# 1

# There is no substitute for water

*Water, water, every where,*
*Nor any drop to drink*
S.T. Coleridge, *The Rime of the Ancient Mariner* (1798)

## 1.1 Our water planet

If extraterrestrial beings ever investigated this planet, it is doubtful they would name it *Earth*. They would almost certainly call it *Water*. Water covers approximately 75% of our world's surface, representing a volume of over one billion cubic kilometers. However, as noted later in this chapter, only a very small portion of this water is fresh and accessible. A second feature characterizing our planet is the incredible number and diversity of life forms. This truly is "the Living Planet" (Attenborough 1984). Water and life are intricately linked. Water makes up about 70% of our bodies. More than half of the world's species of plants and animals live in water, and even our terrestrial-derived food is totally dependent on and often largely composed of water. Civilizations have flourished and collapsed due to changing water supplies: Water can shape history; it can make or break a king (Ball 1999). It is not surprising that over 80% of Americans live within 8 km of surface waters (Naiman et al. 1995). Without water, there would be no life. Plain and simple.

The study of inland waters is called limnology. A common definition of a limnologist is someone who studies lakes and rivers, although the term includes those who work with other inland waters (e.g., ponds, swamps, saline lakes, wetlands). Limnology is a diverse science, which includes physics, chemistry, biology, geology, and geography, as well as a suite of other disciplines. It has strong links to applied fields as well, such as engineering and management. Many applications have a clear environmental focus.

Paleolimnology, which is the theme of this book, is the multidisciplinary science that uses the physical, chemical, and biological information preserved in sediment profiles to reconstruct past environmental conditions in inland aquatic systems. Paleolimnology has many applications. Although pollution studies make up a significant part of the literature, paleolimnological approaches are used to study a wide variety of basic and applied problems.

Most scientists seem to differentiate between limnology and paleolimnology, as if they are quite separate fields. As I have argued previously (Smol 1990a), this seems to me to be an artificial division. I prefer to use the word "neolimnologist" to designate scientists working with present-day aquatic systems, whilst "paleolimnologists" often address similar problems, but do so at much longer time scales, using sediments as their primary research material. Both are limnologists; it is primarily a distinction of time scales and temporal resolution. Whilst neolimnologists can typically use tools and approaches with higher resolution, paleolimnologists can extend many of these studies back in time, and back in time is where many of the critical answers to environmental problems are hidden. The two disciplines are tightly linked and complementary.

## 1.2 Water and aquatic ecosystems

Water ($H_2O$) is a peculiar compound and it is important to understand some of its characteristics (Box 1.1). In contrast to almost any other substance, water is less dense in its solid form (ice) than it is in its liquid form, and so ice floats. Water also has other interesting thermal and density properties in that it is most dense at about 4°C and less dense as it gets warmer, but it also becomes less dense as it gets colder, until it freezes at 0°C (these temperatures refer to pure water; water containing dissolved solutes, such as sea water, will freeze at lower temperatures). Because water layers at different temperatures will have different densities, three thermally (and hence density-) defined horizontal strata will often form in deeper lakes that have strong seasonal temperature differences (Fig. 1.1; the upper, warmer epilimnion; the middle portion of rapid temperature change, or the thermocline, which demarks the metalimnion; and the deep, colder layer called the hypolimnion, often at or near 4°C). In temperate regions, lakes are often stratified in this way throughout much of the summer but mix totally after ice-melt in the spring (spring overturn, which occurs when the lake is isothermal at or near 4°C) and again in autumn, as temperatures begin to cool and thermal stratification weakens. Such lakes are called dimictic, because their water columns mix twice every year. In subtropical regions, only one mixing event in the cold season may occur (monomictic lakes), and other variations occur (a number of limnology textbooks deal with this topic in much more detail: Kalff 2001; Wetzel 2001). These stratification patterns have important ecological and environmental implications. For example, on a very windy, mid-summer day, a lake may appear to be well mixed, with large surface waves. But this is not really the case, as these waves are largely a surface phenomenon, and the deeper waters are still largely segregated into three layers. Thermal stratification is often weak or non-existent in shallow lakes or rivers, where wind mixing or currents are stronger than the density gradients set up by temperature differences, and so these systems mix frequently (polymictic).

In addition to vertical stratification, there are also marked horizontal differences in lakes and rivers (Fig. 1.1). Water depth (and associated light penetration) is often a major factor controlling horizontal zonation in water bodies, with of course shallower water occurring near the shore and deeper water typically farther from the shore (Box 1.2). The littoral zone is often defined as the part of the lake or river where rooted aquatic plants (macrophytes) can grow. This growth is primarily depth dependent, although it can be altered greatly by water clarity (for example, two lakes may have similar morphometries, but the lake with the clearer water will typically have the larger littoral zone). Shallower sites are often referred to as ponds; the distinction between lakes and ponds, though, is not standardized. For example, in some regions, a pond is defined as a water body where the entire bottom can support rooted aquatic macrophytes (i.e., the entire pond is technically a littoral zone). This definition, however, is difficult to apply universally. For example, some highly productive waters are quite shallow and so might intuitively be considered ponds, but because of the large amount of material in their water columns, the photic zone is much reduced and rooted macrophytes cannot grow. In polar

**Box 1.1 The major properties of water**

The water molecule consists of two hydrogen atoms bound to an oxygen atom, forming an isosceles triangle. Water molecules are attracted to each other, creating hydrogen bonds, which influence many of the physical as well as chemical properties of water. Pure water at sea level freezes at 0°C and boils at 100°C. At higher elevations, the boiling point of water decreases, due to the lower atmospheric pressure. If substances are dissolved in the water, the freezing point is lowered (this is why salt is often applied to some roads in winter; it deters ice from forming).

Like other liquids, the density of water is very closely related to temperature, as well as to the amount of solutes it contains. Perhaps the most striking feature of water is that it is less dense in its solid form (ice) than it is in its liquid form, and so ice floats. The highest density of pure water is reached just below 4°C, and so water of this temperature is often found in the deep waters of a lake. The addition of solutes also increases the density of water markedly (i.e., salty water will be denser than fresh water). Both these features influence thermal and chemical stratification patterns in lakes, with important environmental consequences.

Water has a very high specific heat, which is the amount of energy needed to warm or cool a substance. It has amongst the highest specific heats of any naturally occurring substance. This is why, for example, it is often cooler around an ocean or a large lake during summer, as the water remains cooler longer than land. Similarly, regions around large bodies of water are warmer in winter as the water is slower to cool. People who live close to large bodies of water are often said to enjoy a maritime climate, with reduced climatic extremes between the seasons. Farmers benefit as well, as crops are protected from nighttime freezing. In contrast, regions far inland are often said to have continental climates, with striking seasonal changes in temperature. In short, large bodies of water are the world's great heat reservoirs and heat exchangers. People exploit the high specific heat capacity of water when they bring hot water bottles into their beds on cold nights.

Water also has an extremely high surface tension, which is a measure of the strength of the water's surface film. Of the other liquids one is likely to encounter, only mercury (Chapter 10) has a higher surface tension. The epineuston is a community that takes advantage of this surface tension and lives on the surface of the water. Water striders (Gerridae) are insects commonly seen on the surfaces of lakes and ponds; they rely on this surface tension to walk on the water's surface. Another group of organisms, collectively referred to as the hyponeuston, live below the water line, but again attach themselves to the water's surface. This surface tension can also be a deadly trap for some organisms. For example, insects that touch the water may not be able to release themselves from this force.

One of the most important characteristics of water is that it is almost the universal solvent, with extraordinary abilities to dissolve other substances. Consequently, when water passes through soils or vegetation or a region of human activity (e.g., an agricultural field treated with fertilizers and insecticides, a mine tailings heap, a municipal or industrial landfill site, etc.) it changes its characteristics as it dissolves solutes. Even a drop of water falling as rain will dissolve atmospheric gases, and its properties will be altered (e.g., carbon dioxide dissolves readily in water, forming a weak acid, carbonic acid).

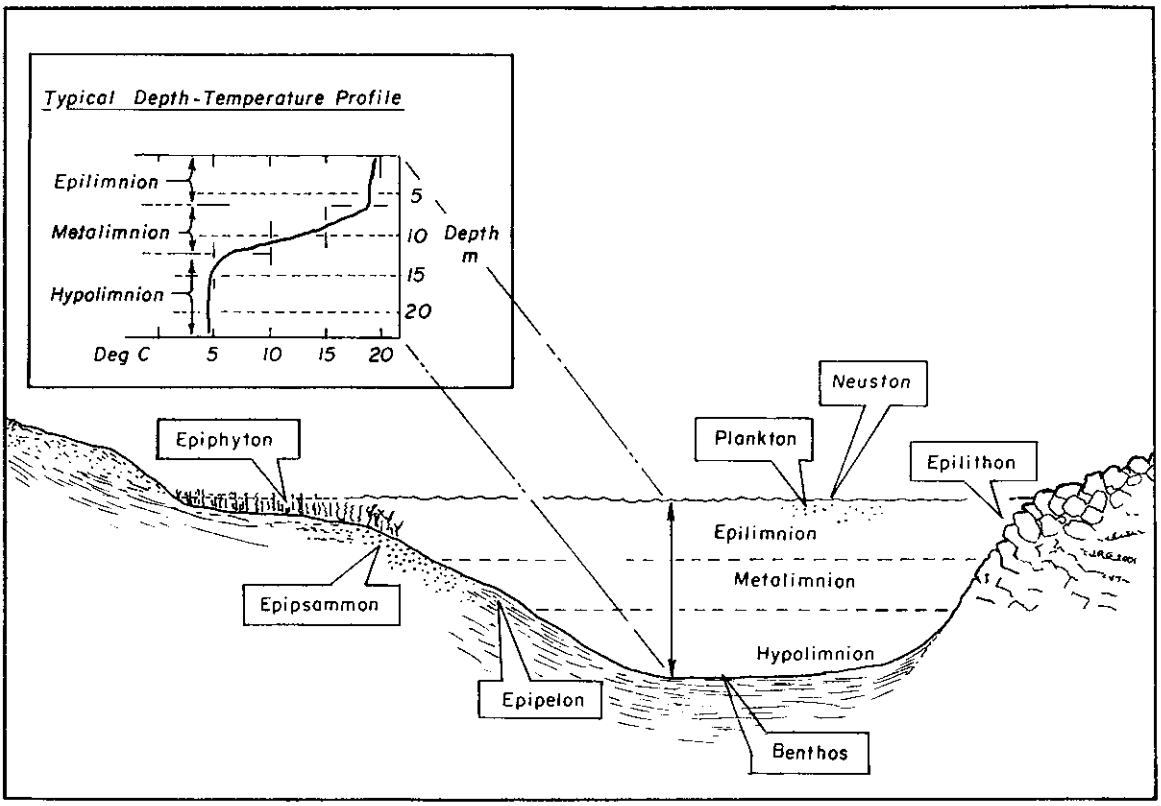


**Fig. 1.1** A cross-section of a thermally stratifying lake, showing the density separation into three layers: the epilimnion, the metalimnion, and the hypolimnion. The lake cross-section also shows the major habitats of a lake, as described in Box 1.2.

regions, a pond is often defined as a water body that freezes completely to the bottom in winter.

Water is always on the move (Box 1.3). Using energy from the sun, over one thousand cubic kilometers of water evaporates from this planet every day. But then this water condenses and returns to Earth in precipitation, which may be in a liquid (rain), solid (snow), or gaseous (water vapor, fog) form. All of these phases can be affected by human activities. Once reaching the Earth, water may be deposited directly into lakes and rivers, but it is more likely to be intercepted by vegetation, or to become part of the surface runoff, which eventually makes its way to rivers and lakes and eventually to the oceans. Some precipitation may land in polar or high alpine regions, and become frozen and then stored in ice caps and glaciers for millennia. Other water may percolate down through the soil and become part of the groundwater system, where it too may remain for a long period of time before resurfacing. About every 3000 years, this movement of water from the Earth to the sky and back again recycles an amount of water equivalent to the volume of the world's oceans.

Human activities alter the quality and quantity of water passing through all these systems by their activities, often with negative repercussions. This book will examine the repercussions of these activities.

**Box 1.2 Horizontal zonation and the major habitats and communities in aquatic ecosystems**

The littoral zone is typically defined as the shallow part of a lake where rooted aquatic macrophytes can grow. Although the littoral zones of some lakes are not very large, a significant, sometimes dominant, portion of the overall production occurs there. Many organisms, such as some fish, feed, find refuge, and reproduce in these areas. Since littoral zones are the closest to land (and to human influences), they are often critical areas in pollution studies.

Organisms, such as algae, living in the littoral zone are often attached to a substrate and are collectively called the periphyton. Substrates typically delineate this region (Fig. 1.1). For example, the epiphyton are organisms living attached to plants, whilst the epilithon are attached to rocks and stones, the epipsammon are attached to sand grains, and the epipelon live on the sediments.

The deeper, open-water region is often referred to as the pelagic region. Plankton live unattached to any substrate in the open-water system, and are largely at the mercy of water movements, although some have limited motility (e.g., with flagella). Plankton that are photosynthetic, such as algae, are called phytoplankton; those that are more animal-like, such as water fleas (Cladocera), are called zooplankton. Animals with strong locomotory capabilities, such as fish and large invertebrates, are called the nekton.

A smaller, poorly studied community, collectively called the neuston, lives closely associated with the surface tension of the water's surface. Organisms living in such a manner above the water line are called the epineuston; those below the water line are called the hyponeuston.

The profundal region typically refers to the deep waters in the middle of the system. Organisms living on and in the sediments are called the benthos.

**Box 1.3 The hydrological cycle**

Water is always on the move, cycling through the various compartments of our planet (e.g., the atmosphere, the lithosphere, the hydrosphere; Fig. 1.2). Driven by energy from the sun, water evaporates as water vapor into the atmosphere, where it can be transported long distances. During this gaseous phase, it can be transformed and contaminated by a variety of pollutants (e.g., acids). Eventually, the water vapor will condense and precipitate back to Earth in either a liquid (rain) or solid (snow) phase.

Some precipitation falls directly on water bodies, such as lakes and rivers, and so will not be directly influenced by watershed characteristics. However, catchments typically have much larger surface areas than the water bodies they drain into, and so much of the incoming water precipitates on land. Water quality is influenced by natural characteristics of the drainage basin (e.g., local geology, vegetation) as well as anthropogenic activities (e.g., industrial contaminants, agricultural fertilizers and pesticides, etc.). Because of water's ability to dissolve many substances (see Box 1.1), and the fact that moving water is often a very effective vector for eroding and

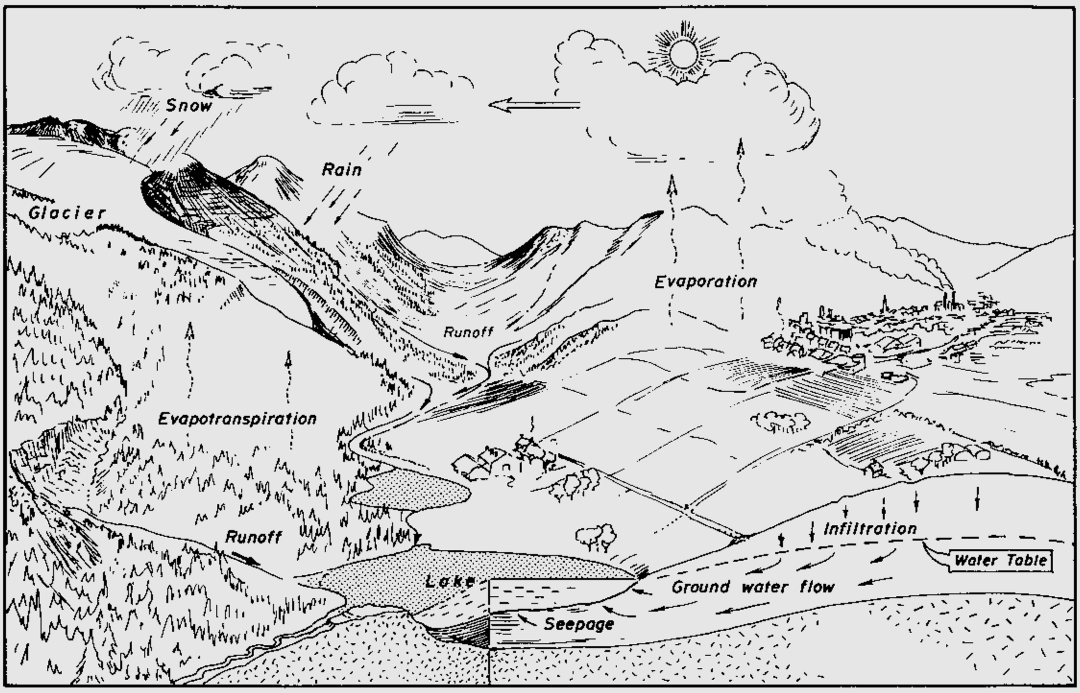


**Fig. 1.2** A schematic diagram showing the major processes involved in the hydrological cycle.

transporting particulates, the water that eventually enters a lake or river can have dramatically different water-quality characteristics than the water droplets that had condensed in the atmosphere.

Moreover, not all the precipitation falling on a catchment will be flushed into the receiving water body. Some will be re-evaporated back into the atmosphere. Some of the water may percolate into the groundwater, where it will continue to move, albeit very slowly. It may stay underground for thousands of years before it resurfaces. The water quality may change dramatically while it is underground, as it is naturally filtered by passing through the cracks and pores in the soil and rocks. In addition, due to water's high solubility characteristics, it is constantly dissolving substances with which it is in contact. It may also be contaminated by human-produced compounds, such as pesticides.

Water may be intercepted by vegetation, taken up by plants as part of their physiological activities, and then released back into the atmosphere through the stomata in their leaves. For example, the roots of a typical birch tree may take up over 300 liters of water each day, but then the tree transpires much of it back into the atmosphere. This is called evapotranspiration. A good way to show how significant terrestrial vegetation is in evapotranspiring water is to remove it (e.g., logging), and then see how much more water is released from the catchment via overland flow (Likens 1985).

## 1.3 Water: a scarce resource, becoming more valuable daily

Although water characterizes this planet, much of it is not available to humans in a form that can readily be used as a source of drinking water or other uses (e.g., agriculture, industry), as the vast majority of it is salty (~ 95.1%) and contained in the world's oceans (Speidel & Agnew 1998). Of the small percentage that is fresh water[1] (~ 4.9%), most of this is inaccessible in groundwater or frozen in glaciers and polar ice. Once you account for this and other sources of water, only about 0.01% of the vast amounts of water on this planet is fresh and available as surface waters in a liquid form – equivalent to about a drop in a bucket. Of this small percentage, much of it is contained in lakes and rivers that are far from human populations. Hence, many of our water reserves are simply not readily accessible.

Certain regions are blessed with large amounts of fresh water. Wetzel (2001) estimates that the Earth contains approximately 100 million lakes that are greater than 1 ha in area, and approximately one million lakes that exceed 1 $km^2$. However, other regions, including areas of high population growth, have very serious water problems. Fresh water is a very valuable resource, and is getting more valuable every day. Each day, our limited water supplies have to be shared by a larger population. You can live without oil, but you can't live without water. As plainly stated by the 19th-century American author, Mark Twain: "Whiskey is for drinking; water is for fighting."

## 1.4 Human influences on water quality

The Earth is about 4.5 billion years old and certainly many natural environmental changes have occurred on this planet during that time. Hominids only evolved a few million years ago, and our species, *Homo sapiens*, has only been around for about the past 150,000 years. If we put the 4.5 billion year history of the Earth on a 24-hour clock, the arrival of our species would only occur in the last 3 seconds before midnight! However, unlike any other species, our short visit on this planet has been very influential.

Throughout most of this approximately 150,000 years, humans made little impact on the environment. Their numbers were too small, too dispersed, and their technology was so primitive that they made little impact on the landscape except for footprints. Things began to change, though, about 10,000 years ago, when the experiment called "civilization" began. Starting at similar times in regions ranging from the Far East and the Near East to the west coast of Peru, people began clustering in larger groups with the development of agriculture. New technological advancements came shortly afterwards, as did food surpluses. Populations started to grow, slowly at first, but then faster – much faster. People first clustered in small groups, then towns, and eventually cities. The impact of humans on the environment grew in step with the population increases, but not on a linear scale. Human influences, due to continued technological developments, increased far more than their rising numbers might first predict. Fifty people with Stone Age technology made far less environmental impact than 50 people with our present-day technology. The human "footprint" became much larger and deeper very quickly, and the potential for a crisis began to loom. Anthropogenic impacts have become so profound that Crutzen (2002) has proposed the designation of a new geological epoch, called the Anthropocene, representing the recent human-dominated period of Earth's history.

[1] There are a number of salinity boundaries used in the literature delineating fresh from saline waters. Most biologists define fresh waters as those with less than 1 $g\,l^{-1}$ salt concentration, although 3 $g\,l^{-1}$ is also commonly used as a boundary, especially amongst geologists.

The human population reached the 1 billion persons level around 200 years ago. Since that time, our population has grown to over 6 billion. Each day, about 200,000 more people are born than die. Humans need about 50 liters of water a day to stay healthy (e.g., for drinking, cooking, washing, sanitation). With increasing populations and increased technological growth, the ecosystems we depend on are under greater stress. The Earth's supply of accessible fresh waters is especially at risk. One out of three people in the developing world does not have access to safe drinking water. The United Nations Environment Programme (UNEP) estimated in 1999 that the present shortage of clean water will only get worse, to the point that by AD 2024 two-thirds of the world's population will not have adequate access to clean drinking water. In addition to municipal uses, water provides us with many other services, such as fisheries and other food resources, transportation, recreation, and other societal needs (Postel & Carpenter 1997). Trends outlined in the recent *Millennium Ecosystem Assessment* (2005) are even less encouraging. The quantity of water will not increase; it will stay the same. The quality of water will almost certainly decline further. Unlike resources such as coal, oil, or wheat, there is no substitute for water. We have a crisis on our hands, and we have to explore and develop new approaches to meet these challenges.

A major problem that faces water managers is that much of what happens in lakes and rivers is out of the sight of the public, below the water line. People tend to respond to obvious problems and symptoms, such as fish carcasses accumulating on a lakeshore or algal blooms fouling water intakes. However, many water problems begin with few obvious signs, but then steadily escalate to full-blown crises. It is often more difficult, or impossible, to correct the problem once it reaches these late stages. Extinction is forever. As Ricciardi and Rasmussen (1999) remind us, since 1900 some 123 freshwater animal species have become extinct in North America alone, and hundreds of other species are considered imperiled. These alarming trends in loss of biodiversity appear to be accelerating each year (Millennium Ecosystem Assessment 2005). Human impacts are clearly implicated in almost every case. The numbers are staggering. For example, Ricciardi and Rasmussen (1999) estimated that species losses from temperate freshwater ecosystems are occurring as rapidly as those occurring in tropical forests. Surprisingly, these data from aquatic ecosystems receive little attention compared to the headline news of species diversity issues from tropical terrestrial ecosystems. We clearly need to use all the information we can garner to help managers and policy makers make responsible decisions to preserve these ecosystems.

## 1.5 Ecosystem approaches to water management

Lakes, rivers, and other water bodies cannot be treated as isolated systems. Although 19th-century naturalists at times referred to lakes as microcosms, often believed to be separate from the environment around them, we now know this is certainly not the case. Freshwater systems are intimately linked to their catchments or drainage systems (watersheds), as well as to the "airsheds" above them. They are also influenced by the quantity and quality of groundwater inflows. Lakes and rivers are downhill from human influences, and so much of what happens in a lake's catchment or watershed eventually has an effect on the aquatic system.

Environmental research requires this ecosystem perspective, involving trans-disciplinary studies explaining the processes and interactions among air, water, land, ice, and biota, including humans. Humans have currently transformed somewhere between one-third to one-half of the Earth's surface with their activities, such as agriculture and urbanization, and the rate of land transformation is increasing at an alarming rate. Furthermore, some industries have been treating the atmosphere as an aerial sewer, with the airways now transporting a suite of pollutants that can affect aquatic systems. The wind carries no passport; we are truly living in a global world of pollution transportation and deposition. Humans are capable of altering and affecting each part of the hydrological cycle (Fig. 1.2), whether via chemical, physical, or biological means. These repercussions, and some of the ways we can track and study them, are described in this book.

## 1.6 Pollution

Webster's dictionary defines the verb "pollute" as "to make foul." There is, however, a large range in the extent of pollution. As will be shown in the subsequent chapters, humans have now impacted all water bodies on this planet to some extent. Some impacts are minor and barely perceptible; others have degraded lakes and rivers to enormous degrees. This pollution is often chemical (e.g., contaminants, acid rain, nutrients) or physical (e.g., heat inflows), although "biological pollution," such as the introduction of exotic species, is also considered a form of pollution in its broadest sense.

Pollutants originate from many sources and are classified a number of ways. Pollutants are often discussed, in a general way at least, with respect to their source, and are divided into "point source" and "non-point source," or "diffuse source," pollutants (Fig. 1.3). A point source pollutant is simply one originating from a clearly defined source, such as a smoke stack from a smelter, an outflow pipe from a factory, or untreated sewage draining into a river. These point source pollutants are often easier to control, as they have a clearly defined origin, they can often be readily

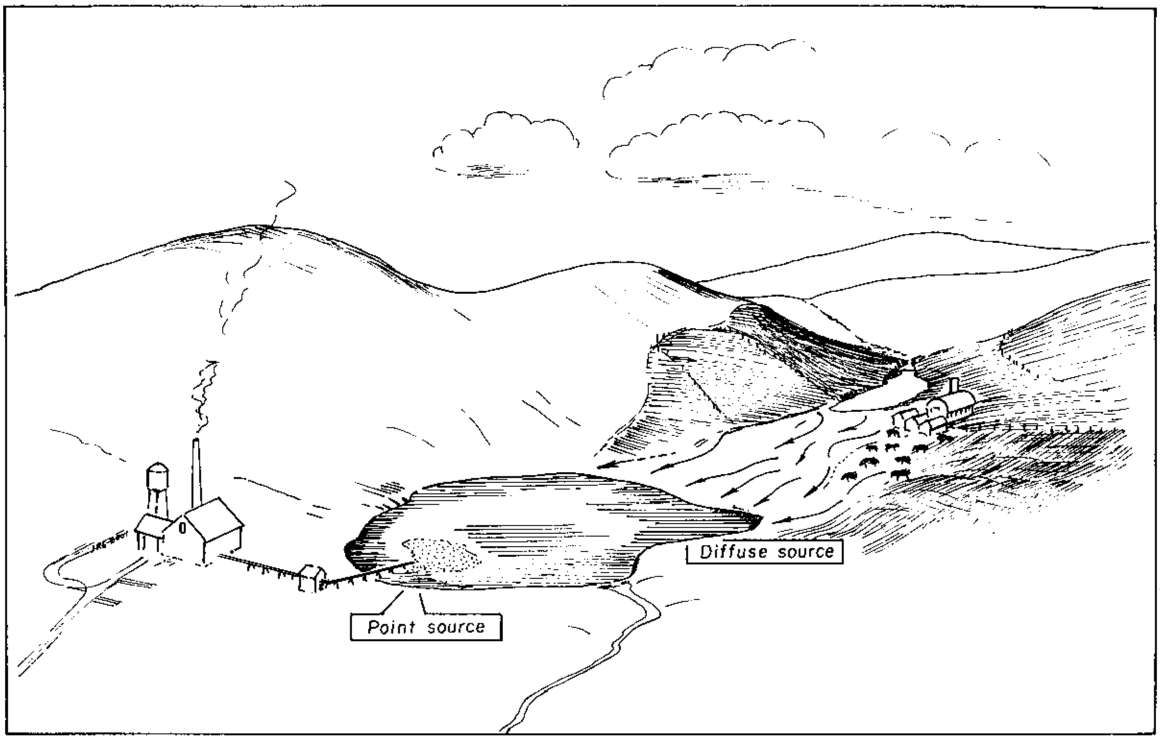


**Fig. 1.3** Surface waters can be affected by both point and diffuse sources of pollutants.

measured and monitored, responsibility can be more easily assigned, and often technological fixes (e.g., a scrubber for a smoke stack or a treatment facility for an outflow) can be implemented more effectively and economically. Non-point or diffuse sources of pollution are often more challenging for managers and scientists. Pesticide or fertilizer runoff from agricultural fields in a lake's catchment would be examples of non-point sources.

## 1.7 The format of this book

This book is about the effects that humans have had on aquatic systems, and the ways in which we can study and assess these problems using long-term perspectives. Following this brief introduction, I discuss the need for long-term data (Chapter 2) and introduce the science of paleolimnology (Chapter 3). A brief overview of the basic techniques used by paleolimnologists and "thumbnail" sketches of some of the primary environmental indicators found in sediments are included in Chapters 4–6. I then explore some of the major pollution problems affecting freshwater ecosystems and show how paleolimnological approaches can be used to assist scientists, managers, and the general public. The first application deals with acidification (Chapter 7), a subject that received intense attention in the 1980s. Paleolimnology played an important role in these debates, and many of the paleolimnological tools that are used in applied studies were honed at this time. Discussion of other contaminants, such as metals and persistent organic pollutants, follow in the next chapters (Chapters 8–10). Collectively, these early chapters are loosely clumped together, as they often have an atmospheric transport component. A series of chapters more closely related to watershed and terrestrial changes follow (e.g., eutrophication, erosion; Chapters 11 and 12). The applications part of this book concludes with chapters that might best be described as dealing with relatively newer environmental problems, such as exotic species invasions and extirpations (Chapter 13), greenhouse gas emissions and the resulting effects of climatic change on water resources (Chapter 14), ultraviolet radiation penetration (Chapter 15), taste and odor problems, and a suite of developing issues (Chapter 16). I conclude with some personal perspectives (Chapter 17) and a Glossary.

The paleolimnological literature is expanding very rapidly, and so many good examples could not be used. I acknowledge that I have tended to use studies with which I am most familiar, but I have attempted to provide examples that are applicable to other regions. My focus is on freshwater lakes, as almost all the pollution-related work to date has dealt with these systems. Consequently, I will often use the terms "lake" and "lake sediments" in this book, but in almost all cases these examples should be taken in a more collective sense, as most standard paleolimnological approaches, with some modifications and due caution, can be used in other freshwater systems, such as rivers, reservoirs, and wetlands. I have included such examples when possible. I have tried to emphasize ecosystem approaches, where individual symptoms are not treated in isolation, but examined and interpreted within a broader, more ecologically relevant framework.

## 1.8 Summary

Our planet is characterized by large volumes of water that cover about three-quarters of the Earth's surface. The vast majority (~ 95%) of this water is salty, and most of the fresh water is stored as groundwater or frozen in glaciers and polar ice. Only a tiny fraction (~ 0.01%) of our water resources is contained in freshwater lakes and rivers. The volume of water on our planet will not change, but its quality can be dramatically altered by human activities. With the establishment of civilizations, the development of technological advances, and a burgeoning human population, we have been polluting and altering our water supplies at an alarming rate. Degradation of lakes and rivers has taken many forms, ranging from the direct input of chemicals and other substances into receiving waters to more indirect sources of pollution, such as the emission of pollutants into the atmosphere that may then be transported long distances before they are redeposited back to Earth. Water is essential to life; we cannot live without it. Many researchers believe that we are fast approaching a crisis in our water supplies. This book explores the diverse ways in which paleolimnological approaches can be used to address some of these pressing environmental issues.