industry. Consequently the water in such lakes becomes even richer in nutrient salts. Lakes of this type are typically eutrophic.

Once a lake basin has been created, two main forces act to destroy it. Firstly, there is erosion of the basin rim, usually at the lake outlet where there is scouring due to the action of water, sand and gravel. Secondly, most lake basins are continually being filled in by sediment washed in from tributaries, and by organic material produced within the lake. Many lakes have disappeared due to either of these phenomena or the combined effect of both. The final process of filling in is often accelerated by the invasion of macrophytes from the edge.

3.2 Physical characteristics

3.2.1 *Stratification*

The process of stratification, created by density differences resulting from differential heating of lake water (Figure 3.2), is of major importance in many lakes. In describing the sequence of events it is convenient to consider a lake which has been well mixed by the wind and is at a uniform temperature of more than 4°C. In the absence of strong winds and with

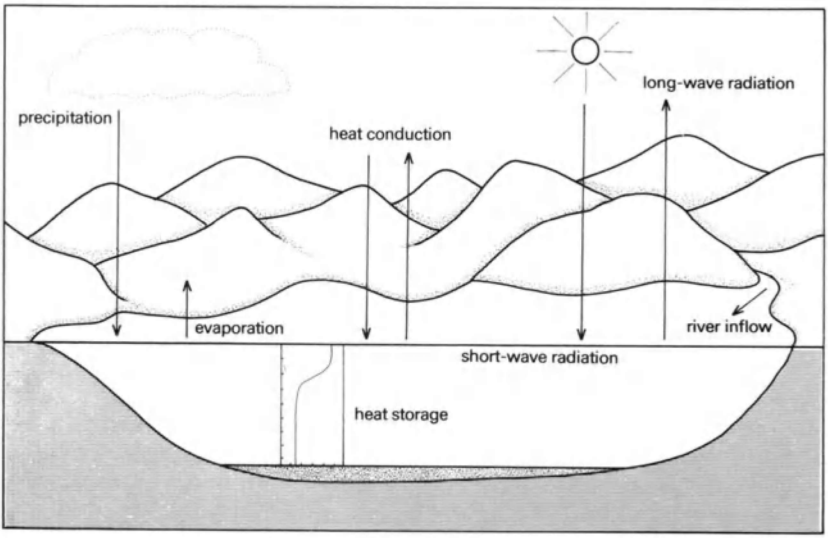

Figure 3.2 The main movement of energy in and out of a lake.

increasing solar radiation, there is a gradual rise in the temperature of the surface waters which, therefore, become less dense than the deeper layers. As this surface layer warms, an increasing density difference appears between it and the deep layer, and they become separated by a narrower layer of water exhibiting sharp temperature and density gradients. The upper layer is known as the epilimnion, the lower layer as the hypolimnion and the region of gradient between them as the thermocline (Figure 3.3). As air temperature and solar radiation decrease, the surface waters cool down again and, when temperatures in the epilimnion and the hypolimnion are similar, their waters start to re-mix.

Partly because of the anomalous expansion of water below 4°C, lakes can stratify in different ways according to the temperature regime imposed through local geography and exposure. In some lakes stratification is permanent, in some seasonal, in others intermittent, and in yet others completely absent. In almost all types, the geographical position of the lake (particularly its latitude, altitude and distance from the sea) is of

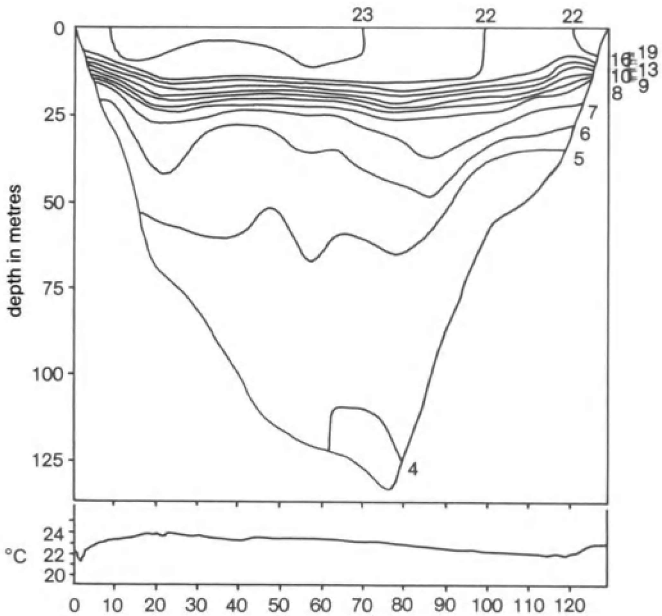

Figure 3.3 Distribution of isotherms in Lake Michigan during stratification (after Carr *et al.*, 1973).

prime importance, but superimposed on this are the combined influences of lake depth and mixing action of the wind. Standing waters may be divided into five major classes according to their stratification (Hutchinson, 1957). However, it should be noted that many lakes can be intermediate in type and may vary from year to year.

(a) Amictic (polar) lakes are permanently covered by ice, and always remain well below 4°C. They never undergo circulation. Such lakes are relatively rare, and occur only at high latitudes and altitudes.
(b) Cold monomictic (arctic) lakes never rise above 4°C in summer, when complete circulation occurs, but are ice-covered in winter, with inverse thermal stratification (i.e. water at the surface is colder than that below).
(c) Dimictic (temperate) lakes circulate completely in the spring when water temperatures rise above 4°C; they stratify during summer, and mix again in autumn, when the lake cools. These lakes are inversely stratified in winter, usually being ice-covered. This is the most complex system, and is discussed in greater detail below.
(d) Warm monomictic (tropical) lakes are thermally stratified during summer, but temperatures never fall below 4°C at other times of the year when there is complete circulation.
(e) Oligomictic (equatorial) lakes are confined to very warm areas. Water temperatures are always considerably above 4°C, and permanent stratification is normal, although this may break down intermittently due to wind.

In dimictic lakes (Figure 3.4) in spring, the water temperature is uniform from top to bottom, and wind action causes regular mixing. With increasing radiation in summer, the lake gains heat and stratification sets in, especially during calm periods. Stratification is evidenced by a gradual rise in the temperature of surface waters, compared with the temperature at greater depths. There is a rapid falling-off in the rate of temperature increase from top to bottom as summer progresses, and a definite thermocline is considered to exist when there is a difference of 1°C or more within any 1 m depth of water. At this stage there is a surface layer of water (epilimnion), about 15 m in depth and of nearly uniform high temperature. Below this is a layer of water of rapidly decreasing temperature (thermocline), and below this again a deeper layer of water (hypolimnion) of uniform low temperature.

Stratification therefore divides the lake horizontally into two parts separated by the thermocline. As the season proceeds, heat gradually

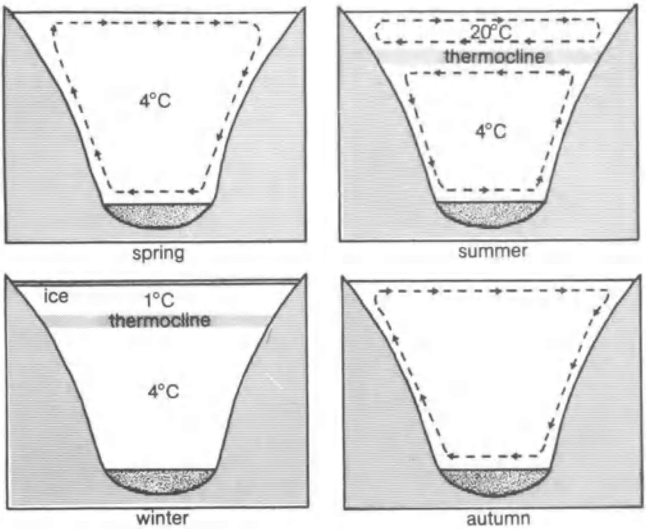

Figure 3.4 The annual thermal cycle and turnover pattern in a typical temperate lake.

transfers from epilimnion to hypolimnion, by conduction and turbulent mixing. With lowered air temperature, while the epilimnion is cooling due to loss of heat to the hypolimnion and at the surface, the hypolimnion temperature continues to rise, even though the lake as a whole is losing heat. Gradually the epilimnion increases in size, the thermocline sinks deeper and the temperature difference between epilimnion and hypolimnion decreases until the lake is again of uniform temperature from top to bottom.

During autumn the lake continues to lose heat, the temperature dropping until at 4°C the coldest water starts to float and the warmer water stays near the bottom, thus allowing inverse stratification to develop. If air temperatures remain below 0°C for long periods, the surface layers start to freeze and eventually the whole lake may be icebound. As winter passes, and with increasing solar radiation, the lake starts to gain heat again: ice melts, water is mixed by wind, and by spring the water column is once more of uniform temperature from top to bottom (Figure 3.5a).

There can also be variations in stratification due to local features of climate, topography or weather conditions (Figure 3.5b). In some lakes, even after stratification, there may be an increase in temperature with depth in parts of the hypolimnion. This is normally caused by a chemical