- 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,

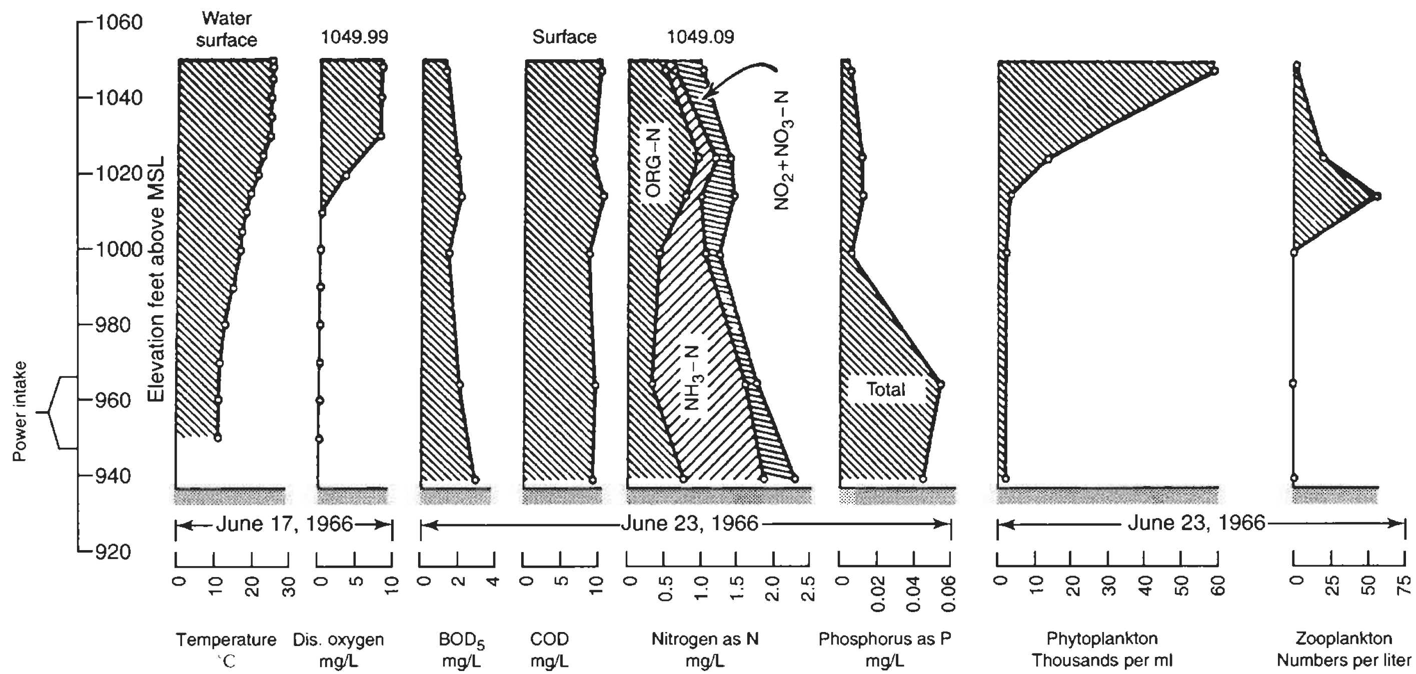

Figure 4-14. Water quality profiles for a water supply reservoir. (From Berthouex, P. and D. Rudd, *Strategy of Pollution Control.* New York: Wiley, 1977.)

there are limits to what soil can remove, and groundwater pollution is becoming an increasing concern throughout the world.

Many soils do have the ability to remove certain types of pollutants, including phosphorus, heavy metals, bacteria, and suspended solids. Pollutants that dissolve in water, like nitrate and ammonia, may pass through soils into the groundwater. In agricultural regions, the nitrogen and other soluble chemicals in fertilizers or animal wastes can seep into the groundwater and show up in alarmingly high concentrations in local drinking water wells. A recent study of the Abbotsford/Sumas aquifer (a water-bearing zone of rock, sand, gravel, etc.), which supplies water to more than 100,000 people in the western portion of Canada and Washington, indicated that 40% of the wells tested had nitrate levels above 10 mg/L (EPA maximum recommended drinking water level), and 60% had nitrate levels above 3 mg/L (a general warning level for nitrate in drinking water).

The agricultural community is becoming more aware of the connection between agricultural practices and groundwater pollution. Many states have begun working with dairy owners and farmers to develop farm management plans that restrict fertilizer applications to periods of active plant growth, which helps prevent groundwater pollution by sequestering nitrate into growing vegetation. These farm plans also include surface water pollution prevention techniques such as restricting animal access to stream banks, setting maximum animal density goals, requiring manure-holding ponds, and revegetating *riparian* (stream side) areas.

Other potential sources of groundwater pollution include leaking underground storage tanks, solid waste landfills, improperly stored hazardous waste, careless disposal of solvents and hazardous chemicals on ground surfaces, and road salts and deicing compounds. Many of the current U.S. Superfund sites (see Chap. 17, "Solid and Hazardous Waste Law") are concerned with the cleanup of materials that have contaminated, or have the potential to contaminate, groundwater.

EFFECT OF POLLUTION ON OCEANS

Not many years ago, the oceans were considered infinite sinks; the immensity of the seas and oceans seemed impervious to assault. Now we know that the seas and oceans are fragile environments and we are able to measure detrimental effects.

Ocean water is a complicated chemical solution, and appears to have changed very little over millions of years. Because of this constancy, however, marine organisms have become specialized and intolerant to environmental change. Oceans are thus fragile ecosystems, quite susceptible to pollution.

A relief map of the ocean bottom reveals two major areas: the continental shelf and the deep oceans. The continental shelf, especially near major estuaries, is the most productive in terms of food supply. Because of its proximity to human activity, it receives the greatest pollution load. Many estuaries have become so badly polluted that they are closed to commercial fishing. The Baltic and Mediterranean Seas are in danger of becoming permanently damaged.