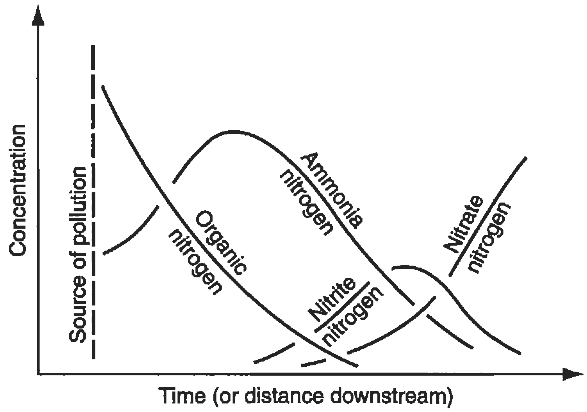

Figure 4-11. Typical variations in nitrogen compounds downstream from a point of organic pollution.

EFFECT OF POLLUTION ON LAKES

The effect of pollution on lakes differs in several respects from the effect on streams. Water movement in lakes is slower than in streams, so reaeration is more of a problem in lakes than streams. Because of the slow movement of water in a lake, sediments, and pollutants bound to sediments, tend to settle out of the water column rather than being transported downstream.

Light and temperature have important influences on a lake, and must be included in any *limnological* analysis (limnology is the study of lakes). Light is the source of energy in the photosynthetic reaction, so the penetration of light into the lake water determines the amount of photosynthesis that can occur at various depths in the lake. Light penetration is logarithmic and a function of wavelength. Short wavelengths (blue, ultraviolet) penetrate farther than long wavelengths (red, infrared). Light penetration at all wavelengths is less in lakes with high concentrations of dissolved organic matter. In pristine lakes, 60–80% of the incident blue/UV light, and 10–50% of the red/IR may penetrate beyond the first 3 ft; in *humic* (boggy) lakes, the presence of large amounts of organic matter causes 90–99% of all wavelengths to be absorbed within the first 3 ft. Because of this, algal growth is concentrated near the surface of a lake, in the *photic zone*, which is limited to the maximum depth where there is still enough light to support photosynthesis.

Temperature and heat often have a profound effect on a lake. Water is at a maximum density at 4°C; warmer or colder water (including ice) is less dense, and will float. Water is also a poor conductor of heat and retains heat quite well.

Lake water temperature usually varies seasonally (see Fig. 4-12). During the winter, if the lake does not freeze, the temperature is relatively constant with depth. As the weather warms in the spring the top layers of water begin to warm. Since warmer water is less dense, and water is a poor conductor of heat, the lake eventually stratifies into a warm, less dense, surface layer called the *epilimnion* and a cooler,

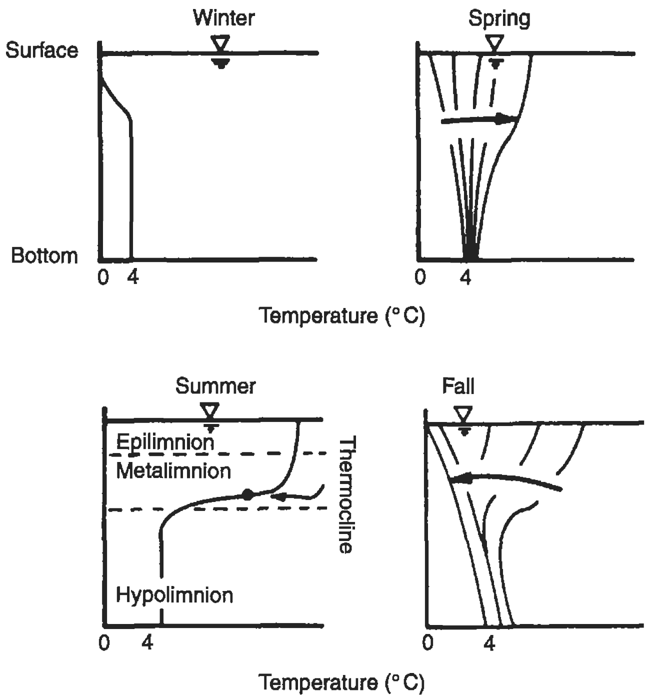

Figure 4-12. Typical temperature–depth relationships in lakes.

denser, bottom layer, the *hypolimnion.* A thermal gradient, the *metalimnion,* is present between these two layers. The inflection point in the temperature gradient is called the *thermocline* (early limnologists used "thermocline" to describe the entire thermal gradient). Circulation of water occurs only within a stratum, and thus there is only limited transfer of biological or chemical material (including dissolved oxygen) between the epilimnion and the hypolimnion. As colder weather approaches, the top layer cools, becomes denser, and sinks. This creates circulation within the lake, known as fall turnover. If the lake freezes over in the winter, the lake surface temperature will be less than 4°C, and the ice will float on top of the slightly denser (but still cold!) underlying water. When spring comes, the lake surface will warm slightly and there will be a spring turnover as the ice thaws.

The biochemical reactions in a natural lake are represented schematically in Fig. 4-13. A river feeding the lake would contribute carbon, phosphorus, and nitrogen, either as high-energy organics or as low-energy compounds. The phytoplankton (free-floating algae) take carbon, phosphorus, and nitrogen, and, using sunlight as an energy source, make high-energy compounds. Algae are eaten by zooplankton (tiny aquatic animals), which are in turn eaten by larger aquatic life such as fish. All of these life forms defecate or excrete waste products, contributing a pool of dissolved organic carbon. This pool is further fed by the death of aquatic life, and by the near-constant leakage of soluble organic compounds from algae into the water. Bacteria use dissolved

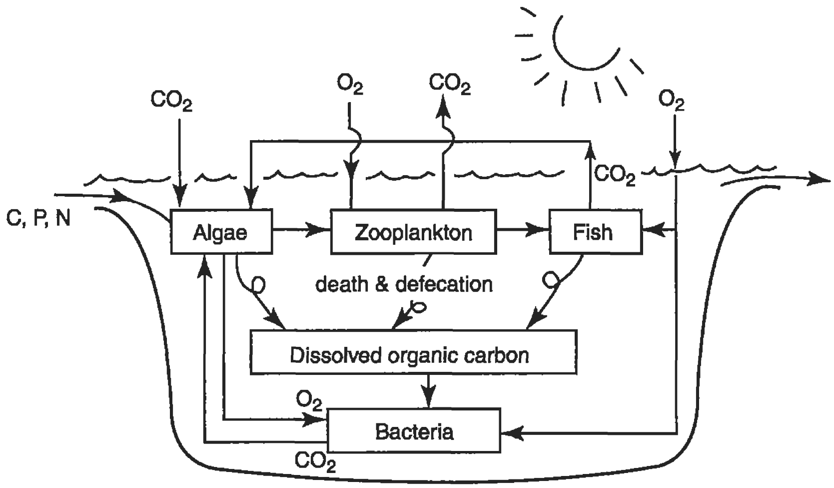

Figure 4-13. Schematic representation of lake ecology. (With thanks to Don Francisco.)

organic carbon and produce carbon dioxide, which is in turn used by algae. Carbon dioxide is also provided by respiration of fish and zooplankton, as well as dissolving into the water directly from the air.

The growth of algae in most lakes is limited by the availability of phosphorus; if phosphorus is in sufficient supply, nitrogen is usually the next *limiting nutrient*. (A limiting nutrient is an essential element or compound that controls the rate of algal growth because the nutrient is not readily available.) Some algal species have special growth requirements that result in co-limitation by other nutrients (e.g., silica is required for diatom growth).

When phosphorus and nitrogen are introduced into the lake, either naturally from storm runoff, or from a pollution source, the nutrients promote rapid growth of algae in the epilimnion. When the algae die, they drop to the lake bottom (the hypolimnion) and become a source of carbon for decomposing bacteria. Aerobic bacteria will use all available dissolved oxygen in the process of decomposing this material, and the dissolved oxygen may be depleted enough to cause the hypolimnion to become anaerobic. As more and more algae die, and more and more dissolved oxygen is used in their decomposition, the metalimnion may also become anaerobic. When this occurs, aerobic biological activity is restricted to the epilimnion.

The increasing frequency of this condition over the years is called eutrophication. Eutrophication is the continually occurring natural process of lake aging and occurs in three stages:

- the oligotrophic stage, which is characterized by low levels of biological productivity and high levels of oxygen in the hypolimnion;

- the mesotrophic stage, which is characterized by moderate levels of biological productivity and the beginnings of declining oxygen levels following lake stratification; and
- the eutrophic stage, at which point the lake is very productive, with extensive algal blooms, and increasingly anaerobic conditions in the hypolimnion.

Natural eutrophication may take thousands of years. If enough nutrients are introduced into a lake system, as may happen as a result of human activity, the eutrophication process may be shortened to as little as a decade.

Because phosphorus is usually the nutrient that limits algal growth in lakes, the addition of phosphorus, in particular, can speed eutrophication. If only phosphorus is introduced into a lake, it will cause some increase in algal growth, but nitrogen quickly becomes a limiting factor for most species of algae. One group of photosynthetic organisms, however, is uniquely adapted to take advantage of high phosphorus concentrations: the *cyanobacteria*, or blue green "algae." Cyanobacteria are autotrophic bacteria that can store excess phosphorus inside their cells in a process called *luxury consumption.* The bacteria use the excess phosphorus to support future cell growth (up to about 20 cell divisions). The cyanobacteria also have the ability to use dissolved N_2 gas as a nitrogen source, which is rapidly replenished by atmospheric N_2. Most other aquatic autotrophs cannot use N_2 as a nitrogen source. As a result, cyanobacteria thrive in environments where nitrogen has become limiting to other algae, and can sustain their growth using cellular phosphorus for long periods of time. Not surprisingly, cyanobacteria are often water quality indicators of phosphorus pollution.

Where do these nutrients originate? One source is excrement, since all human and animal wastes contain organic carbon, nitrogen, and phosphorus. Synthetic detergents and fertilizers are a much greater source. About half of the phosphorus in U.S. lakes is estimated to come from agricultural runoff, about one-fourth from detergents, and the remaining one-fourth from all other sources.

Phosphate concentrations between 0.01 and 0.1 mg/L appear to be enough to accelerate eutrophication. Sewage treatment plant effluents may contain 5–10 mg/L of phosphorus as phosphate, and a river draining farm country may carry 1–4 mg/L. Residential and urban runoff may carry up to 1 mg/L, mostly from pet wastes, detergents, and fertilizer. In moving water, the effects of elevated phosphorus are usually not apparent because the algae are continually flushed out and do not accumulate. Eutrophication occurs mainly in lakes, ponds, estuaries, and sometimes in very sluggish rivers.

Actual profiles in a lake for a number of parameters are shown in Fig. 4-14. The foregoing discussion clarifies why a lake is warmer on top than at lower depths, how dissolved oxygen can drop to 0, and why nitrogen and phosphorus are highly concentrated in the lake depths while algae bloom on the surface.

EFFECT OF POLLUTION ON GROUNDWATER

A popular misconception is that all water that moves through the soil will be purified "naturally" and will emerge from the ground in a pristine condition. Unfortunately,