An underwater photograph showing a shark swimming in the lower left and a diver in the upper right. The water is clear blue with some bubbles and light reflections.

2.1 Chemische oceanografie

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4.1 Cycling of elements through the ecosystem

Nutrient cycles are some of the most important processes that occur in any ecosystem. They show the movement of **nutrients** that are essential for life, such as nitrogen, carbon and phosphorus. These nutrients are used by living organisms and are moved through the food chain by feeding. When organisms die the nutrients are recycled by **decomposers** and return to inorganic forms. The inorganic forms remain in the environment, sometimes for millions of years, before being converted back into organic forms to be used once again, thus continuing the cycle.

The ocean is an important **reservoir** for these elements, which means that they may be held there for long periods of time. Microorganisms are able to fix inorganic substances into organic molecules, which enables them to be used by other organisms. In this way the nutrients are moved from the **abiotic** part of the cycle to the **biotic**. The nutrients may then be removed temporarily from the cycle if they sink to the ocean floor as faeces, or after the organism has died. Some will be incorporated into coral reefs and others will be removed from the ocean altogether by harvesting. Inorganic molecules are returned to the ocean by various processes, including dissolving directly into the water, **run-off** from the land and **upwelling**.

Chapter 3 discussed the effect of nutrient concentration in the ocean. Up to a certain point, the more nutrients present, the more productive the environment. When there

are too many nutrients the productivity can increase too fast and the ecosystem is damaged. Recently, it has been suggested that artificially altering the nutrient balance in the oceans could increase productivity and therefore increase the amount of carbon dioxide used in photosynthesis. This has been proposed as a solution to the increasing levels of carbon dioxide in the atmosphere. However, this solution may have unintended consequences, such as decreasing the pH of the water and damaging animals with shells. It could also lead to harmful algal blooms as discussed in Chapters 3 and 8.

KEY TERMS

Nutrient cycles: the movement and exchange of elements that are essential to life, from inorganic molecules, through fixation and then into living organisms, before being decomposed back into inorganic molecules

Nutrient: a chemical that provides what is needed for organisms to live and grow

Decomposers: bacteria and fungi that break down dead organic matter and release the nutrients back into the environment

Reservoir: part of the abiotic phase of the nutrient cycle where nutrients can remain for long periods of time

Abiotic: the environment's geological, physical and chemical features, the non-living part of an ecosystem

Biotic: the living parts of an ecosystem, which includes the organisms and their effects on each other

Run-off: the flow of water from land caused by precipitation

Upwelling: the movement of cold, nutrient-rich water from deep in the ocean to the surface

4.2 Nutrient cycles

Nutrient cycles are the essential movement and recycling of the elements that are necessary for organisms to live and grow. Globally, the carbon and nitrogen cycles are probably the best known and most clearly understood, but there are many other elements that are important. These include phosphorus, calcium and magnesium. In this chapter you look at why each of these is necessary for life, as well as the mechanisms that add them or remove them from the oceans.

All nutrient cycles have a biotic and an abiotic phase (Figure 4.1). A nutrient moves from the abiotic to the biotic phase when it is absorbed and **assimilated** by producers.

For example carbon dioxide (an inorganic molecule and therefore part of the abiotic cycle) is fixed during photosynthesis into glucose. This can later be converted into the other molecules needed by the producer, for example starch. It has been assimilated and is now part of the biotic cycle. During the biotic phase nutrients are moved from one organism to the next by feeding. So nutrients move along the food chain from the producers to the consumers. Some will be lost from each organism

KEY TERM

Assimilation: the conversion of a nutrient into a useable form that can be incorporated into the tissues of an organism

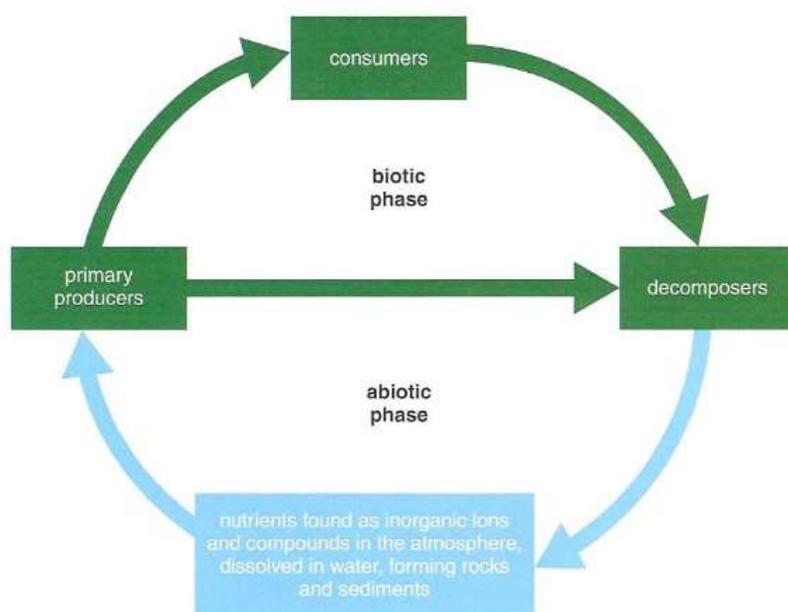


Figure 4.1. A generalised nutrient cycle showing the movement from the biotic to the abiotic phases.

by egestion and excretion and the rest will remain within organic compounds until the organism dies. After death, organisms must be broken down by decomposers, which results in nutrients returning to their inorganic form and therefore the abiotic part of the cycle. During this part of the cycle nutrients can be found dissolved in water, as gases in the atmosphere, or forming sediment that can later become rocks.

Reservoirs in nutrient cycles

A reservoir is part of the abiotic phase of the nutrient cycle where elements can remain for long periods of time. The ocean is an important reservoir for many elements. The **residence time** is the average time a particle spends in a system. Average residence times for nutrient ions in the ocean tend to be very long because some of them fall to the bottom in faeces or dead organisms. They can remain in sediment on the ocean floor for thousands or even millions of years (Table 4.1)

The time the same nutrients spend in just the surface layer of the ocean is much shorter because the nutrients are constantly being used and recycled by the organisms

nutrient	average residence time / years
phosphate (phosphorus)*	20 000–100 000
magnesium	17 000 000
hydrogencarbonate** (carbon)*	100 000
nitrogen	2 000
calcium	1 000 000

*Where the nutrient is found as an ion, the element is given in parentheses

**Sometimes called bicarbonate

Table 4.1. Approximate residence times for different nutrients in the ocean.

living there. This surface reservoir is of particular importance because it enables the high productivity of phytoplankton. Nutrient availability is often the main limiting factor after light intensity for growth of producers.

Phytoplankton are found in the surface layer of the ocean where there is plenty of light. It is therefore the concentration of nutrients that determines the rate of growth. The higher the rate of growth of phytoplankton, the higher the rate of photosynthesis and therefore the higher the productivity. The productivity of the

KEY TERM

Residence time: the average time that a particle spends in a particular system

phytoplankton determines how much energy can be transferred to the next trophic level (see Chapter 3). In general, the amounts of nitrogen and phosphorus limit the rate of growth because they are found in the lowest concentrations in the water. This means that there is usually slightly less than is needed by the producers. If the concentrations increase, the productivity increases. The average concentrations of ions dissolved in the water at the ocean surface are shown in Table 4.2.

ion	average concentration in seawater / ppm
chloride	19 345.00
sodium	10 752.00
sulfate	2701.00
magnesium	1295.00
calcium	416.00
hydrogencarbonate	145.00
nitrate	0.50
phosphate	0.07

Table 4.2. Average concentrations of some of the ions found dissolved in seawater.

SELF-ASSESSMENT QUESTIONS

- Describe what is meant by the words biotic and abiotic with reference to nutrient cycles.
 - Explain how nutrients move from the abiotic to the biotic part of a nutrient cycle.
- Describe how nutrients move within the biotic part of the cycle.
 - Name two places where you would find nutrient ions within the abiotic part of a nutrient cycle.

4.3 Processes that add nutrients to the surface water

There are three main processes that add nutrients to the reservoir within the surface water. These are:

- dissolving in the water from the atmosphere
- upwelling
- run-off.

The relative importance of these processes depends on each nutrient. For nutrients present in high concentrations in the atmosphere, dissolving will add more to the reservoir than run-off, for example.

Dissolving of atmospheric gases

Nitrogen and carbon are both present in the Earth's atmosphere and are therefore both able to dissolve directly into the water. Nitrogen is present in the form of nitrogen gas, N_2 , and carbon as carbon dioxide gas, CO_2 . The amount of gas that can dissolve in the water depends on several factors. These include the:

- temperature of the water
- atmospheric concentration of each gas
- amount of mixing of water at the surface.

In some areas there will be more gas dissolving in the water than there is diffusing back into the atmosphere. These areas are known as **sinks**.

In other areas it will be the other way around, and more gas will diffuse into the atmosphere than is dissolving into the water. These areas are called **sources**. Generally the overall concentration tends to remain at an equilibrium, with the same amount dissolving into the ocean as is removed by diffusion back into the atmosphere (Figure 4.2).



KEY TERMS

Sink: an area where there is a net loss of material (for example where more gas dissolves into the ocean than diffuses into the atmosphere)

Source: an area where there is a net gain of material (for example where more gas diffuses into the atmosphere than dissolves in the ocean)

Upwelling

Upwelling involves cold water from the deep ocean being brought to the surface. These deep waters have higher concentrations of nutrients than those at the surface because of the tendency for the remains of living things to sink. So faecal matter and dead organisms sink from the surface layers to the deeper parts of the ocean. Here they may be broken down by decomposers and the nutrient ions returned to the water. During upwelling this nutrient-rich water rises to the surface where it effectively fertilises the surface layers and increases productivity. Areas with high levels of coastal upwelling tend to be the

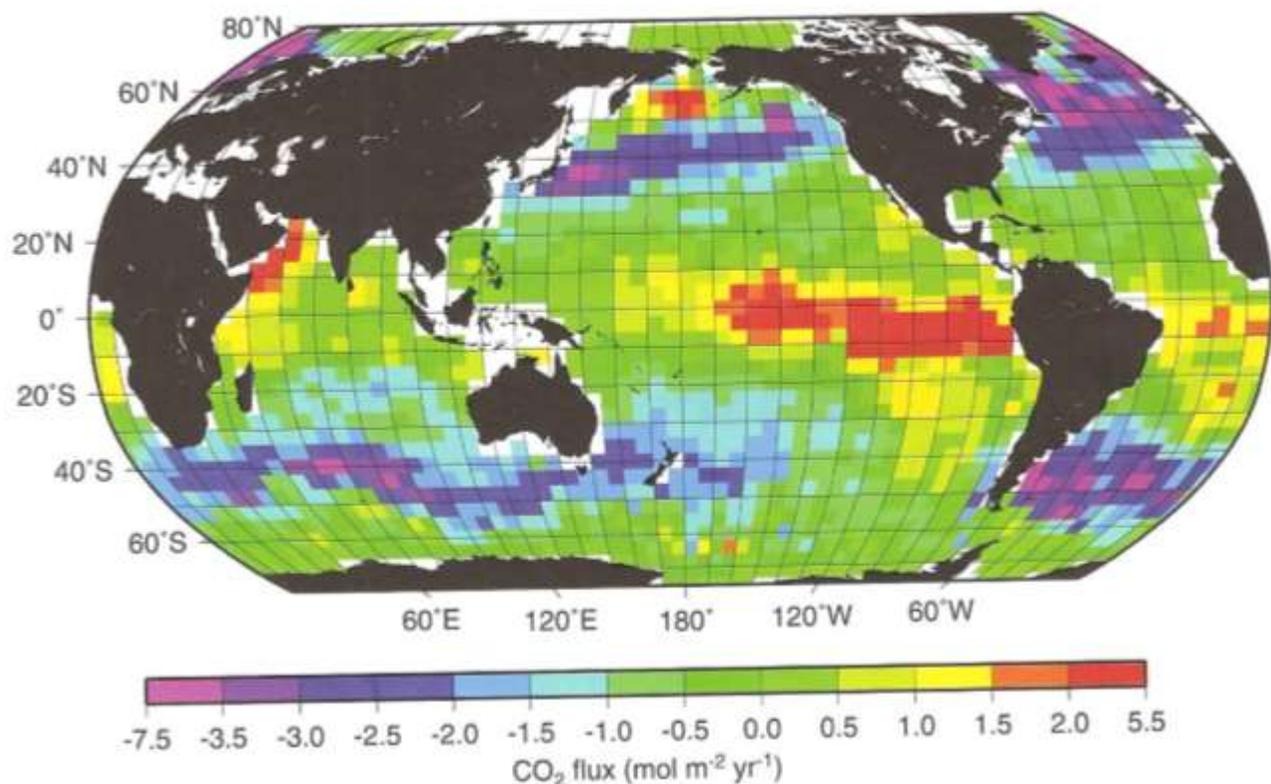


Figure 4.2. Movement (flux) of carbon dioxide into and out of the ocean over the course of a year. Purple and blue areas are carbon sinks; yellow and red areas are carbon sources; green areas are at an equilibrium, with the same amount of carbon dioxide dissolving as being released.

most productive and have high catches of commercially important fish. It has been estimated that 25% of fish are caught from just 5% of the ocean where there are high levels of upwelling.

Coastal upwelling is caused when winds blow parallel to the shore (Figure 4.3). This displaces the warm surface water, which moves further offshore and has to be replaced by water from deeper in the ocean. Other mechanisms of upwelling are discussed in Chapter 7. If the wind is moving in the opposite direction and drives the water towards the coastline, it is also possible for downwelling to occur. This of course removes nutrients from the surface layers of the ocean.

Run-off

Run-off is part of the water cycle in which water flows into streams and rivers and from there to the ocean. During the water cycle, water evaporates from rivers, lakes, oceans and streams. It condenses into clouds in the atmosphere

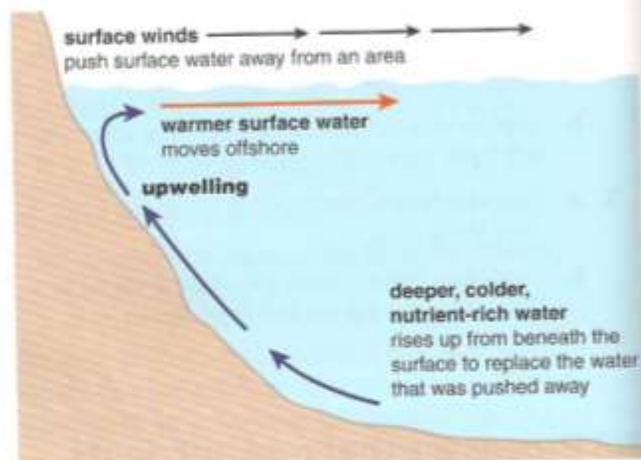


Figure 4.3. Coastal upwelling caused by surface winds.

and from there falls on the land as precipitation (Figure 4.4). Some of the precipitation enters the soil in a process called **infiltration**. The rate of infiltration is affected by the characteristics of the soil. Sandy soil, which

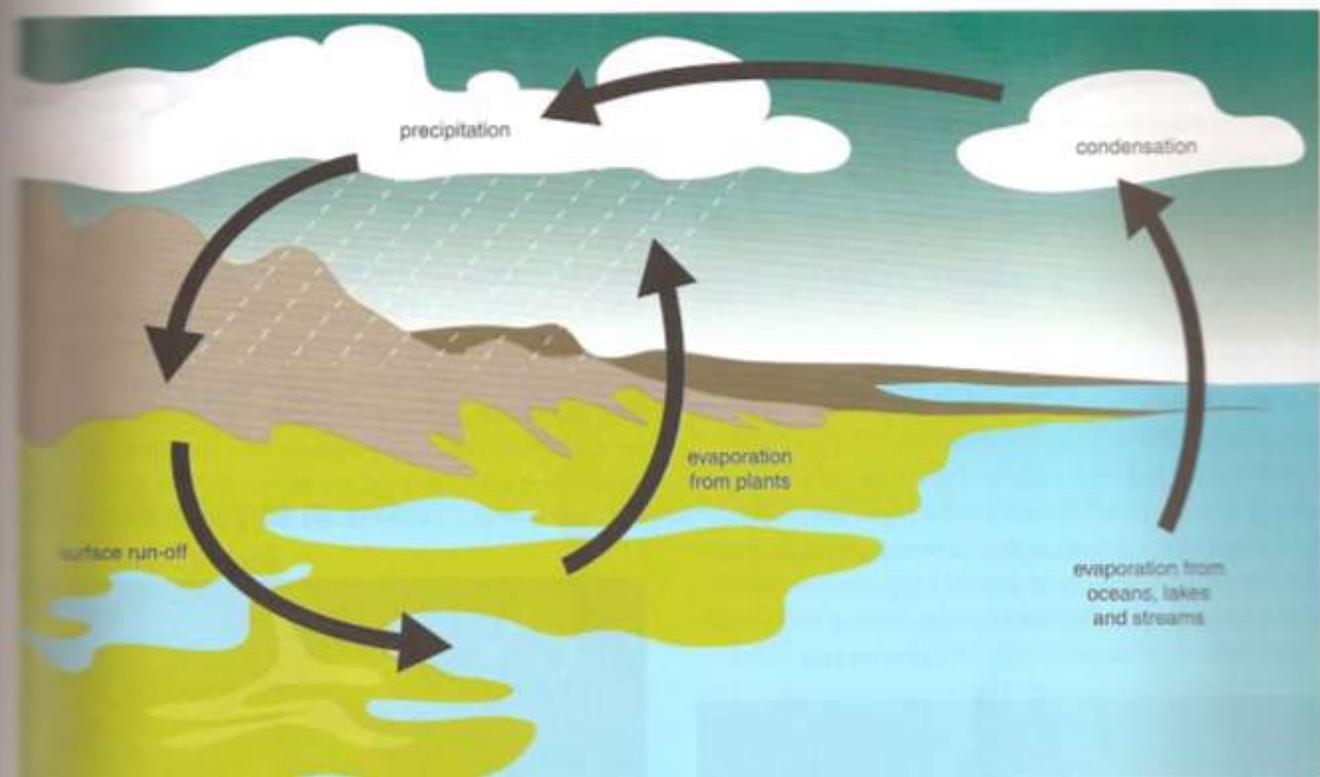


Figure 4.4. Summary of the water cycle.

is formed from large particles with relatively large gaps between them, has a high infiltration rate, compared with clay soil, which has a low infiltration rate. The higher the infiltration rate, the lower the rate of surface run-off. In other words, the more impermeable the ground, the more surface run-off there is.

As the water flows towards the sea it **leaches** nutrients from the soil. This means that water-soluble nutrient ions dissolve in the water. Run-off can also collect other substances as it flows, such as oil, heavy metals, pesticides and sewage. These all end up in the ocean. Excess nutrients in run-off can lead to marine dead zones (Chapter 3) and harmful algal blooms (Chapter 3, and discussed in more detail in Chapter 8).

KEY TERMS

Infiltration: part of the water cycle where water soaks into the soil from ground level and moves underground

Leaching: a process during which water-soluble nutrients are removed from the soil and dissolve in water that is flowing to the sea (run-off)

SELF-ASSESSMENT QUESTIONS

- 3 What effect do you think upwelling would have on a food web?
- 4 Explain why nitrogen and carbon dioxide dissolve in the water from the atmosphere, but not phosphate.

4.4 Processes that remove nutrients from the surface layer

The main way in which nutrients are removed from the surface layer is through uptake and assimilation by producers. They fix the inorganic ions into useable organic compounds that are fed on by consumers. In this way the nutrients are able to move through the food chain. For example, phytoplankton take up nitrate ions and use them to produce amino acids. These are then built up into proteins that form part of the phytoplankton structure. Zooplankton eat the phytoplankton and digest these proteins, using the amino acids released in digestion to produce their

own proteins. Small fish then eat the zooplankton and the process continues. Once the nutrients have entered the food chain there are different paths they can take. Some sink to the floor as **marine snow**, some are incorporated into coral reefs, and some are removed by harvesting.

KEY TERM

Marine snow: particles of organic material that fall from surface waters to the deeper ocean

Marine snow

Marine snow is the name given to the particles of organic matter that fall from the surface of the ocean to the deeper water. It is made up of faeces from the organisms living in the surface layers, as well as dead animals, phytoplankton and zooplankton. It is called marine snow because that is what it looks like, small white particles floating in the water (Figure 4.5).



Figure 4.5. Marine snow in the water.

This continuous fall of organic matter provides food for many organisms that live deeper in the ocean. Some of it is fed on by zooplankton and fish as it falls, some is eaten by filter feeders much deeper down. Much of it is not eaten at all and forms part of the sediment at the bottom of the ocean. Some of the nutrients in the sediment are released into the water by processes such as erosion and dissolving, others remain in the sediment for many years.

SELF-ASSESSMENT QUESTIONS

- 5 Describe the process that removes nutrients from the water and allows them to enter the food chain.
- 6 Describe what forms marine snow and explain where the majority of it ends up.

Incorporation into coral reefs

Coral polyps secrete a hard shell made from calcium carbonate to protect themselves and the zooxanthellae that live within them. Figure 4.6 shows some of the structures produced by coral. Coral eat tiny zooplankton and digest them to gain the nutrients they need. The zooplankton have previously gained their nutrients from phytoplankton. Any type of nutrient can be incorporated into the living parts of the reef and the other organisms that live there. But the hard shells last even after the living part has died. Coral reefs are very large and can last for a very long time, so the nutrients contained in them are removed from the cycling process for a long time. Most established coral reefs are between 5000 and 10 000 years old. Reef formation is discussed in Chapter 5.



Figure 4.6. Structures produced by coral polyps.

Harvesting

Harvesting refers to the removal of marine species by humans. In 2016, it was estimated that the global fish catch in 2010 had been 109 million metric tonnes. This is 30% higher than had been previously thought. Other species are also harvested, including crustaceans such as crabs and lobsters, molluscs such as mussels and squid, and macro-algae such as seaweeds. All the nutrients present in these species are removed when they are harvested from the ocean. However, many of the nutrients eventually find their way back to the ocean through the normal cycling of nutrients. For example, fish may be eaten and digested by humans and some of the nitrogen-containing compounds are then lost in urine, which ends up in sewage. In many areas, sewage is released into rivers and oceans after only being partially

collected. In some areas, raw sewage is released. In this way, the nitrogen-containing compounds present in the original fish return to the ocean.

SELF-ASSESSMENT QUESTIONS

- What are the two important nutrients used by corals to produce their hard shells?
- Explain why harvesting is important in marine nutrient cycles and explain whether you think it is beneficial or harmful.

4.5 Examples of marine nutrient cycles

The processes discussed so far that take place in marine nutrient cycles can all be summarised in the same diagram (Figure 4.7).

Nutrients enter the reservoir of dissolved nutrients in the surface layer by dissolving, run-off and upwelling, and are removed by uptake by producers. Once in the food chain nutrients can sink, become incorporated into coral reefs or be harvested. Each nutrient is needed for a different purpose within organisms, and each nutrient cycle is slightly different.

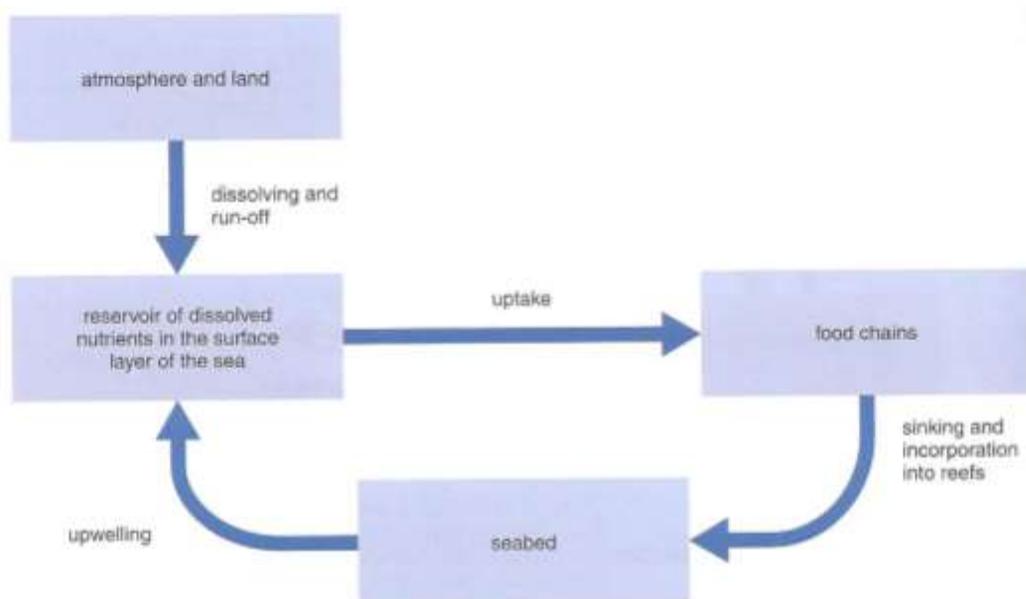


Figure 4.7. A summary of marine nutrient cycles.

KEY TERM

Dissociation (dissociates): a reversible chemical change where the molecules of a single compound separate into two or more other substances

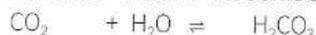
The carbon cycle

Carbon is needed by living things because it is the basis of all organic materials. Carbohydrates such as glucose and starch; lipids; proteins; and nucleic acids such as DNA are all based on chains of carbon molecules. Carbon enters the biotic phase of the cycle through the fixation of carbon dioxide in photosynthesis. Carbon dioxide is then released through respiration by all living things.

The main way carbon enters the ocean is by dissolving of carbon dioxide gas from the atmosphere. Carbon dioxide dissolves in water to form carbonic acid (H_2CO_3). This then **dissociates** into hydrogencarbonate ions (HCO_3^-) and hydrogen ions (H^+) in a reversible reaction. Hydrogencarbonate dissociates further into carbonate ions (CO_3^{2-}) and hydrogen ions (H^+). So in solution there is a dynamic equilibrium between carbon dioxide, hydrogencarbonate and carbonic acid. In seawater 89% of the dissolved inorganic carbon is found as hydrogencarbonate, 10% is carbonate and 1% is dissolved carbon dioxide.

The reactions in this equilibrium are:

carbon dioxide + water = carbonic acid



carbonic acid = hydrogencarbonate ion + hydrogen ion



hydrogencarbonate ion = carbonate ion + hydrogen ion



The algae and photosynthetic bacteria that make up the phytoplankton are able to take in dissolved forms of carbon dioxide and use it in photosynthesis. It is fixed into glucose, which can then be used to form other compounds needed by the phytoplankton. When the phytoplankton are eaten by zooplankton, the carbon-containing compounds are broken down during digestion. The zooplankton then assimilate them into their own biomass. This process is repeated when the zooplankton are eaten by other consumers.

At each stage, the organisms are respiring so they release carbon dioxide back into the water. From here it can diffuse back into the atmosphere. When the organisms die, some of the organic matter is broken down by decomposing bacteria and returns to the water as dissolved inorganic carbon. Some of the organic matter falls to the ocean floor as marine snow, where it may remain for long periods of time (Figure 4.8).

The flux of carbon between the ocean and the atmosphere is around 90 gigatons year⁻¹. In other words, the same amount of carbon dioxide dissolves into the ocean as diffuses back into the atmosphere. However, there are also approximately 2 gigatons of carbon each year added to the ocean through human activities such as burning fossil fuels. This makes the oceans a very important carbon sink in terms of reducing atmospheric carbon dioxide. But the risk is that the ocean will become more acidic because of the extra carbonic acid formed. It has been estimated that since the 18th century, the pH of the ocean has decreased by 30%. This can have negative effects on the ecosystem. For example, a low pH triggers chemical reactions that decrease the concentration of carbonate ions; this makes it more difficult for corals to produce their calcium carbonate skeleton. This can also affect other species with calcified shells, including oysters and clams. If the water becomes even more acidic, it can dissolve the coral skeletons and the shells of other organisms, making them weaker and more vulnerable to damage.

Some scientists have suggested that artificially fertilising the ocean with iron would increase the productivity of the phytoplankton and mean that more carbon dioxide could be absorbed. This has been put forward as a possible way to reduce the amount of carbon dioxide in the atmosphere. The theory is that, since iron is often a limiting factor for phytoplankton growth, adding more will cause increased growth rates and thus increased use of carbon

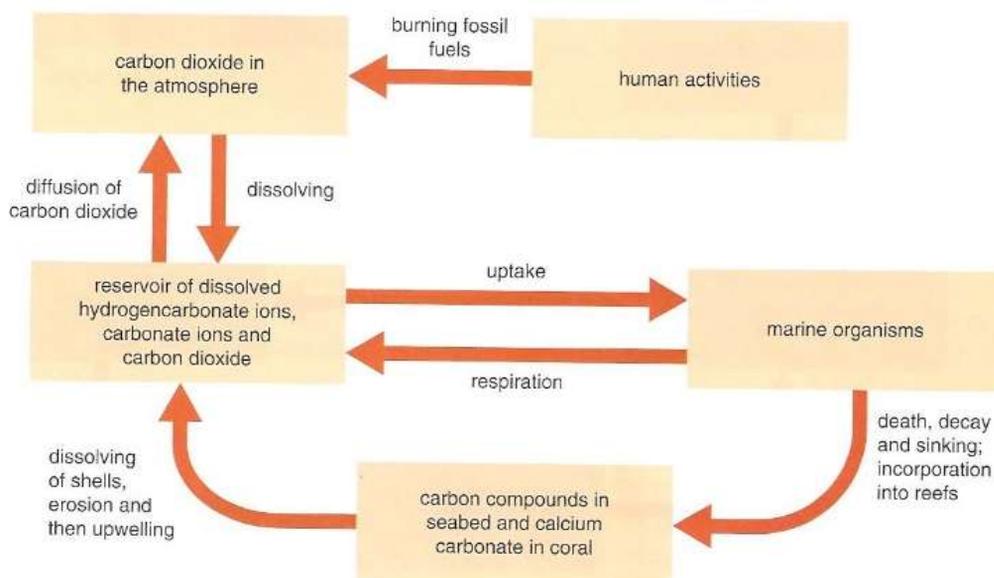


Figure 4.8. Summary of the main processes in the marine carbon cycle.

dioxide. This process is known as ocean seeding or iron fertilisation. Trials have shown that ocean seeding does increase the growth of phytoplankton but there are risks to this procedure. If the productivity increases too much, a harmful algal bloom could take place. The long-term

effects of altering the ecosystem in this way are not clearly understood. If more carbon dioxide is absorbed, the pH of the water could decrease further, causing harm to many different species.

The nitrogen cycle

Nitrogen is needed to form amino acids, which are built into proteins. It is also a component of nucleic acids such as DNA. The nitrogen cycle is more complex than the carbon cycle because most producers are unable to take in nitrogen gas from the atmosphere. The organisms that are able to take in molecular nitrogen (N_2) must convert it into useable forms. In the marine environment this takes place through the action of **diazotrophs** (Figure 4.9). Diazotrophs are bacteria and archaea that can convert molecular nitrogen to substances such as ammonia (NH_3).



KEY TERM

Diazotroph: an organism that is able to grow without external sources of fixed nitrogen because it is able to fix nitrogen gas into substances like ammonia



Figure 4.9. *Trichodesmium*, a genus of marine diazotroph showing its filaments of cells, which are able to fix molecular nitrogen.

Nitrogen fixation requires a nitrogenase enzyme, which needs low levels of oxygen to function. Species that carry out nitrogen fixation therefore need specialised cells with lower than normal oxygen concentrations. *Trichodesmium* have cells that are specialised for nitrogen-fixing rather than carbon-fixing (through photosynthesis). Lack of photosynthesis means the cells have lower oxygen levels.

When the ammonia produced from nitrogen fixation dissolves in water, it forms ammonium ions (NH_4^+), which the phytoplankton are able to take in and convert to protein. Phytoplankton can also take in nitrite ions (NO_2^-) and nitrate ions (NO_3^-) but the oxygen must first be removed, which requires energy. However, because nitrite and nitrate are present in the water in higher concentrations than ammonia, many phytoplankton species do take in most of their nitrogen in these forms.

The proteins made by phytoplankton will be passed to consumers where they are digested by the consumers into amino acids and used to build the consumers' proteins. When consumers and producers die, the proteins are broken down into amino acids by **saprophytic** bacteria and fungi. The amino acids are converted back into ammonia by ammonifying bacteria. Ammonia can then be oxidised into first nitrites and then nitrates in a process known as nitrification.



KEY TERM

Saprophytic (saprophyte): decomposers that feed on dead organic matter ('death eater')

The conversion of ammonia to nitrites is carried out by species of bacteria from the genus *Nitrosomonas*, and from nitrites to nitrates by bacteria from the genus *Nitrobacter*. These species are chemoautotrophic (like the bacteria found at hydrothermal vents) and gain energy from the reaction. The final type of bacteria involved in the nitrogen cycle is the denitrifying bacteria, which convert ammonia and nitrates back into nitrogen gas (N_2). This reduces the amount of nitrogen available for phytoplankton to use and, because nitrogen is normally a limiting factor for growth, reduces productivity.

Nitrates are also added to the oceans by upwelling and run-off, particularly of nitrogen-based fertilisers (Figure 4.10).

SELF-ASSESSMENT QUESTIONS

- Give one positive and one negative effect of increased levels of carbon dioxide dissolving in the ocean.
- Copy and complete Table 4.5 to show the types of bacteria involved in the nitrogen cycle and their functions.

type of microorganism	function in the nitrogen cycle
diazotrophs	
saprophytic bacteria	
ammonifying bacteria	
nitrifying bacteria	
denitrifying bacteria	

Table 4.5. Bacteria and the nitrogen cycle.

The magnesium cycle

Magnesium is needed by producers to synthesise the photosynthetic pigment chlorophyll. Magnesium is found in rocks such as dolomite (calcium magnesium carbonate) and enters water through erosion and weathering. It is also used in many chemical industries and is found in fertiliser. The main way in which it enters the ocean is therefore through run-off after being leached from the soil. Once the magnesium is taken in by phytoplankton it is used to form chlorophyll, which is essential for photosynthesis. Chlorophyll is a large and complex molecule with a magnesium ion at its centre.

The main way in which magnesium ions are removed from the water is by deposition in the sediment at the bottom of the ocean (Figure 4.11). Because magnesium is present in every living cell, it is also removed by harvesting living organisms from the ocean, and incorporation into the organisms in coral reefs.

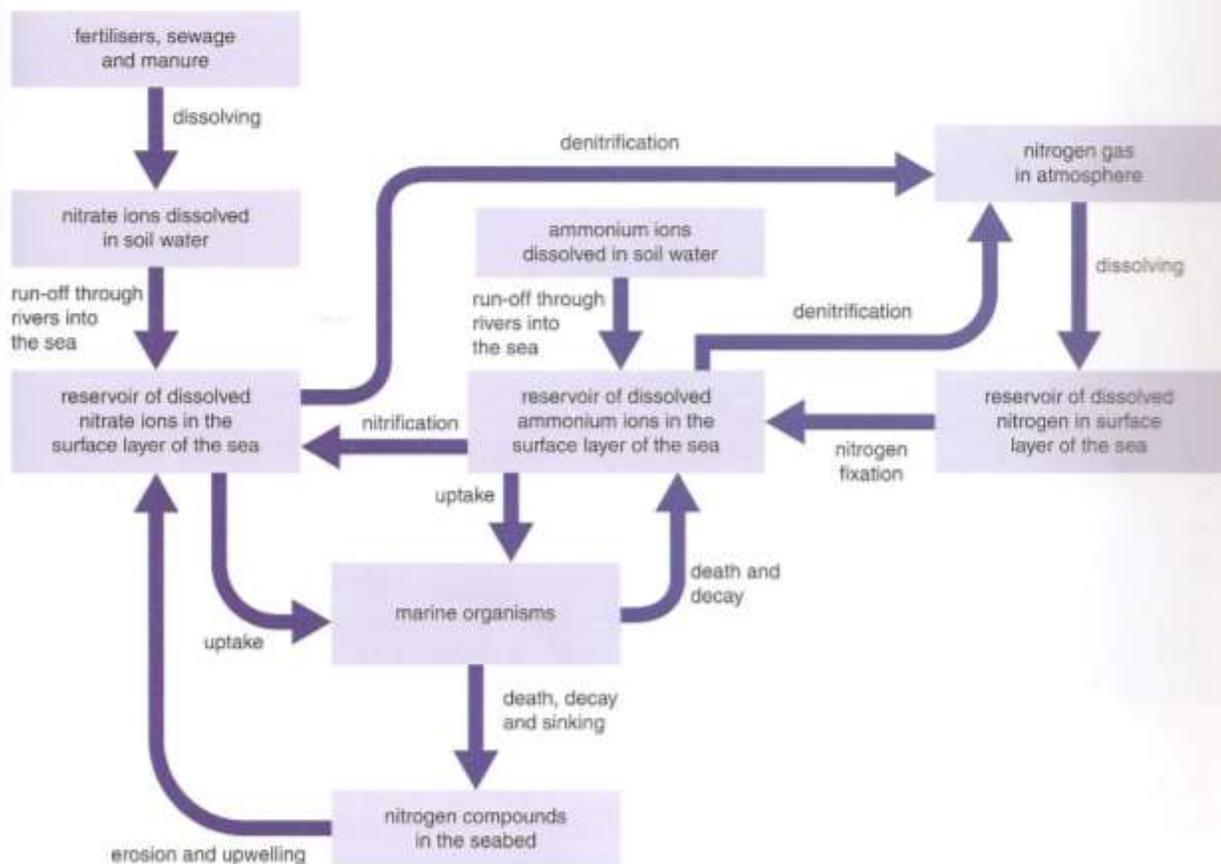


Figure 4.10. Summary of the main processes in the marine nitrogen cycle.

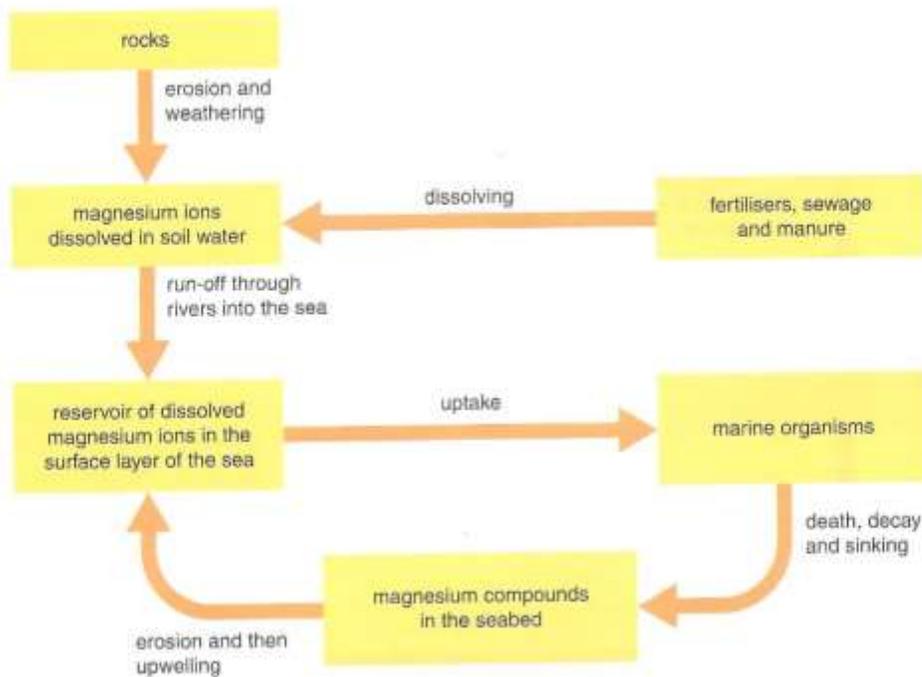


Figure 4.11. Summary of the main processes in the marine magnesium cycle.

The calcium cycle

Calcium is necessary to build healthy bones, coral and teeth so is needed by many marine animals. Rainwater reacts with carbon dioxide gas in the atmosphere to form carbonic acid. This extracts calcium from calcium-rich rocks such as limestone, marble and dolomite and forms calcium hydrogencarbonate. This dissolves in the water and enters the ocean through surface run-off. Phytoplankton such as coccolithophores use the calcium to produce scales called coccoliths from calcium carbonate (Figure 4.12). The scales are transparent and so do not disrupt photosynthesis. It has been suggested that the scales protect the cells from predators or from osmotic changes within the cells. The production of the scales also increases the rate of photosynthesis as carbon dioxide is produced as a byproduct of the precipitation of the calcium carbonate.

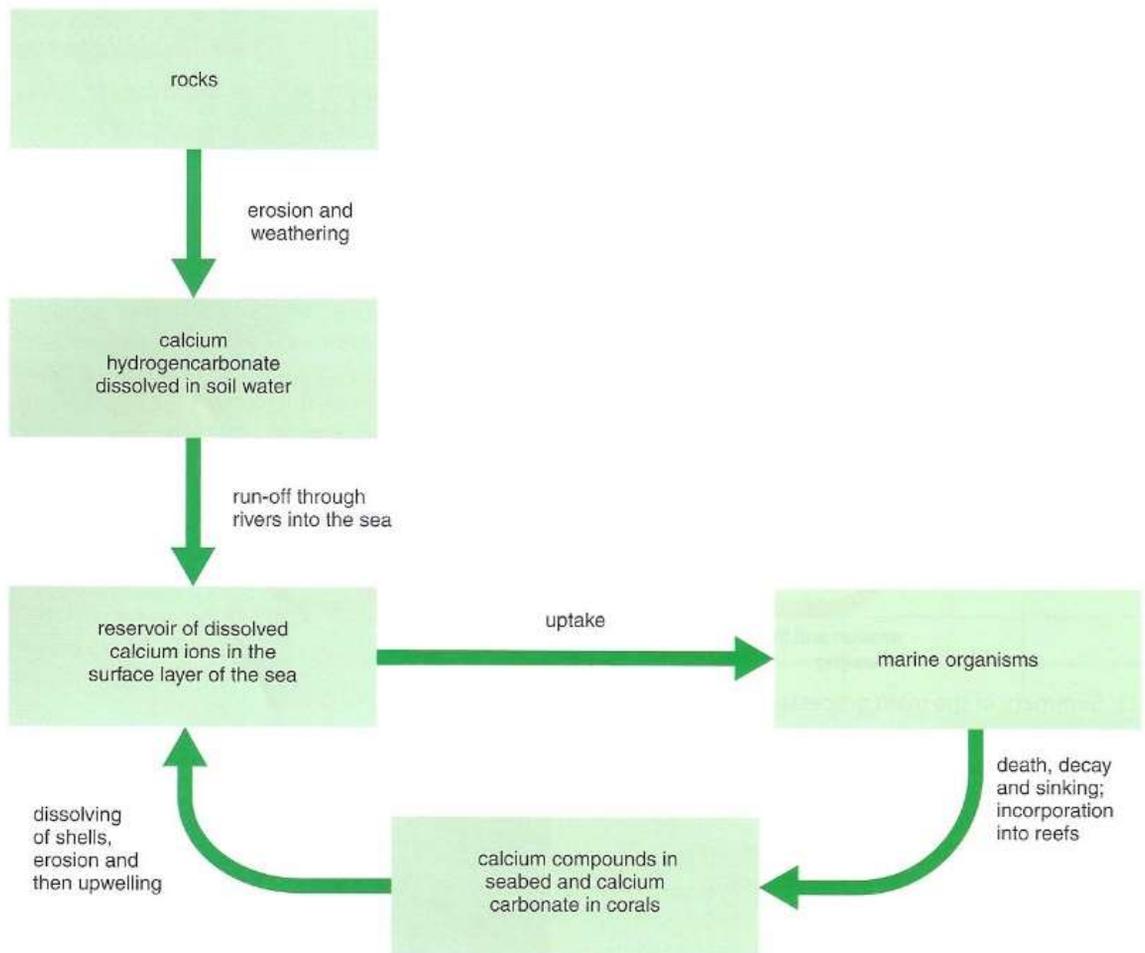
Coccolithophores are eaten by zooplankton, passing the calcium to the animals. After they die, they fall to the ocean floor and become part of the sediment (Figure 4.13). Chalk is formed from coccolithophores that were deposited millions of years ago. As the seabed subsided, the sediment was subjected to heat and pressure, which formed it into rocks. The white cliffs of Dover in England are a famous example of chalk produced in this way from coccolithophores (Figure 4.14).



Figure 4.12. Magnified picture of a coccolithophore.

The phosphorus cycle

Phosphorus is necessary for all living things to form nucleic acids such as DNA. It is also essential for bones in vertebrates. The major environmental source of phosphorus is rocks such as apatite. Phosphorus attaches to soil particles and is therefore added to the water through soil erosion rather than being in solution. Phosphates are also found in fertilisers, manure and sewage, which also contribute to run-off.



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Figure 4.13. Summary of the main processes in the marine calcium cycle.



Figure 4.14. The white cliffs of Dover in England.

Along with nitrogen, phosphorus is an important limiting factor for growth of phytoplankton and therefore photosynthesis and productivity. Once phytoplankton take in the phosphorus, it is assimilated into DNA and also phospholipids in the cell membranes. There is now evidence that many species of phytoplankton are able to alter the composition of their cell membranes depending on the amount of phosphorus in the water. This enables them to survive even when phosphorus levels are low. Animals eat the phytoplankton and incorporate the phosphorus into their own membranes and DNA. When the phytoplankton and animals die, they are either broken down by decomposers, which releases the phosphorus back into the water, or they fall to the bottom of the ocean and become part of the sediment (Figure 4.15).

SELF-ASSESSMENT QUESTIONS

- 11** Copy and complete Table 4.7 to show the uses of the main nutrients.

nutrient	biological use
nitrogen	
carbon	
magnesium	
calcium	
phosphorus	

Table 4.7. Uses of the main nutrients.

- 12** Suggest what type of weather conditions could lead to an increase in the amount of phosphorus in surface run-off.

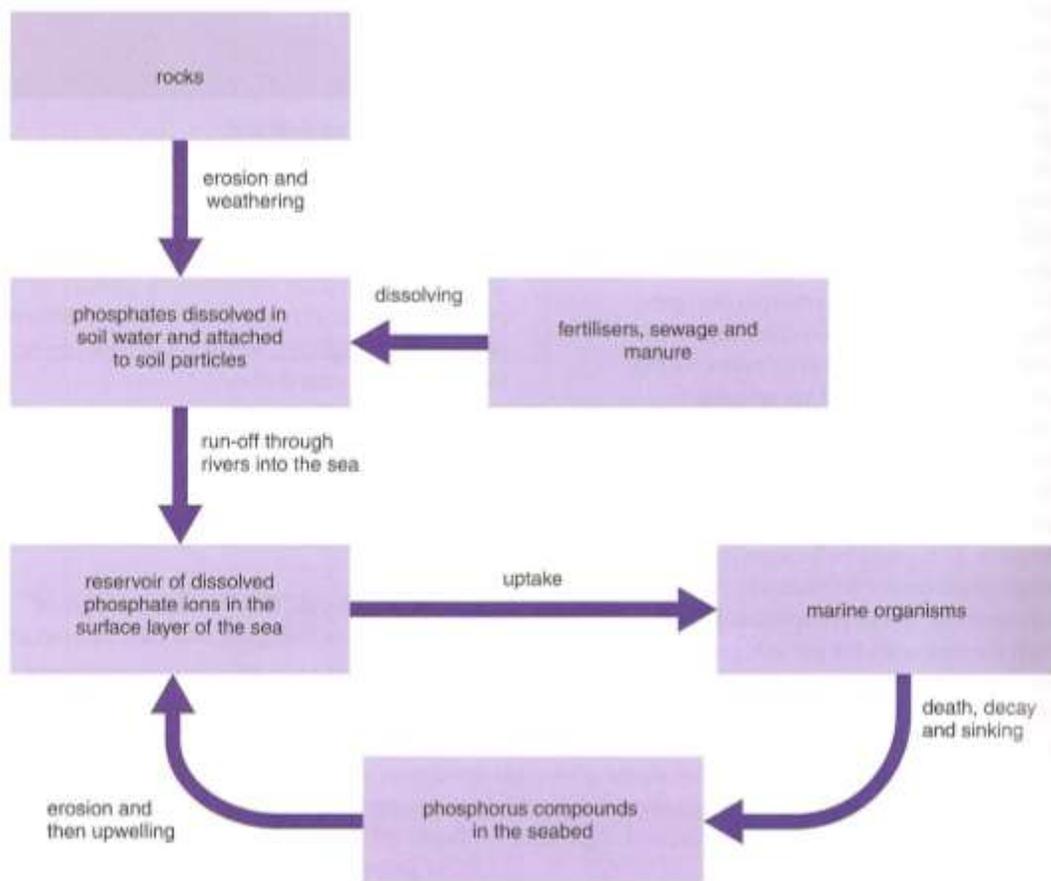


Figure 4.15. Summary of the main processes in the marine phosphorus cycle.

7.1 Understanding the ocean

When scientists study chemical and physical oceanography, they are really studying the forces that make the entire ocean able to function. On the surface, chemical and physical oceanography appears to be merely the study of the ocean's chemistry and physical properties. While that is an accurate definition, it does not touch on the real purpose for studying these fields: most people study the chemistry of water and forces within the ocean to understand how they make life possible. How can organisms exist in waters with nearly zero dissolved oxygen? How can the flooding rains that are blown in with the monsoons be a benefit to the communities affected? How does the ocean moderate the world's climate? What causes the tides that control the mating behaviour of so many animals? All of these questions and thousands more have been answered by studying how the ocean functions.

This chapter covers a broad range of topics under the very large umbrella of chemical and physical oceanography. From minerals dissolved in the ocean's waters to the destructive winds of tropical cyclones and everything in between, chemical and physical oceanography explain many of the mysteries of marine science. However, the most important aspect of all these individual pieces is how they fit together. When scientists study coral reefs, they cannot just study the individual polyps that make up the reef. They must also look at the nutrients available in the water: are there too many or too little? They must look at the run-off entering the ocean from the coast: is it toxic? If so, how toxic? They need to study sea surface temperatures in order to predict both coral bleaching and tropical cyclones. In all aspects of ocean life, the environment around an organism is of paramount importance to its survival.

7.2 Chemical oceanography and the chemical composition of seawater

Chemical oceanography is the study of ocean chemistry and the behaviour of those chemicals found within the ocean. Surprisingly, 'only' studying the chemicals found within the ocean is not particularly limiting. Nearly every element in the Periodic Table has been located, in some form, within the ocean's vast waters. Understanding the movement of these chemicals requires a fundamental knowledge of ocean circulation, climate and the interactions between the atmosphere, geosphere and hydrosphere on this planet.

KEY TERMS

Salinity: a measure of the quantity of dissolved solids in ocean water, represented by parts per thousand, ppt or ‰

Evaporation: a change in state from liquid to gas below the boiling point of a substance

Salinity

When studying chemical oceanography, traditionally you start by looking at the **salinity** of seawater. Salinity is a measure of the concentration of salts within a body of water. There are two methods commonly used to determine the salinity of a water sample.

- **Total dissolved solids (TDS)**
Using this traditional method, a scientist **evaporates** a known volume of water and then weighs the solids left behind. This method is not particularly good for use in the field because of the equipment and time needed.
- **Electrical conductivity**
This more modern method is faster and easier to use when out in the field. An electric current is passed between two metal plates, and how well the current moves between the plates is measured. The more dissolved salts (solutes) in the water, the greater the conductivity (ease of flow) between the plates. The information gained from electrical conductivity can be used to estimate the total dissolved solids.

The unit used for salinity is parts per thousand (ppt or ‰). This unit was originally derived using TDS. Scientists would take 1000 g of seawater and evaporate it. The solutes left behind, usually ions called salts, were then weighed, making them the 'parts' that make up 1000 g of water. After hundreds of years of water samples, scientists now know that the average salinity of the open ocean is 35‰.

Composition of seawater

The first true scientific study of the open ocean happened between the years of 1872 and 1876 on HMS *Challenger*. This 70 000 km scientific voyage was the first of its kind.

Led by Charles Wyville Thomson, the Royal Society of London purchased an old warship and retrofitted it with scientific laboratories. These laboratories enabled scientists aboard to collect data in the fields of natural history and chemistry. More than 4000 new species of marine life were discovered on this journey, along with vital chemical oceanography.

When the *Challenger* returned home in 1876, the water samples taken during the voyage were sent to William Dittmar. After analysing the samples, Dittmar discovered the same six ions made up the majority of the solutes in seawater (Table 7.1). Additionally, he found that, regardless of the concentration of salts in the water, the ions were always present in the same percentages. He termed this phenomenon the 'theory of constant proportions'.

From Table 7.1, you can see that the majority of the salts in the ocean are sodium and chloride. This should not be a surprise as seawater tastes like table salt, which is a common name for sodium chloride (NaCl). Other ions, such as sulfate, magnesium, calcium and potassium, play vital roles in the biology of the ocean. Many other ions are also present but in such small concentrations that they are called micronutrients (for example nitrogen, phosphorus and hydrogencarbonate). Dittmar's theory of constant proportions holds true for the open ocean and, generally, for coastal regions.

However, further research has found that ion concentrations can be changed by local events, such as atmospheric **dissolution**, volcanic eruptions and run-off (Figure 7.1). These are the three major sources of ions in the world's ocean, and each is discussed in this chapter.

**KEY TERM**

Dissolution: the dissolving of a solute into a solvent.

**KEY TERM**

Solubility: the ability of a solute to dissolve into a solvent.

Effect of atmospheric dissolution on the chemical composition of seawater

Gases in the atmosphere (nitrogen, carbon dioxide and oxygen) are in a state of equilibrium with the gases dissolved in ocean water. As the concentration of a particular gas in the atmosphere increases (carbon dioxide, for instance), the concentration of that gas in seawater also rises. Mixing, as a result of turbulence and wave action, works to maintain this equilibrium. The more turbulence there is, the easier it is for gases in the atmosphere to dissolve into the ocean. This can lead to higher concentrations of carbon dioxide and oxygen within the first 200 m depth of the ocean than are found in the atmosphere. Factors contributing to the concentration of gases in seawater include the following.

- The solubility of the gas
Solubility refers to the ability for a particular solute, like carbon dioxide, to dissolve in a solvent, like seawater. Carbon dioxide is very soluble in seawater because of its ability to form carbonic acid, a weak acid, when introduced to water. Oxygen, while more soluble than nitrogen, is less soluble than carbon dioxide. Oxygen and nitrogen are less soluble because they do not chemically combine with the water molecules. This means that the level of carbon dioxide held by seawater is higher than that of oxygen and nitrogen.
- The temperature of the seawater
Cold water is able to hold more gas than water at warmer temperatures. This means that water found near the poles will hold more oxygen than water found in the tropics (Table 7.2).

ion	mean concentration in seawater / parts per thousand (‰)	Ratio of ion : total salts / percentage (%)
chloride (Cl ⁻)	19.35	55.04
sodium (Na ⁺)	10.75	30.61
sulfate (SO ₄ ²⁻)	2.70	7.68
magnesium (Mg ²⁺)	1.30	3.69
calcium (Ca ²⁺)	0.42	1.16
potassium (K ⁺)	0.38	1.10

Table 7.1. Concentrations of the six most common ions in seawater.

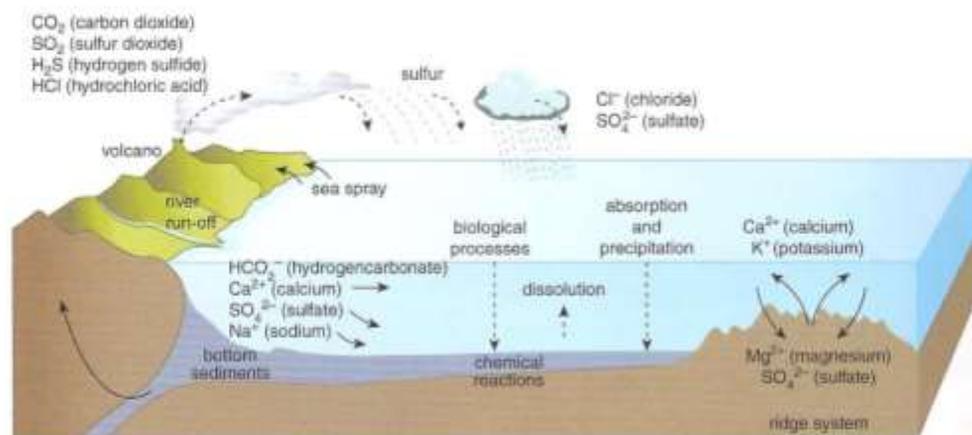


Figure 7.1. How chemicals get into our oceans: atmospheric dissolution, volcanic activity and run-off.

temperature of water / °C	concentration of dissolved oxygen / mg dm ⁻³
0	14.6
5	12.8
10	11.3
15	10.2
20	9.2
25	8.4

Table 7.2. Relationship between temperature and the maximum concentration of dissolved oxygen in fresh water.

- The salinity of the seawater
Gases are able to dissolve better into water with lower levels of salinity. Therefore you would expect to find higher levels of oxygen in an estuary than in the open ocean or the Dead Sea.
- The presence of organisms in the seawater
Organisms play a large role in determining how much of each gas is found in the different layers of the ocean. Nitrogen gas that is dissolved can be transformed into ammonia by nitrogen-fixing bacteria. This makes the nitrogen easier to use for other organisms. At the surface, producers take in dissolved carbon dioxide for use in photosynthesis. Consumers and producers both use dissolved oxygen for respiration.

Effect of volcanoes on the chemical composition of seawater

When volcanoes above sea-level erupt, they pour tonnes of hot ash into the atmosphere. Within that ash are many minerals and gases that impact our oceans. In particular,

carbon dioxide (CO₂), sulfur dioxide (SO₂), hydrogen sulfide (H₂S) and hydrogen chloride (HCl) leave the volcano mixed with the particulates of ash. When these gases enter the atmosphere they mix with atmospheric water, especially water already condensed into a cloud. When the cloud becomes **precipitation**, the dissolved gases rain down into the ocean as part of the hydrological cycle. The addition of these ions into the water changes the ion concentration for a brief time.

Volcanoes that are still submerged can also impact upon the ion concentrations of the seawater around them. These volcanoes, located at either convergent or divergent plate boundaries, erupt releasing the same gases into the water. Submerged volcanoes have been releasing hydrogen chloride and chlorine gas into the ocean since the ocean was first formed. In fact, they have released so much chlorine gas they are considered to be the primary source of chloride ions found in today's seawater.



KEY TERMS

Precipitation: water that falls from the atmosphere to the Earth's surface as rain, sleet, snow or hail

Run-off: the flow of water from land caused by precipitation

Effect of run-off on chemical composition of seawater

Run-off is water that flows over the Earth's surface due to precipitation or melting snow or ice. As this water flows over city streets or through farmers' fields, it dissolves many substances and carries them along. These substances could include vital nutrients, pesticides, fertilisers, oils and other pollutants. Eventually, most of this water, as part of the hydrological cycle, finds its way to

the oceans, either directly or by first flowing into a river. So, while run-off is not considered a pollutant, it is capable of carrying many types of pollution into the ocean.

Many of the pollutants carried by run-off have a very low concentration in the water and are initially seen as non-threatening. However, these compounds can be absorbed into the tissues of producers through uptake. Once this happens, the pollutant concentration increases as it passes from one trophic level to the next within a food chain. This process is known as **biomagnification**.

KEY TERM

Biomagnification: the increasing concentration of a substance, such as a toxic chemical, in the tissues of organisms at successively higher levels in a food chain

Since the Industrial Revolution, many examples of biomagnification have come to light. In the United States, the use of a pesticide known as DDT was responsible for the near extinction of several predatory bird species, including the bald eagle. Another example comes from Minamata city in Japan.

Fertilisers carried to the ocean can also pose a unique risk to marine ecosystems. Most chemical fertilisers contain a mixture of nitrogen and phosphorus. Both of these nutrients are necessary for the growth and health of plants, including algae and phytoplankton, and are normal in the ocean in low concentrations. Nitrogen and phosphorus are considered to be limiting factors in marine ecosystems because their low concentrations help control the population of producers. However, chemical fertilisers contain very high concentrations of these elements and, when dissolved in run-off, their presence can disrupt local coastal ecosystems. Excessive fertiliser in run-off is a primary cause for harmful algal blooms (HABs) that can be toxic to both the environment and humans.

Effects of evaporation and precipitation on salinity

While 35‰ is the average salinity of ocean water, the actual salinity at any given location does vary. In areas with fresh-water run-off or melting glaciers, for example, the salinity may be much lower. This lower salinity is caused by the addition of water, rather than the removal of salts. Precipitation (for example rain or snow) also lowers the salinity of a body of water by diluting the salt in the seawater with incoming fresh water. Estuaries are a great example of salinity varying throughout a body of

water. Near the mouth of the river within an estuary, the water is considerably less saline than the water nearest the ocean. The water lying at the top of the water column in an estuary is also fresher than water on the bottom. This means that salinity levels within an estuary change during high and low tides (Figure 7.2). This phenomenon is discussed later in this chapter.

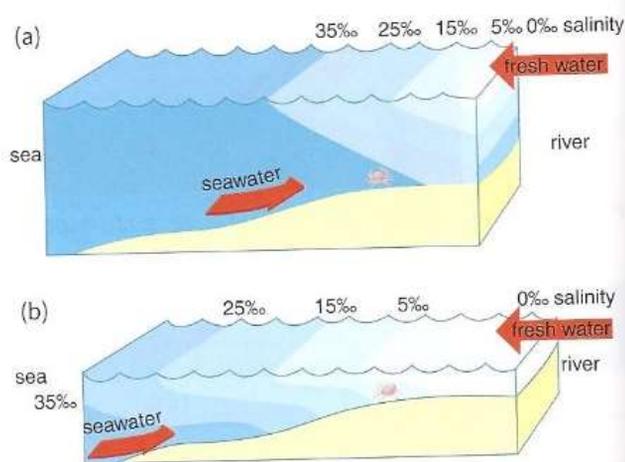


Figure 7.2. Salinity levels in an estuary at (a) high tide and (b) low tide.

Salinity higher than 35‰ is often found in regions with above-average evaporation rates and a limited fresh-water inflow. When the salts are even more concentrated, the water is described as **hypersaline**. One example of a hypersaline environment is the Dead Sea, an inland sea found between Jordan and Israel. The salinity levels are ten times that of the open ocean. Salinity is so high that salt coats the beach as a result of evaporation (Figure 7.3).

KEY TERMS

Hypersaline: when a body of water has a salinity level greater than 35‰

Dissolved oxygen (DO): oxygen that has dissolved into water

Dissolved oxygen and the oxygen minimum layer

The concentration of **dissolved oxygen (DO)** varies throughout the ocean. As mentioned above, both temperature and salinity affect the concentration of dissolved oxygen in the ocean. The higher the water temperature, the lower the oxygen concentration. Also, the higher the salinity, the lower the dissolved oxygen concentration, although this difference is slight.

The area of the ocean with the greatest concentration of dissolved oxygen is the top 100 m of the ocean, known as the surface layer. Within this layer, the dissolved oxygen concentration can reach 'supersaturation'. This means there is more oxygen dissolved in the seawater than it would normally be able to carry. Two major factors work together to increase the amount of dissolved oxygen to supersaturation level: the motion of the water and photosynthesis by producers. The more turbulent the water, the more oxygen is mixed into it by the movement of the waves. Meanwhile, producers, like phytoplankton and algae, use photosynthesis to create glucose and generate oxygen as a byproduct. This oxygen adds to the amount of dissolved oxygen in the surface layer. Dissolved oxygen is removed from this layer by the respiration of organisms.

Below the surface layer of the ocean, the concentration of dissolved oxygen changes dramatically. As the depth of the ocean increases, the level of dissolved oxygen decreases until it reaches the **oxygen minimum layer**. The oxygen minimum layer typically occurs at a depth of around 500 m, but has been found anywhere between 100 and 1000 m deep depending on location. Some organisms are capable of living within the oxygen minimum zone, despite the lack of dissolved oxygen, but they do need special adaptations for survival. Most of the organisms found here are fairly inactive, which reduces their need for oxygen. The gills of the fish in this area are incredibly efficient at extracting oxygen from water, even at the low levels present in this layer. Additionally, many of the organisms here have a very oxygen-efficient form of hemoglobin, a blood protein responsible for carrying oxygen throughout the body.

After reaching the oxygen minimum layer, the oxygen concentration begins to increase deeper into the ocean. Three reasons exist for this subtle increase in oxygen (Figure 7.5).

- First, the organisms found below the oxygen minimum layer are in an area with very few food resources. This lack of food reduces the need for the organisms to respire, so they survive with less oxygen.
- Second, the solubility of oxygen increases as the temperature decreases. As you go deeper into the ocean, the temperature decreases to near-freezing.

The lower temperature means oxygen is more likely to stay dissolved in the water.

- Third, as pressure increases, the solubility of oxygen increases. For every 10 m you sink into the ocean, the pressure increases by one atmosphere. This pressure keeps the water and oxygen molecules packed closely together, allowing for greater solubility of the oxygen.

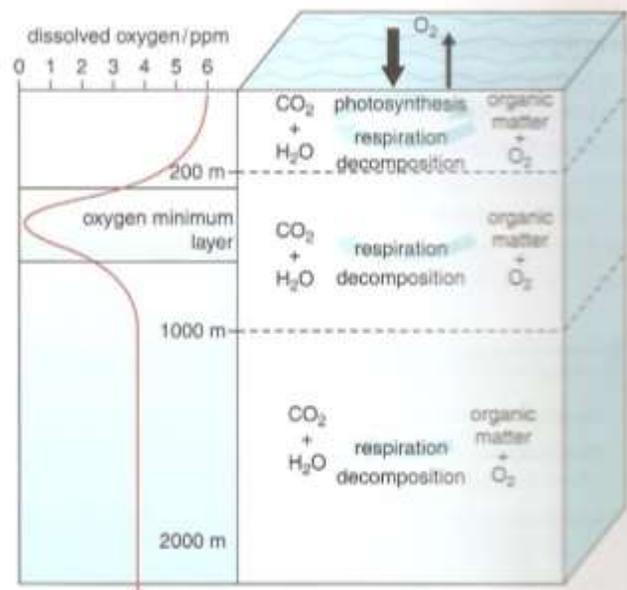


Figure 7.5. Oxygen minimum layer in the eastern tropical Pacific Ocean and the biological processes responsible.



KEY TERM

Oxygen minimum layer: the layer within the ocean where the concentration of dissolved oxygen is at its lowest, typically found between 100 and 1000 m deep

SELF-ASSESSMENT QUESTIONS

- 1 What are the three most important gases in seawater, biologically speaking? How do they impact upon life in the ocean?
- 2 How do volcanoes and run-off change the composition of the world's ocean?

Opdracht bij les 2.1

- Kiezen uit case studies: Dumpen van rioolwater
New York / Het belang van zalm voor de groei van
bomen

Les 2.1 - Het belang van zalm voor de groei van bomen

Een belangrijke manier waarop voedingsstoffen uit het mariene ecosysteem worden gehaald is door de mens. Maar dit gebeurt ook door migraties zoals bijvoorbeeld die van de zalm naar zoet water waar ze gegeten worden door roofdieren zoals adelaars en beren. De zalm brengt het grootste deel van zijn leven in de zee door. De jongen eten zoöplankton en de volwassenen eten krill en kleine vis zoals haring. Elk jaar keren zalmen terug naar de rivier waar ze zijn geboren om zich voort te planten. Hiervoor zijn rivieren nodig die schaduw krijgen van bomen zodat het water niet te warm is. Warm water bevat minder zuurstof, waardoor minder eitjes overleven. De bomen helpen ook om bodemerosie te voorkomen, waardoor er geen sediment in het water komt en het water helder blijft. Grote populaties insecten leven in de bladeren van de bomen en zijn voedsel voor de jonge zalmen wanneer ze uit het ei komen.

Het is duidelijk geworden dat niet alleen zalmen bomen nodig hebben, maar ook andersom. De zalmen zijn een grote bron van voedsel voor roofdieren terwijl ze de rivieren op trekken. Een enkele beer kan wel 700 zalmen vangen tijdens het broedseizoen. Hoewel de beren de zalm in het water vangen, eten ze deze op het land op. De helft van de zalm wordt gegeten door de beer, de andere helft door aaseters en insecten. De dode resten worden afgebroken door reducerende organismen en de voedingsstoffen die daarbij vrijkomen worden opgenomen door de bodem. De zalmen kunnen wel 120 kilogram stikstof per hectare bos leveren, waardoor de bomen drie keer zo snel groeien. Er bestaan verschillende stikstof isotopen (vormen van het atoom) en onderzoekers hebben ontdekt dat grotere bomen meer stikstof bevatten dat afkomstig is uit de oceaan dan kleinere bomen. Bovendien is het zo dat hoe dichter de boom bij de broedlocaties staat, hoe hoger de hoeveelheid voedingsstoffen afkomstig van de zalm. Er is dus positieve feedback, hoe meer zalm er worden gevangen, hoe beter de bomen groeien, en hoe beter de bomen groeien, hoe beter de voortplanting van de zalmen.

1. Onderzoekers hebben verschillende stikstof isotopen gebruikt om de voedingsstoffen van mariene afkomst te traceren. Geef een mogelijke route van de oceaan naar een boom van een stikstofatoom.
2. De meeste stikstof is afkomstig van de dode resten van de zalm. Geef nog een andere manier waarop extra stikstof wordt toegevoegd door de zalm
3. Benoem nog een voedingsstof die aanwezig zal zijn in de zalm en waar.
4. Welk ander organisme heeft ook voordeel van de stikstof in de zalm?
5. Hoe kan een deel van de stikstof uit het bos weer terug komen naar het mariene ecosysteem?



Les 2.1 - Dumpen van rioolwater New York

Tot 1992 werd het rioolwater van New Jersey en New York verzameld en de vaste delen werden afgezonken in tanks. De vaste drab die hierbij ontstond werd dan op riolschepen gezet en deze voeren naar dump plekken in het noordwesten van de Atlantische Oceaan, waar deze drab overboord gegooid werd. Een van de locaties was meer dan 150 kilometer van de kust op een diepte van 2500 meter. Er wordt geschat dat er tussen 1986 en 1992 ongeveer 42 miljoen ton (42.000.000.000 kilogram) natte, onbehandelde riooldrab is gedumpt op deze plek.

Een onderzoek naar de zeebodem werd op deze locatie uitgevoerd eind jaren tachtig van de vorige eeuw. De zuurstofconcentratie in het water rond de dumpplek was extreem laag en hoge concentraties van toxische metalen zoals cadmium en mercurius werden gevonden in het sediment. Zee-egels en zeeekomkommers in het gebied werden onderzocht op concentraties van radioactieve ionen van koolstof, waterstof en sulfaat, die normaal erg zeldzaam zijn in de oceanen, maar die wel gevonden worden in menselijke uitwerpselen. De dieren hadden hoge concentraties van deze ionen, wat betekent dat de stoffen in het riooldrab in de voedselketens terecht kwamen. Sporen van een mogelijk schadelijke bacterie die voedselvergiftiging veroorzaakt werd ook gevonden in het sediment.

Gedurende de tijd dat het riooldrab werd gedumpt, waren er een aantal algenbloeien in de zee rond New York. Mensen die dan in de zee zwommen of naar het strand gingen kregen voedselvergiftiging en afval zoals gebruikte naalden spoelden aan op het strand. Sommige schelpdierbedden stierven door de vervuiling en door het gebrek aan zuurstof. Anderen werden gesloten voor de visserij omdat men bezorgd was over de aanwezigheid van ziekteverwekkers. Stranden werden elk jaar dagenlang gesloten vanwege de schadelijke microben.

Het dumpen van het riooldrab werd gestopt in 1992. Hierna is de zeebodem op de dumpplek snel veranderd. De zuurstofconcentratie nam toe en de soorten organismen die een hogere zuurstofconcentratie nodig hebben om te overleven kwamen terug. De wateren rond New York verbeterden, met meer vissoorten en een hogere biodiversiteit. Er zijn nog steeds algenbloeien, maar de stranden zijn een stuk schoner en veiliger, en worden nog maar zelden gesloten voor de strandgangers. De visserij heeft ook voordelen ondervonden, met grotere vangsten en het minder vaak sluiten van de schelpdierbedden.

1. Leg uit waarom het zuurstofgehalte bij de dumpplek laag was.
2. Leg uit hoe de radioactieve ionen lieten zien dat stoffen uit het riooldrab in de voedselketen terecht kwamen.
3. Waarom was het niet nodig dat de onderzoekers meer soorten onderzochten op de aanwezigheid van schadelijke stoffen?
4. Verklaar waarom de aanwezigheid van mercurius in het riooldrab een probleem kon zijn voor de visserij.
5. Waarom zijn de vangsten van de visserij nu groter?

