slime-forming bacterium *Sphaerotilus natans* (Curtis and Curds, 1971). Algae are generally reduced initially (partly because the high levels of suspended solids prevent photosynthesis), but increase rapidly in abundance downstream as light penetration improves and levels of nitrate and phosphate remain high. *Cladophora* is a particularly conspicuous attached filamentous alga, widely associated with mild organic pollution or with the early stages of recovery from more severe pollution, and appears to be especially responsive to elevated phosphate levels (Pitcairn and Hawkes, 1973; Whitton, 1970).

The animal community (Figure 2.2(D)) also shows a clear pattern of response. The 'clean-water fauna' initially declines, and may be entirely eliminated, in the region immediately below the outfall. Tubificid worms, being typically tolerant of low dissolved oxygen levels and silty substrata, usually dominate the fauna in the more seriously affected areas. The larvae of the midge *Chironomus* (Diptera) spp. typically become established further downstream, followed by the isopod crustacean *Asellus,* and the gradual re-establishment of the 'clean-water fauna' as the river returns to its normal physical and chemical status. In any particular situation, the total number of species involved can be very large. The general pattern, subject to many variations in detail, is of a zonation, with increasing distance from the source of pollution, every bit as obvious as that along the length of an unpolluted river, or along a transect on a steeply-sloping seashore. The distribution of many individual species in response to organic pollution has been studied in detail in many different parts of the world. Hellawell (1986) gives a detailed summary of these observations. Several early investigators attempted to provide systematic descriptions of the zonation pattern of plants and animals observed in response to organic pollution with increasing distance from the pollution source, and one such description is shown in Figure 2.2(E). These descriptive systems eventually gave rise to the idea of indicator organisms, and to the development of numerical indices (pollution indices and biotic indices), which are widely used in the biological surveillance of water quality. These topics are further discussed in Chapter 3.

2.4 Nutrient Pollution

Plant growth in water may be limited by any of several factors, including light and the physical characteristics of the habitat. In many cases, however, the limiting factor is the availability of inorganic nutrients, particularly phosphate (Moss, 1988). Increased input of nutrients can therefore trigger increased plant growth which, if excessive, leads to changes in the biological characteristics of the receiving water. The discharge of organic matter to water is an important source of plant nutrients, since the aerobic decomposition of organic matter results in the release of phosphate, nitrate and other nutrients. Domestic sewage typically contains high levels of phosphate because detergent washing powder formulations normally contain high levels of phosphate. For example, the level of phosphate typically found in treated sewage effluent (Table 2.1) may be compared with the levels normally found in unpolluted waters, which range from about 0.001 to 1 mg l^{-1} (Moss, 1988). Food-processing effluents are often high in nitrate and phosphate, and in agricultural areas runoff from land carries nutrients into the water, especially if artificial fertilisers are used. Many agricultural and forestry practices lead to increased soil erosion, carrying plant nutrients from the land to the water. Intensive rearing of livestock contributes significant nutrient loads to surface waters.

Increased plant growth can sometimes be considered beneficial, especially in oligotrophic waters where primary productivity is nutrient-limited. Moderately-increased plant growth can provide increased productivity of herbivorous and detritivorous animals, leading to increased overall productivity. It is not unknown, for example, for fishermen deliberately to 'fertilise' lakes to increase fish yield. The increased spatial heterogeneity of the habitat can also give rise to an increase in species diversity. Excessive plant growth, however, has four main adverse consequences. The blanketing effect of macrophytes and filamentous algae can result in major faunal alterations owing to physical changes in the habitat. Respiration of dense plant growths can produce depressed dissolved oxygen levels, not only at night when photosynthesis ceases but also during the day if the density of plant growth reduces light penetration. Some algal species, under the influence of elevated nutrient levels, 'bloom'—that is they reproduce rapidly and dominate the flora. These algal blooms give rise to several problems, including tainting and discolouration of the water (rendering it unsuitable for potable supply) and the production of toxins which are harmful to fish and invertebrates. Following an extensive outbreak of algal blooms during 1989 in Britain, the National Rivers Authority produced a useful report which summarises the problems associated with algal blooms (NRA, 1990). Finally, the eventual decay of the plant biomass has exactly the same effect as the input of a large quantity of allochthonous organic matter.

2.5 Eutrophication

The phenomenon of eutrophication is particularly associated with lakes and slow-flowing waters. It is widely, and erroneously, believed that pollution by plant nutrients and organic matter actually causes eutrophication. It is more accurate to say that pollution accelerates what is probably a natural process. To understand the causes and consequences of eutrophication requires some knowledge of the special characteristics of lakes.

In temperate latitudes, most lakes were formed by glaciation. Moving glaciers gouged out hollows in the earth, and when the ice retreated these hollows became filled with water from the melting ice. Such lakes are not, therefore, geologically ancient phenomena. In modern times, substantial man-made lakes have become common in many parts of the world. A lake

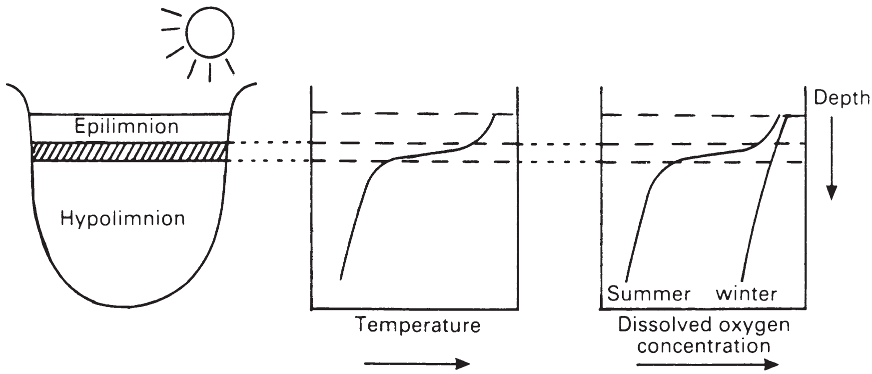

Figure 2.3 Thermocline formation in a typical lake. The diagram on the left shows the stratification which develops, the thermocline being represented by the shaded area. The centre diagram shows the temperature profile. The diagram on the right shows the deoxygenation of the hypolimnion which occurs in eutrophic lakes in the summer. The vertical mixing which occurs in winter tends to abolish the stratification, redistributing oxygen and plant nutrients through the water column

is a body of water which is very slow-moving. Some lakes have rivers flowing into or out of them. Even those which do not, however, are not static; water moves slowly into or out of the lake via the ground. Because the water moves only very slowly, some physical and chemical processes occur in lakes which do not occur in moving waters. Of particular importance are stratification, and temporal variations in chemical quality of the water.

Stratification occurs because the lake water is heated by the sun at the surface. Because warm water is less dense than cooler water, and water is a poor conductor of heat, during the warmer months of the year an upper layer of warm water, the epilimnion, becomes established and sharply delineated from a lower layer of cooler, denser water, the hypolimnion. Between them is a very narrow zone, the thermocline, within which the water temperature drops very sharply with only a slight increase in water depth (Figure 2.3). Little or no vertical mixing can take place, the lake being effectively divided horizontally into two distinct layers separated by the thermocline. Obviously, stratification cannot occur in very shallow lakes.

Photosynthesis can only occur in shallow water, where light can penetrate. At the lake margins, emergent plants and rooted aquatic macrophytes occur, but as the depth of the water increases, primary production is possible only by phytoplankton in the surface waters, within the epilimnion. During the winter, phytoplankton growth is restricted by low temperatures and low light intensity. In spring and summer increasing temperatures and light intensity stimulate phytoplankton growth, leading to an increase in population density and the depletion of nutrients in the water of the epilimnion. Plant growth

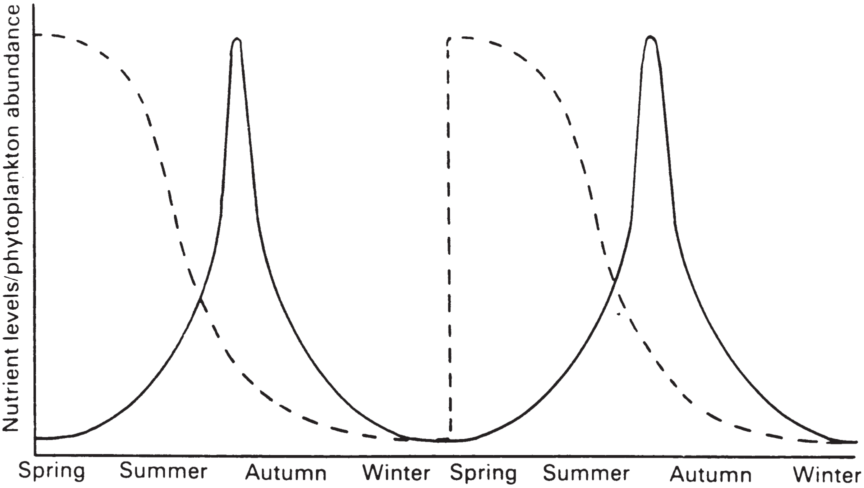

Figure 2.4 Seasonal cycling of nutrients and phytoplankton in the surface waters of a lake. Nutrient levels (dotted line) decline as phytoplankton growth (solid line) takes place. Stratification leads to nutrient depletion of the surface layers, so the phytoplankton population declines and senescent cells fall to the hypolimnion. Abolition of the thermocline in winter redistributes the plant nutrients allowing the cycle to begin again the following spring

and reproduction slow down, and as the plant cells senesce and die, they sink into the hypolimnion and eventually to the bottom of the lake, where they begin to decompose. The inorganic nutrients which are the products of decomposition remain in the hypolimnion, however, as the stratification prevents vertical mixing of the water and upwards diffusion is slow. As the autumn approaches, reduced temperatures, light intensity and limited nutrients accelerate the decline of the phytoplankton population. In the winter, the epilimnion cools and becomes more dense. Its water sinks, displacing the hypolimnion which is now warmer and lighter than the epilimnion. The lake waters become thoroughly mixed, and nutrients from the hypolimnion are brought to the surface, bringing about conditions suitable for the start of the next annual cycle (Figure 2.4).

Underlying these annual cycles is a progressive change in the physical and chemical characteristics of the lake. At its formation, the lake contains few plant nutrients or dissolved minerals of any kind, and a negligible quantity of organic matter. With the passage of time, dissolved minerals including plant nutrients enter the lake from surface runoff and groundwater infiltration, at a rate which depends largely upon the climate and the geology of the surrounding area. As the nutrient levels rise, a flora and fauna becomes established and develops, contributing an increased content of organic matter in the lake. Organic matter is also gradually accumulated from outside the lake, progressively building up a layer of sediment on the lake bottom. Airborne dust also falls into the lake, and the lake begins slowly to fill up. The rate at which this happens varies from the barely detectable up to a few millimetres per year. The gradual deposition of material on the floor of the lake basin causes the lake to shrink, new land being formed at its edges (Figure 2.5). This new land is colonised by terrestrial plants, and in some lakes it is possible, by walking away from the lake's edge, to see clearly the various stages of development of the terrestrial flora, a classic example of ecological succession. In areas where these processes have occurred, for various reasons, at different rates in different lakes, it is possible to see contemporaneously all the stages of a lake's development from nutrient-poor, sparsely-populated lakes of low productivity, through various stages of nutrient enrichment, to swamp or marsh and eventually dry land.

The term *eutrophication* is applied to the process whereby the nutrient levels of lakes increase from oligotrophic (nutrient poor) to eutrophic (nutrient rich). It appears to be a natural process, although some authors have argued that it is not inevitable or intrinsically unidirectional (Moss, 1988). Since its basic cause is, however, the accumulation of plant nutrients and organic matter in the lake basin, clearly anthropogenic influences will accelerate it. The transition from oligotrophic to eutrophic is accompanied by qualitative and quantitative changes in the biota. Since plant growth is commonly limited by nutrient levels, a gradual increase in nutrient levels would be expected to lead to successional changes in the plant community and corresponding changes in the animal community. Animals, in particular, are likely also to be affected by deoxygenation of the hypolimnion. In eutrophic lakes, the stratification which leads to nutrient depletion of the epilimnion also causes oxygen depletion of the hypolimnion. Oxygen demand due to aerobic decomposition of detritus is high in the hypolimnion, but the absence of either vertical mixing or photosynthesis in the hypolimnion prevents re-oxygenation of the hypolimnion from the atmosphere (Figure 2.3). The sensitivity of aquatic animals to dissolved oxygen levels, and its consequences for their patterns of distribution and abundance, has already been discussed.

Moss (1988), Mason (1991) and Jeffries and Mills (1990) discuss in detail some well-studied case histories of eutrophication, and a very full account is given by Harper (1992). Attempts have been made to restore eutrophic lakes, with varying degrees of success, or to manage lakes and their catchment areas in such a way as to reduce the effects of anthropogenic activities on eutrophication (Harper, 1992).

2.6 Thermal Pollution

The extent of the use of water for cooling is formidable. Howells (1983) estimated that in Britain 28% of rainfall and 50% of river flow were utilised

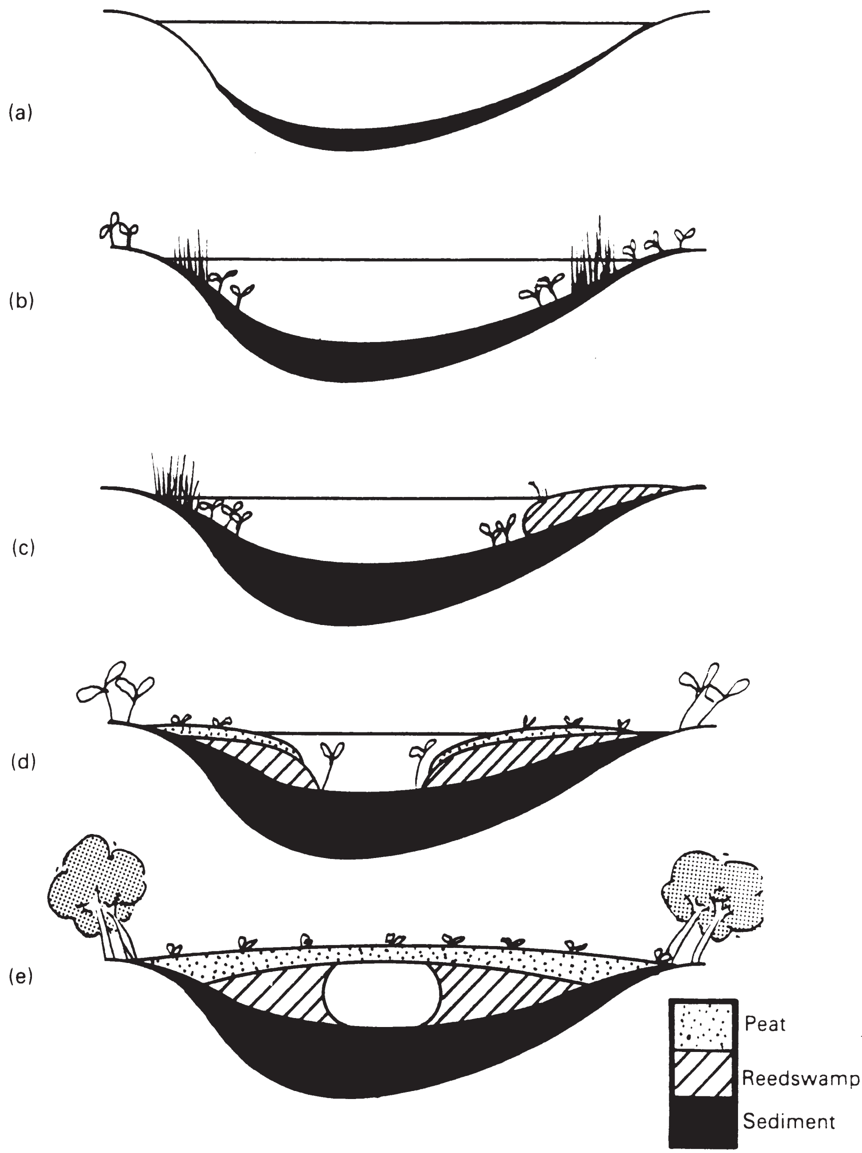

Figure 2.5 Stages of development of a typical glacially-formed temperate lake from oligotrophic (upper diagrams) to eutrophic (lower diagrams)

for this purpose. More recently, attempts to reduce these percentages have been made in view of increasing demands on water for other purposes, and the availability of improved technology. In fact, Britain has relatively few large inland power stations, and the bulk of the demand falls upon a single river system, the Trent (Lester, 1975) which supplies cooling water for approximately one-third of the nation's power-generating capacity; most of the remainder is situated on coastal or estuarine sites. In Britain, direct cooling is rare; water abstracted from the river is recirculated within the plant and much of the excess heat is dissipated through cooling towers. Direct cooling would in fact require far more water than is available from the relatively small rivers. In the USA, direct cooling is more common, and about 10% of runoff is used for cooling (Castenholtz and Wickstrom, 1975). Very large rivers are, of course, more common in large continental land masses; further, the climate in much of the USA is such that river temperatures of 30°C or more are not uncommon, whereas in Britain river temperatures above 24°C are extremely rare. To this extent, the problems of dissipating waste heat differ widely from one location to another.

Temperature is of such profound importance in chemical and biological processes that the effect of temperature alterations on aquatic biological communities is potentially large. Hot effluents from industrial processes and power generation can cause temperature increases in the receiving water of 10°C or more. Some effluents, such as water pumped from deep mines or regulating reservoirs, may be significantly colder than the receiving water, although the effects of cold effluents have received relatively little attention. Because the density of water alters with temperature, hot effluents often form a surface plume rather than mixing quickly with the receiving water. This can exacerbate some of the adverse effects, but may sometimes act to minimise the influence of the effluent on the benthic community, and fish can avoid the elevated temperature by remaining in deeper water.

Elevated temperatures can influence aquatic organisms directly, as the organisms respond physiologically or behaviourally to the new conditions; or indirectly, as the changed temperature influences the chemical environment. For example, increased temperature reduces the solubility of oxygen in water. At the same time, it may increase BOD by stimulating more rapid breakdown of organic matter by microorganisms. Temperature affects the toxicity of some poisons (see Chapter 4) either through its effect on the organisms themselves or because the dissociation of ionisable pollutants (such as ammonia or cyanides, see Section 2.7.2) is temperature-dependent. The direct effects of elevated temperature on fishes have been particularly well studied and may be used to indicate the potential impact of thermal pollution on aquatic animals generally. Varley (1967) gives a very readable introduction to the relationships between fish and their thermal environment, and their consequences for fish distribution patterns. Alabaster and Lloyd (1980) provide a detailed review of the literature relating to the temperature requirements of freshwater fishes, and Hellawell (1986) provides a concise summary of the effects of thermal pollution on the aquatic environment.

The maximum temperature which fish can withstand varies from species to species, and also within a species according to the environmental history of the fish. Generally, fish can acclimate to gradually-rising temperatures, so that the lethal temperature depends to some extent on the temperature to which the fish was initially acclimated. Relatively small, sudden changes

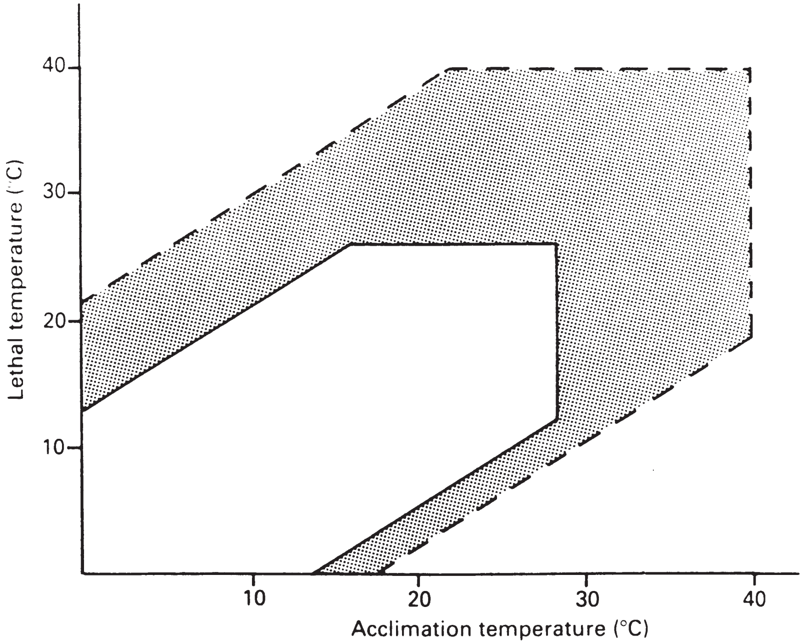

Figure 2.6 Temperature tolerance diagrams for (dotted line) a eurythermal warm-water-adapted fish and (solid line) a stenothermal cold-water-adapted fish. The upper lethal temperature increases with acclimation temperature until the ultimate upper lethal temperature is reached. The lower lethal temperature is also influenced by acclimation temperature. Only temperature changes within the boundaries are tolerated

of temperature which do not allow the acclimation process to occur can be more harmful than larger, more gradual changes. Acclimation to altered temperature is probably achieved by the induction and synthesis of isoenzymes. Many enzymes are known to exist in several forms, each having the same function but each modified to perform optimally at a particular temperature, or under some other specific condition. This is one way in which poikilothermic animals can continue to function over wide ranges of temperature, although the adjustments involved require periods ranging from several hours to several days. The relationship between acclimation temperature and the upper lethal temperature may be summarised in a temperature tolerance diagram (Figure 2.6). The temperature at which the upper lethal temperature ceases to rise with acclimation temperature is termed the ultimate upper lethal temperature. Values range from about 24°C for Salmonid fishes to 40°C or more for fishes characteristic of warmer environments. In general, the ultimate upper lethal temperature for a particular species is several degrees higher than any temperature likely to be encountered in its normal habitat. Therefore death of fish due to high

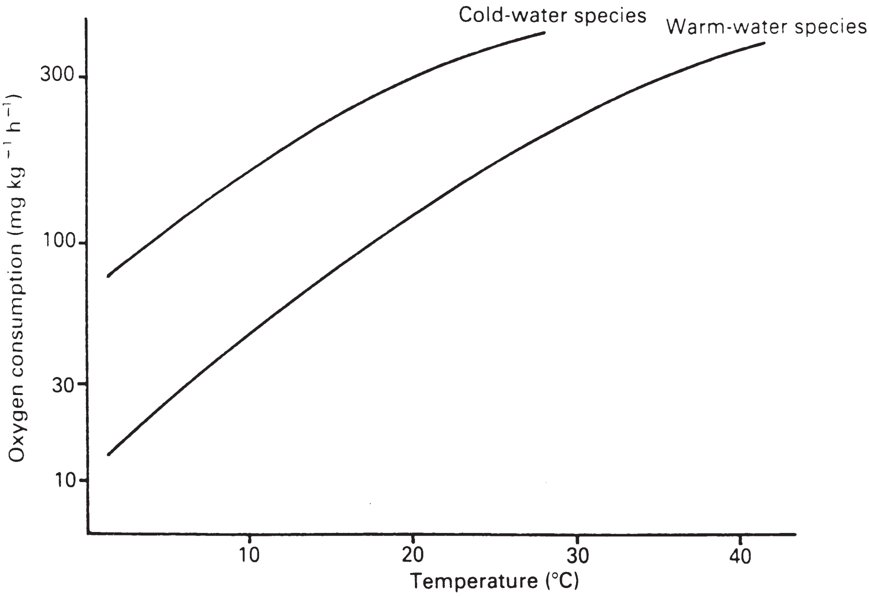

Figure 2.7 Relation between oxygen consumption and temperature for fish at rest. The upper line represents a cold-water-adapted species, the lower line a warm-water-adapted species

temperature alone is probably rare, and the adverse effects of elevated temperature are due to more subtle mechanisms.

The effects of temperature on the respiratory physiology of fish are particularly important. Even under favourable conditions, aquatic animals face formidable difficulties in balancing their needs for oxygen against the meagre quantity available from water and the high energy cost of obtaining it (see Section 2.2). Increased temperature both reduces the amount of oxygen available and increases the animal's demand for it. In addition, for animals in the wild it is not sufficient to survive passively; survival presupposes the need to engage in physical activity, which imposes still further demands for oxygen. In fish, constraints imposed by the size, structure and efficiency of the gills, and by the limited solubility of oxygen in water, limit the maximum possible oxygen consumption to a value of about 400 mg kg^{-1} h^{-1} in most species.

In Figure 2.7, the effect of temperature on the oxygen consumption of two fish species is shown. Warm-water species require to reach the maximum possible rate of oxygen expenditure only at fairly high temperatures. As the temperature falls, their metabolic rate falls until it is too low to permit physical activity, and the fish become torpid. In the wild, they would not survive because they would be unable to find food, avoid predators, or even maintain their position in a current. Cold-water species, such as Salmonids, however, must be active at low temperatures. They are adapted to high rates of oxygen consumption at low temperatures. However, their rate of oxygen consumption increases with temperature at about the same rate as that for cold-water species (Figure 2.7). Therefore they reach the maximum possible rate at a much lower temperature. As argued in Section 2.2, when the fish reaches this condition the energy cost of working the respiratory muscles is such that there is no oxygen available for the tissues, and the fish dies. Further, the need to retain a margin of capacity for physical activity is important. At its ultimate upper lethal temperature, the fish has no scope to indulge in physical activity other than respiratory movements. At very low temperatures, it has little scope for muscular activity of any sort, since the efficiency of muscle tissue decreases with temperature. At intermediate temperatures, the difference between basal metabolism (oxygen consumption at rest) and active metabolism (oxygen consumption during physical activity) reaches a distinct maximum (Figure 2.8). In practice, the temperature regime which is favourable for the indefinite survival of the fish includes a much narrower range of temperatures than that which would allow the survival of the fish under laboratory conditions.

The range of temperatures which is suitable for growth, reproduction and development of fishes is also generally rather narrower than that which simply allows survival. Temperature is, in conjunction with photoperiod, an important trigger for the onset of reproductive cycles. Temperature also governs the rate of development of fish eggs. In most species, the average temperature multiplied by the time taken for the eggs to hatch is a constant. In Salmonids, eggs typically require 410 degree-days; for example, 41 days at 10°C or 51 days at 8°C. This relationship only holds good, however, within a certain temperature range—below about 5°C and above about 15°C, the proportion of eggs successfully developing is markedly reduced. In Cyprinid fishes, development of eggs may be much quicker, typically three days at 20°C in carp, with other species showing intermediate values. Thus quite short-term anomalies in the temperature regime, if they occur at a critical period, can exert a serious effect on fish reproduction. Studies of the growth of many fish species, particularly those which are widely cultured, show that temperature has critical effects on growth rate and on food conversion efficiency (i.e. the ratio between the increase in weight of the fish and the quantity of food consumed). (In fish, sexual maturity normally occurs when the animal has reached a critical size rather than a critical age.) Clearly, temperature anomalies can have a major influence on the reproductive success of fish, without necessarily giving rise to any obvious immediate effects on the adult population. In practice, fish have considerable powers of mobility and in laboratory experiments show clear preferences for particular temperatures, ranging from about 13°C for Salmonids to 37°C for carp (Varley, 1967). Thus areas subject to thermal anomalies may be devoid of fish through avoidance reactions, but without any serious long-term effects on the population, provided that the fish do have access to cooler water.

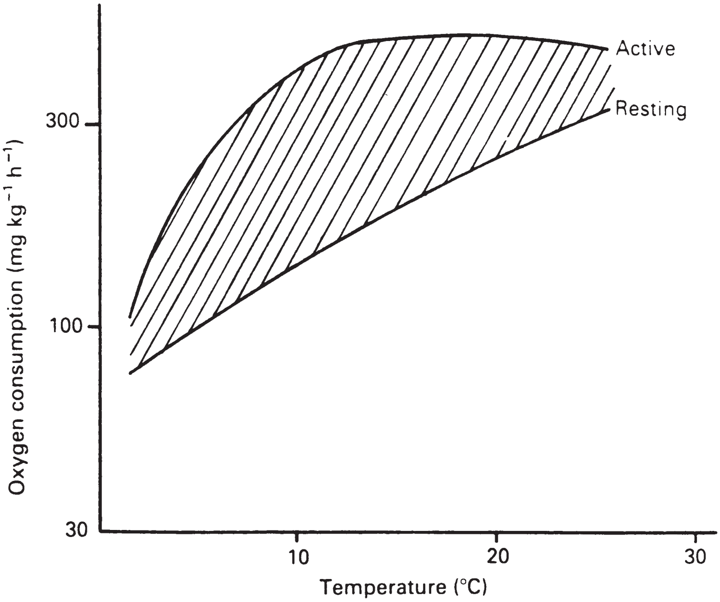

Figure 2.8 Effect of temperature on (lower line) the resting or standard metabolism of a fish and (upper line) the active metabolism. The shaded area represents the 'scope for activity' of the fish

In view of the prevalence of heated effluents, and of the potential importance of elevated temperatures indicated by laboratory studies, it is perhaps surprising that unequivocal examples of ecological damage by thermal pollution are rare. Reviewers such as Castenholtz and Wickstrom (1975), Howells (1983) and Hellawell (1986) cite no clear instances of any readily-detectable adverse effect of elevated temperature, as such, on the ecology of a receiving water, apart from numerous autecological studies whose significance to the overall ecosystem is unknown. Poff and Matthews (1986) did produce some data which appear to show that in a North American stream receiving power-station effluent, invertebrate communities showed reduced diversity and changes in species dominance, compared to nearby undisturbed streams. This is the type of effect which would be expected, but it seems that river communities are often more resilient to thermal disturbance than theory would predict. However, the review of Alabaster and Lloyd (1980), based largely upon research (including field studies) in Eastern Europe which was previously little-known, suggests that temperature increases of between 2 and 8°C do produce significant alterations in the biota of receiving waters.

The apparent difficulty of detecting the ecological effects of thermal pollution may be due to any of several causes. In Eastern Europe, where such effects are more apparent, the prevailing climate is significantly more extreme than in Western Europe or the USA where most studies have been carried out. In many circumstances, heated effluents are discharged to rivers which are also polluted with toxic or organic matter, and the effects of elevated temperature may be difficult to distinguish from other pollution effects. Since *low* temperatures can also limit biological processes, in some circumstances artificially-elevated temperatures may actually be beneficial in terms of overall productivity. Also, local conditions undoubtedly influence the impact of heated effluents. In many countries, power generation reaches its maximum during the winter months when river temperatures are low and river discharges high. In others, depending upon climatic and economic factors, demands for electric power (for refrigeration or air-conditioning) in summer, when river discharges are lowest and temperatures naturally highest, may approach or exceed winter levels. The effects of heated effluents on the ecology of receiving waters may therefore be expected to vary from one region to another. Finally, the effects of elevated temperatures may be difficult to predict or detect without detailed knowledge of specific local circumstances. For example, increased temperature will accelerate microbial decomposition of organic matter. In sluggish, poorly-aerated waters this will accentuate the effects of organic pollution; but in turbulent waters which re-aerate rapidly from the atmosphere, the effect of elevated temperature would be to reduce the extent of the zone within which the adverse effects of organic inputs manifested themselves, and in a lightly-polluted water might lead to a beneficial increase in overall productivity. It is therefore unwise to attempt generalisations on the effects of thermal pollution; each case must be considered individually.

2.7 Toxic Pollution

There are about four million different chemical substances in existence, a number which increases by about 300000 every year. Of these, about 63000 are in common use (Maugh, 1978). Goodman (1974) estimated that about 10000 chemicals are produced in quantities exceeding 500 kg yr^{-1}. A large proportion of these thousands of chemicals are, presumably, only produced and/or used in only a small number of locations. Nevertheless the number of pollutants which can be considered as widespread is still formidably large. A realistic figure is indicated by the 1978 Great Lakes Water Quality Agreement between the US and Canadian governments (reprinted in Nriagu and Simmons, 1983). Appendix 1 of this agreement lists 271 different substances which, on the basis of toxicological and discharge data, are considered hazardous to the North American Great Lakes. Appendix 2 of the same agreement lists a further 106 ‘potentially hazardous polluting substances’.

The present discussion is confined, of necessity, to a general description of the sources and characteristics of some of the major categories of toxic pollutant. The categories chosen are for convenience, and are not necessarily mutually exclusive;