streams and creeks & include rivers, floodplains, marshes, lakes and billabongs. They mostly have freshwater.

v) *Palustrine wetlands* - include bogs, fens, swamps, & marshes that are non-saline & which are not lakes or rivers. It is what people traditionally think of as wetlands. They have more than 30 % emergent vegetation. The word *palustrine* comes from the Latin word palus or marsh.

2. *Artificial wetlands* are wetlands that are not formed naturally but through the activities of man. Examples include;

- Aquaculture/mariculture
- Agriculture
- Salt exploitation
- Urban/industrial
- Water storage areas

Importance of Wetlands

1. *Wetlands Improve Water Quality* - Surface water runoff from cities, towns, roads, agriculture, mining & forestry operations may contain sediments, excess nutrients, viruses & pathogens & a variety of chemicals. If this runoff flows through a wetland, the wetland acts like a filter to remove sediments, absorb nutrients & biologically change many chemicals into less harmful forms.

2. *Wetlands Reduce Flood Damage* - Wetlands can reduce flooding by holding back peak water flows when water levels are high and, in some cases, storing water within the wetland. This results in more gradual discharges of water over a longer period of time, which can protect downstream property owners from flood damage.

3. *Wetlands Reduce Erosion* - Wetland vegetation along the shorelines of rivers, streams and lakes reduces erosion. Plants trap soils in their roots, helping to stablilize shorelines by dampening wave action and slowing water currents.

4. *Wetlands & Groundwater Recharge/Discharge* - Wetlands are essential components of the water cycle and many are a link between surface and groundwater. A wetland is a groundwater discharge area if water enters it by moving upwards from the soils beneath the wetland or from the upland areas surrounding it. These “discharge wetlands” are ecologically important because they help control erosion & maintain water quality. Conversely, some wetlands act as recharge areas, collecting surface water & allowing it to percolate down through the soil & rock to the groundwater. This water recharge helps to maintain water quality & groundwater supplies, especially during dry periods. This contributes to the water required for essential activities such as human consumption & agriculture.

5. *Wetlands provide Habitat* - Wetlands provide food, shelter, breeding and resting places for an incredible number of species of plants, mammals, bird, reptiles, amphibians, fish and invertebrates. Wetlands provide the critical habitat that many such organisms need to survive.

6. *Wetlands & Climate Change* - Peat consists of partially-decomposed plants. Peatlands are wetlands that actively accumulate peat – act as long-term sinks for carbon dioxide in the atmosphere. Carbon dioxide is one of the "greenhouse" gases that contribute to global warming. Carbon is retained in peatlands instead of being released into the atmosphere as carbon dioxide.

7. *Recreation and Tourism* - Wetlands are popular places for non-consumptive recreation e.g. photography, bird watching, canoeing, hiking, relaxation, and spiritual or cultural experiences, etc. Some wetlands have interpretive facilities, boardwalks and viewing towers where people can go to observe wildlife and learn about nature. Such facilities attract people to the wetland and provide an economic return to local communities and the tourism industry. Wetlands can also serve as "outdoor classrooms" and can be extremely valuable to scientific research studies. They are also valuable for more consumptive recreational uses, such as hunting, fishing, trapping, etc. Such activities can also increase tourism and boost local economies.

8. *Sustainable Wetland Products* - Wetlands "produce" a number of valuable plants and animals, which can be harvested on a sustainable basis to provide an economic return. Such "products" include: trees (for lumber, pulp, fencing and firewood), wild rice, cranberries and blueberries, fish and commercial baitfish, bullfrogs and snapping turtles, waterfowl, furbearers (e.g., beaver, muskrat, mink), natural medicines, etc. These products can be harvested from wetlands in a sustainable, ecologically-conscious manner, avoiding degradation of the wetland.

Estuaries – a marriage of two water types

Waters of all lotic systems – rivers & streams – eventually drain into the ocean & the place where they join with the salt water of the ocean is called an *estuary*. Where freshwater & salt water meet, the resulting mixture is called *brackish water*, defined as having salinity between 0.5 ppt & that of full strength ocean water (35 ppt). Thus, estuaries are semi-enclosed bodies of ocean water which are diluted with freshwater from terrestrial watersheds.

Hydrology of Estuaries

Water movement within estuaries depends on tidal currents, estuarine circulation, river discharge, & inflow from ground water, etc. The extent of these movements depends on the morphology of the estuary basin.

River inflow (i.e. current) & salinity shape the life in an estuary. Current is important for the mixing of fresh & saltwater systems, productivity within the estuarine system, & eutrophication of surrounding coastal areas. Current flow varies with season (wet and dry seasons in the tropics; summer, winter spring, and autumn in temperate regions) as well as with the oscillating ocean tides, & wind.

Estuarine salinity varies vertically & horizontally. *Vertical salinity* may be uniform or stratified depending on the strength of the currents & periodicity of tides. In addition, strong winds tend to mix the salt & fresh waters in estuaries. Estuaries can also show *horizontal salinity* variations. Horizontally, the least saline waters are at the river entrance, & the most saline at the mouth of the estuary (Fig. 2.18).

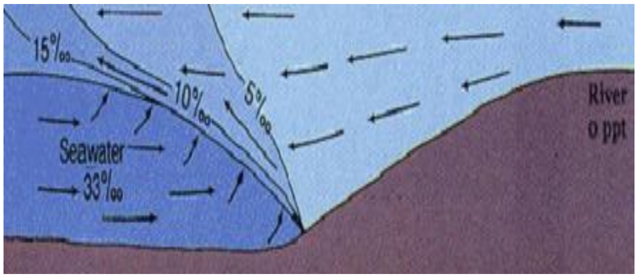


Fig 2.18 Salt wedge in an estuary

Mixing of high density salt water & low density fresh water results in a region of brackish water, the '*salt wedge*', which tends to underlie the freshwater & gives a layered structure to the estuarine water body (Fig. 2.18).

Biological Communities of Estuaries

To survive variable salinities, organisms must be *euryhaline* (i.e. tolerant of a wide range of salinity variations) & be equipped with special physiological mechanisms to eliminate salt. This osmotic regulation is needed because the body fluids of all organisms are similar in chemical composition & thus in ionic pressure.

Marine fish & other organisms that live in salt water are *hypotonic* because they contain less salt than their surroundings & must gain water & excrete salt. Freshwater organisms are *hypertonic* & conserve salts by excreting water from which salt has been removed in the kidney.

The constantly varying salinity of estuarine waters requires both types of osmotic regulation in the same organism. Such a physiological & anatomical flexibility is unusual; most species avoid osmotic changes or periodically switch systems as needed. For example, salmon (*anadromous*) & eels (*catadromous*) convert their osmoregulation from hypotonic to hypertonic, or vice versa as they migrate between salt & freshwater.

Most estuarine inhabitants cannot osmoregulate very well but survive because they either avoid salinity changes or their cells tolerate changes in internal salinity that would kill most other organisms. Since few species of bacteria, fungi, algae, higher plants, invertebrates, or fish can live in brackish water, the flora & fauna of estuaries tend to be poor in species relative to the adjacent habitats of the river & the ocean. In particular insects are virtually absent as they are in the ocean.

Estuarine organisms are mostly of marine origin, & many common forms can survive in the coastal ocean. This is necessary because over geological time estuaries are not very permanent limnological features. However, it is still a region of high productivity that is attributed to the inflow of soluble & particulate materials of rivers & also nutrients brought from the ocean during high tides.

Tropical Estuaries: Mangrove Swamps

In hot climates the typical grass- or reed-dominated salt marsh of the temperate zone is replaced by low trees collectively called mangroves. Several genera dominate mangrove swamps, but *Rhizophora*, *Avicennia*, and *Bruguiera* are common representatives. Mangrove swamps cover huge areas of the lowland tropics & can tolerate salinities from full strength ocean water to freshwater & zero dissolved oxygen (anoxia).

Mangroves grow rapidly & support large growths of attached animals & plants on their root system. The roots form masses of stilt-like branches that grow away from the main trunk & can penetrate anoxic muds to obtain water & nutrients. Some mangrove species produce *pneumatophores* or root branches that grow upwards & assist in root respiration or oxygenation.

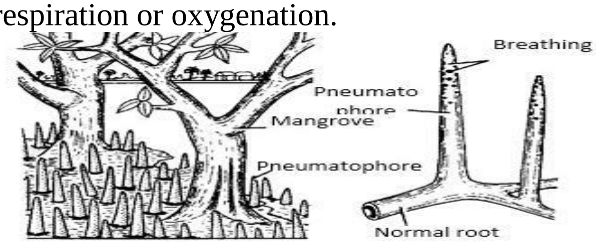


Fig 2.19 Mangrove plant showing pneumatophores

UNIT THREE
FACTORS IMPORTANT IN THE STUDY OF AQUATIC SYSTEMS

Introduction

Every organism in an aquatic system lives in the portion of it where it finds especially good living conditions but it may also have to deal with other factors in that environment that adversely affects it. For instance, several *physical factors* affect aquatic organisms e.g.

- there is *temperature* & its effect in time & space, there is the question of the limits of temperature between which different aquatic organisms can grow or live; temperature also have effects on dissolved oxygen & other gases, etc
- there is *light* – its intensity, the duration of the period of illumination, & the spectral composition or quality of this light; light availability is also affected by *turbidity* or *transparency* of the water which can be due to suspended & dissolved substances;
- there is *wind* which move the waters & affects the physico-chemical & biological factors in aquatic systems; &
- the interaction of wind, temperature, light, etc

Physical Factors Affecting the Conditions of Existence of Aquatic Organisms

The physical factors of importance to the conditions of existence of aquatic organisms are many but the key ones include:

- temperature,
- light,
- rate of flow of running waters, etc

i). *Temperature*

Temperature determines, within the physiological range, the speed & intensity of biochemical reactions. Usually particular organisms tend to be restricted to particular temperature range which is conducive for their growth and reproduction.

Temperature Effects on Lake Mixing

Lakes are not permanently static water; they undergo an annual rhythm of stagnation & circulation (i.e. mixing).

The principle behind lake mixing is essentially based on density of the water in contact with each other. Waters of the same density will mix while waters of different density tend to separate into distinct vertical layers with the less dense water on top of the more dense water. Two factors affect the density of water. These are temperature & dissolved substances. Thus, we have *temperature-induced density* & *chemically-induced density* or a combination of the two.

When lake water receives heat from the sun, the surface waters become heated & become less dense. This separates the lake water into 2 vertical layers – an upper less dense layer called *epilimnion* & a lower more dense layer called the *hypolimnion* (Fig. 3.1 & 3.2).

These 2 layers are usually separated by a layer of rapidly decreasing temperature called the *metalimnion*. The plain within the metalimnion at which the temperature drops most rapidly i.e. 1 °C for each metre of depth is called the *thermocline*.

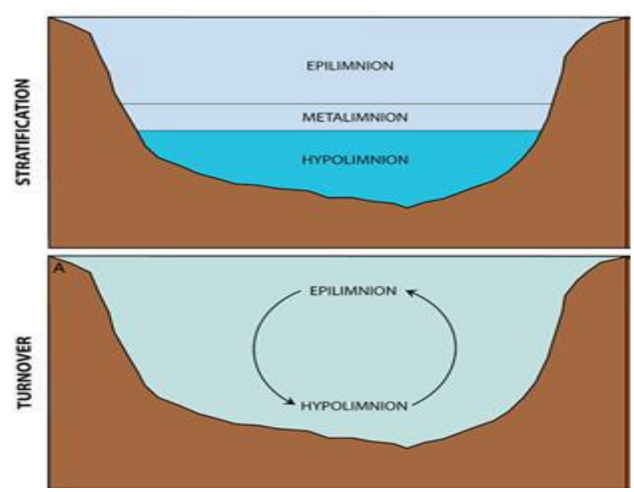


Fig 3.1 Physical structure and mixing of holomictic lake

Because the densities of the epilimnion & hypolimnion are different lakes are not able to mix during such times (Fig 3.1a). When a lake divides into an epilimnion & a hypolimnion as a result of temperature differences, it is said to be thermally stratified (*thermal stratification*).

As the temperature of the surrounding atmosphere of the lake declines, the temperature of the epilimnion begins to'decrease until it becomes equal to that of the hypolimnion. When this happens, the densities of the epilimnion & hypolimnion become the same & the lake starts to mixe (Fig 3.1b).

NB: In lotic systems, because of the continuous flow of water, thermal stratification, & consequent temperature &/or nutrient or chemically-induced stratification usually does not happen or are not pronounced.

However, temperature has other effects in lotic systems. In general, the temperature of small lotic systems such as streams tends to rise & fall with the surrounding air temperature. Rivers with large surface areas that are exposed to the sun generally are warmer than those with trees & shrubs on their banks.

Classifying Lakes According to Mixing
Lakes that do not mix at all in an annual cycle are called *amictic* lakes. They are usually permanently covered with ice. *Monomictic* lakes mix once in a year. *Polymictic* lakes mix several times in a year. *Dimictic* lakes mix twice in a year.
Lakes that mix entirely i.e. to the bottom are called *holomictic* lakes (Fig 3.1b). Lakes that do not mix entirely or to the bottom i.e. mix partially are called *meromictic lakes* (Fig 3.2).

NB: The region of lake water that mixes at a particular period or time is called the *mixed layer* or mixed depth often designated Z_{mix}.

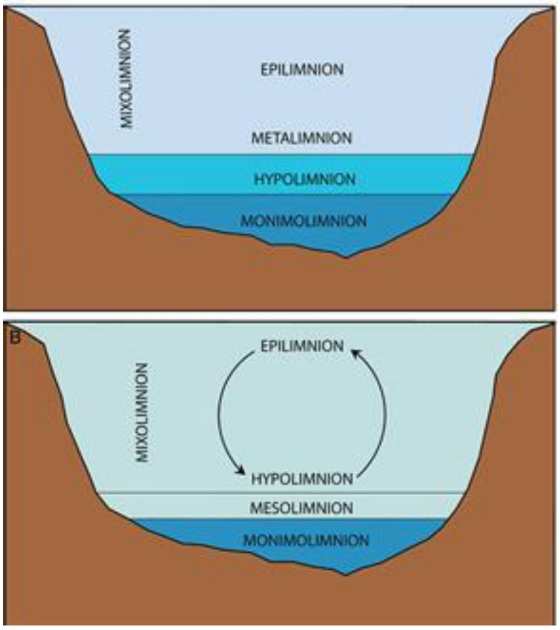


Fig 3.2 Physical structure and mixing of meromictic lakes

Meromictic lakes are divided into 2 portions - the portion that mixes in an annual cycle called the *mixolimnion* & the portion that does not mix in an annual cycle called the *monimolimnion* (Fig 3.2).

Measurement of Temperature in Water
This can be done either by directly using a temperature measuring device to take the temperature of the water directly or by using an appropriate container to take a water sample from the water before taking the temperature. Thus, it can be taken with;
a) <u>fluid thermometers</u> e.g., mercury, thermometer which can be used to directly measure surface but not underwater temperatures

b) thermister electrical thermometers are based on electrical resistance which changes as temperature changes. The apparatus is usually put in the water body &

left there for the duration of the experiment and then taken out.

c) thermobathymograph is an instrument for measuring & recording continuous vertical profiles of temperature with depth

ii). *Light*

Light is important for assimilation by aquatic primary producers & also for the distribution of various aquatic organisms. Aquatic animals depend on it for moving about, detecting prey, & spotting predators. Again, high light intensities can depress primary productivity in surface waters of aquatic systems. In addition, the UV component of light is also damaging to different kinds of aquatic organisms.

Light Zonations in Lakes

Similar to a temperature, a lake can be divided into different layers based on the availability or penetration of light.

Photic zone (Z_{eu}) – is the portion of the lake volume in which autotrophic photosynthesis is on a daily basis, greater than autotrophic respiration. It is operationally defined as the zone in which photosynthetically Active Radiation (PAR) is ≥ 1 % of that entering the water. It is also called the *euphotic* or *trophogenic zone* (fig 3.3).

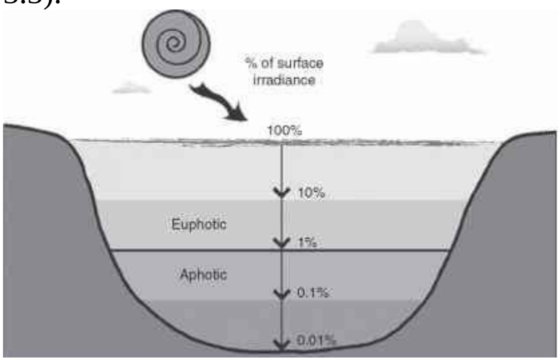


Fig 3.3 Light zones in lentic systems

Aphotic zone – is the volume of water or the area of sediments where PAR is < 1 % of that entering the water & where plant respiration is greater than plant photosynthesis. It is also called the *tropholytic/profundal zone* (fig 3.3).

NB: The depth within the water column at which photosynthesis just equals respiration is called the *compensation depth*. It defines the lower boundary of the Z_{eu} zone.

The thickness of the Zeu can be mathematically expressed as:

$$Z_{eu} = \ln 100/k \text{ or}$$

$$Z_{eu} = 4.6/k$$

where k is extinction coefficient

Measurement of Light in Water

About half of solar energy is absorbed & scattered in the various layers of the atmosphere, so that the amount reaching aquatic surfaces is about 50 % of that received at the top of the atmosphere. Some of this is reflected back into the atmosphere (4 %) from these surfaces (Fig. 3.4).

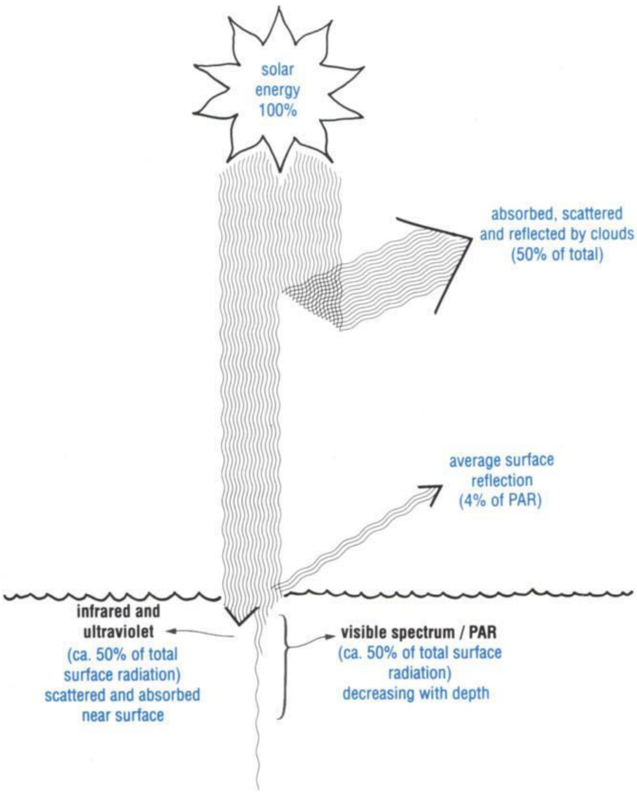


Fig 3.4 Passage of insolation through atmosphere & aquatic surfaces & the proportion of PAR

Of the solar radiation striking aquatic surfaces, visible light (i.e. portion detectable by the eye & important in photosynthesis i.e. 380-780 nm), is one of many forms of electromagnetic (EM) radiation the earth receives. Visible light may be broken down into the familiar spectrum of the rainbow with each colour having its own wavelength & associated energy. A combination of all these wavelengths produces white light.

Aquatic systems transmit the visible light portion of the EM spectrum. About 60 % of the entering or incident light energy is absorbed in the first metre, & about 80 % is gone after 10 m (33 ft), etc. Despite this, water is generally considered to have a *low light absorption coefficient* i.e. the fraction of light absorbed per metre is low in the photosynthetic/visible region (400 – 700 nm) but high in the infra-red region (>780 nm) & UV regions (< 380 nm). Thus, there is an exponential decrease of light intensity with depth. An extinction coefficient, *k*, is calculated to express this decrease of light. Again, not all wavelengths of visible spectrum are transmitted equally (Fig. 3.5).

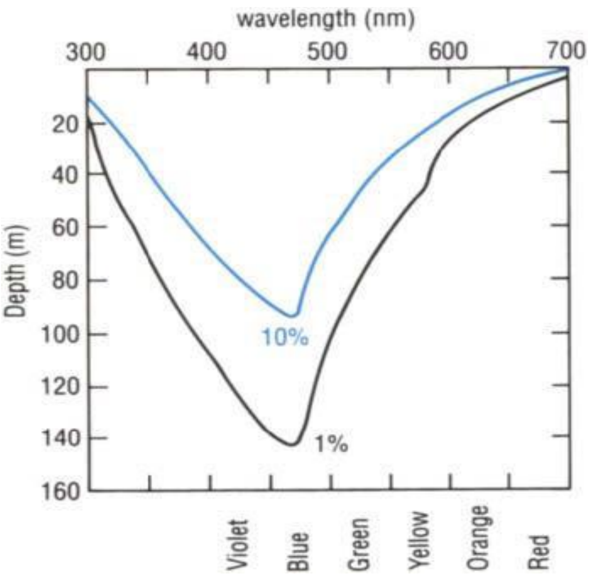


Fig 3.5 Penetration of light of different wavelengths into clear aquatic system: lines indicate the depths of penetration for 10% & 1% of the surface light levels respectively.

The long wavelengths at the red end (650 nm) of the spectrum are lost very rapidly in the first 10 m, i.e. have high *k* of about 0.140 m^{-1} whiles the shorter wavelengths of blue-green light (450 nm) are transmitted to greater depths i.e. have lower *k* of about 0.035 m^{-1} (Fig. 3.5).

Underwater Light/Irradiance

When light passes from air into water it is bent or *refracted* because its speed is faster in air than in water. Also as light passes through the water it is not only *absorbed* & refracted but it is also *scattered* by suspended particles (silt, single-celled organisms, water itself & also salt molecules). Again, despite this, water is believed to have *low light scattering coefficient* i.e. the fraction of light scattered per metre by the water itself is low. Thus, the total extinction coefficient (k_t) is a composite of absorption by the water itself (k_w), suspended particles in the water (k_p), & especially by dissolved compounds (k_c).

$$k_t = k_w + k_p + k_c$$

Measurement of this transmission or absorption can be done in several ways:

The amount of absorption through a given depth of water may be expressed in %;

$$\% \text{ absorption} = 100(I_o - I_z)/I_o$$

where I_o = irradiance at lake surface; Iz = irradiance at depth z

Rather than expressing the amount of underwater PAR as a % of surface PAR, limnologists often use the vertical extinction or attenuation coefficient (k) which is the slope of the graph obtained when a plot is made of successive depths in a lake against the log**e** or natural log of the amount of light measured at that particular depth. This gives rise to an exponential curve described by the equation;

$$I_z = I_o e\text{-}kz$$

$$\text{or } \ln I_o - \ln I_z = kz$$

where I_z is the energy flux or photon density i.e. solar radiation at depth z (m); Io is the intensity a few metres below the surface; e is the base of natural log value of 2.303, &

k is the vertical extinction coefficient (ln units m^{-1}). The above equation can be simplified and expressed in log10 form as

$$k = (\ln I_o - \ln I_z)/z$$

$$\text{or } k = 2.303(\log_{10} I_o - \log_{10} I_z)/z$$

A relatively clear lake will have a shallow slope or extinction coefficient (e.g. $k = 0.1 – 0.7$) indicative of a very gradual rate of light absorption. A relatively turbid lake would have a steeper slope (e.g. $k = 0.8 – 2.0$) indicative of a relatively rapid rate of light absorption.

NB: *k* can be used to derive the depth at which a particular % of light is found e.g. 100%, 75%, 50%, 25%, 10%, 5%, 1%, etc through the equation below:

$$\text{Depth } (x) \text{ \% light} = \ln (100/x)/k$$

The % of light transmitted per metre or *transmissivity* of water is also used as a measure of water clarity. It denotes the amount of light that enters a specific metre of a water body & makes it all the way through that metre without being absorbed & is expressed as:

$$\text{\% transmissivity} = 100*e^{k}$$

where *k* is the slope of the light-depth relationship or the vertical extinction coefficient.

Hence, a relatively clear lake with a *k* of 0.1 m^{-1}, will have a transmissivity of 90.4 % ($100*e^{-0.1}$). In other words, 90.4 % of the light that enters a particular metre of water travels all the way through that metre without been absorbed.

If many particles are present in the water, blue light is scattered more than red, & this affects the colour spectrum of underwater light, resulting in a shift of the most deeply-penetrating wavelength toward a green colour (Fig. 3.5).

Limnologists use a *light metre* in a watertight case to measure the intensity of light, first at the surface & then at increasing depths. Light [quantum] metres measure total available light, or they may be equipped with filters to measure only specific wavelengths.

Two light units used for biological studies in aquatic systems are the einstein (E), which measures photons (1 einstein is 1 mole of photons, or 6.02×10^{23} photons), & the watt (W), which measures the energy of radiation. The energy of radiation depends on the wavelength of the light, but for photosynthetic radiation (400 to 700 nm), 1 W m^{-2} is approximately equal to 4.16 µE m^{-2} s^{-1}.

Visibility

Considerable effort is associated with actually collecting metre by metre measurements of electromagnetic radiation and then analysing the data to derive ***k***. The simplest way of measuring light attenuation in surface water in the absence of a light meter is to use a Secchi disc – a white or black & white, circular disc, with a diameter of between 20-25 cm. This is allowed to sink slowly on a line marked in metres until its outlines just disappear. The depth at which this happens is the depth of visibility & is a measure of the transparency of the water.

In the absence of underwater light measuring instruments, the *k* is estimated from the depth at which the Secchi disc disappears from view (Z_{SD}) by the equation:

$$k = 1.7/Z_{SD} \text{ or}$$

$$k \times Z_{SD} = 1.7$$

The *advantages* of the Secchi disc compared to the photometers & quantum metres include:

- the fact that it does not need adjustment,
- its low costs,
- it never leaks, &
- it never requires replacement of electronic components

iii). *Turbidity*

This is the level of opaqueness of a water body. High turbidity causes light to be absorbed & scattered rather than transmitted. It is caused by suspended inorganic & organic matter. The sources of turbidity include:

a) soil erosion

b) water discharge

c) urban runoff

d) phytoplankton/algal abundance

e) bioturbation (disturbance by organisms) by large numbers of bottom-feeders

f) resuspended sediments from wave action

High turbidity in water systems poses several water quality *challenges* for aquatic organisms as well as humans:

1. It impairs water quality for domestic & industrial users & is a major concern of water treatment operations where suspended particulate matter must be removed prior to use for domestic or industrial purposes.
2. It decreases its visual appeal for recreational users.
3. It causes a decrease in the DO-holding capacity of aquatic systems. This is because many suspended solids have lower heat capacities & hence absorbs heat quickly & warm the water bodies. Since warm waters have lower capacity than cold water to hold DO, this warming leads to reduction in DO availability & potential fish kills due to asphyxiation.
4. Also, because high turbidity reduce clarity of water, aquatic plants at the bottom of rivers, streams, lakes, etc receive less light leading to decrease photosynthesis & a lowering of the system's capacity to support more aquatic organisms.
5. It can also lead to low DO by reducing photosynthesis which produces the oxygen in the first place.
6. In addition, it can clog fish gills & cause them to asphyxiate & die.
7. Moreover, some fishes are visual feeders & require a relatively transparent water to spot & eat their food. High turbidity prevents this & this may lead to a reduction in growth rates & potential starvation to death.
8. Furthermore, fish eggs & larvae may be buried by increased sedimentation of suspended matter at the bottom. This may destroy them or impair their growth.
9. Again, reduction in DO as a result of high turbidity may adversely affect macroinvertebrates many of which serve as food for fish.

Sometimes, however, some amount of turbidity may be good for the fishes in a water body depending on the nature of what is causing the turbidity. For instance, if the turbidity is caused largely by fish-edible phytoplankton, then it may be beneficial to the fishes & vice versa.

Turbidimeters are used to measure the turbidity of water.

iv). *Water Current*

Downstream water movement or flow in a lotic system is called *current* and is probably the single most important factor affecting organisms in a lotic channel. For instance the mechanical pull of the water current creates a constant risk that an organism inhabiting a certain portion of it may be drawn into other areas having less than optimal conditions.

Current velocity is dependent on various factors such as:

1. Friction between with the bottom and sides of the channel, with channel sediments, and with the atmosphere;
2. Sinuosity (bending or curving) of the stream lotic channel; and
3. Obstruction of the channel;

Also, factors such as climate, vegetation, topography, geology, soil characteristics, and land use in and around the lotic *channel* e.g., river channel, stream channel, etc affect current velocity.

Lotic discharge e.g., *stream discharge* or *flow volume* is defined as the volume of water passing through a cross-sectional area of a stream or river channel per unit time & is calculated as;

$$Q = Av$$

where Q is discharge (m^3s^{-1}), A is cross sectional area (m^2), & v is the mean velocity (m^{-1})

Adaptations of Organisms to Lotic Currents

Current in lotic systems is the outstanding feature of lotic systems and the major factor limiting the distribution of organisms. It is determined by the steepness of the bottom gradient, the roughness of the stream bed, and the depth and width of the stream bed. Lotic currents have promoted many special adaptations:

1. Attachment to firm substrates such as logs, stones, leaves, etc. Organisms in this group are primarily made up of primary producer plants and animals e.g. diatoms, green algae, caddis fly larvae, freshwater sponges, etc;
2. The use of hooks and suckers – these organisms have the unusual ability to remain attached and withstand even the strongest rapids e.g. the Diptera larvae *Simulium* and *Blepharocera*;.
3. A sticky undersurface – e.g. snails and flatworms which are able to use their sticky undersurface to adhere to underwater surfaces;
4. Flattened and streamlined bodies – most aquatic macroconsumers or nekton e.g. fishes have streamlined bodies which offer minimum resistance to water current. Some have flattened bodies which enable them to stay under rocks and in narrow places e.g. beetle larva, stonefly nymphs, etc;
5. Positive rheotaxis is an inherent behavioural trait of lotic animals (especially those able to swim) to orient themselves upstream and swim against the current;
6. Positive thigmotaxis is another inherent behavioural trait for many stream animals which cling close to a surface or keep the body in close contact with the surface.

Measurement of Current in Lotic Systems

a) Colour method – Crystals of potassium permanganate or other substances that are strongly coloured & are readily soluble in water are placed on the bottom in glass tubes opened at both ends or with both ends drawn out to a point, & the direction of the coloured stream of water that emerges is directly followed. Its diffusion & the movement of the water can be measured with a stopwatch with some degree of accuracy.

b) Drift method – acts on the principle that an object floating on the surface of a lotic system is carried along at a speed corresponding to that of the water current. If the time required for its transport between two points is recorded, the speed of the current can be calculated.

Chemical Factors affecting Inland Waters

Just like physical factors, chemical factors also affect the condition of existence of aquatic organisms of inland waters. For Instance, there are the:

- *major inorganic substances* like Na, Cl, Ca, bicarbonates, and sulphates which act largely to determine the type of organisms that can be found in particular aquatic environments;
- *minor inorganic substances* or ions such as ammonium, nitrates, phosphates, etc which act to determine the abundance of the different aquatic organisms that can be found in particular environments;
- included in the minor inorganic substances are the so-called *trace elements* as well as the *vitamins*, *amino*, *carboxylic* & other simple acids; and
- finally, there are also the concentrations in which all these inorganic & organic substances occur, either separately or in

relation to each other & how that contributes to the *salinity* & *conductivity* of aquatic systems; &

- there are also the impacts of *gases* like O_2 & CO_2 & their impacts on alkalinity, acid rain, oxidation reduction potential, etc

Some of the chemical conditions or factors of aquatic systems which affect aquatic organism include;

- Hydrogen ion concentration (pH),
- Redox potential (Eh)
- Dissolved Oxygen (O_2)
- Biological Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Nutrients (organic & inorganic compounds e.g. N, P, Si, etc),
- Conductivity, TDS, etc

i) Hydrogen Ion Concentration (pH)

This is an indication of the strength or concentration of the hydrogen ions in water & it has a strong impact on the metabolism of water plants and animals. pH ranges from 1 to 14 on the negative log scale.

pH values from 6 down to 0 indicate increasing acidity whiles values from 8-14 indicate increasing alkalinity. Most naturally- occurring waters vary around a pH of 7.

NB:

i) pH scale though based on [H+] also implies [OH^-]. For instance, a solution of pH = 10 has a [H^+] = 10^{-10} M and an [OH^-] of 10^{-4} M.

ii) Using a log scale for pH also means that one-unit change in pH represents a 10-fold change in H^+ concentration. For instance, a solution of pH 3 is not twice as acidic as a solution of pH 6, but 1000 times more acidic. This means that when the pH of a solution changes slightly, the actual concentration of H^+ and OH^- ions change substantially.

Measurement of pH

This can be done either by colour reactions of organic compounds (pH indicators) also called *colorimetric methods* (e.g. pH paper, etc) or by *electrometric methods* using pH meters. The pH meters are more reliable and less expensive overall than the colour indicators.

Note*: *Acid Rain, Alkalinity & the Carbonate System

Rain water has a pH of about 5.6 due to the formation of weak carbonic acid (H_2CO_3) from CO_2 & H_2O. Acid rain refers to more acidic rain water with pH less than 5.6. It is caused by oxides of nitrogen & sulphur mostly from human activities which react with rain water in air forming the strong nitric and sulphuric acids.

The alkalinity of a solution is a measure of the amount of ions present that can react with, or neutralize, H^+. The higher the alkalinity of a solution, the more difficult it is to produce a pH change in the solution by adding acid. Therefore, the alkalinity of a solution is a measure of its acid buffering or neutralizing capacity. It is also called alkaline reserve or total alkalinity. It is a measure of the ability of water to resist changes in pH caused by addition of acids & hence the main indicator of the susceptibility to acid rain. In addition to OH^-, ions such as HCO_3^- (bicarbonate), & CO_3^{2-} (carbonate) & to a lesser extent borates, silicates, & phosphates, are important components in the alkalinity of natural waters. Bicarbonate can take up 1 H^+ ion while carbonate can take up 2 H^+ ions, in each case, a molecule of carbonic acid (H_2CO_3) is formed. These can be expressed as:

$$H^+ + HCO_3^- = H_2CO_3 \text{ (eqn 1.6)}$$

$$2H^+ + CO_3^{2-} = H_2CO_3 \text{ (eqn 1.7)}$$

The alkalinity of seawater comes predominantly from HCO_3^-, CO_3^{2-}, & OH^- ions. An equation for the alkalinity is expressed by the sum of the ion concentrations multiplied by the number of H+ ions each can take up.

$$\text{Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \quad \text{(eqn 1.8)}$$

The subtraction of $[H^+]$ recognizes that the addition of acid serves to lower the alkalinity of acid buffering capacity of the solution.

The pH of surface seawater is about 8.2 i.e. it has a $[H^+]$ of $10^{8.2}$ or about 7 x 10^{-9} mole L^{-1}. It is expressed in mg/L of $CaCO_3$ or as μeq/L (20 μeq/L = 1 mg/L). *Negative alkalinity* refers to the *acidity* of a system. The alkalinity of surface seawater is typically 0.0023 moles L^{-1} (as HCO_3^-); thus, there are orders of magnitude more HCO_3^- & CO_3^{2-} ions than there are H^+ ions in seawater. This gives seawater a huge capacity to neutralize or buffer, acids. If more H^+ ions are added to seawater, they combine with the HCO_3^- & CO_3^{2-} ions & hence, there is no net change in pH.

The *carbonate system* in aquatic systems involves the following equilibrium equations:

$$H_2O(g) = H_2O(aq) \quad \text{(eqn 1.9)}$$

$$CO_2(aq) + H_2O = H^+ + HCO_3^- \quad \text{(eqn 1.10)}$$

$$HCO_3^- = CO_3^{2-} \quad \text{(eqn 1.11)}$$

$$Ca^{2+} + CO_3^{2-} = HCO_3^- = CaCO_3(s) \quad \text{(eqn 1.12)}$$

The carbonate system is very important since it regulates the pH of aquatic systems & controls the circulation of CO_2 between the biosphere, lithosphere, atmosphere, & the hydrosphere. Recent interest of this system in the ocean has resulted from the greenhouse effect (GHE) of CO_2. Since CO_2 can absorb infra-red energy, this increase may cause the temperature of the earth to increase & could eventually melt the polar ice caps. The increase in CO_2 is related to the burning of fossil fuels (coal, petroleum, & natural gas), & the production of cement. When atmospheric CO_2 becomes available from these processes, it can be used for primary production & weathering processes. The CO_2 can enter the ocean & other aquatic systems by physical processes called the solubility pump & by biological processes called the biological pump. Once CO_2 enters aquatic systems across the air-seawater interface & participate in the equilibrium processes outline in equations 1.90 to 1.12 above, they can also be used by plants in primary production.

Note that although HCO_3^- & CO_3^{2-} ions are created in the carbonate system, there is no net increase in alkalinity through these reactions, but there is a decrease in pH. The alkalinity does not change because for every molecule of HCO_3^- added in the alkalinity equation, one mole of H^+ is created that must be subtracted from the equation. Likewise, for every molecule of CO_3^{2-} added, 2 new H^+ must be subtracted. The new H^+ molecules however, add to the concentration of acid, & the pH decreases. Note that seawater has a lot of excess HCO_3^- & CO_3^{2-}. These ions quickly grab the H^+ molecule & then neutralize them through the reactions above (eqn 1.6 & 1.7) & thus raise the pH of seawater back to its previous value.

It is possible for the CO_2 input to exceed the buffering capacity of an aquatic system. The pH of such a system will then start to fall, but carbonate sediments on the ocean floor may also act as a buffer. If carbonate sediments are present, the decreased pH will cause them to dissolve in the following reaction:

$$H^+ + CaCO_3 = Ca^{2+} + HCO_3^- \text{ (eqn 1.13)}$$

This reaction introduces additional HCO_3^- into aquatic systems, increasing the alkalinity & the buffering capacity & bringing the pH back to its original value. The alkalinity & availability of carbonate sediments gives the aquatic systems a large buffering capacity for CO_2. In fact, the oceans apparently have removed a large fraction of the CO_2 added to the atmosphere by fossil fuel burning without producing a significant change in seawater pH.

ii). *Oxidation-Reduction Potential* (Eh)

This is also called *redox potential*. It is expressed in millivolts (mV) & related to the presence of molecular oxygen or reduced compounds such as hydrogen sulphide, ferrous iron, & sulfhydryl groups. Positive Eh values indicate oxidative conditions & negative Eh values indication anaerobic or reducing conditions. The Eh values of natural waters usually lie between +400 & +435 mV at pH 7.6 to 8.3.

All organisms & also all chemical reactions of biological importance occur within certain pH, Eh, & temperature parameters. If these are known for a given environment, one has gone a long way towards characterizing that environment & can to a considerable degree, predict which kinds of organisms & biological processes may be expected to occur there & which would be excluded. Similarly, if one knows the bounds of these parameters, within which a given organism or a given chemical reaction can occur, one can predict in what types of environment it can be found.

The Eh is controlled by photosynthesis & respiration. Photosynthesis acts on the system by utilizing CO_2 & HCO_3 & releasing oxygen, or removing hydrogen, thus tending to raise both the Eh & pH. Respiration has the reverse effect. The values in shallow or surface waters tend to rise by day & be depressed during the night.

iii). *Dissolved O_2 (DO) Content of Water*

DO provides valuable information about the biological & biochemical reactions going on in waters; it is a measure of one of the most important environmental factors affecting aquatic organisms & of the capacity of water to receive organic matter without causing nuisance (Table 3.1).

Table 3.1 DO requirements of salmonid fishes

a. Embryo and larval stages	**mg/L**
No production impairment	11
Slight production impairment	9
Moderate production impairment	8
Severe production impairment	7
Limit to acute mortality	6
b. other life stages	
No production impairment	8
Slight production impairment	6
Moderate production impairment	5
Severe production impairment	4
Limit to acute mortality	3

Oxygen may be added to water from the atmosphere or as a by-product of photosynthesis from aquatic plants & is utilized by many respiratory biochemical, as well as inorganic chemical reactions.

The oxygen concentration of a water body can also be used to demarcate zones within it. For instance the monimolimnion of meromictic lakes which do not mix at all tend to have very low oxygen levels or no oxygen at all. Similarly lake & river sediments may also lack oxygen. Such zones are called *anoxic zones*. In contrast to anoxic zones, the surface of inland water bodies & oceans are usually well mixed & often contain oxygen that come from the atmosphere & also release from oxygenic photosynthesizers such as phytoplankton, periphyton, macrophytes, etc. Such zones are characterized as *oxic zones*.

Table 3.1, 3.2 & 3.3 below shows oxygen requirement of different types of fishes.

NB: Fish require at least 5 mg/l of oxygen & below about 3 mg/l, many aerobic aquatic organisms cannot survive. *Hypoxia* occurs when oxygen concentrations fall below about 2 mg/l. Fish kills can result when bottom waters become hypoxic. *Anoxia* occurs when concentration reach 0 mg/l.

Table 3.2 DO requirements of non-salmonid fishes

a. Embryo and larval stages	**mg/L**
No production impairment	6.5
Slight production impairment	5.5
Moderate production impairment	5
Severe production impairment	4.5
Limit to acute mortality	4
b. Other life stages	
No production impairment	6
Slight production impairment	5
Moderate production impairment	4
Severe production impairment	3.5
Limit to acute mortality	3

Methods for Measuring DO

Chemical methods: The Winkler method or some modification of it is the most frequently used chemical method for determining dissolved oxygen in water.

Oxygen-sensitive electrodes: provide a rapid and sensitive measurement of DO. For instance, polarographic oxygen sensors consist of platinum anode & a gold-plated cathode, encased in an electrolyte-filled housing and separated from the water by an oxygen permeable membrane. Oxygen must diffuse through the membrane & electrolytic solution to the electrodes. The quantity of oxygen reduced per unit time is directly proportional to the oxygen concentration in the water, & the resulting electrical current is measured with a meter.

iv). *Biological Oxygen Demand* (BOD)

This refers to the amount of readily decomposable organic materials in a sample of water or a measure of the amount of oxygen needed to decompose organic matter in water. A water body with a high BOD has low oxygen concentration because oxygen is being used by bacteria to decompose organic matter. Consequently, a water body with a high BOD is also high in organic matter.

This is measured by usually incubating water samples for 5 days in the dark at 20 °C. The water sample is first taken with 2 or 4 clean glass bottles. Two of the samples taken are immediately used to determine the initial oxygen concentration using the Winkler method while the other 2 are incubated for 5 days at 20 °C in the dark. Thereafter, the DO concentrations of the incubated water samples are also determined. The average DO concentration of the two incubated (dark) bottles is then subtracted from the average of the two initial oxygen determinations to obtain the BOD:

$$BOD_5\ (mgl^{-1}) = [DO]\ \textbf{initial} - [DO]\ \textbf{dark}$$

v). *Chemical Oxygen Demand* (COD)
It is a measure of the amount of oxygen that is required to oxidize all of the organic & inorganic compounds in a particular water body. It is used as an indicator of water or effluent quality. It measures oxygen demand by chemical means using potassium dichromate as the oxidizing agent. BOD only measures the oxygen used in breaking down the biodegradable organic portion in 5 days. COD oxidation takes just 2 hours & the method is thus much quicker than a 5-day BOD assessment. Since the BOD:COD ratio is fairly constant for a given effluent, COD is routinely used for monitoring an effluent once this ratio has been determined. The COD of a water sample is measured by adding concentrated H_2SO_4 and chromium to the sample and then determining the maximum oxygen consumption of the sample.

vi). *Conductivity & Salinity of Water Bodies*
Conductivity is an estimate of the amount of total dissolved solids (TDS), or total amount of dissolved ions in a water body or sample. It can be estimated using the relationship:

TDS (mg/L) = 0.5*1000Conductivity (µS/cm)

Studies of inland freshwaters indicate that those that support good mixed fisheries have a conductivity range of between 150 - 500 µScm-1. Industrial waters can have conductivities that range as high as 10 000 µScm-1.
Electrical conductivity is used to determine a number of applications related to water quality. These include:

a) Determining mineralization or total dissolved solids (TDS) which is used as an index of the ionic effect of a water source. Certain physiological effects on aquatic fauna and flora are often affected by the number of available ions in the water.

b) Noting changes in natural and waste waters quickly

c) Estimating the sample size needed for other chemical analysis, and

d) Determining the amount of chemical reagents or treatment chemicals to be added to a water sample.

e) Determine the salinity of waters.
NB: *Salinometers* are the instruments for measuring electrical conductivity of a water body or sample.

Salinity of Waters
The quantity of chloride ions in a water sample is used to establish the salinity of the sample. To do this, silver nitrate is added to the sample to react with the chloride ions. Once the amount of silver nitrate required to react with all the chloride ions in a sample is known, then the amount of chloride is also known. The chloride concentration measured in this way is termed *chlorinity* (C‰) measured in parts per thousand or grammes of chloride per kilogramme of water sample. When the chlorinity of a sample is known, the concentration of any other major constituent can be calculated using the rule or principle of constant proportions. Chlorinity & salinity are related by the equation:

Salinity (‰) =1.80655 x Chlorinity (‰)

Various nomenclatures have also been developed for various types of water based on salinity (Table 3.3).

vii) *Biolimiting Nutrients & Redfield Ratios*
Some insights into the nutrient requirements of primary producers can be derived from a chemical analysis of their protoplasm. All organisms are made up mostly of the elements CHOPN and P. While different types of organisms may require differing amounts of trace elements, the proportions of these elements are sufficiently consistent that they have been formalized as the Redfield ratio:

$$C_{106}H_{263}O_{110}PN_{16}P_1$$

Ions & other chemical compounds required by organisms for maintenance, growth & development are called *nutrients*. They are the fertilizers of aquatic systems. As on land, plants require phosphorus & nitrogen but utilize them mostly in the form of phosphate (PO_4^{2-}) & nitrate (NO_3^-) ions. Silicon or the silicate ion (SiO_4^-) is needed to form the hard outer walls of single-celled plants called diatoms & skeletal parts of some protozoans in aquatic systems. These 3 nutrients are among the dissolved substances brought to aquatic systems by land runoff from cities, crop & animal farms, factories, etc. Despite their importance, their levels in natural waters are usually very small.

Nutrients are removed from the water as the plant populations grow & reproduce & are then returned to the water as the organisms die & decay. They are cycled into the animal populations as the animals feed on the plants. These animals may be eaten in their turn, & eventually the nutrients are returned to these aquatic systems by way of death & bacterial decomposition. Excretory products of these animals are also added to the water, to be broken down & used again by a new generation of plants & animals.

1. *Phosphorus* is a key metabolic nutrient & its supply often regulates the productivity of natural waters. Natural sources of phosphorus include rainfall, & phosphates from weathering of phosphatic minerals. Anthropogenic sources include quarrying, agriculture, tillage, & sewage treatment, etc. When aquatic ecologists compare nutrient availability with algal community's nutrient requirements, they often find that phosphorus is the nutrient limiting production of algal biomass. Thus, on average, it is the scarcest element in the earth's crust of those elements absolutely required for primary producers & therefore for subsequent trophic levels. Reasons for phosphorus limitation in water bodies include;

- Rock breakdown in watersheds release little biologically available phosphorus to water bodies
- The root zone on land intercepts & retains most soluble phosphorus compounds
- There is no gaseous phase in the phosphorus cycle & so rainwater contains little i.e. there is no reservoir of gaseous phosphorus in the atmosphere like there is for CO_2, O_2, N_2, etc.
- It is relatively insoluble. But any soluble phosphorus released into water bodies is also rapidly adsorbed onto particle or precipitated with other compounds and is not readily available to aquatic primary producers

Phosphorus is needed in the formation of proteins & nucleic acids. The phosphorus cycle is largely abiotic or sedimentary compared to the nitrogen cycle which is regulated primarily by biological activity.

2. *Nitrogen* – For nitrogen, despite the huge atmospheric reserve, it is relatively unreactive & therefore available to only a few organisms called nitrogen-fixers all of them prokaryotes. Nitrogen is converted to available compounds by atmospheric lightening, UV-radiation, & by nitrogen fixers. Like phosphorus, it is also needed in the formation of proteins & nucleic acids.
Thus, fixation of molecular nitrogen by biological, meteorological, or industrial processes is the primary source of inorganic nitrogen for ecological systems. But most nitrogen in organic matter exists as amino groups in protein.

3. *Sulphur & hydrogen sulphide*
Sulphur is important in protein structure but rarely limits the growth & distribution of aquatic biota. This is due to the abundance of the element, primarily in its most energetically stable form, sulphate (SO_4^{2-}).

The complex 3-dimensional structure of enzymes & other proteins is partially due to bridges between 2 sulphur atoms, which stabilize the geometry of the enzyme. This is the main use of sulphur in all cells but it also plays a role in cell division.

Anoxic sediments rich in organic matter release gaseous hydrogen sulphide (H_2S) to produce the familiar rotten-egg smell of decaying vegetation. In lakes & estuaries this H_2S is oxidized to SO_4^{2-} at the mud-water interface so long as there is an oxygenated microzone. Once this layer is reduced by microbial respiration, H_2S is released into the air or overlying water. H_2S may form a highly insoluble black ferrous sulphide precipitate, effectively removing available iron from solution.

Industrialization has greatly affected aquatic sulphur cycle. In recent times much sulphur in some rivers & lakes has originated from the burning of fossil fuels. The major source in most rivers remains that derived from the breakdown of parent material in the drainage basin. Atmospheric pollution caused by burning of fossil fuels is largely in the form of SO_2, which forms sulphuric acid & is the major contributor to *acid rain*. Tide flats & salt marshes also release enormous quantities of sulphur to the atmosphere from bacterial reduction of sulphate to hydrogen sulphides in the mud.

Trophic Classification of Water Bodies

Freshwater bodies can be classified on the basis of nutrient status into three types;

 Oligotrophic freshwaters from the Greek work ‘oligothophos’ meaning providing little nourishment or infertile. In other words, freshwaters having very low nutrient levels. They are usually deep, rocky basin lakes, low in dissolved substances, of low productivity, with a hypolimnion saturated with oxygen. They also characteristically have few or no macrophytes & have salmonid fish.

 Eutrophic freshwaters from the Greek work ‘euthophos’ meaning well-nourished or very fertile or freshwaters having very high nutrient levels. In contrast to oligotrophic freshwaters, eutrophic freshwaters are usually shallow and silted, with high concentrations of dissolved solids, high production, a deoxygenated hypolimnion, extensive weed beds & have non-salmonid fish.

 Mesotrophic freshwaters which have a nutrient status somewhere between eutrophic & oligotrophic freshwater bodies.

 Hypertrophic? *Dystrophic*?

UNIT FOUR
AQUATIC PLANTS AND ANIMALS

Biological Diversity in Aquatic Ecosystems

Aquatic organisms are found in all the three domains of life namely;

– *Bacteria* which are widely represented in all water bodies e.g. blue-green algae or cyanobacteria, other true bacteria

- *Arhaea* which are also ubiquitous in water bodies but are often restricted within aquatic systems to extreme environments e.g., *Methanogens* that produce methane as a waste product from respiration, *extreme halophiles* that live in extremely salty environments, *extreme thermophiles* that live in extremely hot waters &

- *Eukarya* e.g. algae, fungi, fishes, invertebrates, aquatic plants, etc.

Major Organisms of Inland Waters

The groups of organisms most familiar to aquatic scientists include bacteria, fungi, algae, macrophytes, protozoans, rotifers, crustaceans, aquatic insects, worms, mollusks, fish, amphibians, reptiles, birds & mammals.

a) *Bacteria*

The bacteria can be conveniently grouped by which energy source & electron donor they use:

i) chemotrophic bacteria – uses chemical energy & include chemolitotrophic forms which obtain energy from oxidation of inorganic compounds such as NH3, H_2S, & F^{2+} as well as chemoorganotrophic forms which obtain energy from the oxidation or fermentation of organic compounds.

ii) phototrophic bacteria – uses solar energy & include photolitotrophic forms which uses an inorganic electron donor e.g. H_2S or photoorganotrophic forms which depends on an organic electron donor.

Most bacteria of aquatic ecosystems do not contain chlorophyll or carry out photosynthesis, although a special group of anoxic photosynthetic bacteria are found in some lakes & estuaries. Anoxygenic photosynthesizers at the global scale contribute less than 1% of aquatic primary production. Like most unicellular algae, many bacteria can swim by using hair-like flagella.

Collectively, bacteria can mediate more chemical transformation than any other group of organisms. These include nitrogen transformation such as – nitrogen fixation, denitrification, nitrification, cellulose breakdown, degradation of oil, carbon & sulphur mineralization, food spoilage, disease production in plants & animals, etc.

Oxygen plays an important role in the classification of bacteria. For instance, there are obligate forms that absolutely require & others that cannot tolerate it while the facultative forms can grow with or without it.

The main role of bacteria in nature is in the recycling of organic & inorganic materials. Heterotrophic bacteria can cause decay & provide a nutritious layer for detritivorous animals feeding on decaying organic particles in lentic & lotic systems. They can also cause diseases in fish & other aquatic organisms.

Chemolithotrophic bacteria found in sediments or on particles suspended in natural waters are responsible for the oxidations of ammonia first to nitrite & then to nitrate [*nitrification*], hydrogen sulphide oxidation to sulphate, & the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}). Layers of photosynthetic chemolithotrophic purple bacteria are often found in anoxic conditions of aquatic ecosystems especially in lakes.

The rod-shaped coliform bacteria associated with sewage are particularly well-known & are always present in natural waters but high levels indicate water pollution from sewage.

NB: *Cyanobacteria* (blue greens) are true bacteria but because they possess chlorophyll *a* like the algae are often classified with them. They are responsible for many water quality problems in surface waters of lakes, rivers, & water treatment ponds. They affect the colour, taste, odour, etc of water bodies & produce a variety of toxins called cyanotoxins that causes several human health problems like gastroenteritis, dermatitis, body organ effects (primary liver cancer, etc), & sometimes death.

b) *Fungi*
These are heterotrophic organisms which lack chlorophyll & play a major saprophytic role in aquatic environments where they are important decomposition & recycling plant & animal matter together with bacteria. Three major groups are common in aquatic environments – actinomycetes, oomycetes, & true fungi.
But they have also established themselves as major parasites of important groups in fresh water environments. For instance, the fungus *Saprolegnia* sp which is well-known to fisheries biologists is a frequent parasite on dying or injured fish. Others such as chytrids (true fungi) that are common in many lakes can alter the species composition of algae. Fungi are either saprophytic or parasitic.

The thin film of bacteria & fungi present on virtually all submerged organic detritus is a major food source for invertebrates especially in rivers & lakes. Although most bacteria can use detrital cellulose, only fungi & a few bacteria possess the special enzymes that can break down lignin, which is the skeletal material of leaves.

c) *Algae*
Algae are simple mostly microscopic plants lacking roots, stems, & leaves that have chlorophyll *a* as their primary photosynthetic pigment & lack a sterile covering of cells around their reproductive cells (Table 4.1).

Table 4.1 Classification of algae in aquatic habitats

Name & typical colour	Most common aquatic habitat	Examples
Diatoms (golden-brown) Bacillariophyta	Lakes, rivers, estuaries, attached or planktonic	*Asterionella*, *Melosira*, *Nitzschia*, etc
Green algae (grass green) Chlorophyta	Lakes, ver estuaries; or plantonic attached	*Cladophora*, *Oocystis*, *Ulva*
Dinoflagellates (red-brown) Pyrrophyta	Lakes an estuaries; d planktonic	*Peridinium*, *Ceratium*, *Gymnodinium*
Blue-greens (blue-green) Cyanophyta	Lakes; o planktonic r attached	*Anabaena*, *Nostoc*, *Oscillatoria*, *Aphanezomenon*
Chrysophyta (yellow- or brown-green) Chrysophyta	Lakes, streams; planktonic	*Mallomonas*, *Dinobryon*, *Tribonema*
Cryptomonads (various colours) Cryptophyta	Lakes; planktonic	*Rhodomonas*, *Cryptomonas*
Euglenoids (various colours) Euglenophyta	Ponds, lakes; Planktonic	*Euglena*, *Phacus*, *Trachelomonas*,
Red algae Rhodophyta	Estuaries, lakes, streams; attached	*Gigartina*, *Batrachospermum*
Brown algae Phaeophyta	Estuaries; attached, free floating	*Gracilaria*, *Sargassum*

They often dominate primary production in most aquatic systems where they may be present as free-floating *phytoplankton* or attached algae (*periphyton*). The attached algae dominate the shallow areas of clear aquatic systems especially of lakes &

streams whilst the phytoplanktons dominate in the open ocean, larger lakes & the slowest reaches of rivers (Table 4.1).

The primary classification of algae into different divisions is on the basis of pigment composition, how they maintain their energy reserves, locomotory organs, & general structure (Table 4.1).
They contain 2 main groups of pigments – chlorophylls & carotenoids. *Chlorophyll* is a complex molecule composed of 4 carbon-nitrogen rings surrounding a magnesium atom. The loss of the magnesium atom produces the common degradation product – *phaeophyton*. *Carotenoids* are composed of linear unsaturated hydrocarbons called *carotenes* which give the red colour of some zooplankton, some salmon, & trout, etc.

d) *Macrophytes*
Aquatic macrophytes or *hydrophytes* are aquatic photosynthetic organisms, large enough to be seen with the naked eye, that grow permanently or periodically submerged below, floating on, or growing up through the water surface. In other words, they are the macroscopic forms of plants found in water bodies, & include flowering vascular plants including ferns, bryophytes or non-vascular plants (e.g. liverworts, hornworts, & mosses), as well as macroalgae, etc.

Much aquatic plant research has been stimulated by the need to control nuisance or invasive macrophyte species like hydrilla (*Hydrilla verticillata*), water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), *Salvinia molesta* (kariba weed), red water fern (*Azolla filiculoides*), parrot feather (*Myriophyllum aquaticum*), elodea (*Elodea canadensis*), coontail (*Ceratophyllum demersum*), & alligator-weed (*Alternanthera philoxeroides*), etc. Five of these are particularly problematic in Africa - water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), salvinia (*Salvinia molesta*), red water fern (*Azolla filiculoides*), & parrot feather (*Myriophyllum aquaticum*).
Tissue analyses of macrophytes may provide information for evaluating nutrient supplies in natural waters, for determining nutrient requirements for particular plant species or for studying bioaccumulation of trace metals, etc.

Benefits of macrophytes
1. *Provide habitat & protection* for waterfowl, fish, frogs, salamanders, turtles, insects, & other microscopic organisms
2. *Act as food sources* for mammals, birds, fish, turtles, invertebrates (such as insects), etc
3. *Help recycle O_2 & CO_2*: Plants maintain the balance in ponds by taking up CO_2 & releasing oxygen in the water, vital for fish survival & maintaining a healthy pH level.
4. *Prevent shoreline erosion* – Plants that float on the surface of the water, or emerge from the water near shore, act to buffer destructive wave action that could lead to erosion.
5. *Help improve water clarity* – Aquatic plants may act as filters to trap particles and absorb the organic particles in tea-coloured (tannic or humic) water.

Types of Aquatic Plants
Aquatic & wetland plants (macrophytes) can be classified into 4 groups: *emergent*, *floating-leaved*, *submersed*, & *free-floating* (Fig 4.1).

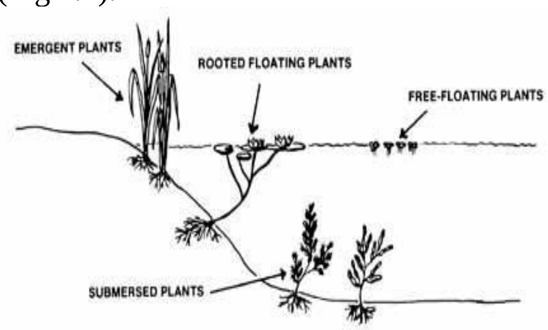


Fig 4.1 Location of aquatic plants in a stream

The distribution & growth of macrophytes depend on depth of water, illumination, nutrient availability, water quality, substrate, water velocity (rooted forms) plus wind for free-floating forms. They are often found arranged in zones corresponding to successively greater depths – the predominant vegetation in each zone been more tolerant of water depth or decreasing illumination. On this basis, they can be classified into four groups:

a) *Emergent macrophytes* are plants that are rooted in the water bottom with their base portions submersed in the water & their tops extending into the air (Fig 4.2).

They grow on periodically inundated or submersed soils. Most emergent macrophytes are *perennials*.
Common examples include bulrushes (*Scirpus* sp.), cattails (*Typha* sp.), reeds (*Phragmites* sp.), spikerushes (*Eleocharis* sp.) maidencane (*Panicum hemitomon*), pickerelweed (*Pontederia cordata*), & duck potato (*Sagittaria lancifolia*). Some emergents like wild rice (*Zizania aquatica.*), develop submersed or floating leaves before mature aerial leaves form.

Figure 4.2. Emergent plant: Bulrush (*Scirpus* spp.)

b) *Floating-leaved macrophytes* are plants that are rooted to the lake bottom, with leaves that float on the surface of the water (Fig 4.3).

Figure 4.3. Free floating plant: *Trapa natans*

They generally occur in areas of an aquatic system that always remain wet. Common examples include waterlilies (*Nymphaea* sp.), parrot feather (*Myriophylum* sp), spatterdock (*Nuphar advena.* – yellow water lily), watershield (*Brasenia schreberi*), *Trapa natans*, *Lemna minor*, etc. Floating leaves are attached to roots or rhizomes with a flexible, tough stem (actually in many cases a leaf stalk).

b) *Submersed macrophytes* are plants that grow completely under the water (Fig 4.4). They are a diverse group that includes coontail (*Ceratophyllum demersum*), quillworts (*Isoetes* sp.), mosses (*Fontinalis* sp.), muskgrasses (*Chara* sp.), stoneworts (*Nitella* sp.), & numerous vascular plants. Others include widgeon-grass (*Ruppia maritima*), various pondweeds (*Potamogeton* sp.), & tape-grass (*Vallisneria* sp.) & *Hydrilla* sp cause some of the worst aquatic weed problems. They tend to grow rapidly to the water surface, & they can form dense canopies in the upper water column that interfere with both the use & the aesthetics of the water body (Fig 4.4).

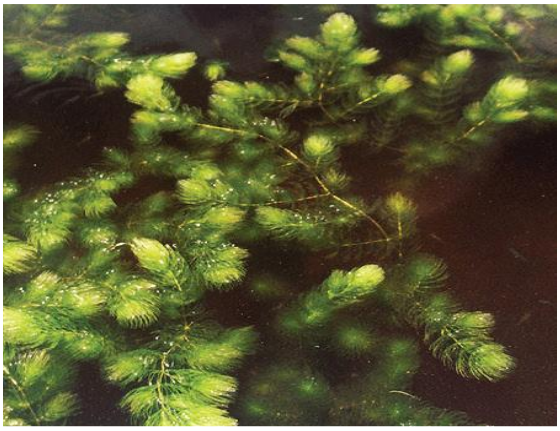


Figure 4.4. Submersed plant: Coontail (*Ceratophyllum demersum*).

d) *Free-floating macrophytes* are a diverse group of aquatic plants that typically float on or just under the water surface with their roots in the water & not in the sediment (Fig 4.5). Small free-floating plants include duckweeds *(Lemna spp.*), mosquito fern (*Azolla caroliniana*), water meal (*Wolffia columbiana*), & water fern (*Salvinia spp.*). Larger free-floating plants, including water hyacinth (*Eichhornia crassipes* – Fig 4.5) & water lettuce (*Pistia stratiotes*), are the number one targets for aquatic plant management in several places around the world. Others include fragrant waterlily (*Nymphaea odorata*), yellow waterlily (*Nymphaea mexicana*) & American lotus (*Nelumbo lutea*).

Figure 4.5 Free floating plant: Water hyacinth (*Eichhornia crassipes*)

Free-floating species are entirely dependent on the water for their nutrient supply. In fact, some e.g., water hyacinth (*Eichhornia crassipes*) have been used in wastewater treatment to remove excess nutrients. If nutrient limitation will work for macrophyte management, this is the group for which it will most likely work. Free-floating plants are also the only aquatic plants not constrained by water depth. The location of these plants is at the whim of wind, waves, & current. They grow & multiply extremely quickly.

Aquatic plants and the Littoral Zone

Rooted aquatic plants inhabit the *littoral zone*, the interface between dry land & open water of lakes & reservoirs or the area from the lake's edge to the maximum water depth where rooted plant growth occurs.

The littoral zone has traditionally been divided into 4 distinct transitional zones (Fig. 4.6):

- *Eulittoral zone*,
- *upper littoral zone*,
- *middle littoral zone*, &
- *lower littoral zone*

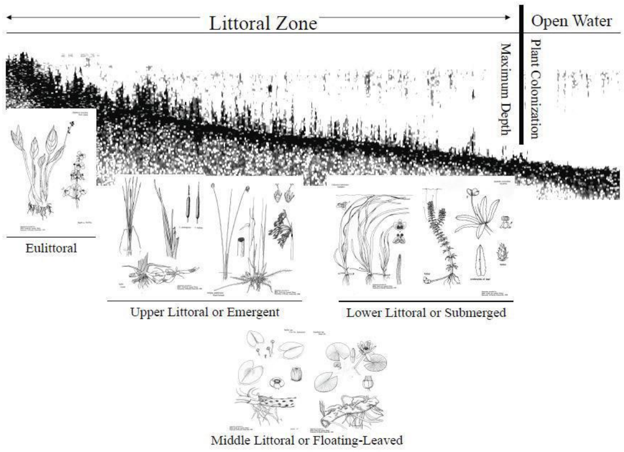


Figure 4.6 Diagram of a lake's littoral zone with different macrophytes

i) The *eulittoral zone* constitutes that part of the shoreline that lies between the highest & lowest seasonal water levels & often contains many wetland plants.
ii) The *upper littoral zone* is commonly called the emergent plant zone & is generally dominated by emergent plants. It extends from the water's edge to depths of about 1 to 2 m.
iii) The *middle littoral zone* is deeper & is generally dominated by floating-leaved plants. It extends lake-ward from the upper littoral zone to water depths of 1 to 3 m.
iv) Finally, the *lower littoral zone* is the deepest zone where most submersed plants are found & typically extends from the floating-leaved plant zone down to the limits of the *photic zone*.

e) *Protozoans*

These are single-celled heterotrophic eukaryotes. They are found in almost all aquatic habitats & tend to be abundant in waters where organic matter, bacteria, or algae are abundant. They are classified based on how they move.

They feed on detritus but also consume free-living bacteria, fungi, yeasts, algae, & other protozoans in lentic & lotic systems. Some are strictly parasitic e.g. *Ichthyophthirius*, which causes white pustules on freshwater fish, *Vampyrella*, which feeds on algae, & *Plasmodium*, which causes malaria in humans. Some such as the flagellated *Ceratium* & *Peridinium*, can photosynthesize & are often classified with the algae.

Protozoans that parasitize freshwater phytoplankton may modify algal species composition. Similarly, they may modify the composition of zooplanktons or fish communities. How?

f) *Rotifers*

These are microscopic invertebrates with a wheel-shaped crown of projecting threads cilia at their anterior end. They inhabit a wide range of aquatic habitats but are mostly found in freshwaters. They form an important part of the zooplankton community of aquatic systems especially lakes. They usually dominate the zooplankton in rivers. They are suspension feeders that feed on bacteria & single-celled algae but they are also preyed on heavily by invertebrates but vertebrate predation is low.

g) *Crustaceans*

These are invertebrates with several pairs of jointed legs, a hard protective outer shell, 2 pairs of antennae, & eyes at the ends of stalks. Most large zooplankton belongs to the class Crustacea which also includes benthic species like shrimps, crabs, & crayfish.

Two groups – the cladocerans & copepods are well known because of their abundance, larger size, & ease of preservation compared to the rotifers.

The *cladocerans* e.g. *Daphnia* (water flea) & *Bosmina* are mostly filter-feeders. They feed on single-celled & colonial algae. Invertebrate predation is moderate but vertebrate predation is high. The *copepods* consist of the filter-feeding calanoids & the cyclopoids, which have a raptorial feeding but can occasionally filter-feed. They also feed on single-celled & colonial algae. Predation by invertebrates is moderate on adults but high on juveniles but vertebrate production is generally low. The cladocerans, copepods, rotifers, & protozoans dominate the *zooplankton* of freshwaters.

h) *Aquatic insects*

The insects, another arthropod group, have been very successful in invading almost all regions of the earth's surface except the marine environment where only a few are found. The majority of insects which spend at least part of their life cycle in marine habitats, belong to Hemiptera, Coleoptera, & Diptera. The other orders with some marine representatives include Collembola, Mallophaga, Anoplura, Homoptera, Trichoptera, & Hymenoptera. In rivers & streams, aquatic insects dominate the trophic level between primary producers & fish. The adults are short-lived aerial forms. Though most aquatic insect larvae are predaceous, many filter drifting particles or graze detritus, & attached algae. Commonly encountered examples of freshwater insect groups include the mayflies (*Empheroptera*), the stoneflies (*Plecoptera*), caddis flies (*Trichoptera*), & the dragonflies (*Odonata*). Insects are an important component of the lake benthos, & emergence of the adults often triggers a frenzy of surface feeding by fish.

Giant water bugs (*Belostomatidae*) are large enough to capture small fish. Among benthic insects of lakes, the chironomid larvae are the most widespread & because they tolerate low oxygen concentrations, may even be found in the anoxic hypolimnion of some mesotrophic & eutrophic lakes.

In the Arctic, blackfly larvae coat the surfaces of rocks in swift streams. In fast-flowing tropical water, blackflies are the carriers of river blindness, onchocerciasis. The predatory *Chaoborus*, commonly called glassworm, lake flies or phantom midge, with its ghostly transparent larvae, is the only major insect member of the plankton.

i) *Worms & molluscs*

Worms & mollusks, like aquatic insects, convert detritus & living plant materials to food for each other or for fish. Marine worms are found in different phyla e.g. Platyhelminthes, Nematoda, Annelida, Chaetognatha, Hemichordata, & Phoronida.

Marine molluscs are thought to have the largest marine phylum. Numerous mollusc also live in freshwaters. Some such as leeches may be predators on large animals or fish & nematode worms are common internal parasites of many aquatic animals. The huge masses of snails found around pond edges can decimate attached algal crops in the same manner as stream insect larvae do. Snails serve as hosts for parasitic schistosomes responsible for the tropical disease bilharzias & the swimmers itch of temperate climates.

l) *Fish*

Fishes are very diverse & are taxonomically divided into 3 major extant classes: Agnata (cyclostomes, or *jawless fishes*); Chondrichthyes (*cartilaginous fishes*), & the Osteichthyes (*bony fishes*).

The cyclostomes are jawless & the most primitive & they include the lampreys & the hagfishes. Freshwater lampreys just like their marine counterparts lack biting jaws & are adapted to life as parasites or scavengers. The sea lamprey normally lives in the sea as an adult but return to freshwater to spawn (anadromous).

The Chondrichthyes includes the sharks & their relatives of which there a few freshwater examples.

The Osteichthyes are called bony fishes & are the most advanced of the fishes. Most of them have gas bladders that make them less dense than water so that they spend less energy in swimming compared to heavy fishes like the sharks. An important family of the Osteichthyes is the Cichlidae, which includes the numerous species of *Tilapia* which are an important source of protein in Africa, South, & Central America, & India. In the oceans, the Pacific & Atlantic salmons – shad & smelt – are *anadromous*. They feed in fertile areas of the ocean & grow to large adults, which must return to freshwater streams to spawn. In doing so, the Pacific salmon which die after spawning, carry in their bodies nutrients from the ocean to unproductive lakes & streams where their progeny will eventually hatch. On the other hand, fish that live in freshwater but must go to the ocean to spawn are *catadromous*. Some fishes undertake regular migrations in large lakes & are referred to as *potamodromous* equivalent to *oceanodromous* fishes who undertake regular migrations within the ocean.

NB:

Amphidromous fishes are those that undertake migrations from freshwater to ocean water & vice versa for purposes (e.g. feeding, overwintering, etc) other than breeding at some stage of their life cycle.

Since *anadromous* or *catadromous* fish must move between fresh water & salty ocean waters, they are especially equipped metabolically to adjust their salt balance or *osmoregulate*. Estuaries usually provide the transitional zone for a more gradual adjustment to salinity changes. Freshwater fish entering salt water must be able to eliminate salts effectively & efficiently to remain hypotonic to their environment, while saltwater fish entering freshwater must conserve the salts in their body fluids to remain hypertonic to their new less saline habitat. Except for the sharks & their allies, which maintain a high urea concentration in the blood, the bony fish balance salt uptake & loss with their gills & kidneys. Some additional salt loss occurs in marine fish through their faeces.

m) *Amphibians, Reptiles, Birds & Mammals*

The *amphibians* require water in their early life stages & must return to water to reproduce. There are no true marine amphibians. A few such as *Fejervarya raja* can inhabit brackish water. Amphibians generally have a permeable skin which needs to stay moist.

Reptiles are able to leave water since their amniotic eggs do not need external water & their impervious skin retains body fluids in terrestrial & even desert environments. Many *reptiles*, however, remain closely associated with water. There are a few marine representatives such as the marine iguanas, sea snakes, sea turtles, seawater crocodiles, etc. In inland waters, small snakes are common predators of fish & amphibians in weedy ponds & streams. Among the more dramatic examples of aquatic snakes is the Amazonian giant anaconda. Major carnivorous reptiles in tropical rivers & lakes include the caimans of South America, crocodiles, & alligators. Although they feed mainly on fish, larger individuals also take small to moderate-sized mammals, including an occasional human.

Wetlands are traditional nesting & feeding grounds for *waterfowl*. They exhibit a great variety of feeding activities & adaptations, since they feed at every level of the aquatic food chain. Examples of sea birds include gulls, terns, skuas, puffins, dovekie, etc. freshwater herons & egrets are known to stalk their prey on long legs while the tropical fish eagle, fish hawk, & osprey pluck living fish when they venture near the surface. Among the most interesting avian fish predators are the kingfishers & the Arctic tern (*Sterna paradisaea*) that hover over the water & dive to capture their prey. Some birds like the flamingos strain algae out of water while other birds peck along the shore in search of snails & small crustaceans. Perhaps the most truly aquatic birds are the grebes (freshwater & marine) & cormorants (marine) which obtain food by directly pursuing & capturing fish under water. The cormorants literally fly through the water.

Mammals have many representatives associated with aquatic ecosystems. Marine mammals are classified into 4 taxonomic groups viz; cetaceans (whales, dolphins, porpoises), pinnipeds (seals, sea lions, walruses), sirenians (manatees, dugongs), & fissipeds (polar bears, & sea otters). Inland water example include beavers, muskrats, otters, etc. Beavers are limnologically important as they create their own aquatic environment. Their small ponds often provide the only relatively still water in upland areas. Though seals are usually considered marine, endemic populations of the freshwater seal – *Phoca sibirica* – exist in Lake Baikal. Among the larger mammals, the hippopotamus has a role in the freshwater ecology of many African lakes & marshes. They consume enormous quantities of terrestrial grasses around the lake, fertilize the nearshore waters with their excrement, & keep the waterways open in the shallow portions of their habitat. During periods of drought or overpopulation they may denude the shore zones & accelerate erosion. They are sometimes to be even more dangerous than the crocodiles in terms of their aggressiveness towards humans. Elephants, Cape buffalo, & bison make a great deal use of water, & in some places some ponds owe their origins to their wallowing.

UNIT FIVE

COMMUNITY STRUCTURE AND DYNAMICS IN AQUATIC SYSTEMS

Aquatic organisms live in *communities* in environments with distinct characteristics that determine which kinds of organisms live there & which do not & in what abundance they can occur. Light availability, type of bottom, the temperature & salinity of the water, waves, tides, currents, & many other aspects of the environment profoundly affect aquatic life. Equally important are the ways organisms affect each other, crowd each other out, & even cooperate.

Certain basic principles apply to all habitats e.g., plants need light regardless of the environment they are found & animals need food. Such interaction between organisms & their environment is referred to as *ecology*.

Organization of Communities

Abiotic environment makes different demands on the organisms that live there (*action*) & the organisms must adapt to those demands (*reaction*). Organisms are also affected by other organisms or the *biotic environment* (*coaction*). Thus, aquatic organisms are distributed throughout life zones in specific groups of interacting producers, consumers, & recyclers that share a common living space. Thus, biological populations interact in complex ways that make the organisms in a community dependent on each other.

NB:

i. *Population* is a group of individuals of the same species that live together.

ii. *Community* is all the different populations of organisms that live in the same place.
iii. *Ecosystem* consists of the communities in a large area plus the physical environment.

Flow of Energy & Materials in Systems

Every ecosystem, in order to function properly, must have a source of energy and nutrients and maintain a relationship with its abiotic and biotic components that allows the processes of energy & nutrient cycling to go on efficiently. Those dynamically balanced components lead to sustainability of the ecosystem. Communities are dependent on the availability of energy. All living things use energy to make & maintain the complex chemicals necessary for life. *Autotrophs* get this energy from the environment, usually in the form of sunlight. They use the energy to make their own food from simple molecules such as CO_2, water & nutrients. As the autotrophs grow & reproduce they become food for *heterotrophs* (i.e. organisms that cannot make their own food & must eat the organic materials produced by autotrophs). When one organism eats another, both the organic material & the energy stored in it are passed from one to the other. Thus, energy & chemical substances flow from the abiotic parts of the ecosystem to the organism & from organism to organism. The pathway taken by energy & materials tells us a lot about how the ecosystem works.

Trophic Structure of Aquatic Communities

The flow of energy & matter through an ecosystem can be traced by observing the food, or *trophic*, relationships among its organisms: who makes the food & who eats it. Thus, organisms in ecosystems can be thought of as chemical machines fueled by energy captured in photosynthesis by the producers (e.g. macrophytes, algae, & some bacteria). They can be divided into 2 broad types: *primary producers*, the autotrophs that make the food, & *consumers*, the heterotrophs that eat it. Not all consumers feed directly on the producers. Many animals eat other animals rather than plants. Thus, the transfer of energy through the system usually takes place in several steps know as a *food chain*. Each of the steps in a food chain is called a *trophic level* (Fig 5.1).

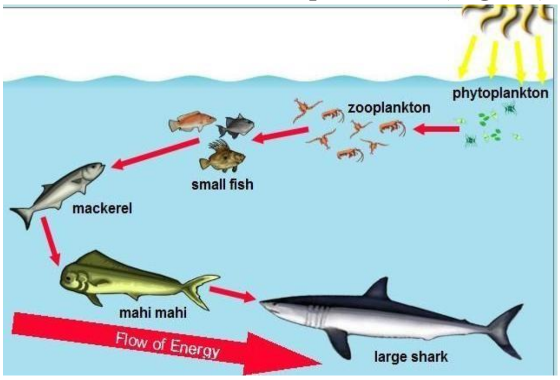


Fig 5.1 E.g. of food chain in the ocean

But, most ecosystems have a number of different primary producers. Furthermore, many animals eat more than just one kind of food, & many change their diet as they get older & larger. For these reasons, trophic structure & hence the pathway of energy is not a simple linear one but usually a complex, interwoven *foodweb* i.e. a number of interconnecting food chains in an ecosystem with numerous organisms at each level, instead of a simple straight-line food chain (Fig 5.2).

Thus, a trophic level is composed of those organisms within an ecosystem whose source of energy is the same number of consumption steps away from the sun e.g. producers trophic level is 1, animals grazing on the producers belong to trophic level 2, & those eating the grazers belong to trophic level 3, etc. So food energy passes through an ecosystem from one trophic level to another. When the path is a simple linear progression like the links of a chain, it is called a *food chain*.

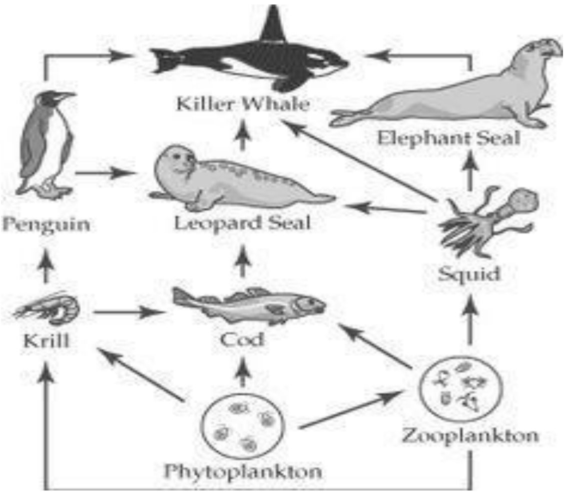


Fig 5.2 E.g. of food web in the ocean

1. *Trophic levels in aquatic systems* – Food chains & foodwebs are a little easier to understand if we consider how many steps, or trophic levels, the energy has travelled. The first step in the flow of energy & therefore the first trophic level is occupied by the primary producers e.g. algae like diatoms, chlorophytes, cryptophytes, cyanobacteria, etc that originally capture the energy & store it in organic compounds. Consumers that feed directly on the producers are called *first level* or *primary consumers*, & occupy the next trophic level e.g. herbivorous zooplankton & fish, etc. At the next level, is the *second level* - or *secondary consumers* – predators that eat the primary consumers e.g. zooplanktivorous & invertivorous fishes, etc. Feeding on the secondary consumers are the third level or tertiary consumers e.g. piscivores, etc. Each trophic level relies on the level below for sustenance. At the end of the food web are *top predators* such as the killer whales.

2. *The Trophic pyramids* – Instead of being passed on to the next higher level, much of the energy contained in a particular trophic level is used up by the activities of the organisms at that trophic level. Energy & organic matter are also lost as waste. Thus, only about 10 % of the energy, on average, is passed from one trophic level to the next. The trophic structure can be represented by the *pyramid of energy* (Fig 5.3a & b).

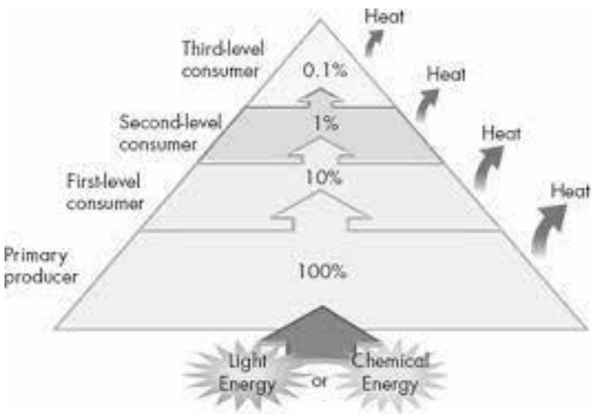


Table 5.3 Pyramid of Energy showing decreasing energy at higher trophic levels

Because there is less energy available at each higher level, there are also fewer individual organisms. Hence, there are fewer primary consumers than producers, & fewer secondary than primary consumers. Thus, to support a given biomass of primary consumers, primary producers must make about 10 times as much living tissue e.g. to support 1000 g zooplanktons, about 10,000 g of phytoplankton must be eaten. In turn, only about 1/10th of the primary consumer's biomass (i.e. 100 g) will make it to the secondary consumers (Fig 5.3b).

Because each level has less energy available, there is a limit to how many levels there can be. Eventually the system just runs out of energy. Hence, most aquatic food webs have 3-4 trophic levels. Thus, the trophic pyramid can be pictured in terms of the number of individuals - *pyramid of numbers* - as well as energy - *pyramid of energy* (Fig 5.3a&b). The pyramid can also be expressed in terms of the total weight, or biomass – called the *pyramid of biomass* – of organisms at each trophic level.

NB: *Inverted pyramids* – Some aquatic systems have inverted biomass pyramids e.g. in a planktonic system dominated by small organisms floating in water, the turnover of phytoplankton at the primary level is very rapid, with zooplankton consuming these phytoplankton so quickly that they are not able to develop large population sizes. Because the phytoplankton reproduce very rapidly, the community can support a population of heterotrophs that is larger in biomass & more numerous than the phytoplankton.

Inverted pyramids are common in ecosystems in which the producers are:

1. microscopic planktonic organisms that multiply rapidly;
2. have very short life spans; and
3. are heavily grazed by the herbivores

As noted, some organic matter is lost as waste instead of moving through a food web of herbivores & predators. But this material is not lost to the ecosystem. Bacteria, fungi & other *decomposers* break down the waste products & dead bodies of organisms into their original components – CO_2, water, & nutrients – a process called *mineralization of organic matter*. Together, the decomposers & the dead organic matter are called *detritus*. Detritus is an important energy pathway in aquatic ecosystems because many organisms feed on it. This funnels the organic matter back into the food web. Decomposers are a vital part of all ecosystems. Without them, waste products & dead bodies would accumulate instead of rotting away. Not only would this make quite a mess, nutrients would remain locked up in the organic matter. When decomposers break down organic matter, the nutrients incorporated into the organic matter during primary production are released, making the nutrients available again to photosynthetic organisms. This process is called *nutrient regeneration*. Without it, nutrients will not be available to autotrophs, & primary production will be greatly limited.

How Aquatic Populations Grow

When the conditions of existence are right or favourable, organisms can produce more than it takes to just replace themselves & thus the population may increase every generation & this may result in population explosion. Thus, were its reproduction left unchecked, any species could grow to cover the earth in a relatively short time (Fig 5.4).

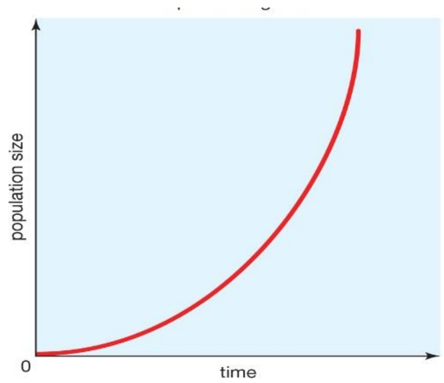


Fig 5.4 Population growth showing unrestricted/exponential rates

However, many factors, predictable or unpredictable, can control, or regulate, the population growth – i.e. it can slow down or even wipe out populations.

There are also mechanisms that limit population growth even if the abiotic environment does not fluctuate. Some animals slow down or stop reproduction when their habitats become too crowded. Others fight themselves or even cannibalize each other. Natural enemies may be attracted when populations get large, & diseases often spread faster under crowded conditions. Large populations can pollute their environment with their own waste. As more & more individuals join the populations, they use up their *resources* – the things they need to live & reproduce, like food, nutrients (i.e. raw materials other than CO_2 & water that are needed by plants for primary production), & living space. Eventually, there are just not enough resources to support any more individuals & the population levels off (Fig 5.5).

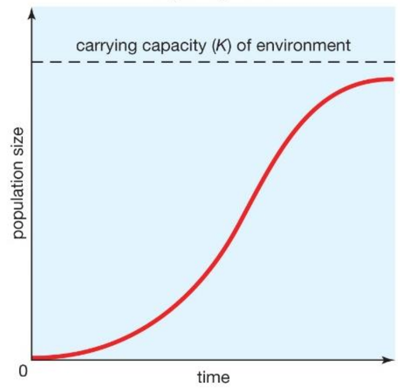


Fig 5.5 Population growth showing restricted rates

Organisms use many different resources. A lack of any these adversely affects growth & reproduction. For instance, a dinoflagellate alga living in the pelagic zone of a lake can be limited by a lack of nitrate (NO_3^{2-}), even if it has plenty of light, CO_2, water, & other nutrients. A *limiting resource* is one whose short supply prevents the optimal growth of a population.

Because of the drain of resources or other effects of crowding, populations do not grow forever. As the size of the population increases, its growth rate goes down. In this sense, the population is self-regulating – i.e. its growth rate depends on its own numbers. Thus, whereas abiotic factors like weather can affect populations of any size, self-regulation only acts when the population is large.

As resources run out, there are not enough to go around. Each individual has to vie with other organisms for what resources remain. *Competition* is the interaction that results when a resource is in short supply & one organism uses the resource at the expense of another. Those who compete successfully survive to replace themselves by reproducing. The unsuccessful competitors do not reproduce themselves successfully & eventually disappear. In this way nature favours the members of the population that are best suited to the environment. Because of this *natural selection*, the population as a whole is a little better adapted each generation. In other words, it evolves.

Ways Species Interact

Members of different species in aquatic systems may have strong effects on each other. The different ways species interact influence the community organization & include & include;

1. *Competition* – Aquatic organisms must compete for resources not only with members of their own species (*intraspecific*), but members of other

species (*inter-specific*). When 2 species use the same scarce resources, the 2 must compete just as if they were members of the same population. One of the 2 species almost always tends to be a little better at the competition. If the 2 species eat exactly the same type of food for instance, one of the 2 will be a little better at obtaining it. Unless something interferes, the inferior competitor loses out & the competitively superior species takes over. When one species eliminates another by out-competing it, *competitive exclusion* is said to occur. Sometimes a competitively superior species is prevented from excluding poorer competitors for instance by changing environmental conditions. Thus, as long as conditions are variable, neither species will be able to exclude the other (*contemporaneous disequilibrium hypothesis*). This is illustrated by the earlier concept of the paradox of the plankton.

Species can also avoid excluding each other if they manage to share the limiting resource, with each species specializing on just part of the resource (*character displacement*). For instance, 2 species of fish that both eat seaweeds might divide the resource by specializing on different kinds of seaweeds or different parts of it.

Again, animals that eat exactly the same thing might live in different places (*spatial separation*) or feed at different times at the same location as the other (*temporal separation*), staying out of each other's way. This sharing of resources by specialization is called *resource partitioning* by ecologists. In other words, species that might others competitively exclude each other sometimes coexist by resource partitioning. Though resource partitioning allows species to coexist when they might otherwise exclude each other, but it does have its price. By specializing, each species gives up some of the resource. The fish that specializes on a particular kind of seaweed, for e.g., will have less food available than if it ate any type of seaweed. With fewer resources available, the size of the population tends to be smaller. On the other hand, the species might be able to use the resource more efficiently by been a specialist than if it were a generalist.

To be successful in the long run, a species might find the right balance between specialization & generalization. Each species has its own special role or *ecological niche*, in the community. The species' niche is defined by the combination of virtually every aspect of its lifestyle, e.g. what it eats, where it lives, when & how it reproduces, how it behaves, etc.

2. *Eating Each Other* – Species do not always compete for resources. Sometimes they use each other as the resource. In other words, they eat one another. When an animal eats another organism, it is called *predation* & the animal that does the eating is called the *predator* & the one that gets eaten is called the *prey*. The term predator is often reserve for *carnivores* – animals that eat other animals. A special case of predation occurs when animals eat plants – a phenomenon called *herbivory* rather than predation, & the animal is this case is called the *herbivore*.

Predation obviously affects the individual eaten as well as the prey population as a whole by reducing their number. If the predators do not eat too much, the prey populations can replace the individuals that get eaten by reproducing. But, if the predation is intense, it can cut down the prey population greatly.

The relationship between the prey & the predator is not unidirectional. After all, the predator depends on the prey for its food supply. If bad weather or disease wipes out the prey, the predators will suffer. Prey populations may also decline if there are too many predators or the predators eat too much. In this case the predator population starts to decline, having used up its food supply.

The more successful an individual predator is at catching its prey the better its chances are of surviving to reproduce. Natural selection therefore favours the most efficient predators in the population. Some of the ways predators get prey include; being swift & powerful (e.g. tunas & whales), sneaking, luring (anglerfishes), drilling through shells (snails), climbing inside & eating the prey from inside (slime eels), etc.

But just as natural selection favours the best predators, it also favours the prey individuals that are more successful at getting away. Some of the ways preys get away from predators include; some are fast & elusive, some use camouflage, spines, shells, or other defensive structures, been distasteful & production of toxins, etc.

Thus, there is a continual "arms race" between predators & their prey & overcoming its defenses. In response, the prey becomes more adept in escaping or developing better defenses. This interplay with each species evolving in response to the other is known as *coevolution*.

3. *Living Together* – Coevolution becomes even more important when species interact more intimately. Members of different species may live in very close association, even with one inside another. Such close relationships are known as *symbiosis*, which literally means "living together". The smaller partner in symbiosis is called the *symbiont* & the larger one the *host*. Biologists often divide symbiosis into different categories. In a *commensal* relationship, one species obtain shelter, food, or some other benefits without affecting the other species one way or the other. For instance, certain barnacles live only on whales. The barnacles get a place to live & a free ride. They feed by filtering the water, & as far as we can tell, the whale is neither harmed nor helped by the barnacles. Another example of commensalism is the association between the pilot fish (*Naucrates ductor*) & shark where the pilot fish dines on the scraps coming from the shark's meal, etc

On the other hand, sometimes the symbionts benefit at the expense of the host. This is called *parasitism*. The giant tapeworm that lives in the guts of whales is considered a parasite since it gets food & shelter from the host. In the process, they may weaken their whale hosts. Parasitism is the most common type of symbiotic association.

Not all symbiotic relationships are one-sided. In *mutualism*, both partners benefit from the relationship. In many places, small cleaner fishes & shrimps have mutualistic relationships with larger fishes. The cleaners remove harmful parasite from the fish, getting a meal in return. The fish which could easily eat the cleaners allow them to poke & prod over their bodies & even inside their mouths. This type of symbiosis is called *cleaning symbiosis*. In the case of cleaning symbiosis, both partners can get by without the other if they have to. Sometimes the partners depend on each other. For instance, crab, *Trapezia* sp, is found nowhere else but on its host coral. The coral supplies not only shelter but food, by producing the mucus that the crab eats. Even though the coral is not really dependent on the crab, it benefits because the crab helps chase away sea stars & other coral predators. The coral provides an example of an even closer relationship, one in which neither partner can live without the other. The tiny zooxanthellae (i.e. photosynthetic dinoflagellates) that live within its tissues helps the coral makes its calcium carbonate ($CaCO_3$) skeleton. The zooxanthellae also make food for the coral by photosynthesis. The zooxanthellae, in turn, get both nutrients and a place to live from the deal.

Types of Adaptive Changes

These are classed as genotypic, phenotypic, behavioural, or ontogenetic.

1. *Genotypic changes* – tend to be great enough to separate closely related organisms into species, such as mutations or recombination of genes. A salmonid is an example that has evolved a sub-terminal mouth (i.e. below the snout) to eat from the benthos;
2. *Phenotypic changes* – are the changes that an organism might make during its lifetime to better utilize its environment (e.g. a fish that changes sex from female to male because of absence of males);
3. *Behavioural changes* – these have little to do with body structure or type: a fish might spent more time under an overhang to hide from predators;
4. *Ontogenetic changes* – takes place as an organism grows and matures (e.g., a coho salmon that inhabit streams when young, and migrate to the sea when older, changing its body chemistry to allow it to tolerate sea water).

UNIT SIX

PRODUCTIVITY, NUTRIENT CYCLING, AND EUTROPHICATION OF AQUATIC SYSTEMS

Primary Production

Primary production is the conversion of inorganic matter to organic matter. The object of primary production studies in aquatic environments is to obtain quantitative information about the system's capacity for the formation of potential energy and the subsequent reconversion of this to other forms of energy usable by aquatic organisms. Another reason for measuring primary production is to estimate the efficiency of energy transfer in the system.

The primary production made by aquatic photoautotrophs also called *photosynthate* can be used in a number of different ways by primary producers. The definite respiratory needs of these producers must first be met before energy can be passed on to other trophic levels usually a minimum of about 10 % is reserved for this purpose. Also, aquatic photoautotrophs must reserve a portion of their production for maintenance of community structure

Primary Production of Phytoplankton

The process of primary production is given by the photosynthetic equation

$$(CO_2)n + H_2O \rightarrow C(H_2O)n + O_2$$

Using this equation, several factors can be measured such as *rate of carbohydrates accumulation* (i.e. $C[H_2O]n$) or the dry weight and O_2 production or CO_2 decline or use rate. In most lakes, dry weight or carbohydrate increases are usually too small to be measured during periods sufficiently short for the natural populations not to have changed quantitatively. Moreover, the total particulate matter in the water include varying amounts of material such as detritus and sediments stirred up from the bottom or freshly transported into a lake by rivers and these will make the determination of algal dry weight unreliable.

O_2 production is usually used to get an estimate of the rate of dry weight production based on their similar stoichiometry i.e. one carbohydrate molecule is produced for every oxygen molecule released. O_2 measurement is done using three types of bottles, so-called Winkler bottles, filled with lake water. The first bottle designated **A** gives the initial O_2 concentration. A second bottle designated **L** is placed in the light while the third bottle **D** is placed in total darkness. Bottles L and D are then incubated for a period of time either *in situ* i.e. within the water body itself or in the lab (i.e. *ex situ*) after which the oxygen concentrations in both bottles are determined using the Winkler method. During the incubation, the O_2 concentration measured in the initial bottle A is expected to decrease to a lower value in the dark bottle D and to a higher value in the light bottle L.

The difference between the O_2 concentrations in bottle A and D represent respiratory activity of the phytoplankton per unit volume over the time period of the incubation i.e.

$$\text{Respiratory loss} = [O]_A - [O]_D$$

The difference between the O_2 concentrations in bottles L and A represents ***net photosynthesis*** i.e.

$$\text{Net photosynthesis} = [O]_L - [O]_A$$

The difference between the O_2 concentrations in bottles L and D represents **gross photosynthesis** i.e.

$$\text{Gross photosynthesis} = ([O]_L - [O]_A) + ([O]_A - [O]_D)$$

$$\text{Gross photosynthesis} = [O]_L - [O]_A + [O]_A - [O]_D$$

$$\text{Gross photosynthesis} = [O]_L - [O]_D$$

NB:

1. Gross primary production (GPP) is the total photosynthesized material before it is consumed and dissipated by both the primary producers themselves and by other organisms.

2. Net primary production (NPP) is the amount of the photosynthate left after it is consumed in respiratory and other maintenance activities of the primary producers.

3. Thus GPP, NPP, and respiration is related by the equation

GPP = NPP + Respiration, or

GPP – Respiration = NPP, or

GPP – NPP = Respiration, or

NPP = GPP - Respiration

Methods of Evaluating Primary Production

a) *Standing Crop – Standing crop* is that part of primary production which is physically present in the system and does not include what is lost in respiration. It represents the result of a continual loss and replacement process. Losses due to death, consumption by grazers as food, removal by out-flowing waters, and other causes must be offset more or less by normal reproduction and growth. Increases or decreases in standing crop are due to excess of production over losses or excess of losses over production. Standing crop, been a measure of the biomass of the system at a single point in time, is measured as calories or grams per m^2.

b) *Productivity* on the other hand, is the rate at which biological production occurs. Using standing crop for measuring productivity is of limited value because changes in the standing crop of phytoplankton reflect only the net effect of many biological & physicochemical events. For instance, standing crop may be greatly reduced by grazing and water movements while at the same time photosynthetic rates may be high.

Chlorophyll, another standing crop surrogate is frequently used but also has several problems. Primary production can be expressed as the rate of formation of new material, per unit of earth's surface, per unit of time. For instance, it can be expressed as calories/m^2/year (energy) or grams/m^2/year.

Limitations of Standing Crop Measures

1. *Number of Cells*

- Differences between big & small cells;
- Requires taxonomic finesse

2. *Chlorophyll a*

- Concentration is subject to the physiological state of a cell;
- Concentration is affected by the degree of light exposure
- Different phytoplankton groups have different chlorophyll contents

3. *Wet Weight Biomass*

- Underestimate of net & other small plankton if correct net size is not used;
- Requires taxonomic finesse

4. *Dry Weight Biomass*

- Differentiating between seston & phytoplankton usually difficult;
- Obtaining the dry weight may require very sensitive equipment for both the drying and weight measurement itself

NB: The ratio of the standing crop to the production (Standing Crop / Production) is equal to the *turnover* of the system. By dividing standing crop (units of g/m^2) by production (units of g/m^2/yr), you can see that the turnover is in units of time i.e. 1/(1/yr) = year in this example. Thus the stock or standing crop of any material divided by the rate of production gives you a measure of time. It is really important to consider this element of "time" when thinking about almost any aspect of an organism or an ecosystem. Learning about how much of something is happening & how fast it is changing is a critical aspect of understanding the system well enough to make decisions; e.g., the decisions of a fisherman may be driven by economic concerns or by conservation concerns, but the "best" choice for either of those concerns still depends on an understanding of the production, standing crop, & turnover of the aquatic system of interest.

Secondary Production

Secondary production refers to the fixation or production of energy by heterotrophs (consumers). It represents the formation of living mass of a heterotrophic population or group of populations over some period of time. It is the heterotrophic equivalent of net primary production by autotrophs.

Organisms that consume the organisms responsible for secondary production are said to be engaged in tertiary productivity.

Components of Secondary Production

It has long been recognized that not all food eaten by aquatic heterotrophs is converted into new animal mass. Consider a stream snail grazing on algae (Fig. 6.1). Only a fraction of the material ingested (I) is assimilated (A) from the digestive tract; the remainder passes out as faeces (F). Of the material assimilated, only a fraction contributes to growth of the snail's mass or to reproduction — both of which ultimately represent production (P). Most of the rest is used for respiration (R). A small portion of energy is lost in excretion (E), but is usually ignored in such energy budgets. Simple equations are used to illustrate the fate of ingested energy, such as;

I = R + P + F + E i.e.

P = I – (F + R + E)

P = I - F – R - E

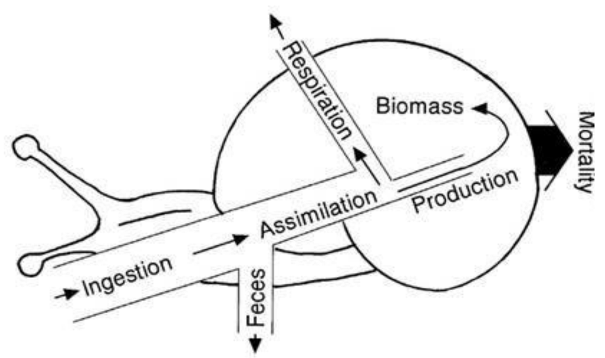


Fig. 6.1: Energy flow of a stream snail population

NB:

All flows (ingestion, assimilation, faeces, respiration, production, mortality) have units of mg dry mass m^{-2} day^{-1}). Production adds to biomass & mortality subtracts from biomass simultaneously. Thus, if production exceeds biomass lost to mortality, biomass will increase. If production is less than biomass lost to mortality, biomass will decline.

Food Chain Efficiency in Aquatic Ecosystems

A *food chain* as we have noted, is a linear sequence that reveals which organisms consume which other organisms in a community. Each species in a feeding relationship requires a *trophic level*. Species in one trophic level may also be consumed by species in a higher trophic level. Note that some species may change levels in the food chain at different stages of their life cycle. Consumers may also feed at several levels in the food chain.

Transfer between Trophic Levels

Transfer of production or energy from one trophic level to another is not complete i.e. not all the production from one trophic level is transferred perfectly to the next as noted earlier. To estimate the potential production at the top of the food chain, such as fish production, we must take into consideration the losses of production or energy along the food chain. These losses result from essentially two factors:

1. *Evasion of consumption* – some proportion of a given trophic level evades consumption through escape, unpalatability, or unavailability.

Phytoplanktons with large spines or toxins are avoided by zooplankton. Phytoplankton cell size may be too small or too large to allow for ingestion.

2. *Inefficient conversion* – some proportion of the food that is ingested is not converted into growth. Ingested food budget can be constructed like this:

$$I = E + R + G$$

Where I = amount ingested; E = amount egested; R = amount used in respiration; G = amount used in growth

Growth is usually partitioned between somatic or body growth & reproduction. Growth is usually a minority of the *ingested* budget. Not all food can be digested & assimilated & some therefore is *egested*. Some of the energy obtained in food is lost as *respiration*, hence is not available to the next trophic level.

The incompleteness of transfer up a food chain can be estimated in terms of *food chain efficiency* (E) defined as the amount of energy extracted from a trophic level divided by the amount of energy supplied to that trophic level. *Growth efficiency*, which is the proportion of assimilated food used in growth can range as high as 30 – 45 %, but food chain efficiency is usually far lower, often in the range of 10 %.

Food chain efficiency can be used to calculate the potential fish production at the top of a food chain using the formula:

$$P = BE^n$$

Where B = biomass of phytoplankton; n = number of links between trophic levels; and P = fish production. A change in E from 0.1 to 0.2 would magnify by 16 the estimate of fish production at the fifth trophic level.

Nutrient Cycling & the Concept of Eutrophication of Water Bodies

Nutrient cycling is the reuse, transformation, & movement of essential nutrients in aquatic systems. Thus, a nutrient cycle is a repeated pathway of a particular nutrient or element from the environment (ecosphere) through one or more organisms (biosphere) & back to the environment. Nutrient cycling is one of the most significant aquatic ecosystem processes because of the importance of nutrients, their relative scarcity in aquatic ecosystems, & their influence on primary producers. Nutrient cycles restore ecosystems to equilibrium state, & therefore play an important role in keeping ecosystems functioning. All organisms, living & non-living depend on one another through nutrient cycles which link them together through the flow of nutrients.

Examples of nutrient cycles important for the maintenance of aquatic ecosystem processes include:

- Carbon cycle
- Nitrogen cycle
- Phosphorus cycle
- Silicon cycle, etc

The various nutrient cycles are generally divided into two types viz, gaseous & sedimentary cycles respectively. Most gaseous cycles are considered to be perfect cycles because nutrients are replaced as fast as they are utilized. On the other hand, sedimentary cycles are considered to be relatively imperfect, as some nutrients are lost from the cycle & gets locked up into sediments & some become unavailable for immediate cycling. In other words, imperfect cycles are biogeochemical cycles in which a nutrient element becomes unavailable to living organisms for prolonged periods, being held in soil or sedimentary rock.

Currently, human activities strongly influence nutrient cycles by removing nutrients from the land & discharging them into aquatic environments, leading to nutrient enrichment of these water bodies – a process referred to eutrophication.

Eutrophication is the nutrient enrichment of waters that stimulates an array of symptomatic changes that can include increased phytoplankton & rooted aquatic plant (macrophyte) production, fisheries & water quality deterioration, & other undesirable changes that interfere with water uses. The trophic state, or degree of fertility, of water bodies ranges from oligotrophic to mesotrophic to eutrophic with increasing supply of nutrients and organic matter (Table 6.1).

Table 6.1 Mean annual values for trophic classification

	Total phosphorus (mg L^{-1})	Chlorophyll a (mg L^{-1})	Secchi disk depth (m)
Ultra-oligotrophic	<4	<1	>12
Oligotrophic	<10	<2.5	>6
Mesotrophic	10-35	2.5-8	6-3
Eutrophic	35-100	8-25	3-1.5
Hypertrophic	>100	>25	<1.5

Eutrophication is most often the result of an elevated supply of nutrients, particularly nitrogen & phosphorus, to surface waters that results in enhanced production of primary producers, particularly phytoplankton and aquatic plants.

Phytoplankton are unpleasant at high densities. The sight & smell of clots or masses of decaying phytoplankton decreases the recreational value of most waters & usually generates concerns among the public. Furthermore, blooms of toxin-producing phytoplankton can cause widespread illness. A bloom is a conspicuous concentration of phytoplankton, often concentrated at or near the surface. It is difficult to quantify what constitutes a "bloom," but a rough estimate places it as a chlorophyll *a* concentration over 30 mg L^{-1}. Toxins produced by dinoflagellates e.g. *Pfiesteria* in marine environments & red tides in tropical waters have caused massive fish kills, millions of dollars in losses to seafood-related industries, human memory loss, paralysis, &even death.

Bloom-forming species of cyanobacteria can produce potent hepato-(liver) toxins termed microcystins that have been implicated in poisonings of domestic livestock, pets, wildlife, & susceptible humans. In addition, an accumulation of dead phytoplankton in bottom waters of eutrophic systems can lead to high decomposition rates by bacteria. Dissolved oxygen consumption by decomposers, combined with a barrier to gas exchange (thermocline or ice cover), can reduce (hypoxia) or eliminate (anoxia) dissolved oxygen in bottom waters.

Oxygen depletion is one of the most harmful side effects of eutrophication because it can cause catastrophic fish kills, devastating local fisheries.

The accumulation of plant biomass depends on the addition of factors that stimulate plant growth. On average, the macronutrients nitrogen & phosphorus are present in marine phytoplankton at an atomic ratio 16:1. The ratio of nitrogen to phosphorus in freshwaters tends to be greater than the ratio in phytoplankton; therefore, phosphorus most often limits the growth of phytoplankton. As a result, phosphorus enrichment of freshwater often causes its eutrophication. In lakes, nitrogen is usually present in concentrations equal to or beyond what is required for aquatic plant growth because, unlike phosphorus, it has an atmospheric source.

In marine systems, nitrogen concentrations are often limiting because bacterial nitrogen fixation, while a considerable source of nitrogen in lakes, not as important in marine waters. A wide variety of prokaryotic organisms (i.e., certain cyanobacteria, heterotrophic, & chemoautotrophic bacteria) can use nitrogen gas directly & incorporate it into organic compounds through a process called nitrogen fixation. Nitrogen fixation is an enzyme-catalyzed process that reduces nitrogen gas (N_2) to ammonia (NH_3).

The biodiversity of most aquatic systems decreases with eutrophication (Fig. 6.1).

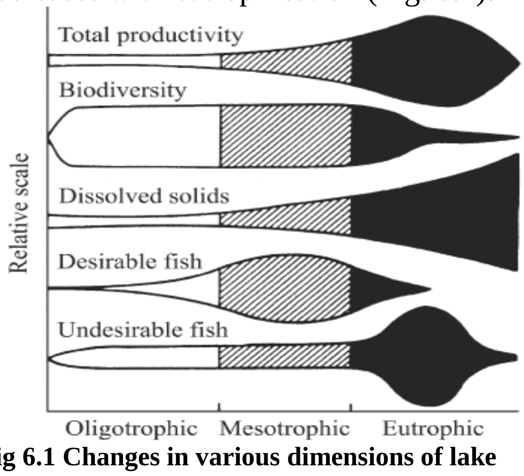


Fig 6.1 Changes in various dimensions of lake with increasing eutrophication

Phytoplankton species diversity is reduced in highly productive systems. Cyanobacteria are usually dominant in eutrophic systems because they are better adapted to conditions of high nutrients. In addition, fish & macro-invertebrate species diversity can decrease with eutrophication. Depletion of dissolved oxygen in deep water is associated with eutrophication & can lead to a loss or displacement of species intolerant of such conditions. In eutrophic lakes of North America, characteristic fish types are surface-dwelling, warm water fishes such as pike, perch, and bass, as compared to deep-dwelling, cold-water fishes like salmon, trout, and cisco.