CHAPTER SEVEN

Wasja / 123RF

Water chemistry and water quality

> In nature there are neither rewards nor punishments, there are consequences
>
> *Robert Green Ingersoll, The reason why*

This chapter deals with water itself, the substances it contains and its physical properties. These features together make up what is often called ***water quality***. The term is usually used loosely to mean the physical and chemical attributes of water (sometimes called physico-chemical properties), while 'poor water quality' implies some kind of pollution. To be accurate, though, we should distinguish between ***physical attributes*** such as temperature and turbidity, ***chemical constituents*** such as sodium or nitrate ions, ***water quality*** – which implies the suitability of water for use (usually by humans) – and ***pollution***. Pollution is one of the most obvious problems associated with inland waters and the public is very much aware of phenomena such as sewage spills, fish kills, smelly green water, and littering. For example, news reports will show children 'tackling pollution' on River Day, clutching large rubbish bags full of discarded plastic, cans and bottles. Pollution is more than litter, however. Even naturally occurring minerals like sodium chloride (common salt) can become pollutants under certain circumstances, while other apparently nasty substances like aluminium may not always be toxic. In contrast, although it is unsightly, and may be a symptom of other, more serious, types of pollution, litter itself is seldom seriously damaging to aquatic ecosystems (but exceptions do occur as illustrated by the photograph on page 228) (While the effects on large animals of plastic waste in the form of plastic bags and drinking straws can be horrific, these are not dealt with here. We do discuss microplastics and toxins associated with plastics on page 269, however.)

Numerous textbooks and websites provide information on water quality and water chemistry. Locally, ***The effect of water quality variables on aquatic ecosystems: a review*** by Helen Dallas and Jenny Day provides an ecosystem approach to water chemistry. Tally (Caroline) Palmer has written on ***How to understand environmental water quality in water resources management;*** both of these are published by the Water Research Commission (WRC). The 'bible' of analytical chemists is 'APHA', a volume on ***Standard methods for the examination of water and wastewater***, now in its 22nd edition. This book is of biblical proportions and is far more detailed than most of us will need. It does provide both the methods for analysing many chemicals in water and a brief analysis of the substance in question, though.

Tom Schwerdtfeger

While solid waste may not actually be toxic, it does block streams and drains and is a nasty eyesore. This waste was removed from the mouth of the tiny Lotus River that feeds into Zeekoevlei. Dumping of waste costs the City of Cape Town about R300 million per year.

'WATER QUALITY' AS A HUMAN CONSTRUCT

The term 'water quality' was coined with reference to the quality of water required for human use: 'good-quality' water is 'pure' and unpolluted and suitable for drinking as well as for agricultural and industrial purposes. We need to recognise, however, that this is entirely a human perspective. Although most freshwater organisms might agree with humans about what constitutes 'good' water quality, this would emphatically not be true for all of them. The most obvious example concerns seawater, which is eminently suitable for marine organisms but utterly unsuitable for humans and for organisms that live in fresh water. This is also true for some inland waters and for all estuaries. Some wetlands, for instance, naturally have highly saline or alkaline waters to which their biotas are adapted. When humans 'improve' the water quality of these systems they are essentially condemning the native plants and animals to death. There are even saline lakes in the Andes where total dissolved solids (TDS) exceeds 200 g/L (about six times the salinity of seawater) and arsenic levels can exceed 200 mg/L (average freshwater concentration <1 g/L). These are some of the richest Andean lakes, supporting large flocks of rare and endangered flamingos in water that would kill a human.

Jenny Day

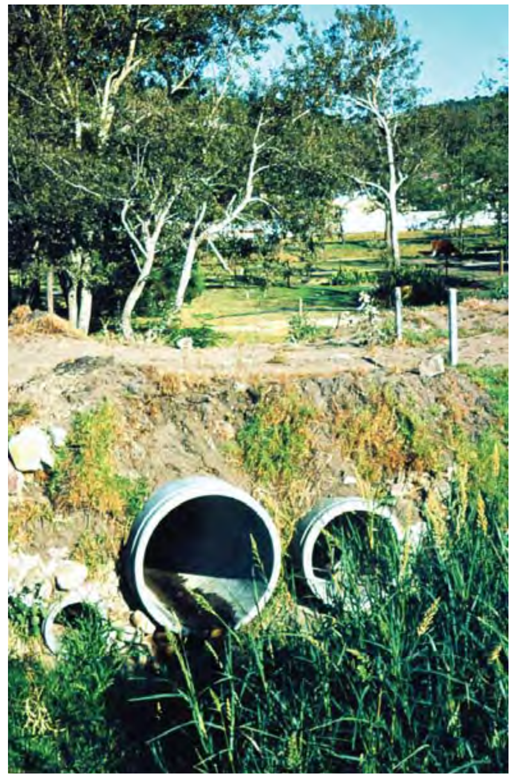
Cachi Laguna, in the Bolivian Andes, supports flocks of flamingos in arsenic-laden water that would kill a human.

WHAT IS POLLUTION?

All natural waters contain a variety of chemicals and particles, both organic and inorganic. Natural waters also have certain physical attributes such as temperature and colour. Aquatic organisms are adapted to living in waters with particular suites of chemical constituents and physical attributes. One of the simpler definitions of pollution is ***the introduction of harmful substances or products into the environment*** (https://www.dictionary.com). A more concise definition comes from the *Britannica Concise Encyclopaedia* (1994-2010): pollution is ***the State resulting when substances are released into a body of water, accumulating to the extent that they overwhelm its capacity to absorb, break down, or recycle them, and thus interfering with the functioning of aquatic ecosystems***. So, by definition, pollution is the altering of features of the environment to the detriment of its inhabitants or users, and 'water quality' is the extent of pollution from the point of view of the organism living in or using the water. Sea water is thus of 'good' quality for a marine fish, for instance, while it is of extremely poor quality for a fish living in a mountain stream, or for a human needing water to drink.

Pollutants often occur as individual dissolved chemicals such as acids or pesticides, and particulate matter, which ranges from coal dust and soil in suspension to rubble, metals, plastics and faeces. Dissolved pollutants seldom occur singly, though. Most often they occur in effluents (waterborne discharges) containing mixtures of chemicals, some harmful and some innocuous. Effluents may be discharged from pipes or stormwater drains into rivers, lakes or wetlands, or directly into the sea. These are said to be 'point-source' discharges. Although point-source discharges may have devastating effects on aquatic ecosystems, they do have two advantages from a management point of view. Firstly, it is possible to measure or otherwise estimate the quantity of pollutants being discharged. Secondly, it is fairly easy to control them, at least in theory. Pollutants entering aquatic systems from point sources may be discharged legally under controlled or semi-controlled conditions (see page 272 on the control of pollution in South Africa), while others are discharged deliberately and illegally, or accidentally. In contrast, sources of pollutants such as seepage from mines, agricultural runoff and atmospheric pollution are diffuse and therefore very difficult both to quantify and to control. Pollutants entering water bodies in this way are said to be of 'non-point-source' origin.

In this chapter we start by looking at some of the features of the chemical and physical conditions in natural aquatic ecosystems and then we examine the more important individual types of pollution and pollutants. Some topics are discussed in more detail in text boxes.



Jenny Day

Stormwater drain directed into a small stream.

THE HYDROCHEMISTRY OF NATURAL WATERS

In the following sections we show why natural waters differ physically and chemically from each other; then we explain the importance of some of the major physical attributes and chemical constituents of water to living organisms, and why some can be considered as pollutants.

WHAT DETERMINES THE PHYSICAL AND CHEMICAL PROPERTIES OF NATURAL WATERS?

The physical attributes and chemical constituents of natural fresh waters differ from continent to continent, and even from region to region, because they are influenced by climate, geomorphology, geology and soils, as well as by the aquatic and terrestrial biotas living in a particular area.

Climate affects water quality in a number of ways. For instance, temperature determines the rate and extent of various chemical interactions. Mean annual rainfall, and seasonal differences in rainfall, determine the amount of water flowing in rivers or entering wetlands at different times of the year and therefore also determine the degree of dilution of natural chemical constituents and of pollutants. Evaporation, on the other hand, concentrates substances dissolved in water. So, the waters of aquatic ecosystems in arid areas tend to be more saline than equivalent systems in mesic areas.

The ***geomorphology*** of the landscape determines, amongst other things, the gradients of its rivers. The greater the amount of energy imparted to flowing water by a steep gradient, the greater the degree of turbulence and thus the greater the quantity of oxygen and other gases that dissolve in the water. The steeper the gradient, the greater the erosive power of a river's water, too. Particles that are brought into suspension by the friction of water on the bed also contribute to turbidity (see page 241).

Fast-flowing turbulent water picks up oxygen and other gases from the air.

Water chemistry is affected by the underlying ***geology*** of the catchment because rocks of different kinds vary in chemical composition. Thus, they and the soils derived from them contribute ions (including nutrients) in different quantities and of different proportions to the waters flowing over, or percolating through, them.

Various components of the ***aquatic biota*** can also affect water chemistry. The combined effects of photosynthesis and decomposition, for instance, can determine both the pH and the amount of oxygen present in water. Terrestrial vegetation in the catchment may also produce organic compounds that, when leached into water, affect pH and inhibit microbial activity. As an example, the waters of many rivers and vleis of the south-western Cape are acid and black because their catchments are vegetated by fynbos (see Fynbos text box on page 276).

While all of the factors described above determine the chemical character of rivers and wetlands, it is the ways in which the land is used by humans that often has the greatest effect of all. Runoff of stormwater, as well as discharges of sewage effluents from cities, may result in high nutrient levels or accumulations of toxins from industrial sources, while agricultural practices result in agrichemicals such as nutrients and antibiotics, as well as high silt loads, reaching rivers and wetlands. Even recreational areas may contribute engine oil from motor boats and – in much greater quantities – nutrients from septic tanks and soakaways.

Finally, the water chemistries of wetlands and rivers often differ in significant ways. For instance, oxygen concentrations are generally higher in flowing waters, particularly mountain streams, than in the still waters of wetlands where aerobic (oxygen-using) bacteria decompose dead plant material. And then wetlands, being aggrading systems, accumulate materials, while rivers flush them away, or at least dilute them.

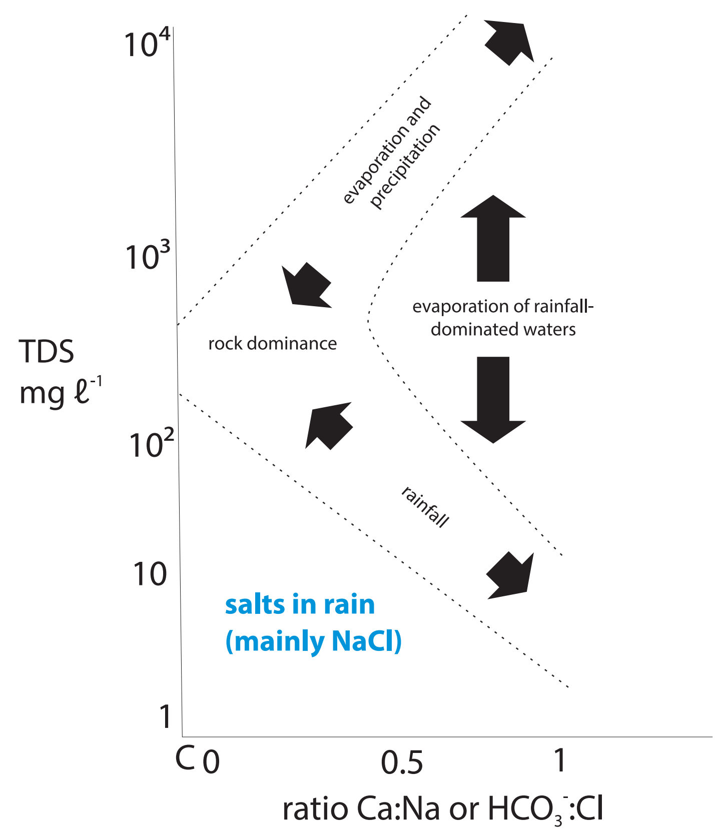
REGIONAL DIFFERENCES IN THE CHEMISTRY OF SOUTH AFRICAN RIVERS

South Africa is diverse in climate, geomorphology, geology and soils, and also in its terrestrial and aquatic biotas, and so each region exhibits differences in water chemistry even when unaffected by human activity. Below we describe what appears to have been the natural situation. We cannot be sure that this is accurate in all respects, though, because we have so few undisturbed rivers and wetlands from which to infer what natural conditions must have been like.

Because of differences in climate and geomorphology, the southern and eastern parts of southern Africa have a more equable climate than the rest of the region. The rivers tend to be perennial and to carry fairly pure water, low in total dissolved solids (TDS: a measure of saltiness). The rivers of the arid west, the arid interior and the 'arid corridor' of the Eastern Cape are mostly seasonal or ephemeral. Notable exceptions are the Orange River and some of its tributaries. During hot, dry periods irrigation waters may undergo evaporative concentration and TDS values may increase tenfold or more.

Furthermore, southern Africa is geologically diverse (see chapter 3). The great central Karoo sedimentary basin is surrounded to the north largely by a complex of igneous formations and to the south and east by the sandstones and shales of the Cape and Malmesbury Supergroups. The youngest of the Karoo rocks form the basalt cap (also igneous) of the Drakensberg. Igneous rocks, such as those of the Bushveld Igneous Complex in the north-east of the country, and the Drakensberg, usually contain sufficient calcium and magnesium that water flowing over or through them picks up measurable quantities of these elements, and of nutrients such as phosphates, nitrates and silicates. In general, waters affected by igneous rocks are dominated by calcium and/or magnesium cations (positively charged ions) and bicarbonate anions (negatively charged ions). They are also slightly alkaline, with a pH higher than 7, and low TDS values. Such waters are said to be 'rock dominated' (see the figure on page 233). At the other extreme, sedimentary rocks, such as those of the Cape Supergroup, may have been derived from sand particles that were already strongly weathered when they were consolidated into rock hundreds of millions of years ago. Very little soluble material is present in these rocks, and so even less can be leached out. Waters flowing over such rocks usually have very low concentrations of salts, including nutrients, and the bulk of dissolved material is derived from rain, snow and other forms of precipitation, in which the major ions are sodium and chloride. Such waters are said to be 'rainfall dominated' or 'precipitation dominated' and are very soft, pure and unbuffered. The figure on p233 shows how the relationship between lithology (rock chemistry) and rainfall can affect the [TDS] and the proportions of the major ions in a body of water. (Note that square brackets indicate 'concentration of' – so [TDS] means 'the concentration of total dissolved solids')

The figure below illustrates the relationships between TDS and the proportions of Ca^{2+} and Na^{+}, or HCO_3^{-} and Cl^{-}, ions, in relation to lithology (rock type). The upper arm of the 'boomerang' outlined by the dashed lines represents the relationships that are known for rivers in areas where evaporation is important (eg in desert climates): [TDS] will be high and the ions mostly Na^{+} and Cl^{-}; the central part of the 'boomerang' represents most rivers flowing in igneous landscapes, being of intermediate [TDS] and dominated by Ca^{2+} and HCO_3^{-} ions; the lower arm of the 'boomerang' represents water in rivers flowing over old, weathered rocks: they will leach out very few ions and so the water will be dominated by Na^{+} and Cl^{-}, the most common ions present in rain. In arid conditions, such as are found widely in South Africa, evaporation of 'rainfall-dominated' waters will result in highly saline conditions (vertical arrow); (see Gibbs, 1970 and Day & King, 1995).



Rock chemistry and climate together affect water chemistry. Salt lakes plot out near the top arrow; most rivers and lakes plot out near the middle arrows on the left; very soft waters like those of the south-western Cape plot out below the bottom arrow. (See text for details.)

HOW WATER CHEMISTRY SHAPES REGIONAL DIFFERENCES IN AQUATIC PLANT AND ANIMAL ASSEMBLAGES

Regional variations are not confined to the abiotic environment. Each species of organism can survive only within certain limited ranges of physical and chemical conditions. These requirements are determined by the evolutionary past of each taxon. Indeed, each species has a history going back to the beginning of life on Earth: survival of any species to the present day implies that its ancestors have been able to adapt to a particular combination of living conditions since the beginning of time. More specifically, each species of aquatic organism is adapted to living in water containing a particular suite of chemicals within certain concentration limits. For instance, some species of small shrimp-like crustaceans called amphipods (Chapter 4) are found only in Cape mountain streams where the TDS is always <50 mg/L. In contrast, a variety of other species of amphipod live in estuaries where TDS may range from 500 mg/L (almost fresh water) to 35 000 mg/L (sea water) over a single tidal cycle. Yet other species live in the sea, where TDS is constantly close to 35 000 mg/L. Each species also requires specific physical conditions. In the rocky bed of a river, for instance, a few species will live on the upper surfaces of stones in fast-flowing currents, while others live under stones in quiet backwaters, or prefer the protection of submerged plants (see Chapter 4).

Zoology Dept / UCT

Do Musibono

(Left) A marine amphipod, Ceradocus rubromaculatus *and right) a freshwater amphipod,* Paramelita nigroculus.

Furthermore, a particular species can be present in a given aquatic ecosystem if the prevailing conditions (water chemistry, available habitat, food supply, etc.) are suitable, but (of course) also if its progenitors were able to reach the area. Thus, barriers such as deserts or forests may prevent 'suitable' organisms from reaching a newly established reservoir, for instance. Since different species may have very different evolutionary histories, their ancestors having originated in different areas and under different environmental conditions, they may also have very different requirements with regard to water quality. It is possible, for instance, that those South African species derived from a tropical African fauna may have a greater tolerance of high temperatures and pH values than those derived from the fauna of the great southern continent of Gondwanaland, whose species may instead have been able to tolerate low temperatures and relatively acid waters. Given that a species is physically able to live in a particular place, its distribution may well also be limited by biotic interactions. Most obviously, an appropriate food-source must be available. But some species are less efficient than others at using their food, or at finding shelter, and may be displaced by superior competitors or predators.

In summary, the actual species of organisms that comprise any aquatic biological community are largely determined by:

- the historical distribution of species (i.e. it must have been geographically possible for a species to have become established in a particular system);
- the physical attributes and chemical constituents of the water;
- the types of biotope available (e.g. stones-in-current, marginal vegetation in a river), the degree of water movement (e.g. lakes *vs* rivers) and temporal changes in flow (e.g. periods of spate and drought);
- other elements of the biota, including parasites, predators and food sources.

AQUATIC BIOTAS AND WATER QUALITY

Why should we worry about the fact that aquatic organisms need to live in water of a particular quality? The simple answer is that if we don't, then more and more species are going to disappear as our waters become more and more polluted. To anyone concerned about the Earth's living resources, this might be an obvious answer. But it is not obvious to many people who are ignorant of, or unconcerned about, their fellow inhabitants on this planet. These people are wrong, though, if they think that the conservation of aquatic ecosystems is just another symptom of sloppy 'green' thinking (see the section on Ecosystem Services in chapter 11).

THE EFFECTS OF ALTERED WATER QUALITY ON AQUATIC ECOSYSTEMS

Since each species thrives optimally in water with particular combinations of physical and chemical attributes, and since optimal conditions differ for each species, alterations in water quality will affect different species to different degrees. Greater and greater changes in water quality may eliminate some species and allow others to invade, until not a single species of the original assemblage remains.

The effects of altered water quality on aquatic communities include:

- a shift in the physical position of a community of riverine organisms (the community of organisms found below fish farms on mountain streams, for instance, is more representative of communities naturally found much further downstream);

- the introduction or loss of key species (for instance, the massive growth of benthic algae in eutrophic waters may result in a 'population explosion' of snails and the loss of mayfly and stonefly nymphs);

- reduction in diversity of fish, invertebrates, etc., as a result of very small increases in the concentration of toxins such as certain trace elements;

- reduction in, and ultimately loss of, decomposers and thus of nutrient cycling in streams and lakes seriously affected by acid rain (see textbox on acid rain).

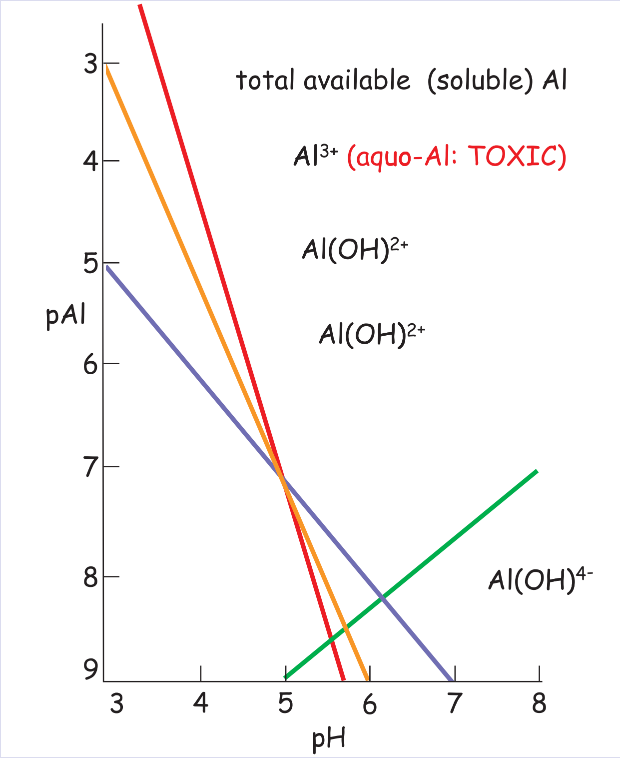
Ultimately, each species can survive only within the limits of their tolerance to all the different chemical and physical conditions in the water that they live in. The outcome is that suites of species with similar requirements will occur in the same part of the river or wetland. This useful feature allows the development of bioassessment techniques based on water-chemistry tolerances of the invertebrates (see chapter 12). We discuss the effects of aquatic biotas on water quality in the section on ecosystem services in chapter 11.


Lani van Vuuren

Kriel Power Station, in Mpumalanga. The Mpumalanga highveld is now considered to be one of the world's worst hotspots for air pollution.

Rain is naturally slightly acid (pH about 5.6) because of the CO_2 dissolved in it. Fifty years or more ago, it became clear that the pH of rain falling in the more industrialised areas of the world, particularly in northern North America and northern Europe, was considerably less than 5.6. We now know that this is the result of atmospheric pollution by sulphur dioxide (SO_2), largely from burning coal and oil, and by various nitrogen oxides (NOxes), mostly produced in exhaust gases from combustion engines. Both SO_2 and NOxes, when dissolved in water, form strong mineral acids. When acid rain falls on a catchment, these sulphuric and nitric acids leach calcium and magnesium from the soil, as well as interfering with nutrient availability. In water, they reduce pH and alkalinity. The effects of acid rain (or more correctly 'acid precipitation', which includes snow and mist) were first noticed in Hubbard Brook, a small experimental catchment in the Adirondack Mountains in the north-eastern USA. At about the same time, Scandanavian ecologists noticed that fish populations were declining and sometimes disappearing from many lakes as a result of acidification of the water. A while later, acid rain was implicated in the die-back of hardwood forests in several parts of northern Europe. The phenomenon must have been developing over some decades but only became obviously problematic in the 1960s. It eventually became clear that acidification was the cause and that it originated from combustion of fossil fuels. The effects were devastating, especially in poorly buffered soils and waters. The entire biotas of many northern European lakes died out; forests senesced, and the trees died in Germany; and high nitrogen concentrations in relatively well buffered lakes resulted in eutrophication. Legislation such as Clean Air acts have improved matters very considerably in the USA and western Europe. (As an aside, it now seems that the die-back of forests may actually have had a number of different causes, from insect pests to climate change to centuries-long removal of timber, acidification being relatively insignificant.)

Of course, as always, things are different in southern Africa, where air pollution matches or exceeds that of most industrialised nations of Europe, largely because South Africa's massive coal deposits provide a relatively cheap source of power, while there are very few large rivers to be used as sources of hydroelectric power. Acid precipitation has been recorded in several regions, most noticeably in the eastern Highveld, home to massive coal-burning power stations, where the lowest recorded pH value for rain is 2.9. A study in 1986 of the catchment of the Pienaars River, near Pretoria, revealed that the mean pH of rain was 4.15, although the acidity was rapidly neutralised on contact with the soil. (This is not surprising, because some soils can absorb a great deal of acid before they are so altered chemically that they can no longer do this.) In 1988, together with some of his colleagues, Professor Peter Tyson of the University of the Witwatersrand published a report detailing the effects of atmospheric pollution, particularly from coal-fired power stations, over a 30 000 km^2 area of the Eastern Transvaal Highveld. They noted that during 1985–6 the pH of rain ranged between 3.9 and 4.6 and they calculated the quantities of emissions over the region for 1984. Things have not improved. The Mpumalanga highveld is now considered to be one of the world's worst hotspots for air pollution. South Africa's reliance on coal influences its emissions policies, allowing 10 times more nitrogen oxide emissions than China and Japan, according to



Aluminium exists as different ionic 'species' at different pH values. The one to note is the highly toxic Al^{3+} (red line), which becomes dominant at pH values <5.

Greenpeace. Nitrogen oxide is also found in tobacco smoke, leading World Health Organization head Tedros Adhanom Ghebreyesus to declare air pollution as "the new tobacco", killing seven million people each year. In microcosm, a 2014 study by the environmental justice group GroundWork (https://qz.com/africa/1441504/highest-concentration-of-deadly-air-pollution-found-in-south-africa/) found that coal-fired electricity generation was responsible for more than half of hospital admissions and deaths due to respiratory illness in the eMahahleni (Witbank) region of South Africa.

Although we have a reasonably good idea of the quantities of emissions, we have very little information on the effects of atmospheric pollution on the natural environment (or, indeed, on human health). At present, air pollution in South Africa is being monitored only in the form of sulphates, NOxes, and a few other variables, and only in Gauteng and the Western Cape. Mogesh Naidoo and colleagues from the CSIR commented in a recent conference paper that this coverage of the country is thoroughly inadequate. Given the shocking lack of planning by ESKOM and Government over the past decades, we know that more power stations are urgently needed to provide power for continued economic growth and employment, and to avoid the chaos resulting from euphemistically labelled 'loadshedding'. It seems, though, as of June 2022, that South Africa intends to shut down several of its coal-fired power stations. If they do that, the problem of acid rain on the highveld should be considerably reduced.

Acid rain and aluminium toxicity

For a long time biologists were flummoxed by the extreme effects of acidification on the biotas of lakes. After all, it was known that decreased pH leads to disturbances in acid-base and water balance in fish but until that time, reduced pH values had not been implicated in widespread deaths of plants or animals. The culprit causing the deaths of fish and other organisms in acid-rain-acidified lakes is surprising. It is aluminium (Al). It had long been known that aquatic animals are particularly sensitive to increased concentrations of available Al, and high levels were implicated in the deaths of brook trout in the acid-stressed Adirondack lakes in New York State. Al is extremely toxic under certain circumstances, interfering with ionic and osmotic balance and, in fish, causing respiratory problems resulting from coagulation of mucus on the gills and reduced excretion of NH_3 (ammonia) from them. It also interferes with Ca^{2+} metabolism, perhaps altering the function of calcium-regulating proteins, calmodulins, in both plants and animals.

But what is the relationship between Al and acidification? It all relates to speciation of aluminium in water. Al is a very common element, forming about 8% by mass of the Earth, and occurring in fresh waters at an average concentration of about 0.3 µg/L. Al ions occur in fresh water as different species depending on pH (see graph below). While $Al(OH)^{2+}$, $Al(OH)^{2+}$ and $Al(OH)^{4-}$ are harmless, and not very soluble, Al^{3+} ("aquo-Al"), which is present at low pH values, is exceedingly toxic. So as fresh water systems become acidified, Al becomes the toxic aquo form and acts as a strong biocide. Al is known to be toxic to various invertebrates and plants as well as fish, although the exact mechanisms are not understood in these cases either. The text box on fynbos water chemistry asks why the very low-pH black waters of the fynbos biome are not affected by Al in this way.

BIO-ACCUMULATION

The amount of a particular chemical substance in the body of an organism is seldom directly proportional to the concentration of that substance in the surrounding water. This is because some chemical substances can be taken into the tissues of aquatic organisms, while others cannot. Most obviously, nutrients such as nitrogen and phosphorus are usually present at rather low concentrations in water but, because they are required for growth and reproduction, they are always accumulated in significant quantities by the bodies of living organisms in a process known as bio-accumulation. Certain toxic chemical substances also accumulate in the tissues of living organisms for other reasons. Although an organism may have no specific mechanism for taking up some of these substances, they may be present in food, or may mimic others chemically and therefore be taken up incidentally. If the rate of uptake is equalled by the rate of excretion, or if the molecule is easily degraded, then the total body load will be constant, and probably small. If, on the other hand, a non-degradable toxic substance is present even in very small quantities, then the lower links in the food chain may accumulate small amounts of it in their tissues. It has only recently become clear that plants take up a great variety of substances from the soil or water in which they grow. This process is related to the properties of the chemical concerned and is not (except for uptake of nutrients) an adaptation on the part of the plant. Adeola Abegunde, a PhD student at the University of the Western Cape, has begun to look at the ability of reeds such as *Phragmites* to take up pesticides, with a view to using the reeds as indicators of pesticide pollution.

Herbivores consuming large quantities of plant material will be exposed to a small amount of the substance in every plant they eat and will therefore accumulate far more of the toxin in their tissues than did the individual plants that they consumed (see diagram of a trophic pyramid on page 96). The bulk of the food will be metabolised but, because it does not degrade, the toxin will be retained in the tissues of the herbivore. This process will be repeated at each level of the food chain, with the toxin becoming more and more concentrated until the top carnivores may have accumulated a lethal dose. In other words, the phenomenon of bioaccumulation results in what is known as bioamplification or biomagnification. In this way toxic materials, such as organochlorine pesticides like DDT, and heavy metals like mercury and lead, tend to accumulate through food chains. And what better example of a top carnivore is there than we humans? It is a sobering thought that many of our water-supply reservoirs are situated in areas where bioaccumulation of heavy metals, some radioactive (near coal and gold mines) and of pesticide residues (almost anywhere near agricultural areas, manufacturing plants and storage facilities) is likely.

The concentration of toxins through food chains has been pinpointed as the underlying reason for the extreme reduction in numbers of many predatory animals. The classic book ***Silent Spring,*** written by Rachel Carson in 1962, described for the first time the effects of the bioaccumulation of biocides on animals throughout the food chain. (This should be the most famous, and is probably the most influential, of all natural history books since Charles Darwin's ***On the Origin of Species***.) Furthermore, numerous reports are emerging about a catastrophic decline in the numbers and species of insects in many parts of the world. Some estimate that total insect biomass in places as far apart as Costa Rica and western Europe are declining at a rate of about 1% per annum. At that rate, many species are likely to become extinct long before the end of the 21st century. (For details, see Wagner et al 2021.)

Smithsonian Institution Archives

Rachel Carson. In 1963 Time Magazine considered her to be one of the 100 most influential women of the previous 100 years. She was instrumental in setting up the US Environmental Protection Agency, in having DDT banned in the USA, and in instigating Earth Day.

One of the best-documented examples of bioaccumulation concerns DDT. Widespread use of this chemical in the 1940s, 1950s and 1960s polluted many inland and coastal waters. DDT, which is fat-soluble and therefore lodges in fatty tissues, became concentrated in fish and fish-eating birds, with disastrous results. In the Great Lakes of North America, for example, concentrations increased 500 000-fold from phytoplankton to fish-eating birds. It is thought that high concentrations of DDT were responsible for the decline of the American brown pelican. The eggshells of these birds became lethally fragile due to accumulation of DDT, which caused alterations in calcium metabolism in the mothers' bodies. Although DDT was totally banned in the United States as long ago as 1972, manufacture of the chemical has continued in other countries, although most have also banned its use at home. It is still in common use in parts of Africa today, mostly for control of mosquitoes (and, hence, malaria: see Chapter 8).

Although DDT has had some direct effects on humans, a notorious and more frightening example of biomagnification concerns the population of the Japanese town of Minamata. It all started in 1953 when cats and birds started showing signs of strange behaviour (the 'staggers') and soon died; some also produced offspring with limb defects. In the mid-1950s, humans began developing headaches, ataxia (disorientation), fatigue, and foetal and mental abnormalities. What had happened? Unknown to all but a few people, inorganic mercury salts from a plastics factory had been dumped into a river leading into Minamata Bay. Here they had been incorporated into the sediments, where the highly toxic compound methyl mercury had formed, together with other organomercury compounds. These accumulated through the food chain from benthic and planktonic invertebrates, to small fish and then to large predatory fish, particularly tuna.

The residents of Minamata were largely fisherfolk, specialising in catching tuna, which is at the top of the marine food chain. They, along with their cats, were the victims of the bioaccumulation of mercury, which attacks the central nervous system of vertebrates. (The character of the Mad Hatter in Lewis Carrol's ***Alice in Wonderland*** derives from the fact that hatters often went mad as a result of using mercury salts in the process of making felt for hats.) About 3 500 people died at Minamata, and at least another 15 000 were affected. In 1963, ten years later, the Japanese government acknowledged that something was wrong and stopped the plastics company from dumping the mercury-rich waste into the river. In 1970, the government acknowledged that 46 deaths were due to mercury poisoning. In 1973, the plastics company admitted responsibility and paid some compensation, while off-loading its assets in order to be able to declare bankruptcy. ***Life*** magazine published a photograph of a blind, deaf and dumb teenage Japanese girl, with limbs so twisted it seems impossible that they have not broken, carried in the arms of her weeping mother in a Japanese bathhouse – lasting testimony to the ignorance and greed that have been hallmarks of the twentieth century. It took more than 40 years for some of the victims of the disaster to be compensated.

John Tenniel's famous drawing of the Mad Hatter's tea party from Alice in Wonderland.

SOME IMPORTANT ASPECTS OF HYDROCHEMISTRY

Below we briefly discuss some physical and chemical factors that affect aquatic organisms. It is important to note, though, that any number of the tens of thousands of known chemicals may conceivably be present in water, particularly in aquatic systems that receive industrial effluents. They may occur in undetectably small amounts and may or may not have toxic effects. Others – the so-called major ions – sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), are present in greater or lesser quantities in virtually every natural type of water. Other inorganic substances are also present but usually at concentrations orders of magnitude lower than those of the major ions. These inorganic substances include compounds of nitrogen and phosphorus (the major plant nutrients) and a host of elements present in trace quantities. Many of the heavier elements (sometimes called the 'heavy metals' or the 'trace metals') are extremely toxic but are seldom present at toxic concentrations under normal ambient conditions.

Although several tens of inorganic substances may occur in natural waters, this number is much less than the number (tens of thousands) of organic compounds that may find their way into our rivers and wetlands. Many are the products of the metabolism or decomposition of organisms and most (but not all) are harmless to the biota. Although many organics are not intrinsically toxic, in large quantities (in sewage, for instance) they may encourage the presence of decomposer microbes, which use up oxygen and so make the water unfit for most plants and animals to live in. Certain industrial effluents, on the other hand, may contain numerous individual toxic organics, sometimes in minute quantities.

In the sections below, we first discuss the effects of a few of the many individual physical and chemical factors (some of those that water managers call 'variables of concern'), and then we look briefly at certain kinds of effluents and other pollutants such as agrichemicals and those produced as a result of mining activities.

TEMPERATURE

Physically, less oxygen can dissolve in warm than in cold water, and in salty than in fresh water. Other things being equal, then, the higher the temperature, the less oxygen is available in water (see table below). The rate at which chemical reactions occur increases with increasing temperature, however. Processes such as photosynthesis and respiration are the result of chemical reactions, so the rates of these also increase with increasing temperature. In fact, the rates of biochemical reactions usually double for every rise in temperature of 10°C (conversely, they halve for every 10°C fall in temperature). This quotient, known as the 'Q_{10}' of biological reactions, indicates that temperature profoundly affects the rate at which physiological reactions take place within living tissues. Under conditions of increased temperatures caused by thermal pollution, organisms live at a faster rate and use up more energy. This, in turn, requires more oxygen, even though less oxygen is available in water at higher temperatures. As a result, systems already lacking oxygen (because of organic pollution, for example), may be placed under even greater stress by the combined effects of organic pollution and increased temperature. Conversely, more oxygen can physically dissolve in cool than in warm water. Lowered temperatures nevertheless result in lower metabolic rates which, in turn, reduce the speed at which animals can move but increase the length of time to maturity, the rate at which eggs can be produced, and so on.

Table 7.1 **Concentration of dissolved oxygen (mg/L) at different temperatures and salinities at sea level.**

salinity	0	10	20	35 (seawater)
Temp °C				
0	14.6	12.9	11.4	11.3
5	12.8	11.3	10.3	10.1
10	11.3	10.1	9.0	9.0
15	10.2	9.0	8.1	8.3
20	9.2	7.8	7.4	7.5
25	8.4	7.5	6.7	6.9
30	7.6	6.9	6.2	6.1

Because of the conflicting effects of high and low temperatures, all organisms have an optimal temperature range at which growth and reproduction, and general 'fitness', are greatest. Individuals can often survive outside this optimal range but if they are not able to reproduce successfully, the species will soon cease to exist at sites where temperatures are unsuitable.

Jenny Day

Black tea (left) is transparent (see-through) while tea with milk is turbid or murky.

John P. Sullivan/Wikimedia/CC BY-NC-SA 4.0

Campylomormyrus phantasticus*, a mormyrid fish from the Sanaga River in Cameroon.*

Jenny Day

Jenny Day

Both the Mbashe River in the Eastern Cape (top) and the Darling River in South Australia (bottom) have naturallly turbid water.

Thermal pollution results from the discharge of heated water into aquatic ecosystems by industries or power stations, for instance. Lowered temperatures, on the other hand, may result from stream regulation by dams or the transfer of water from one river basin to another (see Chapter 9), or from alterations in vegetation cover on the banks of streams and wetlands. Because water temperatures usually vary seasonally, constantly warm effluents, despite being chemically 'clean', may have important effects on the animals and plants living within the affected reaches.

Temperature, or seasonal changes in temperature, act as cues, alerting many animals (and plants, too) that the time has arrived to lay eggs, or to emerge, or to form cysts, or to change diet, or to migrate, or to produce flowers or to set seed. This means that changes in the natural temperature regime may profoundly disrupt normal annual and seasonal cycles, which explains some of the growing concern by ecologists about climate change. Those animals with relatively short lifecycles (say a few weeks or months) will grow more quickly, for instance. A moment's thought will lead you to the significance of this: if an insect normally grows from egg to adult in sixteen weeks, for example, it may take only eight (or ten, or twelve…) weeks at a higher temperature for the adult to leave the water as a flying insect. The adult may now not be able to find the appropriate food, or the air temperature may be too low for it to be able to fly far enough to find a mate, and so on (see Chapter 9). Premature development of this sort can thus influence the number of animals contributing to the next generation. Furthermore, temperature can affect food chains. A larval insect may be the favoured food of a species of fish at the time when the fish require a readily available, rich and abundant food source to achieve reproductive maturity. But the insect may have beaten the fish to it, having grown rapidly, reached maturity and disappeared from the river at the very time that the fish would need to feed on it.

Drs Helen Dallas and Nick Rivers-Moore, colleagues in the Freshwater Research Centre in Cape Town, have been measuring temperatures in streams in the Western Cape and KwaZulu-Natal for several years now. Helen is also investigating the effects of elevated temperature on some of the invertebrates and fishes that live in those streams. Many of them are able to survive for short periods at temperatures up to 40ºC, although a few exhibit signs of stress at closer to 30ºC. If you consider that today, temperatures in mountain streams sometimes reach 30ºC or more, you will realise that some species are in real danger of becoming eliminated from parts of their current distribution ranges. (See reference to Helen Dallas's papers on temperature, and Al Gore's ***An inconvenient truth,*** in the reading list).

SUSPENDED SOLIDS, SUSPENSOIDS AND TURBIDITY

Any particles in the water column are called 'suspensoids' and they contribute to what is called 'total suspended solids' (TSS). Because they interfere with the penetration of light into water, suspensoids also contribute to turbidity, which is the milky or murky appearance of water. Suspended solids include tiny particles of silts and clays, living organisms (zooplankton, phytoplankton and bacterioplankton) and dead particulate organic matter, or POM. The size of particles that remain in suspension depends largely on current speed (see Chapter 4). When water moves very slowly, or not at all, most of the particles settle out of suspension and are deposited on the bottoms of rivers, lakes or wetlands. In South Africa, though, as in many arid lands, some of the very finely divided suspensoids are electrically charged clay particles that form a perpetually suspended flocculate. The waters of rivers and wetlands where this happens are permanently turbid (Chapter 3), a very common feature of the ancient land surfaces of southern Africa and Australia. Note, by the way, that the scattering of light (and therefore turbidity) is caused by any suspended matter in water, while the darkening or colouring of water is caused by the absorption of light by dissolved substances. As an example, tea with milk is turbid, while black tea is coloured, but transparent.

When suspended in the water column, suspensoids have both physical and chemical effects on aquatic ecosystems. Firstly, large numbers of small particles suspended in water are visible as turbidity.

Secondly, because light penetration is reduced, less photosynthesis takes place and less plant material is produced, so less food is available to organisms higher in the food chain. If turbidity is severe, predators that search visually for their prey may be unable to find food. A family of African fishes, the Mormyridae (snoutfish or elephant fish), are adapted to living in very turbid waters. They have evolved a method of detecting prey by generating a weak electric field that, when penetrated, tells the fish that prey is around.

Thirdly, suspensoids that settle out may smother and abrade riverine plants and animals, fill up the interstices between rocks, deprive riverine animals of a firm substratum to cling to, and blanket their food and breathing structures. Aquatic ecosystems subject to excessive sedimentation may be dominated by a few species of organism that are best able to cope with these alterations in habitat. The gills of caenid mayflies, for instance, are protected from fine particles by having the first pair modified to form a cover over the posterior pairs.

Fourthly, because of their small sizes, suspensoids may have a considerable surface area, and many of them carry an electrical charge. As a result, a variety of dissolved substances, including phosphate and metal ions, become adsorbed onto the surfaces of the particles. The consequences can be significant in that adsorbed substances may become unavailable. This is an advantage if they are toxic, like heavy metal ions, but a disadvantage if they are valuable molecules like phosphates. Lastly, the particles themselves may settle to the bottom and become part of the sediments. Here, too, their surfaces may be altered by chemical changes such as a decrease in pH or oxygen, resulting in the release of adsorbed molecules. Adsorbed toxins in sediments are essentially unavailable, but mobilisation of the sediments during heavy spates, or as a result of chemical perturbations such as changes in pH, may result in release of toxins from the sediments.

Natural turbidity in rivers often increases with rainfall, as spates wash particles from surface soils or from the hyporheos (see page 125) into the river. When the flow rate returns to normal, most of these suspended particles drop to the riverbed. Erosion of land surfaces by wind and rain is a continuous and historically natural process. Although we do not know the extent of natural turbidity in southern African streams, we do know that practices such as overgrazing, non-contour ploughing and removal of riparian vegetation accelerate the rate of erosion and result in increased quantities of suspensoids landing up in streams. Various other anthropogenic activities have been implicated in the increasing turbidity of streams. Such activities include the release of sewage and industrial discharges into rivers; physical perturbations resulting from the construction of roads, culverts and bridges; air pollution with coal dust and iron oxides from mining activities; and mismanagement of reservoirs. In cases where anthropogenically-derived increases in suspensoids are as infrequent as natural flooding is, they may well be handled by the communities of organisms living in a stream. Continuously high levels of suspensoids, on the other hand, may have serious consequences for the biota of a river. If silt is continuously present in water, the faunal community of the upper reaches of a stream may come to resemble that of a lower river, as described in Chapter 4. If a massive load of TSS occurs as an isolated incident, though, it may kill the animals and their eggs, and may then wash on its way leaving little trace of its presence. The affected stretch of a river may nonetheless remain barren for months or even years, until recruitment from other areas is successful.

Many South African waters are naturally silty, although more than a handful have seen their silt loads increase noticeably as the result of agricultural malpractices. The Orange River was appropriately named. Each year its turbid waters carry to the sea an enormous sediment load eroded from the mountains and foothills of Lesotho, the rich farmlands of the eastern Free State, the poorer country of the Northern Cape, and the Kalahari sand dunes. Of course, the river carried considerably more in the past, for now lying in the path of the Orange River are the great Gariep and Vanderkloof dams, both creating artificial lakes with surface areas greater than 100 km^2. In particular, Gariep Dam, which was designed to store 56×10^9 m^3 of water, acts as a gigantic sediment trap, so much so that allowance has been made for raising the dam wall, and hence the lake level, when the present lake silts up. This will take place within the lifetimes of many of us, since a 1% silt load in the water of the Orange River will add about 120 mm of sediment every year to the lake bottom.

There is no doubt that much of the sediment now covering the floor of Lake Gariep is topsoil lost from the upper Orange River catchment through inappropriate agricultural practices, as witnessed by the slight but persistent turbidity even in the streams draining the high-altitude sponges of its sources in the Drakensberg Mountains. This is not the only case in South Africa, either. It has been estimated that South African dams are losing about 1% of storage capacity to siltation every year.

Apart from accumulating in the sediments, the finest particles carried into these reservoirs often remain in suspension, causing the water to be pale orangy-brown and turbid, reducing the depth to which sunlight can penetrate, and slowly blanketing the bottom in a soft ooze that smothers bottom-dwelling animals and plants. Wind and wave action in the shallow areas of such lakes stir up the sediment, preventing colonisation of the shoreline by large plants and disturbing the spawning grounds of fish, particularly of those like the tilapias (bream: Family Cichlidae), which construct nests on gravelly bottoms. Excessive quantities of suspensoids, like eutrophication, are a cause for serious concern in South Africa and are therefore subject to a fair amount of attention. The scientific branch of DWS, together with the WRC, is presently designing a 5-year programme from 2021 to 2025 to examine methods for dealing with siltation in South African reservoirs.

Total dissolved solids (TDS), conductivity, salinity and salinisation

the total amount of material dissolved in a water sample is commonly measured as total dissolved solids (TDS), as electrical conductivity (EC) or as salinity. TDS represents the total quantity of dissolved material, organic and inorganic, ionised and un-ionised, in a sample of water. It is measured by evaporating a known volume of water and weighing the residue. EC is a measure of the ability of a sample of water to conduct an electrical current, and is therefore a measure of the number of ions (charged particles) in solution. It is measured with a conductivity meter and the units are Siemens per meter (Sm^{-1}), or more commonly millisiemens per meter (mSm^{-1}). Salinity refers to the saltiness of water and for most purposes can be considered to be equivalent to TDS. It was once measured by titration of chloride ions but today is estimated from EC and is a dimensionless number, having no units. There is an excellent article on EC and salinity at https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/ .

AN IMPORTANT NOTE FOR ANALYTICAL AND REPORTING PURPOSES

TDS is a measure of the actual mass of dissolved material in water, while EC is a useful surrogate that measures the concentration of ions in the water. Because EC machines are convenient to use, EC is normally measured and then used to estimate TDS. Most machines that measure EC also provide a read-out as TDS but this is based on a simple linear equation. *The machine does not separately measure both TDS and EC*. Do not, therefore, use both measures in multivariate analyses because the two are completely autocorrelated. See Dallas & Day (2004) for a more detailed explanation of the relationship between TDS, salinity and EC.

In natural aquatic ecosystems, TDS is determined by the degree of weathering and the chemical composition of rocks, and by the relative influences of evaporation and rainfall in the catchment (see page 44). TDS and conductivity are closely correlated for a particular type of water. The ions that form the bulk of TDS are the sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) cations and the chloride (Cl^-), sulphate (SO_4^{2-}), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) anions. These are collectively known as the major ions. Although they are not toxic ***per se*** and are indeed needed in certain quantities by the biota, artificially increased concentrations resulting from mining activities, for instance, can have detrimental effects, as shown by Tally Palmer and her colleagues (Palmer et al 2004). The relative proportions of the monovalent cations Na^+ and K^+ to the divalent cations Ca^{2+} and Mg^{2+} may be of significance for certain members of the biota but little is known about this phenomenon. Very high levels of SO_4^{2-}, usually as a result of atmospheric pollution or acid mine drainage, result in acidification, which we discuss in the section below on pH and alkalinity.

We do not know a great deal about the effects of small increases in TDS on freshwater organisms, although juvenile stages are often more sensitive than adults and increased TDS may be more stressful in upper mountain streams, where the biota is generally adapted to very pure waters, than in the lower reaches of rivers or in wetlands. It has been shown that truly freshwater organisms normally occur only at TDS values less than 3 000 mg/L, a brackish-water biota generally replacing the freshwater one at about this concentration. This may not always be true, though. Some fascinating but unexpected results were obtained by Debbie Tyson, when an Honours student in Zoology at the University of Cape Town, for the Cape mountain stream amphipod, ***Paramelita nigroculus*** (see page 234)**.** Although this amphipod lives in very pure waters where TDS values virtually never exceed 100 mg/L, tolerance tests in the laboratory have shown that it can survive for at least four days at a TDS of about 11 000 mg/L (nearly a third the concentration of seawater) and for at least four weeks at about 8 000 mg/L. We assume that this ability to survive at these remarkably high TDS concentrations reflects the marine origin of the family of amphipods to which ***P. nigroculus*** belongs.

Lani van Vuuren

Acid mine drainage from an abandoned coal mine running into the Brugspruit, a subsidiary of the Olifants River, in Mpumalanga.

SALINISATION

Salinisation (sometimes termed 'mineralisation') refers to an increased concentration in water or soil of naturally occurring mineral ions, particularly those of sodium, chloride and sulphate. Natural fresh waters contain all of these, together with the other major ions. If these waters are subject to evaporation they will of course become saltier because, although the water molecules will enter the gaseous phase and 'disappear' into the atmosphere, the salts are left behind in an ever-concentrating liquid. Usually, however, this effect is small or insignificant, except in saline pans. High concentrations of salts in water may also be caused by a number of other factors like wind-borne sea spray; ground-water stores of 'fossilised' seawater; sea salt stored in rocks; and easily weathered rocks that naturally contain high concentrations of mineral ions (the Malmesbury of the Western Cape are a good example).

Certain human activities increase salinity. Sewage purification, for instance, subjects the water to evaporative concentration, an unfortunate consequence of the recycling of treated effluent, particularly during dry periods. Furthermore, saline industrial and mine effluents can be a costly problem. A good example is the disposal of large effluent loads into the Vaal River, which provides much of the water for Gauteng. Salinity in the river has increased alarmingly, particularly during the past 30 years or so. In the Vaal Dam, for instance, TDS is rising at a rate of 2.5 mg/L every year. The TDS of the Vaal Barrage, another major supply reservoir for Gauteng, increased from less than 200 mg/L in the 1930s, to more than 550 mg/L in the early 1980s. The cost, ultimately to the taxpayer, of lost agricultural land and increased purification of water for industrial and domestic use is staggering. As long ago as 1984 it was estimated that every rise in TDS of 100 mg/L in the Vaal River would cost R78 000 000 per year to combat, while an increase in TDS in the Vaal Barrage to 800 mg/L would cost a total of R140 000 000. DWS and Rand Water currently monitor the Vaal River salinity carefully, ideally maintaining TDS below 600 mg/L.

ACID MINE DRAINAGE (AMD)

Streams in parts of KwaZulu-Natal and the former Transvaal are severely polluted either by effluents from mines or simply by contamination of groundwater affected by mining activities. The acidity of mine effluents may result partly from acids used in the extraction of metals from ore, but it occurs mostly because mineral ores and coal contain large amounts of sulphur which, when oxidised, forms sulphuric acid. As long ago as 1958, Arthur Harrison studied acid pollution from mines in the former Transvaal, concluding that such pollution tended to mimic conditions similar to those found in peat bogs, which are naturally rich in humic acids. In fact, conditions in streams receiving acid mine drainage are vastly more acid than in any peat bog. Values as low as 2.9 (as acid as vinegar) have been recorded in the polluted headwaters of the Olifants and Limpopo rivers, where natural pH values are usually round about 7.5. Virtually no organisms survive at such extremely low pH values but at a pH of 3.7 and more, Arthur found that the streams supported large numbers of individuals of a few specialised acidophilic (acid-loving) species such as the moss ***Sphagnum truncatum*** (the major inhabitant of peat bogs), the diatom ***Frustulia rhomboides*** and one or two specialist animals including a mite (***Hydrozetes*** sp.) and a chironomid midge, ***Polypedilum anale***. Similar studies carried out on acid-polluted sources of tributaries of the Vaal River showed that recovery commenced some 16 km from the source of the pollution, as indicated by the appearance of species of the common rooted water weed ***Potamogeton***, an organism indicative of neutral pH conditions.

Nature of Scotland

Peat mosses: two species of Sphagnum.

When he wrote his paper more than 60 years ago, Harrison is unlikely to have had any idea as to just how significant a threat acid pollution would become. Today, acid mine drainage (AMD) on the Reef is probably the greatest threat to water quality in South Africa: a ticking time-bomb that could explode at any time. While any activity that exposes sulphur-containing rocks can cause AMD, the area of concern in this case is the gold-mining region of the highveld. As long as the mines were active, water was continuously pumped out in order to keep the stopes (rock faces and passages) accessible to the miners. But today, many of the mines have been

Daniel J. Drew / Wikimedia/ CC0 1.0

A species of the tiny acid-loving mite Hydrozetes.

worked out and abandoned, and the pumps switched off. When this happens, groundwater seeps into the abandoned stopes and shafts, coming into contact with the pyrite (FeS_2) in the rocks and oxidising it, producing sulphuric acid. This process can be a simple abiotic one but it is greatly accelerated by the presence of various 'extremophile' bacteria, such as ***Acidithiobacillus ferrooxidans***. The stopes and shafts become filled with this extremely acid water, which overflows and spills out of the mine and eventually reaches nearby wetlands and rivers. No matter where this process occurs it will have an effect. But on the Witwatersrand the problems are exacerbated by several factors. The first is that large parts of Gauteng, including Johannesburg, lie on dolomite ($CaMg(CO_3)_2$), which is very easily dissolved by sulphuric acid. If AMD comes into contact with the dolomite, it might very well cause large parts of central Johannesburg to capsize into an almighty sinkhole. This is not just a horror story: sinkholes are already a common feature of some of the outlying areas of the Reef – Carletonville, for instance. In mines nearly 6 000 m deep, the water is within 900 m of the surface and in other areas it is already overflowing. Secondly, the acid-contaminated water will eventually spill out into whatever watercourse is closest. One of these is the Blesbokspruit, now listed on the Montreux Record as being too badly degraded to maintain its value as a Ramsar wetland. But that is not all, for the Blesbokspruit and other streams eventually drain into the Vaal River, which is a major water-supply resource for much of the Highveld, as well as for the irrigation farmers of the Free State. As an addendum, much of the AMD from the Gauteng mines is significantly radioactive.

Brendan Hols

Acid mine-water in the Krugersdorp Nature Reserve.

Brendan Hols

A facility treating acid mine-water near Krugersdorp.

The Weather Hooligan

A huge sinkhole in Benoni on the East Rand.

Lani van Vuuren

The abandoned Grootvlei mine outside Springs.

Can anything be done about AMD? Yes, it can – but at a price. The most obvious thing would be to resume pumping – but who will pay? Today, a permit to mine normally comes with very stringent requirements not only about the mining process, but also about the processes to be carried out when decommissioning or closing mines. In theory, at any rate, money for shutting down the mine has to be kept aside as a guarantee of good faith. So, as long as the company concerned does indeed still have money in the bank, pumping (or whatever is required) will continue. When most of the gold mines on the reef opened, though, no-one thought far enough ahead to worry about closing down the mine. They had enough excitement opening more and more new ones. But of course, this means that, once again, the problem generated by previous generations has come to haunt the present one. For instance, in 2010 the South African Department of Minerals and Energy (DME) was forced to bail out Grootvlei mine, in Springs, by providing R7.5 million just to keep the pumps pumping for the first three months of the year. Grootvlei was a marginal mine but was responsible for pumping and treating AMD for several mines. It changed ownership several times, apparently not always in an above-board manner, but until 2009 it was operational. When the company Aurora took over, however, mining stopped, wages were not paid to mineworkers, mine infrastructure was dismantled and sold for scrap; and AMD was no longer pumped or treated. After a long period of unsuccessful litigation, a second set of liquidators sued the Aurora directors in a civil suit, resulting in a judgement holding them liable for the non-payment of workers and the destruction of mine infrastructure. But of course, the AMD problem didn't go away, and we South African taxpayers are still coughing up. The whole sorry story, written by Tracey McKay and Milton Milaras, can be found at http://bit.ly/3wJB5Xv

Technical solutions to AMD are available. For instance, it is possible to neutralise the AMD with lime, as is being done in South Africa to some extent – at great cost. It is also possible to use biocides to kill off the acid-producing bacteria, or to employ other suites of bacteria that can reverse the acid-producing activities of ***Acidithiobacillus ferrooxidans*** and its allies. The mine can be sealed off to prevent water from escaping but, of course, this is not feasible where limestone rocks are involved. The acid water can be brought to the surface and treated, sometimes in constructed reed-bed wetlands, although the reeds are eventually killed by the acid water. (Exactly how these systems do the job is not clear but seems to have something to do with properties of the wetland soil and the bacteria it houses.) Finally, it is possible to extract useful elements from the AMD and recycle the water. This last option seems to be very attractive, but feasibility of all options will depend very largely on economic factors. Regardless of the solutions employed, it is likely that AMD on the Reef will be a problem for centuries to come. Keep an eye, too, on the coal mines that cover huge areas of the north-eastern parts of South Africa, for AMD is not confined to gold mining, and coal is becoming unpopular.

What has South Africa been doing about the problematic AMD in Gauteng? According to the ***Mail & Guardian*** (20.06.2021), relatively short-term interventions included the upgrading or constructing of several treatment plants at a cost of R2.6-billion in about 2014. One of those treatment plants treats water from Grootvlei and surrounding mines – at taxpayers' cost, of course. The plants pump water to the surface, aerate and neutralise it and discharge it into the Vaal and Crocodile West river systems, at a cost of about R290 million a year. The water is pretty saline. Do I hear you say "But wait a minute – isn't the Vaal already highly saline?" You are so right, so this solution is hardly ideal. In fact, water has to be released from upstream to dilute the reclaimed water, effectively wasting more water. As part of South Africa's water and sanitation master plan, though, a R10 billion second phase was intended to produce fully treated drinkable water by reverse osmosis desalination, making a "significant contribution" to water supply in the region. Because of financial constraints this plan has been "provisionally deferred".

Lani van Vuuren

Gauteng is littered with abandoned mines and tailings dams, including this gold-mine on the Far West Rand.

About 60% of the salt load entering the Vaal Barrage is produced by only four mines. As Gauteng Province supports some 20% of the total population of South Africa, it is disturbing to see salinisation occurring at such a pace. The effects of salinisation resulting from mining activities are not confined to the Vaal River, however. The Buffalo, Mkuzi, Phongolo, Wasbank, Mfolozi and Thukela rivers also receive saline mine effluents to a greater or lesser extent.

Serious though the effects of industrial effluents on rivers may be, by far the most devastating form of salt pollution, common to many dryland environments of the world, is salinisation resulting from agricultural activities. On a global scale, it has been estimated that, as a result of various agricultural practices, several million hectares of land have become so saline that they can no longer be used for agriculture.

Long-term irrigation, particularly spray-irrigation in dry areas and/or in areas where the rocks or soils have high concentrations of minerals, results in human-induced salinisation of soils and water. The reason that irrigation results in salinisation is fairly simple: some of the irrigation water may sink into the soil, but some of it evaporates before it reaches the soil surface, leaving behind the salts it contained. If this process continues over long periods, especially if the irrigation water was even slightly saline to begin with, salts build up in the soil. In mesic areas, irrigation is often not necessary and, if it is, the salts that accumulate are soon washed into the groundwater and from there into the river and out to sea. In dry areas, however, salts accumulate in the soil during dry periods and are released when rain flushes them out. Thus, rivers here are characterised by increasing concentrations of salts, and pulses of particularly salty water after rain. As one might expect, in regions where the water already has a large salt load because of the nature of the geological formations of the area, the entire process of salinisation is exacerbated.

South Africa is fortunate not to suffer terrestrial salinisation on the scale seen in the Murray River Basin and in the south-west of Australia, though. There, bizarrely, it is the felling of trees that caused the problem. When they were present, the woodlands of large eucalyptus trees transpired enough water to keep the water table below the surface of the ground. For more than a century, and over vast stretches of the southern part of the continent, trees have been felled to make way for pasture, mostly for sheep. Now that the trees have gone, being replaced by pasture grasses whose roots are too shallow to reach the ground water, the water table reaches the surface in low-lying areas. Here the relatively saline groundwater evaporates, leaving salts on the surface. Not only will the soil not support crops in such areas, but the process leads to desertification when the growing plants die. Huge areas of once-productive land now look like snowfields, but the 'snow' is salt. Enormous amounts of money are currently being spent in an attempt to find ways to combat the problem and return the land to productive farming.

Not snow, but salt in salinised soil in South Australia.

Although we in South Africa do not have the particular problem of salinisation resulting from clear-felling of trees, salinisation of rivers is recognised as one of the major threats to South Africa's water resources. Indeed, the water quality of many South African rivers, particularly the Great Berg and Breede rivers in the south-western Cape, and the Sundays and Fish rivers in the Eastern Cape, is rapidly declining as a result of irrigation-induced salinisation. In the Sundays River, for instance, TDS levels exceed 1 000 mg/L for almost half of the time, while an inter-basin transfer of water from the Orange River was designed to dilute the salinising water of the Great Fish River.

pH AND ALKALINITY

The pH of water is a measure of the concentration of hydrogen ions, written as '[H^+]'. (Note that square brackets around a chemical symbol mean 'concentration of'.) Technically, pH is the negative log_{10} of the hydrogen ion activity (equivalent to concentration for most purposes): $log_{10}[H^+]$. So, by definition, as the $[H^+]$ increases, so pH decreases and the solution becomes more acidic (a decrease in one pH unit means a tenfold increase in $[H^+]$); as $[H^+]$ decreases, pH increases and the solution becomes more alkaline. 'Alkalinity' is measured as 'acid neutralising capacity', which in fresh waters is usually due largely to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions.

The pH of natural waters is determined by geological influences and biotic activities. Most fresh waters are relatively well buffered (fluctuations in pH are low) and more or less neutral, with pH values ranging between about 6 and 8. One of the main ways in which pH affects aquatic ecosystems is by determining the chemical species, and thus the availability and the potential toxicity, of many heavy metals and other substances. Note that in the chemical sense 'species' are different ionic forms of an individual element. They have different properties and may differ in toxicity. Aluminium, for example, is highly toxic, but only in very acid waters where the low pH results in the formation of the toxic species known as the aquo-Al^{3+} ion.

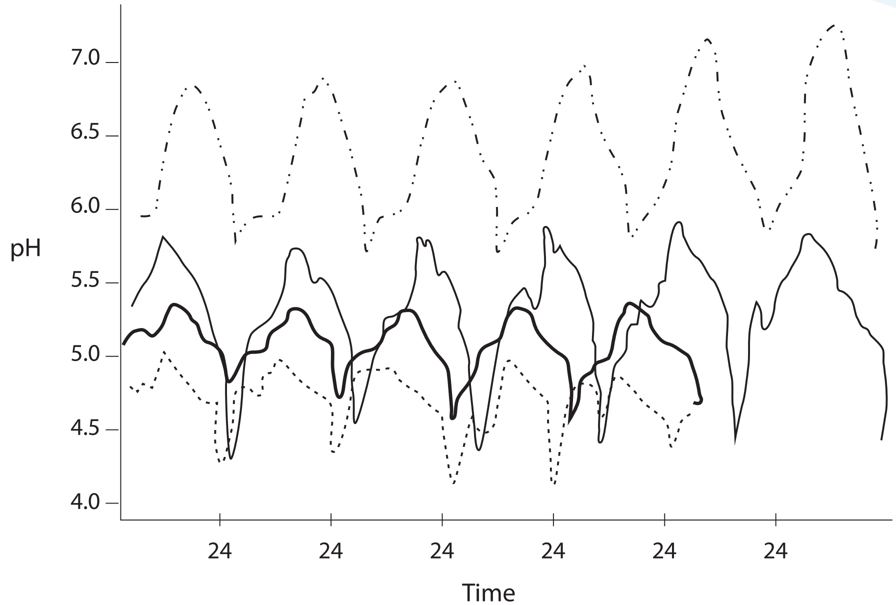
Changing the pH of water changes the concentration of both H^+ and OH^- ions, which in turn affects the ionic balance of aquatic organisms. Relatively small changes in pH are not normally lethal, although growth rates may be impaired and fecundity reduced as a result of increased physiological stress placed on the organism outside its optimal pH range. It seems, though, that the lethal effects of decreased pH are nearly always the result of the mobilisation of toxic substances, particularly the conversion of unavailable and non-toxic aluminium species to the bioavailable and very toxic aquo-Al^{3+} ion.

Human-induced acidification is the result of effluents, such as those from the chemical and pulp-and-paper industries, entering a body of water, while water draining from mines is usually very acidic, and 'acid rain' has been a major source of pollution in industrial parts of the world. See text boxes ***Acid Rain*** on page 236 and ***Acid mine drainage*** on page 247.

DISSOLVED OXYGEN

Dissolved oxygen (DO) is an important abiotic requirement of most aquatic organisms. Under natural conditions DO in water fluctuates diurnally, depending on the relative rates of photosynthesis and respiration. It is usually lowest near dawn, increasing during the day, peaking in the afternoon, and decreasing at night as photosynthesis waxes and wanes. The amount of oxygen that can be dissolved in water depends on the rate of aeration from the atmosphere, temperature, air pressure and salinity (see table on page 240), while the actual amount in a given body of water depends on the relative rates of respiration by all organisms and of photosynthesis by plants. Oxygen levels are naturally low where organic matter accumulates, because aerobic decomposer microorganisms need oxygen. Certain oxygen-consuming chemical effluents reduce oxygen levels in water, but the most common anthropogenic causes of low oxygen levels are organically rich effluents such as raw sewage, and eutrophication.

The extent to which an organism is affected by low concentrations of dissolved oxygen is determined by its dependence on water as a medium. Fish are particularly susceptible, as are larvae of stoneflies, caddisflies and mayflies, which respire with gills or by direct cuticular exchange. Very low concentrations of dissolved oxygen are lethal to aerobic (oxygen-requiring) organisms, while relatively low concentrations may cause changes in behaviour, blood chemistry, growth rate and food intake. The commonest cause of low oxygen concentrations in water is decomposition of organic matter by aerobic bacteria. This extent of this process can be measured as Biological Oxygen Demand (BOD). A sample of water is incubated at a particular temperature (usually 20°C) for a given length of time (usually 5 days). The difference in oxygen concentration before and after incubation is proportional to the amount of biological (usually bacterial) activity. Note that rapid changes in DO, pH, TDS and so on are often far more damaging to organisms than slow, steady changes. Inhabitants of rivers and wetlands are physiologically adapted to slow seasonal changes, but organisms are often unable to cope with rapid changes outside the normal range to which they have become adapted over generations.



Diel variation in pH at various sites in the south-western Cape, reflecting differences between sites, and the effect of photosynthesis on pH (from Dallas and Day, 2004).

NUTRIENTS AND EUTROPHICATION

Various elements, including carbon, oxygen, hydrogen, sulphur, potassium, nitrogen and phosphorus, are required for normal growth and reproduction in plants. Nitrogen and phosphorus are the most common ***limiting*** nutrients, however, in that they are implicated in excessive plant growth resulting from nutrient enrichment (i.e. eutrophication) of aquatic systems. Most nutrients are not toxic to aquatic organisms, even in relatively high concentrations. Exceptions include nitrite ions (NO_2^-), as well as ammonium ions (NH_4^+), which become converted to the highly toxic un-ionised ammonia (NH_3) at pH values >8. At high concentrations, nitrate (NO_3^-) is toxic to vertebrates, particularly infants, whose haemoglobin becomes disabled. When present in aquatic systems in high concentrations, on the other hand, nutrients may significantly alter the structure and functioning of biotic communities because they stimulate plant growth, which in turn affects all the other components of the ecosystem. The quantity of nutrients dissolved naturally in water depends on various characteristics of climate and catchment, but the actual concentrations may be significantly modified by the activities of the biota. See brief descriptions of biogeochemical cycles of C, N and P in chapter 3.

Nitrogen occurs abundantly in nature and is an essential constituent of proteins and nucleic acids. In water, it usually occurs in the form of nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) ions, and as a wide variety of nitrogen-containing organic compounds. Nitrate is seldom abundant in natural surface waters because it is incorporated into cells or is chemically reduced by microbes and converted into atmospheric nitrogen. The global nitrogen cycle is described and illustrated in Chapter 3. Nitrite is an intermediate in the interconversion of ammonia and nitrate, and is toxic to aquatic organisms even at low concentrations. Ammonia occurs in low concentrations in natural waters and is also a common pollutant associated with sewage and industrial effluents. It can occur either in the free un-ionised form (NH_3) or as ammonium ions (NH_4^+). In its un-ionised form, ammonia is

PHOSPHORUS - NEARLY AS PRECIOUS AS WATER?

Phosphorus (P) is a remarkable element. It is soft and waxy and glows in the dark. It is so highly reactive that it will undergo spontaneous combustion when in contact with air, so pure P has to be stored in mineral oil. I remember my science teacher demonstrating its flammability by floating a piece the size of a small pea on water. It started to burn and whizzed dementedly around on the surface of the water until it fizzled out, having dissolved to form phosphoric acid. No doubt Health and Safety won't allow schools to possess the stuff today, let alone demonstrate its properties – which is a pity, because I think that tiny piece of P was one of the main reasons for me wanting to study chemistry all those years ago.

Phosphorus burning in oxygen.

The element phosphorus was discovered in the seventeenth century by alchemists trying to turn 'base metals' into gold. Using huge quantities of human urine (which contains retrievable quantities of P), they produced minute amounts of a granular substance that glowed in the dark. They would have preferred it to be gold, but they soon found that this material was more than just a curiosity, because of its propensity to burn. Eventually alchemists realised that bone also contains phosphorus, so a greater supply became available. Its first use was in the manufacture of matches.

Phosphorus is crucial for living things. It forms part of DNA and RNA; it is involved in the structure and functioning of cell membranes; in the form of ATP (adenosine triphosphate) it is the molecule responsible for cellular energy transfer; and in vertebrates it is a structural component of bones and teeth. Many soils are deficient in P, particularly if they have been farmed for many years, and so P-containing fertilisers have to be added to the soil if farms are to be productive. A reason for the slash-and-burn agriculture in tropical forests is that the soils contain very little P, so after a couple of years the soils become depleted and unable to support crops. The new farmers therefore move on to slash and burn another part of the forest. The abandoned farms may never recover because the P in them was removed with the crops.

Before suitable phosphate-bearing rocks were identified and used to produce fertilisers, guano was the greatest source of P. Seabird excreta build up on many offshore islands around the world, and a few enterpreneurs became fabulously wealthy by hiring labourers to scrape the guano ('white gold') off the rocks and selling it to farmers. In the nineteenth century 200 000 tons of guano, which had accumulated over thousands of years, were removed from the 'guano islands' off the west coast of southern Africa, to the detriment of the seabirds of the area. Penguins were particularly affected because they make their burrows in guano, and in its absence the birds were forced to nest in exposed areas under rocks.

Biogeochemical cycling of phosphorus is rather different from cycling of many other substances such as nitrogen or carbon. There are two main reasons for this. Firstly, P occurs in gaseous form only at very high temperatures, so it is does not circulate in the atmosphere to any extent, except in dust particles. Secondly, phosphates are very 'sticky', adsorbing onto many different kinds of compounds and particles, so it is seldom easily available in dissolved form. As a result, while the turnover times of N and C are commonly of the order of days to months, P turns over at a rate of 20 000 to 100 000 years. The biogeochemical cycle of phosphorus is illustrated and discussed in Chapter 3.

Essentially, then, we can think of P 'cycling' on land or in rivers as a slow loss to the bottom of the sea. Here it becomes incorporated into the sediments and ultimately into rocks. The only way in which that P is returned to the land is by immensely slow uplift of land from the bottom of the ocean, or by volcanoes, generated by tectonic activity. And here's the problem: we have been mining P-bearing rocks for fertiliser for decades now, and the supply is running low. We need to interrupt that pathway, retrieving P from sewage, for instance.

Isla Roca Partida, Mexico, is entirely covered by a thick layer of guano.

According to Phosphorus Futures (2021), in 2015 the US Geological Survey reported that "Morocco, China, Algeria, Syria & South Africa together control 88% of the world's phosphate. … The US used to be the world's largest producer, consumer, importer and exporter, yet now has approximately 20 years of reserves remaining, while China has recently imposed a 135% export tariff to secure domestic fertiliser supply, which has halted most exports." Demand for P is said to be growing at twice the rate that the human population is expanding. Most is used for fertilisers but it is also converted to organophosphorus compounds for use in detergents, pesticides and nerve agents. Given the expanding human population, we need to feed more and more people every year and much of the "green revolution" relies on providing crops with significant quantities of fertiliser, particularly P. Jeremy Grantham, writing in Nature in November 2012, considers that use of the element "must be drastically reduced in the next 20 to 40 years or we will begin to starve". Others argue that since phosphorus comprises about 0.1% by mass of the average rock, the problem in future will be finding sufficiently concentrated forms of P for efficient agriculture. Sea-bed mining is a possibility. Furthermore, about 80% of P is lost "from mine to field to fork", so it should be possible to use it more conservatively.

For more detail on the use and exploitation of natural resources chapter 11.

very toxic but it forms a significant proportion of the total NH_4^++NH_3 only when the pH is above 8 or so. Nitrogen concentrations in water are usually reported as the dissolved forms NO_3^-, NO_2^- and NH_4^+ and Total Nitrogen (often called "Kjeldahl Nitrogen"), which is assayed by digesting the sample to release the nitrogen from organic and particulate material in the water.

Phosphorus is required in numerous life processes and is an integral part of DNA. In nature, inorganic phosphorus occurs almost entirely as the soluble phosphate ion (PO_4^{3-}). Immediately available Soluble Reactive Phosphorus (SRP) is seldom found in quantity in non-polluted water because it is taken up by plants, or is adsorbed onto suspensoids, or bonded to ions such as iron, aluminium, calcium and a variety of organic compounds. Phosphorus concentrations in water are usually reported as dissolved SRP and Total Phosphorus, which is assayed by digesting the sample to release organic and particle-bound P. The global phosphorus cycle is described and illustrated in Chapter 3. See text box on page 254 for more details about P.

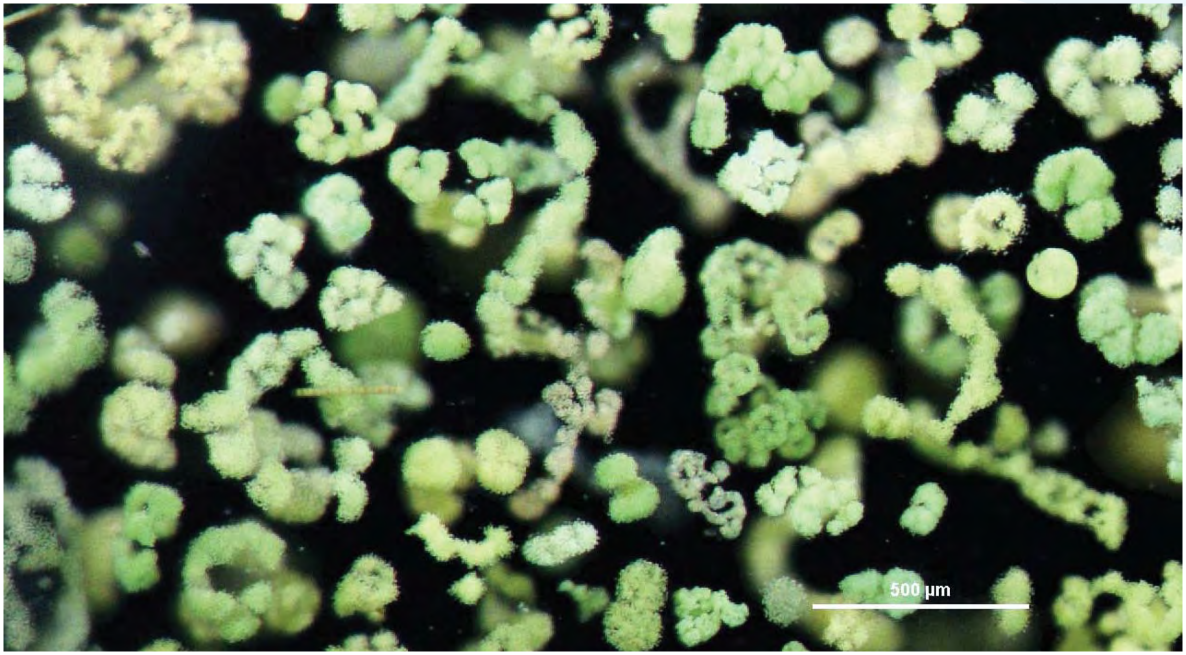
Eutrophication

Large quantities of nutrients may enter aquatic ecosystems in effluents from industry but by far the greatest proportion of nutrients comes from sewage and agricultural activities, including intensive animal culture like dairy farming. As mentioned in Chapter 2, wastewater treatment works are able to mineralise organic waste, converting it into its basic components. The carbon dioxide and water are easily disposed of, but the nutrients are not. Except in the most sophisticated (i.e. tertiary-level) treatment plants, purified sewage effluent is very rich in nutrients, especially phosphorus. We should note, too, that even in advanced treatment plants, volumes may be so large that the low-nutrient effluents still represent a formidable load of N and P. Farmers, on the other hand, fertilise their lands with nutrients (frequently in excess) in order to increase crop yields, but nutrients are becoming more expensive as demand increases. Smart farmers therefore use sophisticated means of fertilizing with optimal quantities of nutrients, sometimes using sophisticated apps on fertilizing machines to deliver appropriate quantities of nutrients to each part of a field. Since only a proportion of nutrients applied to agricultual crops is taken up by plants or retained in the soil, the rest leaching into groundwater and from there into rivers or lakes, the less that is applied the better for both the farmer and the river.

Nutrients from fertilisers are as effective at increasing plant production in water as they are on land (usually more so), stimulating the development of blooms of algae or floating invasive plants or expanding stands of naturally-occurring rooted plants, any of which may reach pest proportions. The sight of a river, reservoir or wetland with water that looks like pea soup, or one clogged from bank to bank with aquatic plants, usually alien, is familiar throughout the country (see https://bit.ly/3gTwKfP). Let us repeat what we have said before, though: eutrophication simply means 'good feeding' and can be a completely natural process in both lakes and rivers as they mature. It is only when aquatic systems are severely perturbed by unnaturally high nutrient loads of anthropogenic origin that the species composition of biological communities is altered. Below fish farms on rocky-bed streams, for instance, the rocks may become coated with luxuriant growths of algae, which outcompete the normal periphyton and thus remove the food-supply for epilithon-feeders, but provide a good living for alga-eating snails, which might otherwise not be present at all.

Human-induced ('cultural') eutrophication is a particularly insidious form of pollution because nutrient accumulation is invisible and the early consequences are often seen as advantageous because moderate eutrophication leads to increased production of fish, for example. Eutrophication is likely to occur in reservoirs, in endorheic (inward-draining) wetlands and in reservoirs, particularly if their catchments drain urban areas or land under intensive cultivation. As long ago as 1976, phosphorus in surface runoff from 'hardened' urban areas was estimated to vary between 540 t/y in Johannesburg and 155 t/y in Cape Town.

Classic examples of impoundments made eutrophic mostly by urban influences include Hartbeespoort and Roodeplaat in Gauteng, and lakes Chivero and Manyame near Harare in Zimbabwe. Continual enrichment by nitrogen and phosphorus favours a few particularly fast-growing species of animals and plants, to the detriment of others: the naturally wide variety of species is reduced in favour of a few exploiters. Unfortunately for us, many of the species that do 'cash in' on eutrophic conditions can become pests (see Chapter 8). The situation is akin to that in your garden where weeds run riot, given half a chance, especially if the soil is well fertilised. One



Colonies of Microcystis aeruginosa *cells; each cell is about 5 µm in diameter.*

such 'nuisance' organism is the planktonic cyanobacterium ***Microcystis aeruginosa***, a blue-green that blooms in enriched waters such as Zeekoevlei on the Cape Flats and Hartbeespoort Dam, eventually forming thick, bright green, sometimes toxic, floating scums (***Microcystis*** in Zeekoevlei is discussed in detail in Chapter 6.)

Cyanobacterial and algal blooms are economically expensive in several ways. The algae may die, wash up on the shores and form evil-smelling masses of decaying material, detracting from the recreational value of amenities. When potable water supplies are involved, costly and complex filtration and purification plants are required. Not only are the algae toxic to many organisms, but their decaying remains use up large amounts of oxygen in the water. On occasion, fish are asphyxiated when microbial decomposition of large quantities of dying algae uses up the available oxygen in the water. Far more alarming is the fact that certain species of cyanobacteria may become toxic (see Chapter 6). According to a report recently published in Britain by Ian Stewart and colleagues, risks are high for people participating in water-contact sports such as windsurfing. Other pest species exploiting eutrophic conditions include infamous weeds such as the water hyacinth ***Eichhornia crassipes*** (now ***Pontederia crassipes)*** and Kariba weed, ***Salvinia molesta*** (see Chapter 8).

TRACE ELEMENTS AND HEAVY METALS

The terms 'trace elements' and 'heavy metals' are almost interchangeable. The term 'heavy metals' refers to all metals with atomic weights greater than that of calcium (40), and so includes metals like iron, manganese, zinc, mercury and lead. The 'trace elements' include all elements, both metallic and non-metallic, that occur in small (trace) quantities in the natural environment. They include light elements like beryllium and boron, and also the rarer heavy metals. Trace elements occur in all natural waters, sometimes in minute quantities, because they are products of geological weathering.

Some trace elements are harmless and some are actually essential for biological systems. Humans, for instance, need iron for haemoglobin, while copper, zinc, molybdenum, manganese, selenium, strontium and chromium are used in various metabolic processes and cobalt is a component of vitamin B12, otherwise known as cobalamin. Plants also use boron, nickel and vanadium in metabolic processes, and magnesium forms an integral part of the chlorophyll molecule, as iron does of haemoglobin. Many of these trace elements are required only in minute quantities and are toxic at higher concentrations. It is difficult to ascertain the actual effects of trace metals in water, though, because their toxicity is controlled by a number of chemical and physical factors, particularly the chemical species of the metal, the presence of other metals and organic compounds, the flow rate and volume of water in which they occur, the nature of the sediments, the temperature, the pH and the salinity. As an example, aluminium is one of the most toxic of the trace metals, and yet we use aluminium cooking pots, and our drinking water is often purified with alum (aluminium sulphate) in water-treatment plants. It is only when the pH drops to less than about 5 that aluminium becomes available as the highly toxic and soluble aquo-aluminium ion, Al^{3+}. The overall consequences of trace metal contamination of aquatic ecosystems is a reduction in biological species richness and diversity and a change in species composition because of the selective elimination of less tolerant species. Various heavy metals regularly find their ways into aquatic environments as a result of human activities. A highly publicised local case was the poisoning with mercury and other heavy metals of workers at the Thor Chemicals plant in KwaZulu-Natal in the early 1990s. Details of this horrible case can be seen at the related link in the reading list.

As well as mercury, aluminium and beryllium, other toxic trace metals include cadmium, lead, nickel, copper, chromium, selenium and zinc. Antimony and arsenic, although not metals, are also highly toxic trace elements. Such pollutants cause all sorts of harm to vertebrates: mercury and lead irreversibly damage the central nervous system; nickel and beryllium damage the lungs; and cadmium damages the kidneys and liver. Although we know that these elements are highly toxic to other organisms too, we have very few details about their effects on organisms other than vertebrates.

Mines are the most obvious sources of trace metals in the environment, not least because the procedures used for extracting useful metals often also release others in soluble form. Pollution by trace elements also stems from heavy industries, including those that manufacture cars and other products (refrigerators, washing machines, etc.) that contain metals as structural elements, and from industries using very small quantities of metals in the manufacture of objects such as batteries and electronic goods..

The trouble with metals is that, being elements, they cannot be broken down and so they are very persistent pollutants. In particular, many of them form charged ions in water and may become adsorbed onto suspended particles. If the particles settle out, the adsorbed metals are incorporated into the sediments, where they may remain indefinitely. In a sense this is advantageous, because in sediments they become immobilised, but if the sediments are disturbed, or if chemical conditions alter, then the metal ions may be remobilised in toxic form. Furthermore, they can become concentrated up the food chain and eventually reach levels at which they are toxic to the organisms containing them, or to carnivores such as humans (see page 238 on bioaccumulation). The disposal of toxic 'hazardous wastes' is expensive, so it is not surprising to find that a good deal of illegal discharge or dumping of toxin-containing waste occurs.

Extraordinarily, it is not only illegal and dangerous dumping of toxic waste that occurs. Even well-meaning but ignorant guardians of the environment have occasionally misinterpreted the significance of trace metals in aquatic ecosystems to the point of causing serious pollution. Some years ago, a number of (then) greatly endangered bontebok were translocated to the Cape Point Nature Reserve. Conservators soon noticed that the animals were beginning to suffer from swayback, a disease in mammals resulting from an absence of copper in their diets. A suggested solution was to spray copper sulphate all over the reserve, which contains some unique, naturally acidic, vleis as well as an impressive number of endemic fynbos plants. Copper is highly toxic to most aquatic organisms and to many fynbos species, some of which occur in the reserve and nowhere else. Fortunately, the plan was not put into operation. Copper tubing was, however, dumped into the vleis. Ironically, one of the vleis in the reserve, Sirkelsvlei, had been used as a shooting range during World War II, and when the vlei dried out on one occasion, truckloads of spent brass shell cases (containing copper) were recovered from it. The ultimate irony, though, arises from an interesting feature (which no-one knew at the time) of the humic compounds that impart a dark brown colour to the acid vleis of the reserve. These substances complex with, and precipitate out, virtually all of the copper, so that it was not available either to kill the water ***goggas***, or to provide enough copper for the deprived bontebok. Recent enquiries to SanParks Rangers at Cape Point show, however, that no trace elements of any kind are currently provided for the bontebok at Cape Point, and they show no trace of any deficiencies: an interesting mystery. Maybe the original bontebok taken to the Park suffered Cu deficiency acquired in their previous home? Maybe there is enough Cu in soil and/or water at Cape Point as a result of the ordnance left there after the war?

Jenny Day

A healthy-looking bontebok in the de Hoop Nature Reserve.

POLLUTION BY ORGANIC COMPOUNDS

Organic compounds by definition contain carbon. Many of them are the normal compounds (proteins, fats, carbohydrates, nucleic acids and so on) produced by living organisms and are not toxic. Organics can be of concern in two very different ways, though. Some are indeed highly toxic (see below), while others form the bulk of 'organic waste' in sewage. Dissolved and particulate organic matter (DOM and POM) are derived from biological activity, including the decomposition of dead material. In rivers, POM is an important source of food for benthic detritivores and decomposer bacteria (see Chapter 4). Some of these bacteria are aerobes (requiring oxygen) and, when present in large quantities, can consume all the available oxygen, making the water anoxic. Enrichment by organic matter from sewage and sewage effluents is probably the most common and the most extensively documented type of pollution in rivers. Nonetheless, most organic material in sewage is not directly toxic to aquatic life. Because it results in oxygen depletion, though, it may significantly alter community structure by encouraging the survival of very hardy species while eliminating those sensitive to anoxia.

EXPLAINING SOME TERMS

oxic	-	with oxygen
anoxic	-	without oxygen
aerobic	-	(organisms or processes) using oxygen
anaerobic	-	(organisms or processes) not using oxygen

The main sources of organic waste are raw sewage, incompletely processed sewage effluents, food processing plants, animal feedlots and abattoirs. We have already mentioned that decomposing organic matter is 'oxygen-demanding', in that many decomposer microbes use up oxygen. But organic waste usually consists mostly of particulate matter, resulting also in increases in suspended (and ultimately in deposited) solids and also in turbidity. Mineralisation of nutrients from organic compounds increases the potential for eutrophication of waters receiving sewage effluents, even if they are purified. Details of carbon cycling and sewage treatment are to be found on page 98.

Effluents from fish farms and other industries such as paper and beer manufacturing, threaten some of South Africa's more pristine streams. In the south-western Cape, trout farms are major sources of disturbance in some mountain streams. Generally, water is taken into the farm from the stream, passed through the ponds, and released a little further downstream. This abstraction of water sometimes reduces the flow in the stream to a trickle in summer, but the most important effect relates to the fact that the effluent is usually very rich in uneaten food, faeces and urine, fish scales, and so on, all of which form a thick organic 'gloop' that settles to the bed of the river, especially when the flow is low. Communities of benthic invertebrates in the river are as much affected by this sort of organic pollution as they are by any other. A simple solution would be to require the polluters to draw the water for their own activities from ***below*** their outfall: karma of a kind.

TOXIC ORGANIC SUBSTANCES

The most toxic organic compounds known are produced by a variety of organisms from bacteria (botulinum toxin, for instance, from the bacterium *Clostridium botulinum*) and phytoplankton (such as microcystin from a number of Cyanobacteria) to plants (such as ricin from castor oil beans) and animals. Interestingly, the exceedingly toxic tetrodotoxin - 'Botox' – found in some newts and fishes is actually produced by symbiotic bacteria and not by the animals themselves. Substances like these are very seldom found free in nature in toxic quantities (toxic cyanobacterial blooms are a result of human-induced eutrophication: see Chapter 6.) In contrast, many exceedingly toxic synthetic organic compounds enter aquatic ecosystems in industrial or agricultural effluents and may persist in the environment for many years. Some of these chemicals are produced specifically as biocides (and are thus particularly effective as environmental toxins), while others are only incidentally toxic. Many of these compounds occur in extremely low concentrations. In the following pages we talk about persistent organic pollutants (POPs), agrichemicals and CECs – chemicals of emerging concern.

Alexxx79 / Wikimedia / CC BY-SA 3.0

Leaves and fruit of Ricinus communis*, the castor oil plant, whose seeds produce one of the deadliest toxins known.*

Chuck Spidell / Wikimedia /CC BY 3.0

Rough-Skinned Newt, one of the sources of tetrodotoxin ('botox').

POPS: PERSISTENT ORGANIC POLLUTANTS

Some organic compounds that are toxic and particularly long-lasting in the environment have earned the nickname 'POPs'. There is little amusing about them, though. In fact, they are of such concern that the international Stockholm Convention was set up in 2001 to regulate and discontinue their use. The convention defines POPs as organic compounds that "remain intact in the environment for long periods, become widely distributed geographically, accumulate in the fatty tissue of humans and wildlife, and have adverse effects to human health or to the environment". The introduction to the Convention notes that, "Exposure to POPs can lead to serious health effects including certain cancers, birth defects, dysfunctional immune and reproductive systems, greater susceptibility to disease and even diminished intelligence. Given their long-range transport, no one government acting alone can protect is citizens or its environment from POPs". The Convention "requires Parties to take measures to eliminate or reduce the release of POPs into the environment". And what are the POPs? The original twelve include pesticides like lindane, aldrin and DDT, industrial chemicals (e.g. PCBs: polychlorinated biphenyls) and industrial byproducts such as the dioxins. Note that, while DDT is on the list, its use is permitted under specific exceptions such as mosquito control in malaria-prone areas, including KwaZulu-Natal in South Africa (see information on malaria starting on page 301). A further twenty or so substances, including flame retardants as well as other pesticides and byproducts, have since been added to the list and more are waiting in the wings, as it were. Arising from his PhD studies, Cornelius Rimayi recently published a paper on POPs in Hartbeespoort

Dam, showing the several were detected at most of the sites sampled.

Pesticides

Pesticides are a category of substances known as biocides – 'life-killers' – which are toxic chemicals produced specifically to kill pest organisms, although any lethal toxin is in effect a biocide. Common categories of biocides include herbicides, insecticides and fungicides, all of which may be of concern in aquatic ecosystems. They may reach aquatic environments in various ways: directly, when aquatic pests like bilharzia snails are being controlled; in industrial effluents and sewage; by leaching and runoff from soil; and by deposition of aerosols and particulates. Chemicals used in agriculture are discussed next.

Agrichemicals

Farmers use a very wide range of chemicals, including biocides, on their farms. Many of the other substances used on the farm are not intentionally toxic although most are detrimental to the natural environment, particularly aquatic ecosystems, and to non-target animals, including humans. The major types of agrichemical are fertilisers, pesticides, antibiotics and hormones. We have already discussed the effects of fertilisers (nutrients) on aquatic ecosystems. Now let us consider the biocides. (See page 265 for a brief discussion on antibiotics and hormones.)

Biocides have been developed to control everything from weeds to fungi and from roundworms and mites to insects and molluscs. Here we discuss insecticides in particular because they are the most widely used of the biocides and are arguably the most detrimental to non-target systems. Insecticides (often referred to as 'pesticides', although pesticides technically also include things like snail-killing molluscicides) vary considerably in toxicity and in their modes of action. Generally, organochlorine insecticides like DDT and dieldrin are the most hazardous for the natural environment, and for humans, because they are persistent, are largely insoluble in water, are photostable (i.e. they are not broken down by light) and are highly toxic to many organisms, including humans. Further, they tend to accumulate in living organisms (many are fat-soluble) and thus become biomagnified through food chains. Because biocides are so varied in nature, and are toxic in minute quantities, detection and quantification of these compounds in aquatic systems is complex and expensive. Indeed, the concentrations in the water column of some biocides may be way below detection limits, but they may still accumulate in sediments and in the biota. Furthermore, since they are usually complex organic compounds, many pesticides break down into smaller molecules, some of which are at least as toxic as the parent compound; some of these may also persist in the environment for long periods. (See text box on endocrine disrupting chemicals.)

In theory, the use of pesticides is strictly controlled in South Africa, with very narrow limits set for the types and quantities that may be used for any particular purpose. In practice, however, many users – both the farmer and the labourer who actually applies the pesticide – tend to be lax about the storage, preparation and use of pesticides. In her Master's thesis of 2018, Meryl Patience showed that over a five-year period about 20 pesticide-related deaths were recorded per year at a single Cape Town mortuary. Data are still scanty, though. Razwiedani and Rautenbach (2017), looking at organophosphate poisoning in Tshwane, concluding that regulatory controls on pesticide use in South Africa are inadequate and that this is probably related to the fact that there is too little data to trigger a response by regulators, even though 'Agricultural or stock remedy poisoning' is a Category 2 notifiable medical condition.

Worldwide, in 2004, the World Health Organization estimated that there were about three million cases of severe pesticide poisoning per year, with about 250 000 deaths. Tragically, more than half of these may well have been suicides, many of them in less developed countries where pesticides are probably the cheapest and most accessible poisons.

In addition, because it is difficult and costly to analyse water for pesticide residues (and thereby to prove illegal use), there are few effective controls on their use other than the rather unpredictable responsibility of the user. Indeed, we have seen operators using pesticides on apple farms, spraying clouds of noxious chemicals into the air regardless of the wind direction and without recourse to respirators or protective clothing. Pesticides may also be stored irresponsibly and are often kept way past their 'sell-by' dates. On occasion, the use of pesticides has become extremely contentious in South Africa, with furious arguments centring on the intensive use of pesticides against swarms of locust hoppers and also against huge flocks of red-billed queleas, birds with appetites as awesome

USDA Forest Service

Helicopter spraying insecticide onto spruce trees to control the Western Spruce budworm in the USA (1977).

Radium Spray Company

Who would have thought that the highly radioactive element radium would be used as a general-purpose spray? This is a genuine advert from 1909.

as those of locusts. In our view, one set of ills (consumption of crops by animals competing with humans for food grown in monoculture) seldom justifies another (indiscriminate elimination of insects and birds in an attempt to control one species). As we mention below, 'organic' farmers often expect to lose about 10% of a crop to pests as an alternative to using pesticides.

It seems that pesticides are seldom deliberately dumped into water in this country. The residues that do occur in our rivers usually arrive there either by way of leaching ***via*** groundwater, from direct surface runoff, or by wind-blown dust. Insecticides are specifically designed to kill insects, however, so they will obviously cause considerable mortality in the insect-dominated communities of natural streams. Elegant PhD studies on pesticides in the south-western Cape are James Dabrowski's work on the Lourens River, and Silke Bollmohr's on the estuaries of the Eerste and Rooiels rivers. Both were students at UCT.

Pesticides are used extensively and sometimes indiscriminately in more tropical rivers to control organisms like snails, blackflies and mosquitoes, all of which may be vectors of parasitic diseases of humans or stock animals. Sometimes pesticide use is really crucial for human wellbeing. A good example comes from KwaZulu-Natal, where the incidence of malaria mushroomed some years ago. One can sympathise with health officials for using DDT in this instance, because many strains of mosquito in KwaZulu-Natal are resistant to every single insecticide other than DDT. (The mosquitoes in the area are sensitive to DDT ***because*** it had been banned, so they had not been exposed to it for many years. See page 301 for further discussion on mosquitoes and malaria.)

It is hard to argue against the responsible use of pesticides, which can make the difference between a farmer being able to sell a crop for a profit (farmers have to make a living too), and facing a field devastated by some gluttonous insect. Over-use of pesticides is common, though, and residues easily accumulate on fruit and vegetables. Fortunately, the European Union is very fussy about the amount of pesticide residue left on farm products. As a result, South African farmers servicing the European market are careful about which pesticides they use, and how much. Pesticide manufacturers, too, have research teams examining the most effective and least risky ways of using their products.

There is a trend, among people who can afford them, to prefer 'organic' food products. (Where ***did*** that name come from? ***All*** food is organic in that it is made of a combination of organic compounds – compounds containing carbon.) Today, foods are considered to be organic if they have been grown without the use of artificial chemicals such as pesticides, hormones and antibiotics, and have not been genetically modified. Food products can only claim the label 'organic' if they contain no artificial preservatives, sweeteners, colorants and so on. Organic farms tend to use natural fertilisers like manure, but because biocides are not used, farmers accept that there will be a loss of part of the crop (commonly 10%, it seems) to insects and other pests – which explains in part why organic produce is more expensive than regular produce. (I was going to say 'traditional' produce but of course traditional farms didn't use any of these modern artificial chemicals either)

HORMONES AND ANTIBIOTICS USED IN FARMING

Stock farmers administer a variety of hormones to regulate growth and reproduction in farm animals, and antibiotics not only to prevent or treat disease, but also to improve the efficiency with which feed is converted to mass in cattle (although no-one seems to understand exactly why this happens). Hormones are active even in minute quantities, and several are excreted more or less unchanged in the urine. This means that water draining from pastures and feedlots contains active hormones. This water infiltrates into the ground, into groundwater, from there to rivers and wetlands, and ultimately into our taps. Some of the consequences are discussed in the text box on EDCs on page 267.

Antibiotics are biocides whose targets are bacteria. When bacterial populations come into contact with antibiotics, some individual bacteria become resistant if random mutations co-incidentally confer resistance to the antibiotic. Such bacteria are able to thrive even in the presence of the antibiotics, whether in a human body or a waste dump. As a consequence, strains of many pathogenic bacteria that cause human diseases have become resistant to one or more (or sometimes all) antibiotics. Because bacteria have the remarkable ability to exchange genes with each other, the antibiotic resistant genes (ARGs) seem to have found their way around the world and have been found even in Madagascar and the Galapagos Islands. The consequences of the widespread use of antibiotics are likely to be a lot more severe than they seem at first sight. On the one hand, bacterial resistance to antibiotics is again making bacterial diseases as much feared as they were a century ago, when the chances of surviving a bad wound were less than even. Multiple-drug-resistant (MDR) TB (tuberculosis) and ***Staphylococcus*** are common in South Africa, particularly in hospitals – the other places where antibiotics are over-used. Worldwide, antibiotic-resistant infections are expected to claim 10 million human lives by the year 2050.

Several studies have looked at the prevalence of antibiotic resistance in effluent from hospitals in Europe. In a similar study in the Eastern Cape, Folake Fadare and Tony Okoh from Fort Hare found that "… hospital wastewater is laden with potentially pathogenic [multiple-drug-resistant] bacteria with various antibiotic resistance genes." (See citation in Further Reading at the end of the chapter.)

On the other hand, as we have already pointed out, the natural decomposition of organic matter, from dead bodies to leaves and sewage, is dependent on free-living bacteria which, being bacteria, are also destroyed by antibiotics. As yet, nobody seems to have looked at the effect of widespread use of antibiotics on the process of decomposition in the wild. Will this be another example of the Law of Unintended Consequences in action? Or maybe not. A paper published by Chinese biologists in the journal ***PubMed*** shows that ARGs are found in bacteria in kitchen waste. So perhaps this is one good thing about antibiotic resistance: the decomposers on whom we depend to keep our waste under control are able to combat the effects of antibiotics because they carry ARGs. How weird. How fortunate.

The legislative scene with regard to the use of antibiotics in the USA is a reflection in microcosm of the effect of the Donald Trump presidency. In 2014, Barak Obama had issued an Executive Order aimed at combatting antibiotic-resistant bacteria (ARBs). During the Trump presidency, long-term staff of the US Environmental Protection Agency (the EPA) were replaced by (how can I put this nicely?) Trump lackeys, with disastrous consequences. Among many other things, testing of antibiotics was cancelled and in 2019, the ***New York Times*** noted that, "Ignoring warnings from the CDC [Centers for Disease Control] and FDA [the USA Food and Drug Administration], the EPA approved expanded use of streptomycin and oxytetracycline (two antibiotics) for the spraying of citrus crops. The approval allowed for up to 300 tons (650 000 pounds) of streptomycin to be used annually in agriculture, whereas humans in the US currently use 6 tons (14 000 pounds) of the antibiotic each year." Three hundred ***tons***? On ***citrus trees***? Yes. It turns out that a bacterium called ***Candidatus liberibacter*** causes citrus greening, a nasty disease that has devasted citrus orchards in various parts of the USA. The bacteria are transmitted by a tiny bug, the Asian citrus psyllid. In 2021, virtually as the presidency of the USA changed hands, the EPA issued a new directive restricting the use of antibiotics on citrus trees, and authorising the use of aldicarb, an insecticde that is very effective against the psyllid bugs. Aldicarb is highly toxic to humans and wildlife, though. I guess that if you want orange juice for breakfast, you have to choose your poison one way or the other.

CONTAMINANTS OF EMERGING CONCERN (CECS)

As analytical chemists have become adept at measuring extremely low concentrations of organic compounds, we are beginning to realise that many household and personal care products linger in the aquatic environment long after they have been produced and used. Most are not toxic in themselves, but many medicines and hormones are excreted unchanged in urine, ending up in sewage or rivers and wetlands, and being recycled into drinking water. 'Second-hand' medicines have the same effects the second time around, so we may be inadvertently consuming a cocktail of very dilute but active pharmaceutical products in our drinking water. So far, it seems that concentrations of many of these substances are too low to have an effect on humans – with the major exception of hormone mimics (see text box on EDCs). As yet, we have very little information on the effect of these products on aquatic biotas.

Some of the pharmaceuticals identified in purified sewage effluents include hormones such as oestrogen and testosterone; analgesics and anti-inflammatory drugs such as ibuprofen; antiepileptic drugs such as carbamazepine; blood lipid regulators such as clofibrate; and β-blockers such as propranolol. Personal care products (PCPs) include ingredients from cosmetics, shampoos and perfumes, while the newest non-nutritive sweetener, sucralose, is now being found in sewage effluents wherever people can afford to buy sweeteners. It is extremely stable, so it doesn't break down and is even being used in the USA as a marker of treated effluent in the environment. Its environmental effects are poorly known but early indications are that it can affect the physiology of water fleas, the aquatic 'guineapigs' of toxicity labs. Cannabinoids from marihuana, and cocaine and other opioids, are easily tracked in sewage effluents and are able to pinpoint areas where use is high. It has even been shown that in cities on the River Rhine in Germany, cocaine is most commonly found in effluents on Saturdays and Sundays. At least this indicates that users are responsible enough not to pitch up high for work during the week! Links to three excellent reviews on these topics can be found in the reference list at the end of this chapter. They are How & El-Din (2021) on cannabinoids, Cernansky (2017) on sucralose and Liu & Wong (2013) on pharmaceuticals and personal care products (PPCPs).

ENDOCRINE-DISRUPTING COMPOUNDS (EDCS) OR HORMONE MIMICS

Hormones are organic substances that are produced in one part of the body, circulate in the bloodstream, and have various effects on target organs elsewhere in the body. The best-known hormones are testosterone and oestrogen, which are involved in reproduction in vertebrates, although many others affect everything from metabolic rate (thyroid hormones) to the digestion of food (gastrin, secretin and others).

The first hint that chemicals in the environment might have an effect on human reproductive function came from the apparent feminisation of men working in factories producing 'the pill', the main constituent of which is a form of oestrogen. Oestrogen is a pretty robust substance that is not easily broken down and it has long been known that oestrogen excreted by women can pass through WWTWs and land up in aquatic ecosystems. Independently, in the 1990s Louis Guillette from the University of Florida began to notice deformations in the reproductive systems of male alligators living in Florida's swamps. Even earlier, medical doctors had noticed what seemed to be a trend in reducing sperm counts in human males over the previous three or four decades. Today there is evidence of reproductive abnormalities in fish and frogs as well as reptiles. Is there any connection between these disparate but scary facts? The story is a long and complicated one (see Deborah Cadbury's excellent book ***Altering Eden: the feminization of nature***, and Anthea Gore's 2015 review of the topic) but in a nutshell, it seems that many different man-made substances have effects on endocrine systems from ovaries and testes to the prostate and the thyroid glands, as well as affecting the embryonic

A Mississippi alligator.

development of reproductive systems and brain function in humans. These substances include several POPs and numerous other pesticides and their breakdown products. There is even some evidence (see the review mentioned above) that the phyto-oestrogens in soya beans can have an effect on sperm count in men consuming large quantities of soya products.

A bewildering number of man-made substances has been identified as EDCs. At first glance the effects seem to be entirely random, but a careful examination (as in Anthea Gore's volume) shows that certain classes of chemical are mostly responsible. They are

- bisphenol A, a plastics precursor found so widely in the western world that it has been said that "virtually everyone is continuously exposed"; 93% of Americans have it in their urine; some women have it in breast milk;
- phthalates, used mostly as liquid plasticisers and in personal care products;
- atrazine, a herbicide widely used in South Africa and the most widespread herbicide used in the USA (it is persistent and cheap …); the US EPA worries about its effects on aquatic ecosystems;
- polychlorinated biphenyls (PCBs), which are classified as POPs and also sometimes as EDCs because they have effects on the thyroid gland, as well as oestrogenic and anti-androgenic (anti-male) actions;
- DDT and its metabolites, which have been associated with endocrine-related diseases such as testicular, endometrial, pancreatic and breast cancers, and type-2 diabetes.
- per- and polyfluoroalkyl substances (PFAS), used for instance in non-stick cookware and flame-retardants (known as 'forever chemicals' because they break down so slowly)
- Various other substances, such as the elements cadmium and arsenic, are also classified as EDCs because they can interact with parts of the reproductive system.

In a nutshell, EDCs mostly have effects on both male and female reproductive systems, and/or promote obesity and/or diabetes. Some of them seem to alter gene regulation, often via epigenetic actions, to the extent that the effects may even be inter-generational. Epigenetic effects are the result of certain substances turning genes permanently 'on' or 'off', which is why the effects last beyond just a single generation.

It is a frightening thought that, for instance, contamination of a pregnant woman can affect the ovaries of her girl foetuses, whose own sons may be particularly susceptible to testicular cancer.

Endocrine, developmental, and epigenetic disruptions have also been reported in animals other than humans that have been exposed to trace levels of PCBs and other EDCs. Responses may be much more subtle than cancer or death and may, for instance, affect fecundity or lifespan (as it may well do in humans too). The WRC has been running a programme on research into EDCs in South Africa for a number of years.

Understanding the origins, effects and fate, and even the identification and measurement, of many of these substances is currently in its infancy so the extent of the risk posed, particularly to male vertebrates (including humans) is still not clear. It is clear, however, that these substances are potentially very dangerous and need to be carefully monitored. Shanna Swan's book ***Count down*** is a frightening account of EDCs and,in particular, of the well documented decline in human sperm counts over the last 50 years or so.

The Endocrine Society has produced two Scientific Statements about EDCs. The web links are provided in the reference list.

PLASTIC POLLUTION

400 million tons of plastic waste are produced per year. It is now clear that discarded plastics of all kinds are found everywhere on Earth. Minute plastic particles are even being found in Antarctic snow. ***National Geographic*** has an excellent article on plastic pollution in general. Here I focus mostly on microplastics.

NANOPARTICLES AND MICROPLASTICS

We have come across the prefix 'micro-' before in this book. In general usage it means 'very small' and in scientific notation it means 'a millionth'. The prefix 'nano' comes from the Greek nános, meaning dwarf. Used as a prefix, 'nano' indicates a minute quantity – a billionth – as in ***nanogram*** (10^{-9} g, written as ng) or ***nanometre*** (10^{-9} m, written as nm). Nanoparticles, then, are defined as particles smaller than 100 nm (microparticles range between 100 and 1 000 nm). Obviously, there are large quantities of minute particles on Earth and until recently, all were of natural occurrence, or the result of natural breakdown of larger man-made particles. The science of ***nanotechnology*** has resulted in the manufacture of all manner of minute particles, often referred to as nanomaterials, which have a wide range of uses from delivery of drugs in the body to treatment of industrial effluents. By their very size they can get into places that larger particles can't. Magnetite nanoparticles, for instance, formed by heating of metals in car exhausts as well as in industrial processes, are common in urban, airborne particulate matter – and have been found in human brains. Numerous other nano-sized particles are found in the air, and no doubt also find their way into our bodies, particularly in polluted air. Silver nanoparticles seem to be the modern miracle materials, being used as everything from antibiotics and water purifiers to wound dressings. As is so often the case, Wikipedia provides an excellent introduction to the topic: https://en.wikipedia.org/wiki/Silver_nanoparticle; and the WRC has been funding research in this area for some years (see, for instance, Greyling et al 2017).

As analytical techniques continue to improve, and scientists become aware of the extent of pollution throughout the world, attention has started to turn to pollution by plastic particles smaller than 5 millimetres across. The study of micro- and nano-plastics has grown enormously over the last few years, and it is now clear that they are literally everywhere: in the deep sea; in the Arctic and Antarctic; in our food and water (and beer); and in the air or falling in rain over mountains and cities. They are, in effect, a subset of nanoparticles. Is this a problem? After all, we live with a continuous bombardment of dust, including micrometeorites, all the time. The problem is that microplastic particles are made of plastic. And many plastics take decades or more to degrade. What is more, as you may recall, some of the nastiest toxins such as phthalates, PCBs and Bisphenol-A (see page 267) are used in the manufacture of plastic. As the particles become smaller and smaller, these horrible toxins leach out of them as they degrade. The extent to which this is detrimental to the health of the inadvertent consumer is still under investigation. One of the few experiments looking at the effects of microplastics was carried out on marine zooplankton, finding that the animals' eggs were smaller and less likely to hatch in water contaminated with microplastics. I am sure that a lot more investigations will be carried out and I am also sure, being a realist (some might call me a cynic) that the outlook is not good. As Glen Cook (author of ***Shadow Games***) said, "Every ounce of my cynicism is supported by historical precedent."

What more can be said? We have known for a long time now that, despite their usefulness, plastics of all kinds have very large and damaging footprints. Marine vertebrates consume plastics and sometimes their guts become entirely blocked by them. Most of us have seen horrible pictures of a turtle with plastic drinking straws stuck in its nose. Yet we continue to accept groceries wrapped in plastic (sometimes two or more plastic wrappings per item) and to buy drinking water in plastic bottles. Most of this is single-use plastic. We are even advised not to reuse plastic water bottles because some of those nasty endocrine-disrupting phthalates and so on leach out of the plastic over time (although manufacturers are more than happy for them to be used only once, of course). The question is, why manufacture a material that can last for hundreds of years, and use it for a few minutes before it is discarded? My challenge to you, dear reader, is two-fold: in a supermarket, insist on receiving goods in paper packaging where possible, and avoid purchasing plastic supermarket shopping bags (you just have to get used to bringing your reusable shopping bags with you when you shop); and ***don't buy bottled water***. Buy yourself a good reusable water bottle and remember to keep it filled. The quality of tap water in most South African cities is great, but if it isn't, simply boil your tap water and use that.

Muntaka Chasant/Wikimedia/CC BY-SA 4.0

Plastic pollution on a beach in Accra, Ghana.

Sarie Silberbauer

'SoDis': water in plastic bottles being disinfected in the sun at Kiwoko Hospital in Uganda.

'Coralling' floating plastic in the Great Pacific Garbage Patch.

Finally, a tip on purifying water to drinking standard. Put the water in a 2-litre plastic cooldrink bottle and leave it in the sun for a day. This will almost certainly kill any pathogenic (disease-causing) bacteria in the water. And of course, it is unlikely that you will have to buy that cooldrink bottle, because you will come across empty ones that someone else has thrown away. But if you do buy one, at least it will no longer be a single-use purchase! (As I write this, I realise that there will probably be leachates from the plastic in your bottle … Ah well – you can't have everything, unless you can find suitable glass bottles. I see that Asiimwe and colleagues in Uganda have compared the effectiveness of bacterial inactivation in glass and PET (polyethylene terephthalate) bottles and find that glass is almost as effective as PET. So, if you can find glass bottles, use them.) The technique is known as SoDis (Solar disinfection) and a useful website is shown at the end of the chapter.

The ultimate decrease in plastic pollution will happen when we run out of fossil fuels but before then there are a couple of good news stories. One is that an organisation known as Ocean Cleanup is deploying gigantic nets in the ocean to sweep up plastic in places like the Great Pacific Garbage Patch (more formally known as the Pacific trash vortex). The vortex is an ocean gyre, 1.6 million km^2 in extent, in the North Pacific. Ocean Cleanup is generating great controversy among marine scientists, some of whom call it a scam, and others pooh-pooh it as a drop in the ocean, as it were. Of course, it does collect only large pieces of plastic, leaving the smaller particles behind, but at least these will not literally be in a position to degrade into microplastics in the future.

Another interesting development is the recognition of enzymes that can degrade PET plastic. The bacterium responsible, ***Ideonella sakaiensis,*** was first found in a plastic bottle recycling dump in Kyoto, Japan. It seems that the bacterium has a mutation of a gene producing an enzyme, cutinase, that breaks down plant cuticles. How cool is that?

CONTROL OF POLLUTION IN SOUTH AFRICA

Policies regarding water quality in South Africa are decided primarily at national level, being a responsibility of the Department of Water and Sanitation (DWS) according to the National Water Act. DWS's approach is one of managing for 'receiving water quality objectives' (RWQOs). The management objective is to permit no more effluent to enter any river than will allow its waters to be 'fit for use' by all potential users, including the environment The critical issue is to ascertain 'acceptable' levels of any pollutant for each user and for each river. This is done by defining water quality guidelines, which represent attempts to describe, quantify and evaluate the effects of each 'variable of concern' for each user. South African guidelines were set up by DWA in the 1990s and form the basis of their RWQ objectives. In this way, water quality is included when deciding on the 'Reserve' of water needed to maintain aquatic ecosystems (for details, see Chapter 10). There are benefits in this approach, because each river is assessed individually, and because the needs of the riverine biotas are taken into account. On the other hand, the intention of DWS's approach is to use what it calls the river's 'assimilative capacity' to the full. The idea of 'assimilative capacity' is appealing to managers, because it suggests that every river can 'assimilate' a certain amount of pollution without any detriment. This cannot happen, of course. Rivers can dilute pollutants and, as we have seen for organic waste, they can assimilate or remove certain pollutants, but to use the word 'assimilate' is to pretend that rivers are magical removers of waste (which they are – but ***only*** for organic waste). The intention of using a river's 'assimilative capacity' is to keep it permanently just below the level at which detrimental effects occur. As we know, though, all sorts of subtle and hidden stresses can affect the biota even at very low levels of pollution; and we are not very good at identifying a 'suitable' level of pollution.

Operationally, potential polluters (e.g. industries, wastewater treatment plants, mines) are required to apply for a licence to discharge effluent into a river or wetland (or the sea). The RWQOs are calculated so that the polluter knows how much effluent may be discharged. Monitoring to check that polluters are complying with their licence conditions is carried out using two lists: 'water quality standards' and 'effluent standards'. These provide the upper concentrations of a variety of chemicals that could legally be discharged into rivers under the old Water Act of 1956. The 'General Standard' is less rigorous than the 'Special Standard', which was designed as additional protection for trout streams: "The wastewater or effluent shall contain no other constituents in concentrations which are poisonous or injurious to trout or other fish ***(sic)*** forms of aquatic life." (Govt. Gazette 18 May 1984 no 9225). Effluent standards will probably always be needed for legal purposes, because of the difficulties of interpreting water chemistry data of the receiving stream below effluent discharge points (where and when exactly should one take the samples?).

DWS uses two further principles in deciding whether or not to grant a 'licence to pollute'. These are the 'precautionary principle', and the 'polluter pays' principle. With regard to water quality, the precautionary principle essentially says "if an effluent is likely to cause a problem in the receiving water, don't allow it to be discharged". The polluter pays principle is that the polluter must pay, either by cleansing the effluent on site and at own expense, or by paying a waste-discharge fee. It seems that while such charges are on the cards, as it were, they have not yet been implemented. It is supposed that when Catchment Management Agencies (CMAs – see Chapter 10) are fully operational, they will institute such charges, but this remains to be seen (as does the launching of several CMAs).

In support of their mandate as custodians of the country's water quality, DWS has developed a massive and hugely valuable database of physical attributes and concentrations of chemicals, collected since the late 1960s, at more than a thousand sites around the country. This valuable information has been used by Christa Thirion and Nolu Jafta to produce internal DWS reports but a great deal more could be done with it. These data should be considered as a legacy of the past, however, since over the last few years the number of sites and of reliable gauging stations has been drastically reduced and the Department's water quality laboratory is no longer accredited. How shameful.

The real world is a bit different from the ideal as described above, however. While policies regarding water quality are set at national level in South Africa, they are carried out by local authorities, and this is where things start to fall apart. At present, because of a lack of technical capacity, fewer than

10% of municipalities are able to meet the standards set by DWS for effluent from their WWTWs, or for drinking water entering the reticulation system. The Ministry is keenly aware of the problem and is attempting to increase the technical capacity of those municipalities that are the worst offenders. A website ('Blue and green drop' in the reading list) provides detailed information on the level of compliance reached by each municipality in the country. 'Blue drop' status is awarded to those complying with standards for drinking water and 'green drop' for WWTW effluents. Blue and Green Drop reports were released annually for a number of years, showing that most municipalities in the country were failing miserably in managing water quality adequately. In fact, the reports have been kept secret (or not produced at all) since 2014, allegedly because they offer such a dismal view of water quality in South Africa's urban areas. (I have been reliably informed that the decision was at least partly political: the best-performing municipalities were all in the hands of opposition parties.) The good news is that in July 2021 President Cyril Ramaphosa told DWS to reinstate the Blue and Green Drop programmes. Let's hope that this will encourage municipalities to improve their water management capabilities rather than embarrassing us all again. Links to the relevant websites are given in the reading list at the end of this chapter.

A former Director-General of the then Department of Water Affairs, Mike Muller, has written a detailed analysis of some of the things that have gone wrong in South Africa's water sector. The report makes horrible reading but does explain a lot of the seemingly mysterious happenings in the sector in the last couple of decades.

BIOASSESSMENT OF WATER QUALITY

One of the problems in controlling pollution is that most authorities define pollution based on only a few, very specific, chemical features. It is important to realise, though, that it is almost impossible to provide guidelines for the dozens, if not hundreds, of other possible pollutants, some of which are hazardous under certain circumstances. Bioassessment is one way of tackling this problem from a different angle. Bioassessment is any process whereby living organisms are used to provide information about the systems in which they are living. While chemical analyses can give very accurate measures of the concentrations of individual substances in water, they reflect only the conditions in water at the moment of collection: they are instant 'snapshots' of the environment, usually taken during the day when fly-by-night polluters are unlikely to be discharging waste illegally. Biological monitoring, although less detailed, provides a 'bigger picture' of both the past and the present conditions in a wetland or river because the organisms living there must have been able to survive whatever chemical conditions they had been subjected to for as long as they had been alive.

Just as a fish-kill indicates that a toxic spill may have occurred, so the invertebrates present in a stream will reflect 'good' or 'poor' water quality from their own point of view, as it were. The late Dr Mark Chutter was a leader in this field. Indeed, in the early 1970s he was responsible for the formulation of a ***Biotic Index of Water Quality*** for South African rivers, in a paper that is regularly quoted wherever people write about bioassessment using invertebrates. By carefully analysing the distribution of species recorded in rivers, he was able to identify those species that were tolerant or intolerant of organic pollution. More recently, he developed a technique for the rapid assessment of riverine water quality, also using invertebrates. This technique, which he called SASS (the South African Scoring System), is based on identification of families of invertebrates living in a river. Today SASS is used regularly as a means of assessing the condition of South African rivers. South African scientists, particularly Helen Dallas of the Freshwater Research Centre in Cape Town, have been involved in extending SASS to a number of other southern African countries. SASS offshoots are currently used in Namibia, Botswana, Zimbabwe, Zambia and Tanzania. These topics are discussed in more detail in chapter 12.

> "All sorts of subtle and hidden stresses can affect the biota even at very low levels of pollution; and we are not very good at identifying a 'suitable' level of pollution."

WRC archives

This and previous page: A few years ago mini-SASS, a simplified version of the SASS biomonitoring tool was developed to allow citizens to monitor the health of their own community rivers and streams. It has since become a valuable citizen science tool, used by communities all over the world.

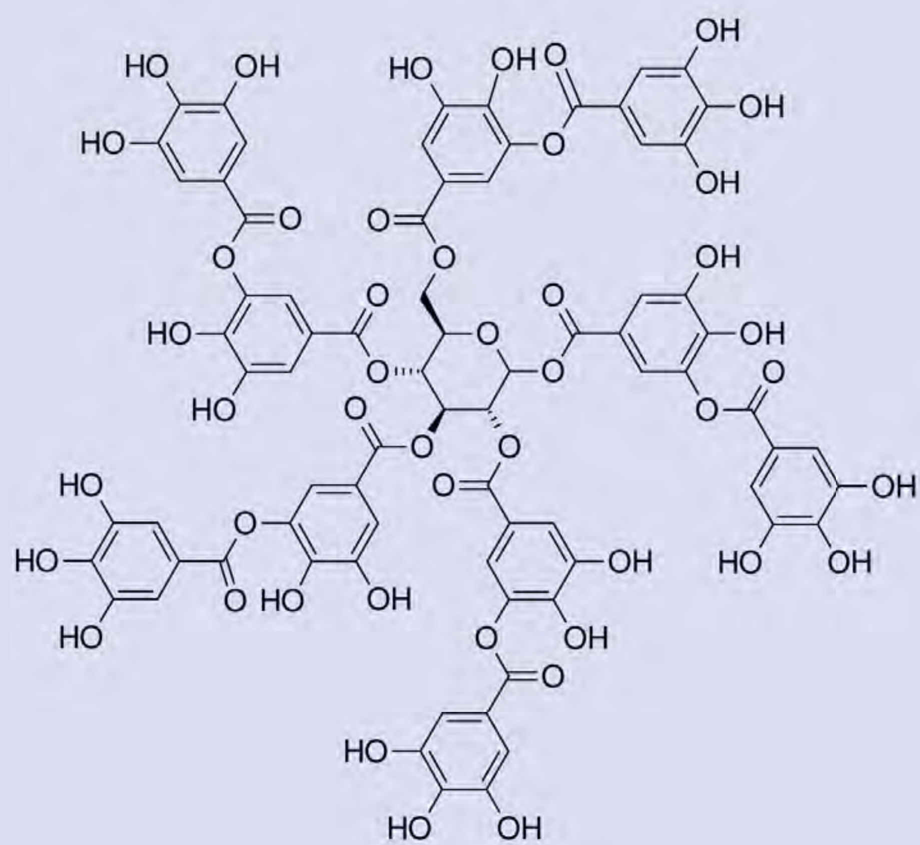
Jenny Day

Fynbos vegetation on the Agulhas Plain.

Fynbos is one of the major vegetation types of the winter-rainfall region of the south-western Cape. It grows on the oligotrophic (nutrient-poor) soils of the ancient Cape Fold Mountains and is characterised by very high plant diversity and endemism, for reasons only poorly understood. As well as oligotrophic soils, the region experiences summer drought and high winds, often resulting in fires. Water in rivers and wetlands in the fynbos biome is very dilute, low in nutrients, often very dark in colour, and acidic. We have recorded pH values as low as 3.2 in water draining the Bettys Bay mountains during spates. (Such darkly-stained waters are also called peat-stained, black or humic.) Why should these waters be coloured, and why are they so acidic? The story is an interesting one. Since nutrient levels in the soils are so low, plants cannot 'afford' to use N or P in protective compounds but they produce large quantities of carbon-rich but nitrogen- and phosphorus-free substances known as secondary plant compounds. These substances, which include humic and fulvic acids, and tannins, are large, complex and poorly characterised polyphenolic molecules. In plants these substances are strongly aromatic and astringent, presumably because this deters herbivores (and of course, where nutrients are in short supply, each leaf is precious because it represents a store of N and P). When a leaf dies and decays, these polyphenolics (which are often very long-lived) leach out of the dead leaf and into the water, either on the ground or below the surface. Because in solution they colour the water and act as weak organic acids, the waters of aquatic ecosystems affected by fynbos vegetation are also acidic, and usually darkly coloured. These waters, running off ancient, weathered TMS, are poorly buffered because concentrations of calcium and magnesium are low, the major ions consisting almost entirely of sodium and chloride derived from sea spray. This means that even a small quantity of acid can reduce the pH significantly.

That isn't the end of the story. On the one hand, many species of aquatic invertebrates are adapted to these unusual chemical features of fynbos waters, to the extent that they seem unable to live elsewhere (see also chapter 11). This has consequences when the natural water chemistry is perturbed, by construction activities, for instance. Even a small quantity of cement dust entering a little blackwater stream can raise the pH enough to kill off its local inhabitants.

On the other hand, the polyphenolics (see the diagram below) are the answer to the question we posed above (page 237): why are the acid waters of the fynbos biome not affected by aluminium toxicity in the same way that acid-rain-acidified waters are? The answer is so cool! Polyphenolics tend to be very 'sticky', in that they attach to (sequester) many dissolved substances, particularly metal ions. Aquo-Al is a metal ion, and polyphenolics sequester them, making them unavailable (and therefore non-toxic). So Al ions are present in these coloured waters but the coloured molecules mop them up and make them irrelevant. And by the way, the tea we drink is also coloured with polyphenolics, including tannin!



FURTHER READING

APHA (American Public Health Association) (2017) ***Standard Methods for the examination of water and wastewater***, 22nd ed. American Water Works Association, and Water Pollution Control Federation, Washington, DC.

Brown CA & JM King (1995) The effects of trout-farm effluent on benthic invertebrate community structure in south-western Cape rivers. ***Southern African Journal of Aquatic Sciences* 21:** 3-21

Bruton MN (1985) The effects of suspensoids on fish. pp. 221–242 in: BR Davies and RD Walmsley (eds), Perspectives in Southern Hemisphere limnology. ***Developments in Hydrobiology* 28**. Dr. W. Junk, The Hague. 263 pp.

Cadbury D (1999) ***Altering Eden: the feminization of nature.*** St Martin's Press, New York

Carson R (1963) ***Silent spring.*** Hamish Hamilton Ltd, London. 304 pp.

Cernansky R (2017) Artificial sweeteners are used to track water pollution. ***Scientific American*** November 2017

Chutter FM (1972) An empirical biotic index of the quality of water in South African streams and rivers. ***Water Research* 6**:19-30

Chutter FM (1998) Research on the rapid biological assessment of water quality impacts in streams and rivers. Water Research Commission Report no. 422/1/98

Dabrowski JM, SKC Peall, A van Niekerk, AJ Reinecke, JA Day & R Schulz (2002) Predicting runoff-induced pesticide input in agricultural sub-catchment surface waters: linking catchment variables and contamination. ***Water Research* 36**: 4975-4984.

Dallas HF & JA Day (2004) ***The effects of water quality variables on aquatic ecosystems: a review.*** Water Research Commission Report no. TT 224/04

Dallas HF & JA Day (2007) Natural variation in macroinvertebrate assemblages and the development of a biological banding system for interpreting bioassessment data – a preliminary evaluation using data from upland sites in the south-western Cape, South Africa. ***Hydrobiologia* 575**: 231-244.

Day JA & HF Dallas (2011) Understanding the basics of water quality. Pp. 68-89 ***in***: Grafton, Q. (ed.) ***Water resources planning and management.*** Cambridge University Press, 777 pp.

Dalvie MA, L London, S Mbuli & E Cairncross (2004) ***Knowledge and attitudes in the rural Western Cape towards pesticides in water sources. Water SA* 30** (1): 43-50

Day JA & JM King (1995) Geographical patterns, and their origins, in the dominance of major ions in South African rivers. ***South African Journal of Science* 91**: 299–306.

de Moor FC & JA Day (2013) Aquatic biodiversity in the mediterranean region of South Africa. ***Hydrobiologia* 719**: 237–268 DOI 10.1007/s10750-013-1488-7

Diamanti-Kandarakis E, J-P Bourguignon, LC Giudice, R Hauser, GS Prins, AM Soto, RT Zoeller & AC Gore (2009) Endocrine-disrupting chemicals: An Endocrine Society Scientific Statement. ***Endocrine Reviews* 30**: 293-342

Emsley J (2000) ***The 13th element: the sordid tale of murder, fire and phosphorus.*** John Wiley & Sons, USA

Fadare FT & AI Okoh (2021) Distribution and molecular characterization of ESBL, pAmpC β-lactamases, and non-β-lactam encoding genes in Enterobacteriaceae isolated from hospital wastewater in Eastern Cape Province, South Africa. ***PloS One*, 16** (7), e0254753. DOI:10.1371/journal.pone.0254753

Gore AI (2006) ***An Inconvenient truth: the planetary emergency of global warming and what we can do about It.*** Rodale Books, Emmaus Pennsylvania. 328 pp.

Gore AC, VA Chappell, SE Fenton, JA Flaws, A Nadal, GS Prins, J Toppari & RT Zoeller 2015. EDC-2: The Endocrine Society's Second Scientific Statement on Endocrine-Disrupting Chemicals. ***Endocrine Reviews* 36**: E1-E150 https://pubmed.ncbi.nlm.nih.gov/26544531/

Gore AC, K Krishman & MP Reilly (2019) Endocrine-disrupting chemicals: Effects on neuroendocrine systems and the neurobiology of social behavior. ***Hormones and Behaviour* 111**: 7-22.

Greyling CJ, VG Fester, JC Ngila, EFC Chaúque & W Edwards (2017) ***Nanotechnology for the treatment of industrial-scale effluents – particularly the removal of organic contaminants from textile effluents using nano-TiO_2***. Water Research Commission Report no. 2386/1/17

Harrison AD (1958) The effect of sulphuric acid pollution on the biology of streams in the Transvaal. ***Verhandlungen Internationale Vereinigung für theoretische und angewandte Limnologie* 13**: 603–610

How ZT & MG El-Din (2021) A critical review on the detection, occurrence, fate, toxicity, and removal of cannabinoids in the water system and the environment. ***Environmental Pollution* 268**: doi: 10.1016/j.envpol.2020.115642

Johnson BD & KB Hallberg (2005) Acid mine drainage remediation options – a review. ***Science of the Total Environment* 338**: 3-14

Johnson MR, CR Anhaeusser & RJ Thomas (Eds.) (2006) ***The Geology of South Africa***. The Geological Society of South Africa, Council for Geosciences: Pretoria, South Africa, 691p

Liu J-L & M-H Wong (2013) Pharmaceuticals and personal care products (PPCPs): A review on environmental contamination in China. ***Environment International* 59**: 208-224 https://www.sciencedirect.com/science/article/pii/S016041201300130X

Muller M (2020) ***Money down the Drain: corruption in South Africa's water sector***. Braamfontein, Johannesburg: Water Integrity Network / Corruption Watch. https://www.researchgate.net/publication/339935962_Money_down_the_drain_-_Corruption_in_South_Africa%27s_water_sector

Myers JP, LJ Guillette Jr, P Palanza, S Parmigiani, SH Swann & FS Vom Saal (2004) The emerging science of endocrine disruption ***In***: RC Ragaini (ed.), ***International Seminars on Planetary Emergencies,*** 30th Session: 105-121. World Scientific Publishers, Singapore

Palmer CG, WJ Muller, AK Gordon, P-A Scherman, HD Davies-Coleman, L Pakhomova & E De Kock (2004) The development of a toxicity database using freshwater macroinvertebrates, and its application to South African water resource protection. ***South African Journal of Science* 100**: 643-650

Palmer CG (2018) ***How to understand environmental water quality in water resources management.*** Handbook 9, Project K5/2248, South African Water Research Commission, Pretoria

Razwiedani LL & P Rautenbach (2017) Epidemiology of organophosphate poisoning in the Tshwane District of South Africa. ***Environmental Health Insights* 11** DOI: 10.1177/1178630217694149

Rimayi C, L Chimuka, D Odusanya, J de Boer & J Weiss (2017) Source, characterisation and distribution of selected PCBs, PAHs and alkyl PAHs in sediments from the Klip and Jukskei Rivers, South Africa. ***Environmental Monitoring and Assessment*, 189** (7), **1–16.**

South Africa (1984) Government Gazette 18 May 1984 no. 9225 (Special and General Standards)

Stewart I, PM Webb, PJ Schluter & GR Shaw (2006) Recreational and occupational field exposure to freshwater cyanobacteria – a review of anecdotal and case reports, epidemiological studies and the challenges for epidemiologic assessment. ***Environmental Health* 5**: https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-5-6

Swan SH & S Colino (2021) ***Count Down: How our modern world is threatening sperm counts, altering male and female reproductive development, and imperiling the future of the human race.*** scribner, NY.

Van Halderen A, WR Harding, JC Wessels, DJ Schneider, EWP Heine, J Van Der Merwe & JM Fourie (1995) Cyanobacterial (Blue-Green Algae) poisoning of livestock in the Western Cape Province of South Africa. ***Journal of the South African Veterinary Association* 66:** 260–264.

Wagner D, EM Grames, ML Forister, MR Berenbaum & D Stopak (2021) Insect decline in the Anthropocene: death by a thousand cuts ***Proceedings of the National Academy of Science* 118:** e2023989118

USEFUL WEBSITES (ACCESSED NOVEMBER 2022)

Acid mine drainage in South Africa
http://www.miningweekly.com/article/acid-mine-drainage-single-most-significant-threat-to-sas-environment-2009-05-08

https://mg.co.za/environment/2021-06-12-state-halts-its-r10bn-long-term-plan-to-fully-treat-acid-mine-water/

https://www.researchgate.net/publication/320966970

Agrichemicals
https://www.unlockfood.ca/en/articles/farming-food-production/hormones-and-antibiotics-in-food-production.aspx

Air pollution in South Africa
https://qz.com/africa/1441504/highest-concentration-of-deadly-air-pollution-found-in-south-africa/

Antibiotics – resistance to
https://www.epa.gov/pesticide-registration/antimicrobial-pesticide-registration

https://www.usda.gov/sites/default/files/documents/usda-antimicrobial-resistance-action-plan.pdf

https://apic.org/advocacy_update/epa-allows-expanded-use-of-antibiotics-for-agriculture/

https://www.frontiersin.org/articles/10.3389/fcimb.2022.873989/full

https://pubmed.ncbi.nlm.nih.gov/32492618/ :

Artificial sweeteners
https://www.scientificamerican.com/article/artificial-sweeteners-are-used-to-track-water-pollution/

Blue- and Green-drop reports
https://mg.co.za/environment/2021-02-17-why-we-need-the-blue-and-green-drop-reports-everyone-in-sa-lives-downstream-from-a-sewage-discharge-point/

https://www.gov.za/speeches/water-and-sanitation-reinstates-blue-and-green-drop-programmes-7-jul-2021-0000

https://www.iol.co.za/capeargus/news/western-cape-has-safe-drinking-water-but-water-quality-is-still-of-concern-536376fb-8490-4a31-a285-e93cbbbf42ec

City of Cape Town, Inland water quality Technical Report.
https://resource.capetown.gov.za/documentcentre/Documents/City%20research%20reports%20and%20review/Inland_Water_Quality_Report_FULL.pdf

Cyanobacterial toxins
https://ehjournal.biomedcentral.com/articles/10.1186/1476-069X-5-6

DWS's Directorate of Water Quality Management
https://www.dws.gov.za/iwqs/wms/default.aspx

Endocrine disruptors:
http://www.niehs.nih.gov/health/topics/agents/endocrine/index.cfm

https://www.dffe.gov.za/sites/default/files/docs/pesticides_endocrine_disruption_sa.pdf

International Panel on Climate Change, IPCC
http://www.ipcc.ch/

Microplastics
https://en.wikipedia.org/wiki/Microplastics

Nanoparticles
https://en.wikipedia.org/wiki/Nanoparticle

https://en.wikipedia.org/wiki/Silver_nanoparticle

Organic foods
https://www.healthline.com/nutrition/what-is-organic-food

Phosphorus
http://phosphorusfutures.net/the-phosphorus-challenge/the-story-of-phosphorus-8-reasons-why-we-need-to-rethink-the-management-of-phosphorus-resources-in-the-global-food-system/

Plastic pollution
https://www.nationalgeographic.com/environment/article/plastic-pollution

https://en.wikipedia.org/wiki/Great_Pacific_garbage_patch#

https://oceanservice.noaa.gov/hazards/marinedebris/plastics-in-the-ocean.html

https://theoceancleanup.com/

https://www.youtube.com/watch?v=VSPpKrGbNUM&t=278s

https://www.energy.gov/sites/prod/files/2019/12/f70/beto-05-plastics-wkshp-dec-2019-beckham_0.pdf

POPs convention

http://chm.pops.int/Convention/tabid/54/language/en-US/Default.aspx#convtext

Salinisation

https://www.agric.wa.gov.au/climate-land-water/soils/managing-soils/soil-salinity

https://www.researchgate.net/publication/283969475_World_salinisation_with_emphasis_on_Australia

Siltation programme, South Africa

https://mg.co.za/special-reports/2021-07-09-water-research-commissions-siltation-programme/

Solar disinfection (SoDis)

https://www.cdc.gov/healthywater/global/household-water-treatment/solardisinfection.html

https://pubmed.ncbi.nlm.nih.gov/24334847/

Toxic 'forever chemicals'

https://www.usatoday.com/story/news/health/2020/01/23/pfas-toxic-forever-chemicals-found-drinking-water-throughout-us/4540909002/

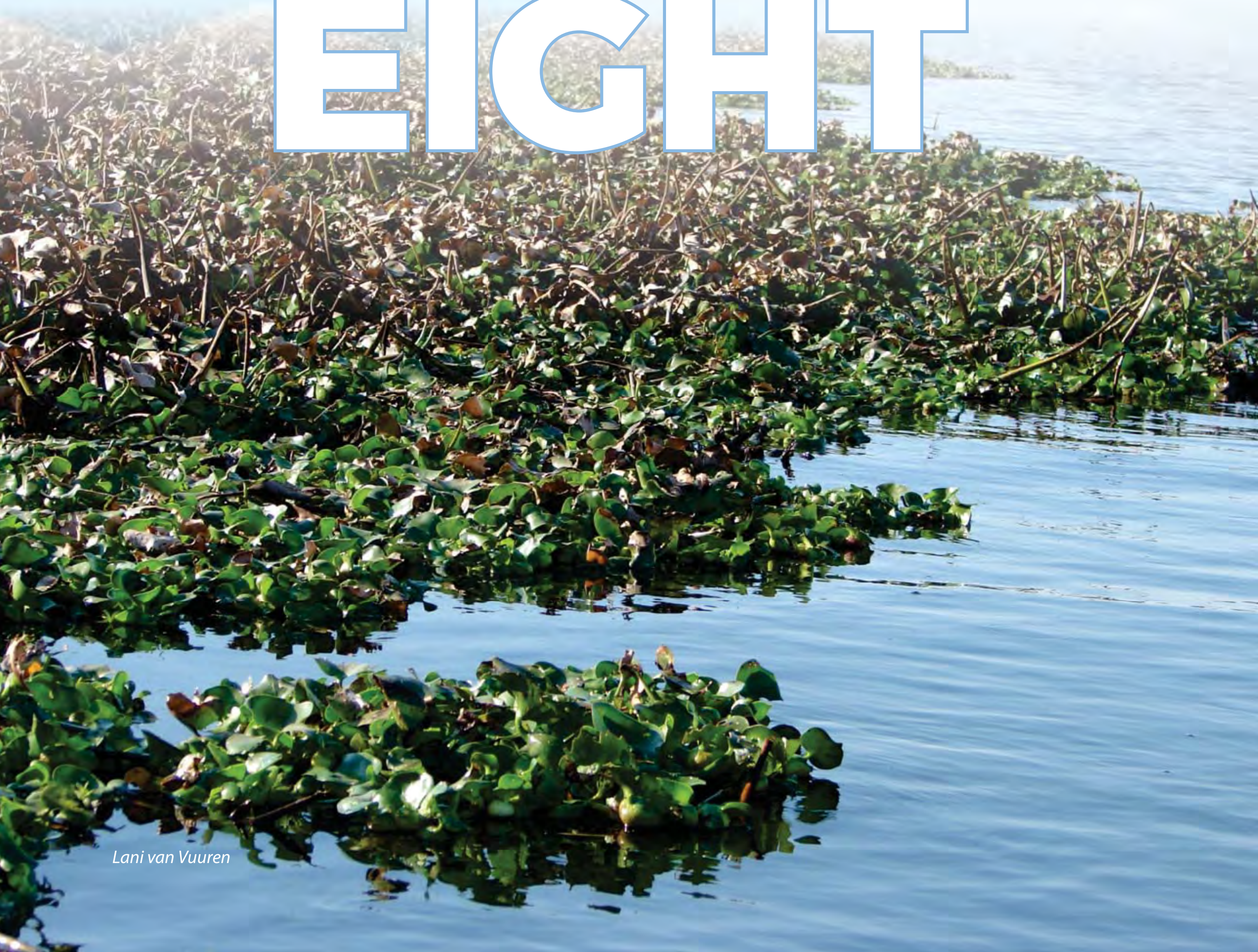
US Government's Environmental Protection Agency, Office for Water

https://www.epa.gov/aboutepa/about-office-water

Water quality information

https://usdasearch.usda.gov/search?query=water+quality+information&affiliate=www.nal.usda.gov&op=Submit+Search

CHAPTER EIGHT



Lani van Vuuren

Alien species: plants, animals and microbes

Alien species are usually thought of as species that are in the wrong place – but of course that depends on one's point of view: 'wrong' for whom? Most alien plants and animals have been distributed around the world by humans in one way or another, although some have made it all on their own – tiny insects on air currents, or marine creatures caught in ocean currents, for instance. Alien microbes are a bit different. We still know remarkably little about the free-living bacteria and fungi that drive biological processes such as decomposition and mineralisation and so we do not discuss them further here. We do know quite a lot about the microbes that cause human diseases, though. We also know that a lot of them are related to water, and so they occupy the second part of this chapter.

INVASIVE SPECIES AND THEIR CONTROL

Wherever we look, we see more and more plants and animals that have escaped from their native lands and are now invading the rest of the world. In South Africa, the most obvious are trees such as the eucalypts (gumtrees of the genus ***Eucalyptus***) and, in the south-western Cape, the Australian acacias that spread like the proverbial green cancer, invading thousands of hectares of lowland fynbos. (Ironically, at the same time various fynbos species are invading the southern parts of Australia). Japanese seas are pulsating with giant jellyfish two metres across. The Great

Jenny Day

A dense stand of alien eucalypts and acacias on the Agulhas Plain.

Lakes of North America have been devastated by the invasion of a small bivalve, the zebra mussel, ***Dreissena polymorpha***, that has caused huge shifts in the food webs of the lakes. The highly endemic little fishes of the fynbos region have been squeezed into a few small streams where they are – at least for the present – protected from the voracious appetites of the invasive bass and trout that now rule the rivers. Scientists studying 'invasion biology' are able to pinpoint where most of the invaders have come from, why they have become successful (ideal conditions, no natural predators or parasites, …) and even how they got here (Europeans wanting the lands they 'invaded' to be more like home; ships' ballast water; the aquarium trade; anglers; well-meaning people not wanting to kill off the fish or the turtle that go too big for its aquarium ....). What is less clear is how to deal with the problems created by this 'homogenisation of nature'.

Zebra mussels (about 20 mm in length) look innocuous, but they have caused immense damage to the biodiversity of the North American Great lakes.

Smallmouth bass pose a greater danger to our small redfin minnows than habitat destruction or pollution.

Let's get a few terms straight before we proceed. An ***alien*** (or ***exotic***) organism is one that doesn't naturally occur in an area. An ***invasive*** organism is one whose numbers increase greatly, often at the expense of native species, when conditions are favourable. Both native and alien organisms may be invasive, depending on conditions. While we are about it, an *indigenous* organism is one that occurs naturally in a particular place, while an ***endemic*** organism is one that is found only in the area in question. So, for instance, three little redfin minnows are the Maluti redfin (***Pseudobarbus quathlambae)***, the Clanwilliam redfin (***Pseudobarbus calidus***) and the Twee River redfin (***Pseudobarbus erubescens***). They are all indigenous to southern Africa but ***P. quathlambae*** is endemic only to the mountains of Lesotho, and ***B. calidus*** and ***B. erubescens*** to particular tributaries of the Olifants River in the Western Cape. The smallmouth bass, ***Micropterus dolomieu***, on the other hand, is native to the USA and an invasive alien in South Africa. The sharptooth catfish, ***Clarias gariepinus***, is native to the northern parts of South Africa but has recently been found in several rivers in the Western Cape, where it is both alien and invasive.

INVASIVE AQUATIC PLANTS

A number of introduced water weeds, mostly from South America, are major economic pests, often referred to as ***noxious weeds***. They include Kariba weed (a free-floating fern named ***Salvinia molesta***), water hyacinth (the famous ***Eichhornia crassipes,*** sometimes now known as ***Pontederia crassipes,*** also free-floating), parrot's feather (***Myriophyllum aquaticum***, a floating or rooted plant), and ***Azolla filiculoides***, another floating water-fern. The Nile cabbage or water lettuce (***Pistia stratiotes***) has made an unwelcome appearance either from North Africa or possibly from Australia, where it seems to be native in the tropical north-east. All of these, as well as dense water weed (***Egeria densa***), Canadian water weed (***Elodea canadensis***) and spiked water-milfoil (***Myriophyllum spicatum***) are Category 1 'declared weeds' in South Africa. This means that they "may no longer be planted or propagated, and all trade in their seeds, cuttings or other propagative material is prohibited. They may not be transported or be allowed to disperse" (CARA – Conservation of Agricultural Resources Act, No 43 of 1983). CARA legislation regarding alien and invasive plants is still pertinent but the later National Environmental Management Act (NEMA, Act No107 of 1998) and its subsidiary the National Environmental Management: Biodiversity Act (Act No 10 of 2004) also deal with aspects of alien organisms. NEMA has published lists of prohibited and restricted plants and animals – see website at the end of this chapter. An excellent resource for information on invasives is the Invasive Species Compendium of CABI (the Centre for Agricultural and Biosciences International – see list of websites at the end of the chapter).

The collective importance of these weeds stems from the fact that they all exhibit the potential for explosive growth, particularly in eutrophic conditions, and may cover and choke vast areas of standing and slowly-running water. They are widespread throughout South Africa and have already cost the country tens of millions of Rands in attempts to eradicate them. Water hyacinth, for instance, prevents boating, angling and skiing, disrupts water flow in irrigation channels, and blocks sluices. It may also create ideal breeding habitat for malarial mosquitoes and bilharzial snails. Its presence in the Vaal River, in Mpumalanga, in KwaZulu-Natal and in many south-western Cape rivers and vleis is well known.

In South Africa, Hartbeespoort Dam near Pretoria has seen a most spectacular growth of ***Eichhornia.*** This weed, like many of the others, can double its mass every four days or so, given warm and eutrophic conditions. So, one does not need much imagination to see how the plants can become problematic, particularly as Hartbeespoort has an overload of plant nutrients from treated effluents entering the system from WWTWs on the Crocodile River. In some cases, growth can become so dense that the floating weed-beds become a substratum for the establishment of a more terrestrial type of vegetation, eventually supporting grasses, shrubs and even small trees. This development on top of a floating mass of weed is known as secondary 'sudd' development, after the Sudd swamps of the Upper Nile Valley in the Sudan, where such masses develop naturally. During the 1970s, most of Hartbeespoort reservoir was covered with water hyacinth. The floating mats became so massive that the hulls of boats were crushed like eggshells by wind-blown islands of the floating weed. Eventually a herbicide-spraying programme was initiated in the late 1970s, sending over 45 000 t dry mass of *Eichhornia* – and a helicopter – to the bottom of the lake. Fortunately, no lives were lost. The spraying programme had an unexpected, although entirely predictable, outcome. Because of the continued supply of nutrients to the lake from sewage effluents, coupled with the rapid decomposition of the dead *Eichhornia* on the lake bottom, and the fact that light could now penetrate into the water, the blue-green *Microcystis aeruginosa* bloomed to become the next pest in the sequence, at its worst covering the lake in a bright-green glutinous scum up to 20 cm thick (see pages 80 and 81). Nature, as the old saying goes, abhors a vacuum. The lesson is simple: don't treat the effect, treat the cause – the cause in this case being the continuous pollution of the reservoir by excessive quantities of plant nutrients in the sewage effluents entering the Crocodile River. As of January 2022, there have been blooms on and off of hyacinth and now also of a small *Salvinia* – ***Salvinia minima.*** The prognosis seems to be continued masses of weed, with short periods of clear water, for the foreseeable future unless nutrient inflows are drastically reduced.

One has to admire water hyacinth for its tenacity and it beautiful mauve flowers, despite its unlovely habits. Although several different kinds of insect (including weevils, moth caterpillars and bugs), as well as a variety of rusts and other fungi, have been used as biological control agents, nothing seems to be able to eradicate the weed completely from the systems that it infests. For many years it covered huge areas of Lake Victoria. Biological control agents hugely reduced its extent, but of course as soon as the plants were reduced in number, so were the insects that attack them, allowing the plant to expand once more. Currently, the control agents are able to keep the hyacinth under control in most parts of the lake, but are unable to eliminate it completely.

Some of the most troublesome invaders of aquatic ecosystems in southern Africa are floating plants. If the tiny invasive fern ally, Azolla filiculoides *(A) covers huge areas (B) it can prevent oxygen from reaching the water; the beautiful flowers (C) of water hyacinth bear seeds, allowing the plant to spread far and wide; water hyacinth can form dense stands, as seen here (D) on the Vaal River near Leeudoringstad; the water lettuce* Pistia stratiotes *(E) is probably the least problematic of the floating invaders, while Kariba weed,* Salvinia molesta *(F), is one of the worst.*

Do Musibono

In the 1990s water hyacinth was so thick on Lake Victoria that boats could not be launched.

Because it soaks up nutrients, the tissues of hyacinth are rich in nitrogen and phosphorus. As a result, relatively successful attempts have been made to use it as a 'green manure' in rice paddies and fishponds. It also has the ability to take up heavy metals even in fairly low concentrations, though. On the one hand, this means that the plant should not be used as a green manure in metal-contaminated areas because the metals might land up in the foodstuffs being grown; on the other hand, there is scope for using the hyacinth as a means of concentrating and removing heavy metals such as cadmium, chromium, iron, lead and copper from contaminated water. An additional use might be in the production of biofuels.

Kariba weed, ***Salvinia molesta,*** is another South American native that is a major menace in southern Africa. At one stage it covered more than 2 200 km^2 of the surface of Lake Kariba, with mats more than half a metre thick. Under these circumstances, it also created conditions ideal for mosquitoes and snails, the vectors of malaria and bilharzia. (The only advantage of the plant is that small mats may provide cover for fish) Instead of herbicides, a biological control agent, the grasshopper ***Paulinia acuminata***, was used to control the weed on Lake Kariba. ***Paulinia*** comes from South America, which also happens to be the native home of ***Salvinia.*** In fact, ***Salvinia*** is the normal food of the grasshopper. After long and very painstaking screening (to ensure that it would not attack commercial agricultural crops), ***Paulinia*** was released on Lake Kariba. The populations of ***Salvinia*** were rapidly reduced and the plant is now pretty much under control. But here lies another irony: scientists are still not sure if it was the insect that was responsible for the rapid decline in ***Salvinia*** or if the weed simply became nutrient-limited as Lake Kariba stabilised (see Chapter 9). Either way, the plant is under control and the insect is still present. In southern Africa today the weed is found mainly in Limpopo, KwaZulu-Natal and the Eastern Cape in South Africa, the Caprivi of Namibia and the Okavango swamps of Botswana. These areas may benefit from the controlled release of ***Paulinia***. Note that another species, ***Salvinia minima***, also from South America, has recently been found in southern Africa. It looks very like ***S. molesta*** but is quite a lot smaller and is relatively resistant to desiccation so it can't easily be killed by removing it from the water.

The grasshopper Paulinia acuminata *is very successful in the biological control of* Salvinia.

In addition to the effects mentioned so far, floating water weeds actively pump water through their tissues and release it into the air in the process of evapotranspiration, thereby increasing the loss of water from lake surfaces by as much as six-fold. This represents an enormous economic loss in a water-thirsty country such as South Africa. Hence the control, and indeed the eradication, of pest plants is essential. Transporting these weeds, throwing them out of your ornamental pond or fishpond when it becomes choked, or allowing plant-breeders, importers and nurserymen to sell them is tantamount to wasting water. Selling them to the public is a criminal offence. Get to know the alien weeds and report them to the authorities whenever you see them. The Agricultural Research Council's website and others in the reading list will help you to investigate this problem in more detail.

Why should ***floating*** alien plants be such a problem in this country, especially in reservoirs? Well, one thought that comes to mind concerns the very nature of aquatic ecosystems in southern Africa. Because of the climate and topography of the region (see Chapter 2), very few natural lakes exist and virtually none of these (except some coastal lakes) has permanently open waters. And why is this significant? It seems to us that all the alien plants we have mentioned are floating plants that evolved in large, slow-flowing lowland rivers or in open waters and wetlands (of the Amazon, for instance) that have been subject to regular hydrological cycles for a very long time. Such plants are adapted to exploiting such permanent and 'predictable' waters. Because we had no such biotopes in South Africa, we have no indigenous plants of this kind. By developing artificial lakes, we have obligingly created biotopes which, until now, have essentially been missing from much of the subcontinent. Further, the plants have arrived without their herbivores, parasites and seedeaters and so they have been able to flourish in the luxury of trouble-free, often eutrophic waters.

INVASIVE BUT MAYBE NOT ALIEN

Stable banks of many vleis, rivers and estuaries are inhabited by large grass-like reeds, often called macrophytes. There is some debate as to which are aliens but there is no doubt that several of them can be very invasive and that they can become important components of the ecosystems they invade. The cord grass ***Spartina maritima,*** for instance, forms dense intertidal stands on several west- and south-coast estuaries. Janine Adams and Guy Bate note that "Whether or not ***S. maritima*** is an exotic [there has been a long-standing debate about this], it has become an important primary producer in a number of South African estuaries". On the other hand, the related but larger ***Spartina alterniflora,*** which is native to the east coasts of North and South America, is an aggressive invader. It was found by Janine and her colleagues in the Great Brak estuary in 2004; after an aggressive eradication programme led by the South African National Biodiversity Institute (SANBI), it had completely disappeared by 2016 – a good news story and an important example of rapid action averting the establishment of yet another aggressive invader on our shores. Another macrophyte, ***Phragmites australis,*** the fluitjiesriet, is widespread throughout the country and is thought to have a naturally cosmopolitan distribution. It occurs wherever there is shallow standing water or perennially damp soil, and can be very invasive. Its sister species, ***Phragmites mauritianus,*** mostly occurs further north and is commonly found around tiny brackish springs in the Namib Desert. It seems to be both indigenous and non-invasive. Two species of ***Typha*** (cattail, bulrush or papkuil), occur in southern Africa, ***T. capensis*** in the south and east, and ***T. domingensis*** in the north and west. Both are invasive, ***T. capensis*** particularly so, and it seems that both are native to the area. Reeds tend to be dominant competitors, often crowding out smaller plants. Because of their rhizomatous root systems, they are able to stay in place even in the face of strong currents. Reeds are also ideal plants in treatment wetlands, being able to stabilise sediments and act as water filters, as well as providing building and weaving materials and acting as wildlife refuges. So, although they can be very invasive and therefore often a major nuisance, the benefits they bestow are numerous.

Jenny Day

The cord grass Spartina maritima*, together with the filamentous algae* Enteromorpha*, in Knysna lagoon.*

Jenny Day

The desert-adapted Phragmites mauritianus *growing near a saline spring in the Namib Desert.*

Jenny Day / Inset: Sharon Mollerus / Wikimedia / CC BY 2.0

Typha capensis*, the local bulrush, has virtually eliminated the last remnants of Zoarvlei in the Salt River catchment, Cape Town. Inset shows Typha's dark brown seed-heads.*

As well as invasive aquatic plants, a wide range of terrestrial invaders particularly enjoy moist habitats, such as the banks of watercourses. ***Sesbania punicea*** (rattle box or scarlet wistaria) and the black wattle, ***Acacia mearnsii***, are such species. Their dense growth blocks channels and smothers natural vegetation. In addition, the shallow roots of some of these species are not tenacious enough to hold on during spates, so erosion of river channels often accompanies their invasion. As in the case of the floating plants, scientists from South Africa have been collaborating with their Australian counterparts (the invasive acacias are all Australian in origin) in attempting to discover insects that may act as agents to control the pest plants. Indeed, controlled releases of a moth and of a gall-forming wasp have been highly successful in combating channel encroachment by several species of ***Acacia*** in some rivers of the Western Cape. Furthermore, South Africa's Working for Water programme (see chapter 10) is clearing large areas of plant invaders. It is possible that we will win the war against the green invaders, as long as we can prevent more of them from being introduced. It is worrying, though, that inter-basin transfers of water can transport seeds of these plants, and their animal counterparts, around the country.

Acacia mearnsii*, the black wattle, invades river banks over much of South Africa. It clogs rivers, evapotranspires large amounts of water and reduces biodiversity both on the banks and in the river itself.*

Biological control: a fungus causes flower buds of the invasive alien Acacia saligna *to develop galls, preventing seed set and eventually killing the plant.*

INVASIVE AQUATIC ANIMALS

Alien animals have been introduced by humans, often deliberately, into a variety of rivers and wetlands. Aquarists and aquaculturalists have, for instance, illegally brought various freshwater crayfish into South Africa from different parts of the world. The American red swamp crayfish, ***Procambarus clarkii***, was introduced into the former Transvaal, possibly as early as 1980. By 1988, a population was known to be present at Driehoek Farm, in the headwaters of the Crocodile River near Dullstroom in Mpumalanga; specimens were also being sold illegally by the pet trade. The then Transvaal Nature and Environmental Conservation Directorate started an eradication programme by reducing the water level in the dam and physically removing crayfish by hand. It seemed that the elimination programme was completely successful but a survey of the same farm in 2016 caught a single, very much alive, adult male. Since individuals of the species do not live for longer than 6 years or so, several generations have clearly survived in the dam since the 1980s. These crayfish are exceptionally destructive predators that have already been responsible for the elimination of invertebrate communities, and thus vital fisheries, in Lake Naivasha in Kenya (see text box on Lake Naivasha on page 298). Today, they occur in numerous streams and ponds over several hundred square kilometres of Central and East Africa. Although this species is detrimental in many ways, it does seem to have one good use: it eats snails as part of its diet, and where it occurs the number of bilharzia-hosting snails is considerably lower than they would otherwise be.

KKPCW/ Wikimedia /CC BY-SA 4.0

Procambarus clarkii*, the highly invasive crayfish from North America.*

It seems that ***Procambarus*** has not been able to establish itself elsewhere in South Africa, but several other species of crayfish have been introduced, three from Australia, and one from Europe. They are spreading over large parts of central Africa and conservationists are very concerned that one or more of these species will find its way into the Okavango swamps or Lake Victoria, with disastrous consequences. To find out more about these dangerous invaders, see the article in ***The Conversation*** by Ana Louisa Nunes from the Centre for Invasion Biology at Stellenbosch University (link in the list of websites at the end of this chapter).

It is well known that freshwater fishes are the most threatened single group of animals on the planet. The major reasons for this, other than fishing, are pollution, abstraction of water and physical degradation of habitat. In some places, like the CFR, however, these threats pale into insignificance in relation to the devastation caused by invasive alien fishes. The species that has the greatest effect is probably ***Micropterus dolomieu***, the smallmouth bass, a voracious piscivore (fish-eater) from the USA. Other species of bass have also been introduced into South Africa, but they are less common in the fast-flowing mountain streams where most of our highly threatened native fishes occur. Trout, particularly the rainbow trout, ***Oncorhynchus mykiss,*** were introduced to the region before bass were, and were the first invaders to have significant effects on the distribution ranges of the native fishes. The question is, why do small local redfins tend to disappear when trout invade a stream? Do the trout eat the redfin, or out-compete them for food or living space? In his PhD thesis, Jeremy Shelton showed that predation is a factor, in that large trout can consume small redfins, although the mystery is not entirely solved because trout are not essentially fish-eaters (as bass are), nor do they have identical food requirements.

Rainbow trout Onchorhynchus mykiss*: a favourite target of anglers but an exotic competitor of our local minnows.*

We have numerous other introduced species of fish in South Africa. In his PhD thesis, Sean Marr investigated the effects of introductions in general on fish assemblages in South Africa and mediterranean-climate regions elsewhere (see reading list). He estimated that about 17 species of alien fish have successfully invaded the waters of the CFR. They include carp and bluegill sunfish, as well as various small aquarium fishes. Perhaps the greatest threat at the moment is ***Clarias gariepinus***, the sharptooth catfish, which is native to all of Africa bar the south-western Cape, and also occurs in the Middle East. This fish grows to a length of nearly two metres (some fish!), eats virtually anything, and is able to survive in waters of very poor quality. Specimens have recently been found in various streams and vleis in the south-western Cape. We don't know who put them there, or why, but if any fish can cause havoc with our remaining small fishes, this one can. We can only hope that it is not introduced into the small streams where most of our ghieliemientjies (the small redfin minnows) live because even if the catfish cannot survive there for long, they are likely to fatten themselves up on a diet of little natives before they themselves die out.

Catfish aside, how do we conserve these vulnerable native fishes? Obviously, an improvement in habitat quality, water availability and water quality will help, but all of these will be of no avail if the alien fishes are not removed. As we write, controversy rages. On the one hand, many people like to fish for bass and trout. On the other hand, there is no doubt that they threaten the existence of local fishes. In an attempt to cater for both angling and conservation interests, CapeNature has divided the rivers under its jurisdiction into zones, the idea being that alien fishes will be permitted to exist in certain rivers, particularly those in which they are well established, while certain other rivers should be kept free of invasive fishes

Hanay /Wikimedia /CC BY-SA 4.0

Clarias gariepinus*, the sharptooth catfish, is a highly efficient piscivore. It can move over land and climb or jump over small barriers in the water.*

and managed specifically for the conservation of native fishes. Now that's all very well, but the next question is, how do we get rid of the alien fishes in the 'native fish' streams? Many of them can be caught by rod-and-line or netting, or even by electro-fishing, where an electric current passed into the water causes the fish to float to the surface, from which they can be collected. But it is virtually never possible to catch and remove ***all*** of the fish from a stream in this way. The only remaining option seems to be to eliminate them from the river by poisoning them – and there's the rub. There are actually two entirely different reasons for people opposing the use of poisons such as rotenone to eliminate invasive fish. The first is that rotenone is not selective and will kill any gill-breathing organisms in the water, including insects and tadpoles. This is clearly a valid concern, and the use of rotenone has to be used with great care to see that the damage done to non-target species is minimal. The second is the mistaken idea that any attempt to remove exotic angling fishes is 'the thin end of the wedge', and that eventually all non-native fishes will be eliminated from our rivers. No ecologist would advocate the first – the use of poison – if there were any other choice, but there does not seem to be an alternative at this stage. Those of us who support the use of rotenone do so simply because the native fishes are under such extreme threat that several species could disappear forever at any moment. Many of them have not yet become extinct only because they live in the uppermost reaches of streams, above waterfalls or other barriers that prevent the alien fish from reaching them. If the barrier fails, or some idiot throws a few bass or trout into the stream above the barrier, then that population of natives will undoubtedly become extinct. In summary, the use of rotenone is an emergency measure necessary to preserve the biodiversity of our native fishes. It is not advocated for removal of alien fishes generally but sometimes it is the best, maybe the only, solution to a difficult problem.

***Oreochromis mossambicus**, the Mozambique tilapia.*

Angling has been popular in South Africa for more than a hundred years.

We should point out that many populations of native fishes throughout the world are threatened by introduced alien fishes of all kinds. Two other examples from Africa demonstrate slightly different issues. The first is a typical example of the effect of a voracious predatory fish on native fishes: the introduction of the Nile perch (***Lates niloticus***) into Lake Victoria, threatening and causing the extinction of dozens of species of small cichlids in Lake Victoria. A detailed account is given in Tijs Goldschmidt's book ***Darwin's dream pond*** and the documentary ***Darwin's nightmare***. The other example is a little different. As well as the small fishes threatened by the perch in Lake Victoria, Africa has many larger-bodied species commonly known as tilapias or chamba. These fishes are extremely important sources of protein for local communities, so several species have been translocated from one water body to another, either to support commercial or semi-commercial fisheries, or for aquacultural (fish-farming) purposes. Cichlids tend to interbreed quite easily

Rixie / 123RF

A local fisherman casting his net in the shallower waters of Lake Naivasha.

Lake Naivasha, a large lake by South African standards, is situated in the African Rift Valley in Kenya. Although it has no surface outflow (i.e. it is endorheic), the water remains fresh because of subsurface drainage. In its natural state it was oligotrophic with blue water lilies on the surface, and dense stands of several species of ***Potamogeton*** in the water. The fringe of papyrus filtered river water entering the lake. As far as I can ascertain, there was a biodiverse invertebrate assemblage of about 80 species, while the lake's only fish was the endemic ***Aplocheilichthys antinorii***, a small killifish in the family Poeciliidae; ***A. antinorii*** was last recorded in 1962.

The number of alien species that have been deliberately introduced to the lake is astonishing. It seems that largemouth bass were the first to be introduced – in the 1920s – for sport fishing, together with a small bream (a common name for tilapias) as a forage fish for the bass. Several other species of bream followed and a gillnet fishery opened in 1959. Then sometime in the early 1970s, ***Procambarus clarkii*** was found in the lake. Apparently, it had been imported to eat the weed that was entangling the propellors of motorboats being used by guests at the new hotels popping up around the lake. The crayfish soon became a staple commercial catch, together with the bream. By 1975, fishermen on Lake Naivasha were exporting 15 tons of crayfish a year to Scandinavia, whose native crayfish populations had recently crashed.

In the meantime, an entrepreneur in the area imported coypu, large South American rodents, for the fur trade. Some coypu escaped and made their way to the shores of the lake. Now like rodents everywhere, coypu are vegetarians. They and the crayfish killed off most of the submerged macrophytes and virtually all of the water lilies in the lake. This left a 'vacant niche' on the water surface, which was quickly colonised by the next invader – ***Salvinia molesta***, or Kariba weed. Today ***Salvinia*** comes and goes, covering fairly large areas at times, but it is often driven into small bays by the wind. It seems not to be a major problem and there have been only minor biological control programmes to deal with it. Also, in the mid-1980s, water hyacinth, the arch-villain of plant invaders, appeared in the lake. It has been problematic ever since, sometimes forming dense stands covering large areas. It has been subject to some attempts at biological control but, as is the case almost everywhere that the weed occurs, these efforts have not been particularly successful.

On the bottom, the crayfish, which had been provided with good cover by the submerged weeds, had nowhere to hide and were feasted on by the bass. Bream declined in numbers too, though, because they no longer had cover for their eggs, which were also consumed by the bass. We haven't finished yet, however. Flower farmers in the area were opposed to the presence of the coypu, which ate their crops. So, they decided to combat the coypu by introducing pythons along the shores of the lake. The locals did not like the idea of living with an additional snake population so they beat the pythons to death.

From the 1980s to 2000, catches were dominated by bream. The next villain in the invader train was the European carp, ***Cyprinus carpio***, said to have been introduced accidentally in 2002 – although it's not clear how this is possible: dropping a couple of wriggling carp out of your pocket when you are looking for your cellphone, maybe? Anyway, following their accidental introduction, carp appeared in catches in 2002 and by 2010 comprised almost the entire catch. Carp now sustain a major fishery, filling a previously vacant benthivorous niche; they compete with crayfish and each seems to keep the other's populations in check. In just the last few years, though, there has been yet another shift. This time it is not in the presence of species, but the size of populations of the commonest species. The Nile tilapia, one of the breams, now dominates commercial catches. But watch this space: the sharptooth catfish, ***Clarias gariepinus***, one of the most voracious predators of the fish world, now has a toe-hold (fin-hold?) in the lake. Remarkably, though, that other villainous alien, the Nile perch (***Lates niloticus***), which did occur briefly in Lake Naivasha some years ago, has not been seen in the lake for decades now. Odd, and interesting.

Lake Naivasha is a remarkable living laboratory. It has changed from being a biodiverse oligotrophic lake with a single species of small fish supporting a few lakeside dwellers to a cauldron of productive introduced fishes supporting a huge commercial fishery of about a thousand tons a year. The increased productivity must be driven by the nutrients entering the lake from the flower and other horticultural industries on the shores. The lake is also affected by pollutants entering from the growing town of Naivasha, while considerable quantities of water are abstracted for irrigating flower farms. Kenya is currently the third-largest exporter of cut flowers in the world.

Nahhan / 123RF

A close-up of Kariba weed (Salvinia molesta), one of the alien invaders introduced into Lake Naivasha and in several large reservoirs or lakes where they have been introduced, the original species appear to give way to hybrids. Concern has been voiced that the original species may soon disappear, to be replaced by just one or two hybrid 'species' throughout the continent: extinction by hybridisation.

The Law of Unintended Consequences relates to the introduction of alien organisms as much as it does to so many other human activities. We need to remember that, out of their natural environments and away from their natural predators and diseases, introduced species are an enormous threat to natural environments and native species. If there is any intention to introduce a 'new' species to an area, careful research needs to establish the limits of its potential as a pest. Even then we are unlikely to be able to predict all possible responses of the species to the set of environmental conditions into which we plan to introduce them, nor can we guarantee that they will confine themselves to the conditions into which we place them. We should never forget that one of the characteristic features of living organisms is an ability to adapt to new conditions by the process of natural selection, the mechanism whereby evolution occurs.

ALIEN SPECIES: MICROBES AND WATERBORNE DISEASES

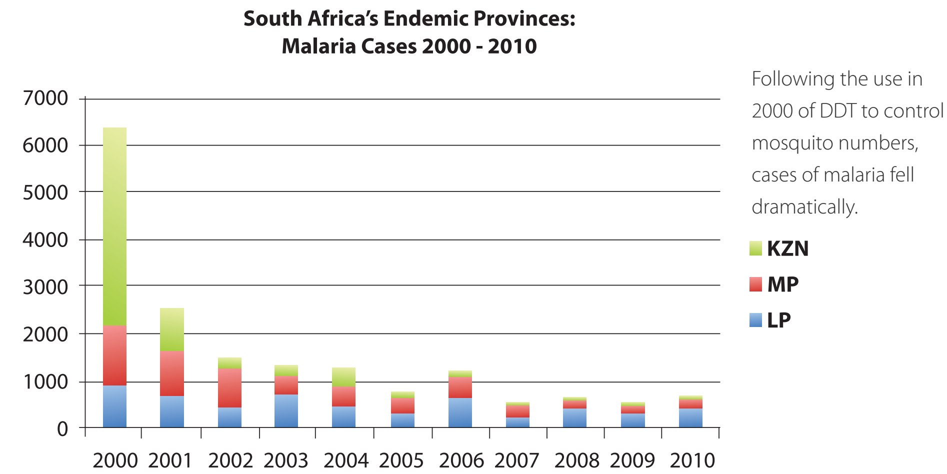
Even pristine aquatic ecosystems support some species that look upon humans as suitable hosts. Standing waters are habitat for snails and mosquito larvae and copepods, for instance, while certain pathogenic microbes are able to survive in standing or running water, sometimes for long periods of time. Nonetheless, many South Africans do not realise that rivers, wetlands and impoundments may foster the vectors of parasitic diseases such as malaria and bilharzia, as well as infectious diseases such as cholera, diarrhoea and typhoid. Furthermore, new reservoirs create new environments for disease-transmitting organisms and alter the rivers below them, sometimes creating new and more favourable conditions for the spread of certain human diseases. Such environmental changes are particularly problematic throughout Africa because this continent is home to many water-associated diseases. Populations of disease-transmitting organisms such as mosquitoes and bilharzia snails may build up in new lakes, since both snails and the larvae of many malaria-transmitting mosquitoes prefer to live in still backwaters, usually where there is some rooted vegetation. In the case of bilharzia, snails may be free of the disease in a new lake until just one person suffering from the disease infects them by defaecating or urinating near, or in, the water. Thus, unhygienic habits, and chronic lack of adequate sanitation, will inevitably lead to infection of the snails, and subsequently of people swimming or fishing in such areas. Given the effects of climate change, the potential for the further spread of bilharzia and malaria in rural populations is very high throughout virtually the entire continent of Africa. Currently the vectors of both diseases do not occur in the south-western tip of the continent but if global warming continues as expected, malarial and bilharzial vectors may well become established in Cape Town.

These are not the only water-related diseases, of course. Many of our rural populations are ill-equipped to avoid diseases such as typhoid and cholera because of poor sanitation and minimal medical care resulting from geographical isolation, lack of funds or ignorance on the part of the people themselves. As we pointed out in our introduction to this book, provision of clean water and sanitation are probably the most urgent tasks facing most developing countries. Without clean water, waterborne diseases ravage poor communities. Every year at least 4 million people, mostly children under the age of five years, die from diarrhoeal infections including cholera, typhoid and rotavirus. In 2019, of a world population of 7.7 billion people, some 2.2 billion around the world did not have safe, easily accessible drinking water; 4.2 billion did not have adequate sanitation and 3 billion lacked handwashing facilities in their homes. A while ago an article in ***New Scientist*** indicated that diarrhoea and infestations by intestinal worms alone amounted to over 10% of the total burden of human diseases in developing countries, all because of poor sanitation and inadequate water supplies. By geographical accident, we in southern Africa are relatively well off, in comparison with the rest of Africa, as far as waterborne diseases are concerned. More tropical parts of the continent are exposed to scourges like onchocerciasis (river blindness), dracunculiasis (guinea-worm) and elephantiasis, as well as diseases familiar to us – malaria, typhoid, cholera and bilharzia. Below, we discuss some of the major waterborne diseases of Africa.

MALARIA

Malaria, one of the better-known parasitic diseases, is alive and well and spreading in southern Africa and in the rest of the world. It currently infects over 300 million people every year, and between 1 and 3 million of them will die, mostly African children. Within South Africa, control of malaria is considered to be more important than the control of any other parasitic disease and is the only notifiable illness of its kind. (Bilharzia, more widespread here, is not a notifiable disease, while the bacterial disease cholera and typhoid are.) Malaria is endemic to most of the northern parts of South Africa, including northern KwaZulu-Natal, as well as to northern Botswana and the Caprivi and all countries further north in Africa.

Until a few years ago fewer than 5 000 cases were recorded in South Africa every year, almost all of them in Mpumalanga, Limpopo and KwaZulu-Natal. In the mid-1990s, the number shot up, reaching more than 40 000 in KwaZulu-Natal in 2000, probably because of an increase in insecticide-resistant strains of mosquito and drug-resistant strains of the malarial parasite, as well as the influx of people from Mozambique looking for work in South Africa. In such an emergency, DDT

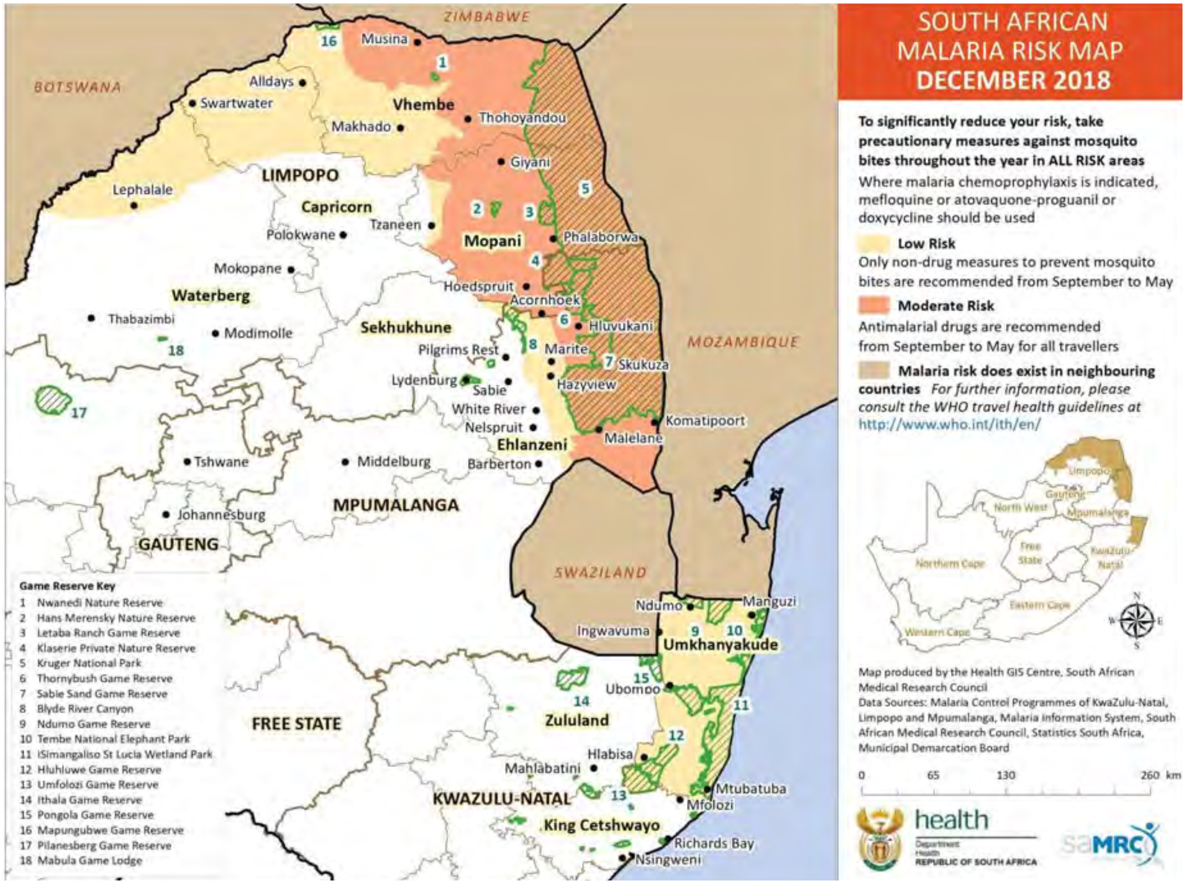


Number of cases of malaria in South Africa from 1989 to 2006 (from Moonasar D et al, 2012)

US Department of Health and Human Services

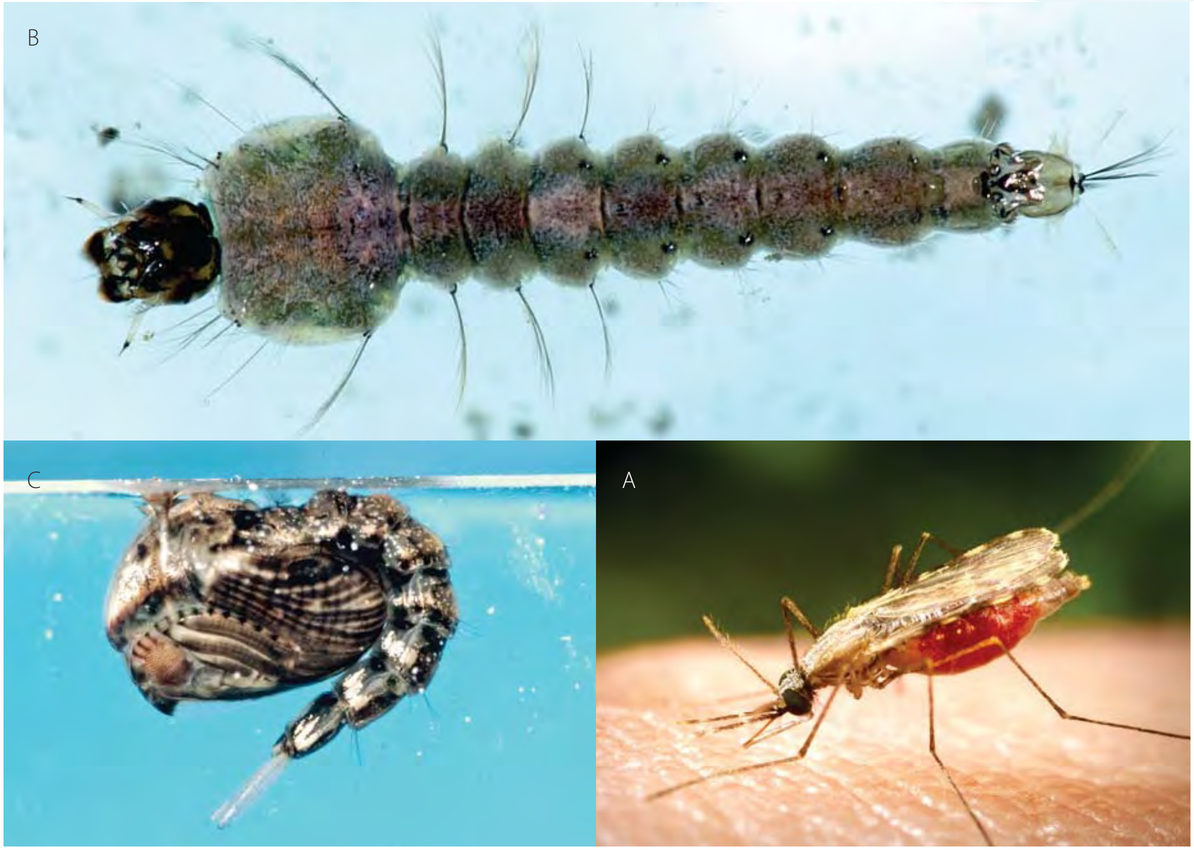
A house in Kenya being sprayed with insecticide to combat malaria.

DoH / MRC



Malaria risk map for southern Africa. Malaria is currently found only in the north-east of South Africa but is likely to spread further south and west as temperatures rise.

became the insecticide of choice, and a new anti-malarial drug, artemisinin, was used to combat the disease itself. Why DDT? Because it had been banned (even in South Africa) since the 1970s, so mosquitoes were not resistant to it, even though they were to virtually all other available insecticides. Control of mosquitoes was very successful, particularly in KwaZulu-Natal. At that stage there would have been no need to continue to use DDT because pyrethroids were effective against all other mosquitoes in the area, and there was a serious threat that they would become resistant to DDT. Furthermore, to guard against resistance of target species the sensible way to use insecticides is to rotate them so that there is no time for the insects to become genetically 'used to' them. The efficacy of the combination of the anti-malarial drug artemisinin, and DDT was remarkable. Within the space of a couple of years, the number of cases (and deaths) was brought back to pre-1995 levels. This case illustrates various things, not least the incredible ability of organisms (in this case both mosquitoes and malarial parasites) to become resistant to chemicals that are toxic to them.



Stephen Marshall

Stephen Marshall

James Gathany/USA CDCs

The stages in the lifecycle of a mosquito. Females (A) lay eggs in slowly flowing or still water. The larvae (B), after feeding on particles in the water, pupate (C) and two or three days later emerge as adults. Males feed on nectar but females need a blood meal to provide protein for their eggs.

More and more cases were seen in Mpumalanga and Limpopo, though. It is difficult to ascertain if the mosquitoes there could have been controlled by less harmful insecticides, but DDT has in fact been used from that day to this. Now it is very interesting that DDT may no longer be imported (and the only three countries currently manufacturing it are – have a guess – China, North Korea and India), and yet stockpiles in South Africa seem to be growing rather than shrinking. Numbers of cases of malaria varied between 10 000 and 30 000 over the years 2015-2019 and so the National Department of Health has developed plans to eliminate the disease (i.e. no ***local*** transmission) by 2023. They plan to achieve at least 95% coverage with "key vector suppression strategies and interventions" for the period 2019-2023, although these strategies are not spelt out. They must include a continued mosquito-spraying programme, I presume (and using which insecticides, I wonder?).

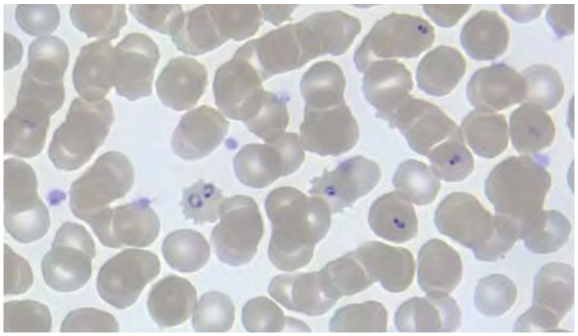
Malaria is caused by several species of the protozoan parasite ***Plasmodium.*** The parasites are transmitted by female mosquitoes of the genus ***Anopheles,*** themselves blood-sucking parasites of mammals. (The word 'parasite' has an interesting etymology: from the Greek: ***para*** = beside; ***sitos*** = food. The word was given by ancient Greeks to 'friends' who habitually visited as the family was sitting down to the main meal of the day and who, out of courtesy, were invited by their hosts to join them at table.) The mosquitoes are equally parasitized by ***Plasmodium,*** becoming hosts but also suffering from the mosquito equivalent of malaria themselves. The lifecycle of malarial parasites is illustrated on page 303.

In southern Africa, two species of mosquito are vectors of malaria. They are ***Anopheles funestus*** and ***Anopheles arabiensis.*** Their larvae and pupae live in quiet, sheltered, slow-moving or still waters ranging from irrigation canals, reservoirs, ponds and vleis to farm dams and shallow, short-lived rainstorm puddles, not to mention water-tanks and abandoned tin cans and motorcar tyres. Females lay rafts of eggs on the water surface. The eggs soon hatch and the young larvae feed by sweeping small particles of detritus into their mouths. After moulting four times, the larvae pupate and soon after, the adults emerge. If an adult male feeds at all, he feeds on nectar and other plant juices. But a female needs a protein-rich meal so that she has sufficient energy and nutrients to mature her eggs. If the mammal from which she feeds has been parasitised by ***Plasmodium,*** then when the mosquito feeds, she may take up blood containing malarial parasites and herself become parasitised. If this occurs, the parasites will grow and develop, eventually reaching the stage known as the sporozoite in her salivary glands. When she bites a human, she injects an anticoagulant that prevents her delicate mouthparts from becoming clogged with clotting blood while she feeds, and also a short-acting anaesthetic so that the host does not feel the bite. (Components of this anticoagulant cause irritation and itchy weals on our skins.)

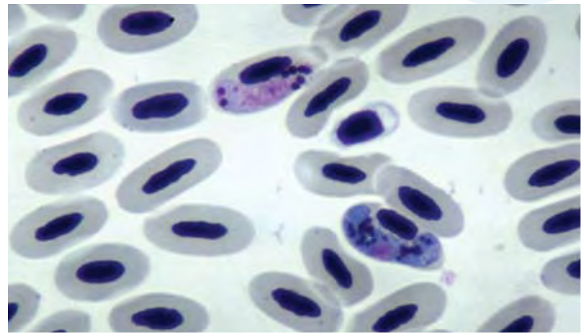
The malaria parasites take a free ride from the salivary glands of the mosquito directly into the bloodstream of their new human host. After a short time, the sporozoites will enter liver cells, where they reproduce by fission (splitting: asexual reproduction or cloning that builds up numbers). The hundreds of new parasites (now called merozoites) eventually rupture the vandalised and now-dead liver cell and re-enter the bloodstream of the human host. Each may either re-invade a new liver cell, producing more merozoites, or may attack red blood cells. Those merozoites entering blood cells will multiply again to produce more and more merozoites, which eventually rupture those red cells. Many infected red cells tend to burst more or less simultaneously, each releasing a large number of parasites and all their accumulated waste products. While the parasites go on to infect new liver and blood cells, perpetuating the cycle, the waste products in the blood cause symptoms of the disease in the host. These products are toxic and cause a shock to the system, resulting in fever and torpor. The constant-temperature environment within the warm-blooded mammalian host ensures that reproduction is synchronised. So parasites escape from the red cells approximately every 24 or 48 hours, resulting in the regularly recurring or cyclical fever that is a characteristic feature of some forms of malaria.

The key feature (zoologically speaking) of this cyclic event now comes into play. Sooner or later, some of the merozoites within infected blood cells start to prepare for sexual reproduction, changing into forms called male and female gametocytes. At the same time, the fever caused by the synchronised release from damaged red cells of parasites and their wastes makes us torpid and very hot, so pushing up the rate at which we burn energy. We breathe shallowly and rapidly, exhaling large quantities of carbon dioxide into the atmosphere with each breath. Now mosquitoes normally home in on their hosts using heat-sensitive and carbon-dioxide-sensitive sense organs. And here we are, producing even more heat and carbon dioxide than usual: we are unwittingly acting as beacons, saying to a mosquito, "I am a particularly attractive food-source and rather helpless too". So, when the unsuspecting mosquito feeds, she draws in a parasite-laden blood meal, full of gametocytes that are now ready to reproduce in her, while we are too ill even to swat her! The cycle is completed when a male and a female gametocyte fuse (undergo sexual reproduction) in the intestinal wall of the mosquito. The results of reproduction are new sporozoites, which migrate to the salivary glands, waiting to be injected into a new host when the mosquito has her next meal.

Different species of ***Plasmodium*** infect a wide variety of vertebrates, from humans to lizards and birds. Five species are known to infect humans. Of these, ***P. falciparum*** is the most life-threatening; ***P. vivax*** and ***P. ovale*** are less dangerous. ***P. malariae*** generally causes less serious illness but the parasites may remain hidden in the liver for many months after infection, and can unexpectedly cause a new bout of fever at any time. A fifth species, ***P. knowlesi,*** which commonly infects various monkeys has only recently been recognised as also infecting humans in south-east Asia. It, too, can be fatal if untreated.



MichaelZahniser, public domain



Plasmodiumlady /Wikimedia/ CC BY-SA 4.0

Malaria-infected red blood cells: left: several infected cells in a human blood smear; right: just two of these bird blood cells are infected; in both cases the parasites have been stained with a purple dye to make them visible as small purple enclosures within the blood cells.

In the 1960s, malaria disappeared from many parts of the world in which it had been endemic. This was the result of a massive, almost global, campaign to eradicate malaria. The campaign was successful in most of Asia, all of Europe, Australia and North America. Africa was more or less ignored. Today, however, malaria is spreading once again instead of decreasing. For many reasons, the original impetus was lost in the 1970s. More so, the feeble attempts in Africa allowed a reservoir of infected people and mosquitoes to remain on the continent. At the same time, we were spreading the habitats of mosquito larvae by building artificial lakes and farm dams, by not supplying prophylactics in sufficient quantities, by social upheaval and warfare (particularly problematic in African countries recently), and through air travel. Despite a good deal of research, effective vaccines have still to be perfected (but see below). To add to our troubles, an alarming number of people are dying as the result of a strain of ***Plasmodium falciparum*** resistant to all drugs except artimisinin, although since it has been on the market for a decade or more now, there are probably resistant strains even to this. Having just typed those words, I looked at the internet only to find that – yes, malarial parasites resistant to artemisinin and its allies have already emerged – this time along the border between Cambodia and Thailand. It won't be long before they travel with their human hosts to other parts of the world.

Recent reports have given some glimmer of hope for the future, however. The first vaccine against ***Plasmodium falciparum*** has recently been approved by the World Health Organization (WHO) for infants between the ages of 5 and 17 months. Unfortunately, the biology of the parasites means that it is very difficult to develop an effective vaccine (see the website listed at the end of this chapter), not least because humans who have recovered from the disease do not readily develop immunity to it.

Research workers in various parts of the world are currently participating in a programme with a different target, though: the mosquito, and not with chemical insecticides but with a natural and deadly enemy of mosquitoes, a bacterium, ***Bacillus thuringensis***. An ability to control mosquitoes using biological agents is very exciting from a number of points of view. Firstly, it eliminates the environmentally destructive use of insecticides against the adult mosquito. Secondly, damage to the aquatic environment by the use of oils (that prevent mosquito larvae from coming up to breathe) and larvicides can be avoided. Thirdly, the bacterium can be mass-produced. Lastly, it is harmless to organisms except for mosquitoes and other related insects. (Having said that, I hope that statement is correct. We have blithely made similar claims before, only to find out later that we were wrong!)

Another completely different approach is to produce transgenic (genetically modified) mosquitoes. ***Aedes aegypti*** is a mosquito that does not transmit malaria, but it does transmit a number of very nasty diseases such as zika, dengue, chikungunya and yellow fever. Batches of male ***Aedes aegypti*** have been modified to contain a gene that kills their daughters while the daughters are still larvae. The males will mate with normal females, who will produce genetically modified sons, and daughters that die before 'adulthood'. The first batch was released into various areas in the Everglades in Florida (USA) in mid-2021. The boxes of transgenic males were strategically hidden in various places in the swamps. Why hidden? Because various groups of human residents are opposed to the release of the insects and have threatened to spray insecticide onto the released males and kill them. Why? Maybe the mosquitoes represent another vile conspiracy on the part of the EPA!

If the dependence on DDT doesn't scare you, have another look at the section on organochlorines like DDT on page 238 and on EDCs (endocrine disrupting compounds) on page 267. Then also see the paper by Heather Malan and colleagues (Malan et al 2009) that asks the question, "Wetlands and invertebrate disease hosts: are we asking for trouble?"

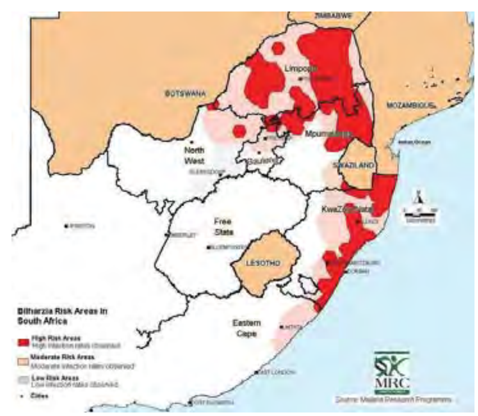
BILHARZIA (SCHISTOSOMIASIS)

"Africa has great potential, but with every mile of waterway 'opening' Africa, goes bilharzia with its 'quiverful of arrows', striking man down, and to put it at its lowest, making him an uneconomical labour unit." This 1956 quotation from William Alves, for many years the Director of the Malaria and Bilharzia Research Laboratory in Salisbury, Southern Rhodesia (now Harare in Zimbabwe), poignantly reminds us that bilharzia is a major force to reckon with in Africa. Indeed, it has a long history: bloody urine caused by one form of the disease (urinary bilharzia) has been recorded in at least 50 ancient Egyptian papyri and calcified eggs have been found in Egyptian mummies dating from about 1200 B.C. Ironically, water-development projects that are designed to uplift humans rather than to bring disease upon them are still unwittingly spreading the disease through the creation of favourable habitats for snails.

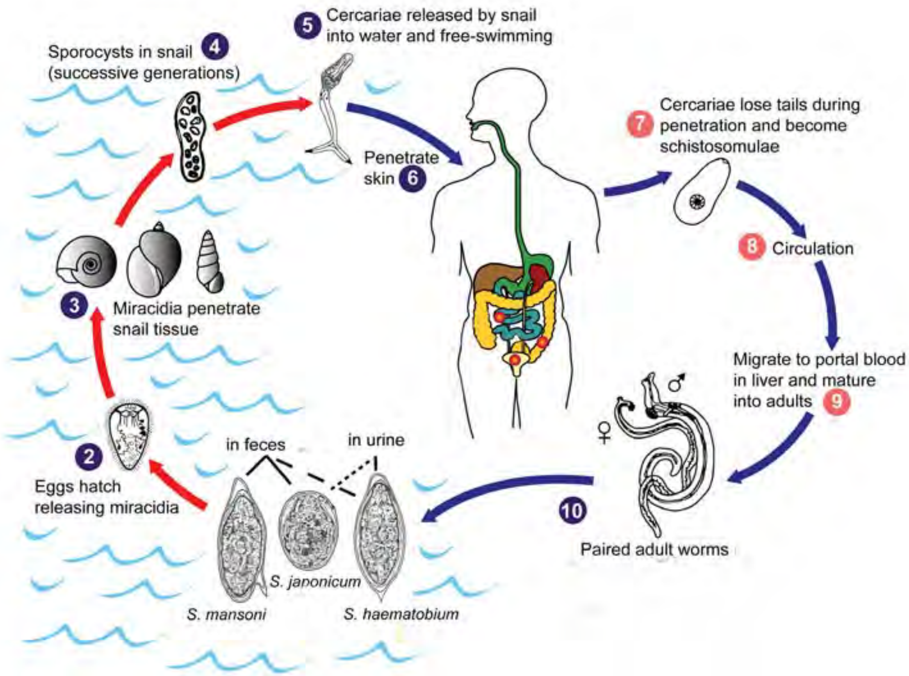
Bilharzia (schistosomiasis) currently afflicts approximately 240 million people worldwide, including 2 million in South Africa, although possibly only 10% of infected people show serious symptoms of the disease. Even so, 10% translates into 200 000 sufferers. In addition, even those who do not show full symptoms of bilharzia are apparently predisposed to a wide variety of other chronic diseases. Yet many Africans treat bilharzia with disdain. Indeed, in some cultures, the disease has become an integral part of custom and ritual. In parts of Africa the ability to pass black, or discoloured, urine – a symptom of urinary bilharzia – is considered an essential part of initiation and the transition from childhood to the mysteries of adulthood.

Bilharzia is caused by parasitic flatworms belonging to the Phylum Platyhelminthes. The disease is not just the prerogative of South Africans. It is found throughout Africa, and indeed worldwide, with a number of species in the Middle East, Southeast Asia, the West Indies and parts of South America. In Africa, three species infect humans: ***Schistosoma mansoni*** and ***Schistosoma intercalatum*** parasitise the blood vessels draining the intestines of humans and cause intestinal biharzia, while ***Schistosoma haematobium,*** which lives in the blood vessels of the bladders of humans, causes urinary bilharzia. ***Schistosoma japonicum*** is the intestinal form of the parasite in the Far East, while ***S. mansoni*** also afflicts humans in the north-eastern parts of South America. All species are parasites of both humans and a vector organism, an aquatic snail. Because this book focuses on southern African issues, we will be dealing with the two bilharzial organisms most common here: ***S. mansoni*** and ***S. haematobium*** (see distribution map below). In the case of ***S. mansoni,*** the snail vector rejoices in the name of ***Biomphalaria pfeifferi,*** while ***S. haematobium*** infects one called ***Bulinus*** (***Physopsis***) ***globosus.***

Quayle et al. 2010



Bilharzia risk map for South Africa. Bilharzia, too, is currently found only in the north-east of South Africa but is likely to spread further south and west as temperatures rise.



Lifecycle of Schistosoma*; see text for details.*

A beach cleaner holds a handful of freshwater snails pulled from the banks of Lake Victoria in Uganda. These small snails often harbor schistosomes.

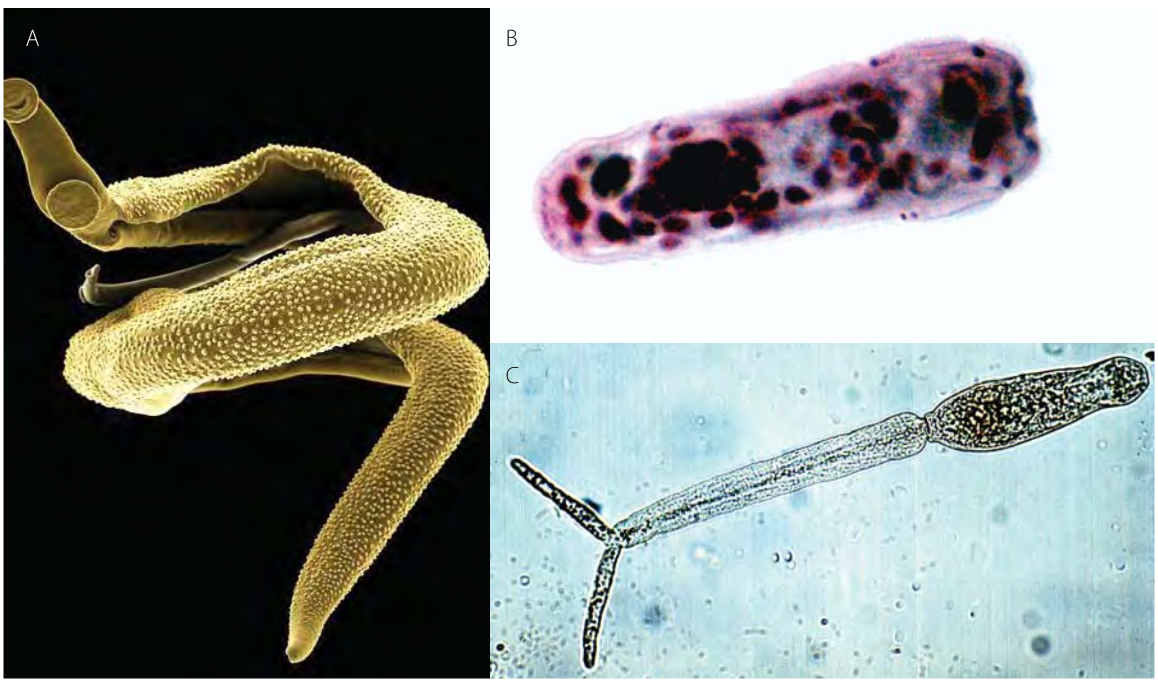
Both species of snail live in and feed on vegetation that grows in marginal shallows and backwaters. Infection of humans takes place when thousands of small larvae called cercariae (the 'arrows' in the quotation above from Alves) escape from the liver of an infected snail into the surrounding water. The cercariae are sensitive to light and swim towards illuminated areas, thereby staying in upper or shallower waters. Using a variety of chemical and physical cues, a cercaria will swim around and if it finds a human it will attach to the skin and then secrete a suite of powerful enzymes that rapidly penetrate through the skin, alllowing it to enter the body. One of the many remarkable features of this phase of the transmission of the disease to humans is that cercariae emerge from their snail hosts at those times of the day when people are most likely to be collecting drinking water, washing clothes, or just cooling off after the activities of the day – times when people are most vulnerable and most likely to be near water. The migration of the larva through a human body is remarkable for its complexity. After it has penetrated the skin it finds its way to the lymphatic system and eventually into the bloodstream, where it is passively transported around the body: through the heart and into the lungs in the venous system, back to the heart in oxygenated blood and from the heart in the arteries, ultimately entering the blood vessels draining the intestines or bladder wall. Here the worm matures, feeding on blood cells and plasma. The adults are remarkably well adapted to their mode of life. Living in narrow, tubular blood vessels, they are themselves elongated and cylindrical, about 10 – 30 mm long but only 0.1 – 1.0 mm wide. Unusually for the group of worms that they belong to, human schistosomes, have separate sexes and must find a mate. The male is stouter than the female and, once mated, the female lives in a ventral groove in the male for the remainder of her life. Like many parasites, schistosomes live in their food. Expending no energy for foraging, the females turn their energies to reproduction. The parasitic lifestyle, although providing many advantages, also has many hazards, not least of which is the mortality incurred in the chancy business of finding the next host and reaching maturity. So several hundred eggs are laid daily in a continous production line that, over the half dozen years or so that the female may live in a human, will ultimately amount to tens or to hundreds of thousands of eggs. There is no direct route of escape from the human body for the eggs, which are flexible and bear a hook. As eggs are swept along in the bloodstream, the hooks catch in blood vessel walls, causing blockages and an accumulation of other eggs behind them. This ultimately leads to rupture of the blood vessel and allows at least some of the eggs to reach the outside world in the faeces (in the case of ***S. mansoni***) or urine (***S. haematobium***) of the host. In heavy infestations it is often at this stage that the victim first notices signs of trouble, when damaged blood vessels bleed into the bowel or the bladder, and the breakdown products of blood, often black, become visible. People with heavy worm infestations (and heavy loads of eggs that fail to escape from the body) often become tired and listless, and generally feel 'under the weather'.

Poor sanitation aids the spread of the disease, for eggs deposited in or near water, either in faeces or urine, will eventually hatch to produce a small ciliated larva called a miracidium (plural: miracidia). The miracidium can swim and is equipped with sense organs that can locate the snail that will form its host for the next phases of the lifecycle. If it finds a suitable snail, the miracidium bores into the snail's body and makes its way to the liver. Here the miracidium undergoes asexual reproduction to produce many new larvae called sporocysts. Each sporocyst in turn also reproduces asexually to produce many so-called 'daughter sporocysts'. Ultimately, each daughter sporocyst produces many cercariae, also by asexual reproduction. Eventually many thousands of cercaria, derived from a single miracidium, are ready to leave the infected snail and find the next human host. Be careful where and when you swim: the snails favour slow-moving water with plenty of vegetation.

Both of us have taught many aspects of zoology: indeed, together we somewhat frighteningly 'clocked up' more than 70 years of teaching experience! One of the many delights of teaching is the feedback we receive from our audiences, particularly our students. The story below is a case in point. Bryan taught parasitology to first-year students at UCT for well over a decade. During one of the lectures in 1995, a student, whose surname is Bilharz, made herself known and anxiously enquired if she could expect lectures on bilharzia. (The lectures followed very soon after.) Her family name was just too much of a coincidence and although asked her origins – German – she had no idea that there might be any direct connection between her name and 'bilharzia', the common name given to schistosomiasis. A short while after her examinations Ms Bilharz unearthed an article in a parasitology text that was unknown to us. The article contained some fascinating anecdotes (some of which were quoted in the opening paragraph of this section), relating to the history of the 'discovery' of the disease and its importance in the development of the science of parasitology. For instance, we read that the surgeons accompanying Napoleon Bonaparte's conquering armies in Egypt at the turn of the eighteenth century were the first Europeans to note the disease, because 'haematuria', or bloody urine, became a common feature of life for the invading troops. Discovery of the causal agent was to wait a further 50 years until a young German, Theodor Bilharz, linked haematuria to a worm he named ***Distomum haematobium***. Tragically Bilharz died prematurely, aged 37, from typhus. He was Ms Bilharz's great-uncle. A little later, in 1858, researchers noted that owing to its peculiar structure, the worm named ***Distomum*** by Bilharz had to be renamed, and a scientist called Weinland renamed the worm ***Schistosoma haematobium*** because of the 'split body' of the male worm. Independently, a few months later another scientist, Cobbold, named the genus ***Bilharzia*** after its discoverer. Unfortunately, according to the International Code of Zoological Nomenclature no organism may have more than one Latin name. Although the term 'bilharzia' became the popular one, so much so that soldiers in the First World War had the slang name 'Bill Harris' for the disease, the first revised name, ***Schistosoma,*** given by Weinland, took precedent. Theodor Bilharz is still remembered, though, in that most people still call the disease bilharzia and most have never even heard the formal medical term 'schistosomiasis'.

In terms of its importance in the development of parasitology as a science, schistosomiasis became a source of scientific controversy by the turn of the nineteenth century. With the discovery of eggs possessing differently positioned spines, terminal or lateral, doubts were raised as to whether ***S. haematobium*** was one or two species. Confusion was exacerbated by the discovery of both types of egg in the faeces of individual humans. Ultimately, one of the founders of modern parasitology, Sir Patrick Manson, decided that there were two forms of the worm, one associated with the urinary tract, the other with the intestines. The second of these now bears his name: ***Schistosoma mansoni***. Interestingly, Manson came to his conclusion when he found laterally-spined eggs of ***Schistosoma*** in the faeces (but no eggs of either type in the urine) of a man from the West Indies who had never been to Africa. (Indeed, the occurrence of schistosomiasis in the New World is due primarily to the slave trade.) So ***S. mansoni*** possesses eggs with lateral spines, and ***S. haematobium*** with terminal spines.

Although some parasitologists agreed with and adopted



Jenny Day

Chris Appleton

The stages in the lifecycle of Schistosoma*, the parasite that causes bilharzia. A) a pair of breeding adults (false colour, scanning electron microscope image): note (top left) the two anterior suckers of the male. The robust male, about 10 mm long, holds the slender (only partly visible) female in a groove in his body; B), the minute aquatic miracidium larva (about 25 μm) that bores into the skin of its snail host, where it reproduces many times, eventually producing numerous cercaria larvae (about 250 μm) (C), which bore into human skin.*

Manson's view of the two forms of the disease, others did not, and some heated debates and wonderfully witty comments are associated with the argument. For instance, the eminent German parasitologist Professor Looss disagreed with the notion of two species and even went so far as to say that he had noted both forms of egg in the uterus of ***S. haematobium.*** This 'observation' elicited the remark from a proponent of the two-species notion, a scientist named Sambon, that until Professor Loos could "…show me an actual specimen, I am bound to place the worm capable of producing the two kinds of eggs with the phoenix, the chimaera and other mythical monsters."

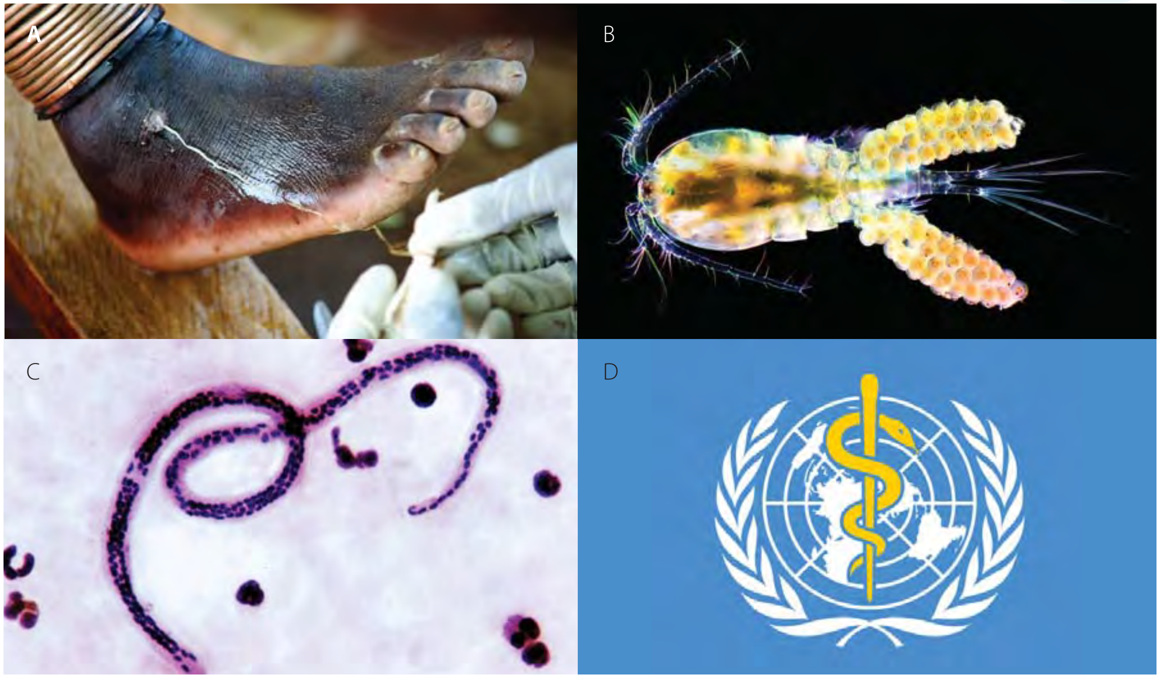
Over the past few years, the WHO has pushed for the elimination of snails as the best solution to the problem of schistosomiasis worldwide. It has provided guidance on the use of molluscicides by public health institutions. Two documents have recently been published by the WHO, one on field application of molluscicide and the other containing guidelines on the evaluation of molluscicides. It also encourages pesticide producers to develop new molluscides. It is disappointing at the very least to see that the WHO seems to rely entirely on toxic chemicals for controlling this disease and makes no mention of any potentially detrimental side-effects on other aquatic organisms or the environment itself. South Africa, I am pleased to say, has taken a different approach. School children are treated with the anti-bilharzial drug Praziquantel, which is said to be very safe and effective. If the cycle of infection is broken in this way, the disease will eventually disappear in the treated areas.

OTHER HELMINTH DISEASES

Guinea worm (Dracunculiasis) of West and Central Africa is caused by the nematode roundworm ***Dracunculus medinensis*** (the Biblical 'fiery serpent', or guinea worm). The disease is waterborne in that it is contracted by humans when they drink untreated water containing living copepods of the genus ***Cyclops.*** Copepods are tiny filter-feeding crustaceans that in some waters are infected with roundworm larvae. If humans drink water containing infected copepods, the bodies of the copepods are digested by the human digestive juices and the larval worms, which are resistant to digestion, are released. They penetrate the gut wall of the human host, grow, reach maturity, and mate in subcutaneous tissues during the following twelve weeks or so. After mating, the adult female worm (usually just one), which may reach a length of almost a metre, migrates through the subcutaneous tissue to the host's foot or ankle, arriving in position some nine months or so after the original infection. Here, she releases fluids that blister the skin of the host. Eventually the blister bursts, causing a weeping and painful ulcer. Into this ulcer she gives birth to as many as a million tiny first-stage microfilarial larvae over the next month or so (note that living young, not eggs, are produced). Humans with such lesions of the skin will naturally seek relief by regularly bathing them in water; at this stage the larvae enter the water, at least some to be ingested by other specimens of ***Cyclops*** and so to complete the lifecycle. Interestingly, this awful disease is one of the oldest for which treatment is recorded. Described in the Old Testament of the Bible, the treatment involves bathing the lesion to induce the female to protrude her posterior, as she gives birth to her young, and then placing a thin stick over her body. Apparently, she frequently coils her body around the stick and can then be slowly (and painfully) twisted around the stick until the entire worm is removed. (Is this the source of the medical caduceus – a serpent coiled around a staff?) This is not a very pleasant process and is not to be recommended!

As well as being one of the first human parasites to be recorded, it may well be that ***Dracunculus*** will also be the first to become extinct. Former US President Jimmy Carter began a campaign to eliminate it in 1986, at which stage there were about 3 million cases per year. The campaign has been remarkably successful. The parasite was last recorded in India in 2002. In 2010, Nigeria triumphantly announced that the disease had been eliminated from the country. In 2022, the number was down to 14 cases: 1 in Ethiopia, 2 in Mali, 7 in Chad and 4 in South Sudan. Can you think how Carter and colleagues solved the problem? It's incredibly simple. First, local people were told about the lifecycle of the worm, so they knew not to drink water until it has been boiled. But where this wasn't possible, they were provided with drinking straws with a very fine mesh on the end. They realised that boiling drinking water would kill the larvae, but also that if they drank river water through the straw, copepods would be filtered out – and the disease would be avoided.

It looks as if the world will soon see the last of the Fiery Serpents, but there is one last thing to report. There is a group of people calling themselves the ***Save the Guinea Worm Foundation***. I can't quite decide if this is a tongue-in-cheek



Louis Gubb / The Carter Centre

Andrei Savitsky / Wikimedia / CC BY-SA 4.0

Jenny Day

WHO

A) A female guinea worm being extracted from the foot of its human host; B) a cyclopoid copepod, about 1 mm long; C) a microfilarial larva, about 300 µm in length, in human blood; D) the rod of Asclepius on the flag of the World Health Organization.

exercise, or if they are serious, but they are advocating a campaign to save "the world's most endangered species". I guess that they are volunteering to host the remaining guinea worms in their own bodies (see http://www.deadlysins.com/guinea-worm).

Filariasis, which is arthropod-borne, is caused by parasites of a number of related nematodes that have tiny thread-like microfilarial larvae. Not everyone who contracts the disease is badly affected, but sometimes the larvae get caught in lymph nodes of the host. ***Elephantiasis*** occurs when these microfilarial larvae block lymph nodes and cause massive swelling and deformation of extremities, particularly the legs, vulva, breasts and scrotum. The disease is known as elephantiasis because legs can swell to several times their normal diameter; there are also reports of male sufferers having to transport their scrota in wheelbarrows. ***Wuchereria bancrofti,*** the nematodes that most commonly cause this debilitating and visually horrible disease, is found in Africa and the Far East, and is transmitted by mosquitoes of the genus ***Culex***.

Another filarial disease is ***River Blindness***, which is endemic to West Africa but also occurs in parts of central and South America, a relic of the slave trade. The microfilarial larvae of the nematode parasite ***Onchocerca volvulus*** tend to accumulate inside the eyes of their hosts, eventually causing blindness. The disease is known as River Blindness because it is transmitted by blackflies (the aptly named ***Simulium damnosum***), whose larvae live in rivers.

Guinea worm and all other nematodes with microfilarial larvae have been known on occasion to cause elephantiasis. About 250 million people worldwide are presently infected with filarial worms, 120 million of them with elephantiasis.

SOME WATERBORNE DISEASES OF THE GUT

CHOLERA

Cholera is a waterborne bacterial disease all too familiar in southern Africa. The relationship between cholera and inadequate water supplies has long been known, and yet the disease still regularly takes its toll. Good sanitation is a prerequisite for the elimination of this scourge, but good sanitation costs money. The availability of clean water for drinking and washing is still inadequate in most of our rural areas, townships and informal settlements, so outbreaks of the disease are likely to continue. The recent outbreak in Harare was a result of the complete breakdown of the water purification system as that city ran out of funds during the hyperinflation of the Zimbabwean dollar. Cholera, caused by the enteric bacterium ***Vibrio cholerae,*** can spread with frightening rapidity. Routes for infection include any untreated or unboiled water; vegetables or fruit washed in contaminated water; food handled by infected people; contamination of food or water by faeces from an infected person; contamination of food by flies that have been in contact with infected people or their faeces; and direct contact with an infected person.

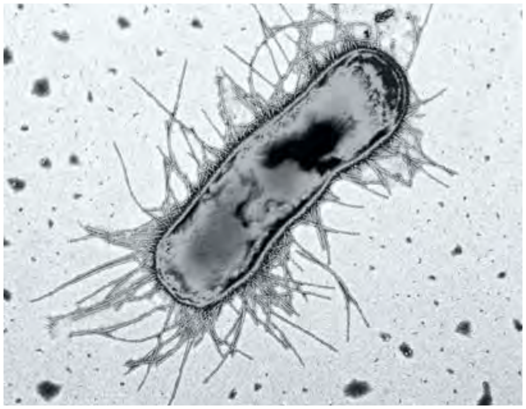
The fact that cholera is waterborne was established as long ago as 1854 in London, well before bacteria were discovered. Ingested *Vibrio* bacteria multiply rapidly in the human gut, irritating the wall of the intestine and causing massive outpourings of fluid, accompanied by acute diarrhoea. It is not the diarrhoea that kills but the accompanying uncontrolled loss of body fluids, which leads to rapid dehydration and shock: death can occur within a frighteningly few hours of initial infection. The spread of the disease is complicated by the fact that people may unwittingly 'carry' the disease while showing no symptoms whatsoever. Effectively, cholera should be a rare disease but a common infection. Simply boiling water before drinking, washing or preparing food will destroy the organism, so cholera is an easily preventable disease. The symptoms can be just as easily treated by providing the victim with a dilute salt solution (what is known as oral rehydration therapy: sachets of the appropriate salts are readily available) to drink, although very serious cases may require intravenous administration of fluids. Of great concern, but hardly surprising, Zimbabwean microbiologists have shown that in the 2018 outbreak, *Vibrio cholerae* was resistant to several antibiotics previously effective in curing the disease.

OTHER DIARRHOEAL INFECTIONS

Many other waterborne diarrhoeal diseases lie in wait for the unwary. For instance, although **typhoid** is commonly contracted through the ingestion of food or milk contaminated with the typhoid bacterium ***Salmonella typhi,*** the disease can also be waterborne. Water supplies may become contaminated by human faeces when sewage enters water supplies. A common feature of the disease is its prevalence when water purification systems break down during natural disasters such as floods and earthquakes, or when civil wars break out, or when refugees congregate in massive numbers in makeshift camps. Like the pathogen that causes cholera, *Salmonella* is a bacterium. It causes gastroenteritis accompanied by headaches, abdominal pain, vomiting and diarrhoea. Young children and the frail are most vulnerable to the disease and, as in the case of cholera, a permanent supply of clean water, reduced overcrowding in human settlements, and provision of adequate sanitation will go a long way toward reducing the ravages of this disease.

Another common waterborne diarrhoeal disease of Africa (indeed, common globally in the tropics and subtropics) is **amoebic dysentery**, which can also be caused by ingesting contaminated food. Unlike cholera and typhoid, amoebic dysentery is caused by a protozoan parasite but, like them, it inhabits the intestines and may also invade the livers of humans. In most people, the amoeba, ***Entamoeba histolytica,*** causes no harm, but if the organism invades the tissue of the intestine through a fissure or rupture, then diarrhoea follows, with an accompanying loss of blood. Fortunately, the disease is relatively easily controlled if medical support is at hand.

Escherichia coli or *E. coli* is a bacterium that occurs universally in the intestinal tracts of warm-blooded vertebrates: humans, other mammals, and birds. Most strains are harmless and are probably useful members of the intestinal flora. Some strains of ***E. coli*** cause an 'upset tummy', while a few, including the infamous strain 0157:H7, cause severe diarrhoeal illness known as haemolytic uraemic syndrome, attacking the intestine and kidneys. 0157:H7 is a leading cause of death in young children in the USA and causes the deaths of children and the frail in Africa and elsewhere. Its natural home seems to be the intestines of cows, which explains why children occasionally pick it up when they visit a farm. It will come as no surprise to the reader to note that multiple-drug-resistant strains of ***E. coli*** have been found in Europe (which probably means that they occur worldwide).



University of Washington

An electron micrograph of E. coli*, about 2µm long.*

E. COLI AS AN INDICATOR OF FAECAL CONTAMINATION

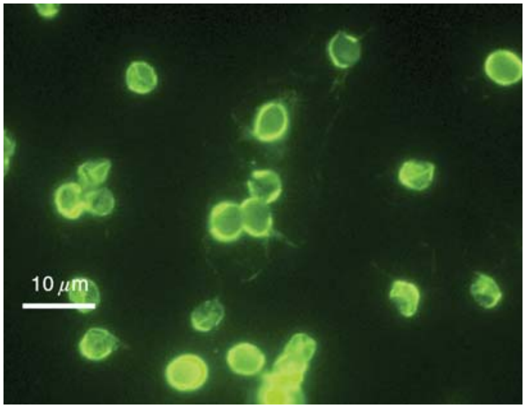
E. coli is a famous organism because it is the microbial equivalent of a guinea pig, being very commonly used in bacterial research. Because it is found universally in the guts of humans, it is also widely used as an indicator of human faecal contamination of water. Various ways can be used for measuring the numbers of ***E. coli*** in a sample of water (see the US Department of Agriculture website listed below for details). The European Union (EU) uses a standard of zero cells of ***E. coli*** per 100 ml for drinking water and 1 000 cells per 100 ml for the recreational use of water. Above 1 000 cells 100 ml, water is regarded as unacceptably contaminated for recreation (swimming, boating and so on). Of interest is the fact that the aptly named Black River in Cape Town has been so badly contaminated by sewage overloads on occasion that the 'faecal coliform count', as it is known, reached several ***billion*** cells per 100 ml of water – a truly horrendous figure. Later, water quality in the river improved enormously as a result of upgrading of the Athlone WWTW but once again ***E. coli*** counts are well above the EU--recommended levels down the entire length of the Liesbeek and Black rivers.

Indeed, it is likely that many South African rivers and wetlands, both urban and rural, are severely contaminated by faecal pathogens, particularly where informal settlements house poverty-stricken communities with no waterborne sanitation and meagre water supplies. Liz Day has produced an excellent report on Cape Town's water quality that deals in some detail with ***E. coli*** and sewage contamination in general (see Reading List).

Finally, we must add ***giardia*** and ***'crypto'*** to our list of waterborne intestinal diseases (and there are many others that we do not have space to mention here). ***Giardia intestinalis*** is a flagellated single-celled protozoan, a parasite of the human gut and urinary tract. It normally does little harm, but recently a number of strains have developed that are difficult to get rid of and can cause severe diarrhoea. Fortunately, giardiasis can be relatively easily treated if medical assistance and the appropriate drugs are to hand, but this is frequently not the case in rural Africa. ***Giardia*** is hard to remove from drinking water using current water-purification treatments.

Eva Nohýnková /Wikimedia /CC BY 4.0

The intestinal protozoan parasite Giardia lamblia *(10-20µm), stained to show cellular details.*



HDA Lindquist, Microbiology, US EPA

The intestinal protozoan parasite Cryptosporidium parvum *(5μm), immunofluorescence image.*

Cryptosporidium is another waterborne protozoan parasite that is becoming more common – or perhaps it has always been fairly common but is only recently becoming recognized as a source of gastroenteritis (diarrhoea, nausea and stomach cramps). 'Crypto' is a small protozoan parasite found naturally in the intestines of cows and sheep. It is problematic when it gets into public water supplies because it is very small, and therefore hard to remove from water by filtration, and it is also resistant to chlorination, the most common way of disinfecting drinking water. It is fortunately easy to treat at household level because it is easily killed by bringing the water to boiling point. The largest outbreak was in Milkwaukee in 1993, when 400 000 people were infected as a result of a meat corporation dumping infected animal waste into a public storm sewer (Naughty!). While most people survive infection with Crypto after a couple of days of discomfort, young children and the frail are particularly susceptible to the organism.

If contamination of water is so common, **how do we deal with it?** Obviously the most important thing is to maintain the strictest standards of hygiene, ensuring that hands are washed after going to the toilet, that food is carefully washed before it is eaten, and that water that is in the least suspect is boiled before drinking or even for washing fruit and vegetables. Poor people often do not have these luxuries, though, especially where fuel is in short supply so that there is no boiled water for washing. Sometimes water purification tablets, which contain small quantities of hypochlorite (bleach), are provided by aid agencies. Although effective, these taint the water so that it tastes odd, and so they are often ignored by the people to whom they are given. (See a brief discussion of SoDis on page 269 and at https://www.cdc.gov/safewater/solardisinfection.html.)

ARBOVIRAL DISEASES

Arbovirus ('arthropod-borne virus') diseases are transmitted by blood-sucking arthropods. As far as water-related arbovirus diseases are concerned, the most important vectors are blackflies of the family Simuliidae. Blackfly larvae are filter-feeders in fast-flowing streams, while adults (usually only females) are ectoparasitic on mammals, sucking their blood. Because the larvae feed on particulate material being washed down a stream, they thrive where humans have increased the flow of water in rivers. Many species of ***Simulium,*** the most common genus, occur in Africa. Although in southern Africa they do not transmit any severe human diseases, blackflies have become important to us because of their economic impact and also because of their sheer nuisance value, particularly below the dams on the Vaal and Orange rivers. Feeding adult blackflies may transmit arboviral diseases, which can cause enormous stock losses. But they do not have to carry a disease to have an effect on mammals. Unlike mosquitoes, blackflies do not have neat piercing-and-sucking mouthparts. Instead, they make a jagged hole in the skin and pour saliva onto the wound to prevent clotting while they lap up the blood. Thus even the simple feeding attentions of a large swarm of blackflies can be painful enough, and cause sufficient loss of blood, to result in spontaneous abortions in cattle and sheep, or to kill relatively large stock animals simply through anaemic shock as a result of loss of blood. One can easily imagine the irritation that swarms of blood-sucking flies could cause humans if they can bleed a cow to death. And a single bite can be ***very*** painful.

Some years ago staff of DWAF, the Veterinary Research Centre at Onderstepoort, and the CSIR experimented by varying discharges from the dams of the Orange-Vaal River system, alternately flooding and drying out the riverbed in an attempt to kill off larval blackflies. Steve Mitchell (***pers. comm.***) mentions that "the economic cost of controlling ***Simulium*** larvae in the late winter by cutting the flow back for a limited period might be worthwhile. Basically, there is

Left: A local blackfly, Simulium ruficorne. *Right: The bite of a single female blackfly.*

Blackfly larvae attached to reed.

a conflict between what this would mean in terms of loss to irrigated agriculture by stopping the flow and the loss of livestock production by not stopping the late winter flow." He notes that blackflies were not a problem before irrigation kept water in the river in late winter, allowing large numbers of larvae to overwinter and resulting in a big blackfly outbreak in the spring. Manipulating flow does cause less havoc downstream than simply pouring insecticides into the water (as has been done in this country and many others in the past) but it may well play havoc with the biotas of the downstream stretches of the rivers. On the other hand, drying the river bed may also affect the blackflies' natural enemies. Blackfly larvae can replace their numbers very quickly, since they grow very rapidly from egg to mature aerial insect, while some of their invertebrate predators have much longer replacement times. More recently, bacterial control agents have been employed in the same way that we have already described for the control of malaria, but using blackfly-specific strains of the bacterium ***Bacillus thuringiensis.*** Recently Rob Palmer assessed the efficacy of this environmentally-friendly approach to blackfly control at Upington and, despite a scare when a helicopter came down somewhat precipitously (fortunately with no serious injury), there appears to be a great future for this approach. The programme seems currently to be inactive, though.

READING LIST

Bilharz T (1852, translation 1982) A contribution to human Helminthology. ***Reviews of Infectious Diseases,* 4**: 727–732.

Brown DS (1980) ***Freshwater snails of Africa and their medical importance.*** Taylor & Francis, Ltd, London. 487 pp.

Farley J (1993) Schistosomiasis. Pp. 992–997 ***in***: K.F. Kiple (ed.), ***The Cambridge world history of human disease,* VIII:**124

Goldschmidt T (1998) ***Darwin's dream pond***. MIT Press, Cambridge, Massachusetts. 280 pp.

Hill MP, JA Coetzee, GD Martin, R Smith & EF Strange (2020) Invasive alien aquatic plants in South African freshwater ecosystems. Pp 97-114 ***in***: B van Wilgen, J Measey, D Richardson, J Wilson & T Zengeya (eds) ***Biological Invasions in South Africa. Invading Nature -*** Springer Series in Invasion Ecology, vol 14. Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3_4

Jones K (1994) Waterborne diseases. Inside Science no 73, ***New Scientist,*** 9 July, 1994, 4 pp.

Le Maitre DC, BW van Wilgen, RA Chapman and DH McKelly (1996) Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. ***Journal of Applied Ecology* 33**: 161–172

Malan HL, CC Appleton, JA Day & JA Dini (2009) Wetlands and invertebrate disease hosts: are we asking for trouble? ***Water SA* 35**: 753-768

Marr SM, LME Sutcliffe, JA Day, CL Griffiths & PH Skelton (2009) Conserving the fishes of the Twee River, Western Cape, South Africa: revisiting the issues. ***African Journal of Aquatic Science* 34**: 77–85

Marr SM, MP Marchetti, JD Olden, E García-Berthou, DL Morgan, I Arismendi, JA Day, CL Griffiths & PH Skelton (2010) Freshwater fish introductions in Mediterranean-climate regions: are there commonalities in the conservation problem? ***Diversity and Distributions*** https://doi.org/10.1111/j.1472-4642.2010.00669.x

Palmer RW (1996) Invertebrates in the Orange River, with emphasis on conservation and management. ***Southern African Journal of Aquatic Science* 22**: 3–51.

Percival S, M Embrey, P Hunter, R Chalmers, J Sellwood & P Wyn-Jones (2004) ***Microbiology of water-borne diseases: microbial aspects and risks.*** Academic Press. 480 pp.

Quayle LM, CC Appleton & CWS Dickens (2010) ***The effects of stream flow manipulation on the invertebrate hosts of malaria, bilharzia and liver fluke disease.*** Water Research Commission Report No. TT 456/10

Riddin T, E van Wyk & J Adams (2016) The rise and fall of an invasive estuarine grass. ***SA Journal of Botany* 107:** 74-79

van Wilgen B, J Measey, D Richardson, J Wilson & T Zengeya (eds) (2020) ***Biological Invasions in South Africa. Invading Nature -*** Springer Series in Invasion Ecology, vol 14. Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3_4

Wieber A, Longbottom J & 14 others (2017) Geographical distributions of African malaria vector sibling species and evidence for insecticide resistance. ***Malaria Journal* 16,** 85 https://doi.org/10.1186/s12936-017-1734-y

SOME USEFUL WEBSITES (ACCESSED 11.11.2022)

Anti-malarial vaccines:
http://www.malariasite.com

https://en.wikipedia.org/wiki/Malaria_vaccine#:~:text=A%20malaria%20vaccine%20is%20a,%2Dto%2Dhigh%20malaria%20transmission.

Artemisin-resistant *Plasmodium*
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4612278/

CABI Invasive Species Compendium
https://www.cabi.org/ISC

Diarrhoea statistics
https://www.cdc.gov/healthywater/global/diarrhea-burden.html

Dracunculiasis
http://www.deadlysins.com/guinea-worm

https://ourworldindata.org/guinea-worm-path-eradication

Introduced crayfish
https://theconversation.com/freshwater-crayfish-the-forgotten-invaders-wreaking-havoc-across-africa-58450

Invasive organisms, SA
https://www.arc.agric.za/arc-ppri/weeds/Pages/Legal-Obligations-Regarding-Invasive-Alien-Plants-in-South-Africa.aspx

https://www.sanbi.org/resources/infobases/invasive-alien-plant-alert/

https://www.dffe.gov.za/sites/default/files/gazetted_notices/nemba10of2004_alienandinvasive_specieslists2016_0.pdf

Lake Naivasha
https://www.researchgate.net/publication/224852502

https://www.academia.edu/45305153/The_aquatic_plant_communities_of_the_Lake_Naivasha_wetland_Kenya_pattern_dynamics_and_conservation

Malaria vaccine
https://www.who.int/news/item/06-10-2021-who-recommends-groundbreaking-malaria-vaccine-for-children-at-risk

https://www.malaria.org.za

Medical Research Council, SA, information on malaria
http://www.malaria.org.za/

Microbial water analysis
http://en.wikipedia.org/wiki/Bacteriological_water_analysis

Parasitology texts, free lownloads
http://get2pc.com/human%20parasitologyod38-1-w-0-0

SA malaria elimination plan
https://www.nicd.ac.za/wp-content/uploads/2019/10/MALARIA-ELIMINATION-STRATEGIC-PLAN-FOR-SOUTH-AFRICA-2019-2023-MALARIA-ELIMINATION-STRATEGIC-PLAN-2019-2023.pdf

SA legislation on invasives
https://invasives.org.za/national-legislation/

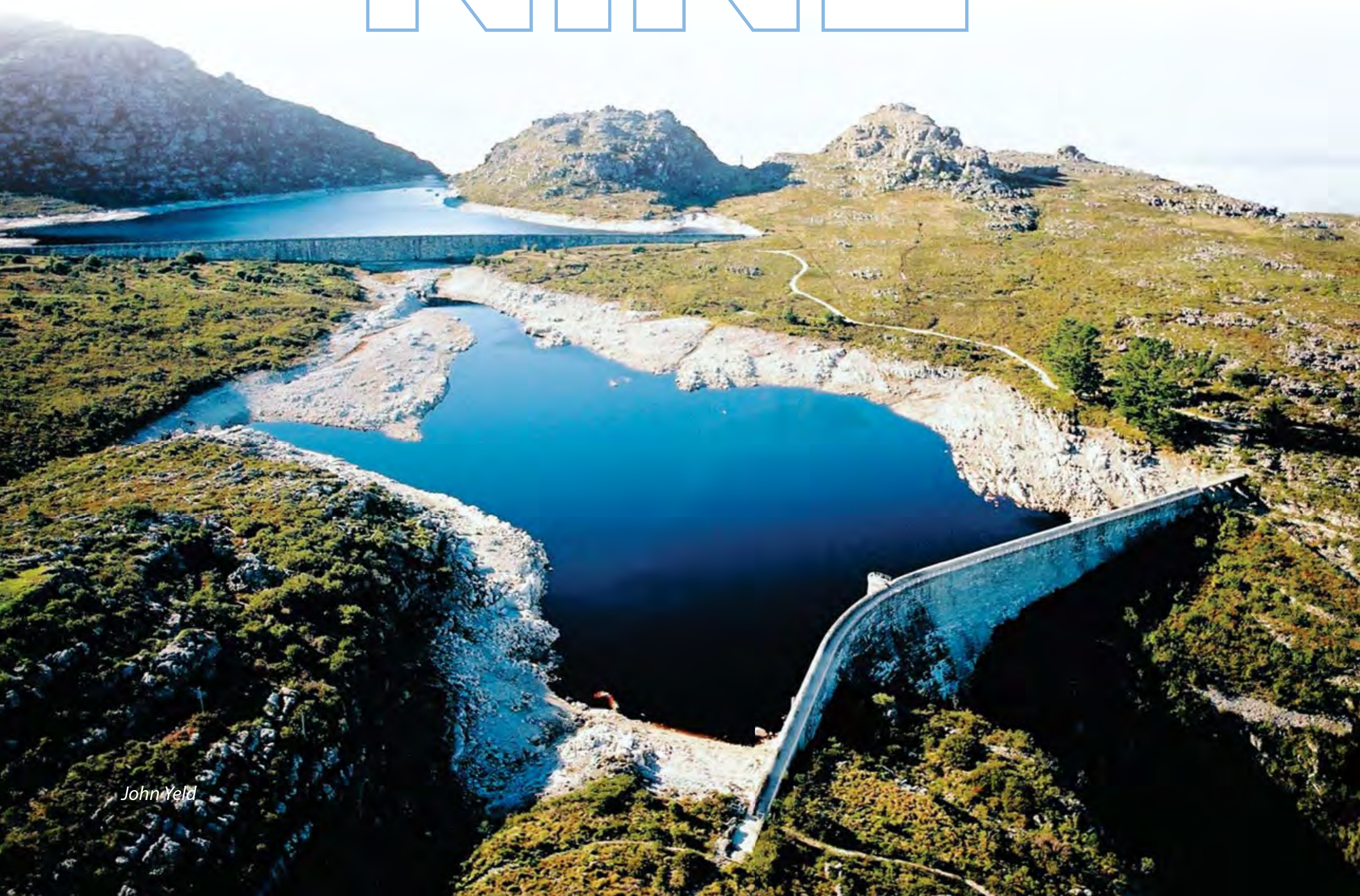
Transgenic mosquitoes
https://www.nature.com/articles/d41586-021-01186-6

US Department of Agriculture, microbial testing
https://www.fsis.usda.gov/sites/default/files/media_file/2020-08/1-EIOA-Micro-Sampling-Testing.pdf

Western Province State of Biodiversity Report 2018
https://www.westerncape.gov.za/eadp/files/atoms/files/04_Biodiversity%20and%20Ecosystem%20Health.pdf

WHO Global Health Risks
https://scholar.google.co.za/scholar?q=who+global+health+risks+2020&hl=en&as_sdt=0&as_vis=1&oi=scholart

CHAPTER NINE



John Yeld

Damming: the change from river to lake[1]

> There is far more important information about the history of hydroelectric (dam) construction in the USSR in Alexander Solzhenitsyn's Gulag Archipelago than in all the textbooks on hydraulic engineering.
>
> *Zeyev Volfson, The Destruction of Nature in the Soviet Union*

THE QUEST FOR WATER

In 1994 the South African Government promised to deliver piped water and sanitation to all South Africans before the 1999 elections. This promise was laudable, for adequate clean water is vital for the health and welfare of the people. The country also needs water in vast quantities to produce enough food, power, minerals and other goods to increase the Gross Domestic Product, to generate foreign exchange and to support the burgeoning human population. We face a dilemma, however, because aquatic ecosystems also need water for their very existence. We presently remove from rivers more than two-thirds of the amount of water that is, on average, available (that is, exploitable) every year. This means that in wet years quite a lot of water may be left in our rivers, but in dry years there is very little, if any. So, on the one hand, rivers are under serious threat because they cannot be rivers if they carry insufficient water. On the other hand, the amount of water available in South Africa is inadequate to supply even fairly modest demands. What is likely to be the fate of our rivers and wetlands? In Chapter 1 we mentioned the 'water crisis' that is facing us, noting that we are already in water deficit in many provinces. Water abstraction has converted many rivers from perennial streams to seasonal torrents that flow only during wet periods, and almost every South African river has been impounded, some by a series of dams[2] along their lengths. Rivers simply cannot sustain an ever-increasing loss of water: a point will inevitably be reached at which they are no longer rivers and are, therefore, unable to provide the ecosystem services that we expect rivers to provide (see Chapter 11). In an effort to counter the inequitable distribution of water in both time and space, gigantic and hugely expensive dams and inter-basin water transfer (IBT) schemes have been constructed in order to provide water in times of drought and to transfer water from river basins with water surpluses to those with deficits. Furthermore, damming of rivers for hydropower production is increasing globally. This chapter discusses the effects of dams, abstraction and transfer of water on the rivers involved.

GLOBAL 'QUICK-FIX'

How many dams are there on our planet? In his 1996 book ***Silenced Rivers,*** Patrick McCully estimated that there were then more than 40 000 large dams worldwide, as well as 800 000 or more smaller dams. The Paris-based International

[1]The effects of dams and inter-basin transfers of water on rivers was Bryan Davies' passion. I have updated this chapter but otherwise left it more or less as Bryan wrote it - Jenny Day

[2]The term 'dam' is often incorrectly used in South Africa. In most of the world, except here and in Australia, the dam is the wall that holds back the water, while the resulting water body is the reservoir or lake. Thus 'Hartbeespoort Dam' would be the dam wall, while 'Lake Hartbeespoort' would be the reservoir of water so formed. In this book we stick to the accepted South African use of 'dam' to mean both the wall and the water.

Commission on Large Dams (ICOLD) defines a large dam as one with a wall 'equal to or higher than 15 metres from base to crest' (about the height of a four-storey building). ICOLD has an additional category: major dams. A dam qualifies as major if the wall is more than 150 m from base to crest; or if the dam has a water storage capacity equal to or greater than 25 km^3, or if it can generate more than 1 000 megawatts (MW) of electricity (enough to power a European city of 1 million inhabitants). These are truly enormous structures. McCully estimated that there were ten such structures in 1950, and 305 scattered around the globe in 1995. Of the 40 000 large dams in existence at the time, all but 5 000 had been built since 1950. Currently nearly 50 000 major dams have been built, about 19 000 of them in China.

Some of these structures, testimony to the human drive to alter the planet's surface, have dimensions that stretch the mind. For instance, the highest dam in the world (at the time of writing) is the Jinping-I dam on the Yalong River, a tributary of the Yangtse River in China. At an extraordinary 305 m in height, the wall is an artificial mountain taller than the Eiffel Tower. (Tadjikistan has been attempting to build the 335-m high Rogun Dam for the last 40 years or more but currently does not have the money to complete the project.) Major dams are being constructed all over the world and it is difficult to rank them according to size. Table 9.1 provides some statistics of the world's largest dams, with a few African examples for comparison. Almost all very large dams are constructed primarily for generation of hydropower. Unlike the situation in water-stressed Africa, water for irrigation is seldom a consideration.

The gargantuan size of the Three Gorges Dam is emphasised by two massive ship locks.

Other statistics are equally staggering:

- Until recently the dam with the world's largest installed power capacity (12 600 MW) was the Itaipú, on the border between Brazil and Paraguay. Now the Three Gorges Dam delivers almost twice this: 22 500 MW. It produced a record-breaking 112 Terawatt-hour (TWh) in 2020, after a particularly wet monsoon season.
- The greatest area of land flooded by a dam is 8 500 km^2, flooded by the Akosombo Dam, which forms Lake Volta in Ghana. (The lake covers more than 4% of Ghana's land mass)
- The most water is stored by the Owen Falls Dam at the outlet to Lake Victoria. (This dam added a volume of 270 km^3 to the lake)
- China is planning to build a dam on the Brahmaputra River in Tibet to generate as much as 300 TWh a year. China has already built eleven large dams on the Brahmaputra River in Tibet, much to the concern of India, which lies downstream.

***Table 9.1.* The world's, Africa's and southern Africa's biggest dams (from various internet sources)**

Dam	River	Height & length m, km	Volume km^3	Length of reservoir km	Date
JinPing	Yalong	305, 568	7.4	150	2014
Three Gorges	Yangtse, China	215, 2 300	39.3 *	660	2006
Kariba	Zambezi, Zim & Zam	128, 579	180	280	1959
Aswan High	Nile, Egypt	111, 3 830	111	550	1970
Merowe	Nile, Sudan	67, 9 000	12.5	174	2010
Gariep	Orange, South Africa	88, 918	5.5	100	1971
Katse	Malibamat'so, Lesotho	185, 710	1.9	35	1997

**This seems very small, but the figure is apparently correct.*

On an international scale it is not surprising that China, the former USSR and the United States lead the field with regard to the number of large dams they have constructed. China's Great Leap Forward is illustrated by the fact that the country had only eight large dams at the time of the Communist revolution in 1949 and now has well over 22 000. With burgeoning populations and huge social problems, many developing countries have been seduced by developed-world technologies and have placed themselves in massive debt to build these monstrous structures – not all of which are as useful as they might be. Of direct interest to us is South Africa's seventh ranking in terms of the number of large dams. Engineers have certainly been busy. But have their efforts generally been beneficial? The answer is equivocal. As we mentioned above, most big dams are constructed for hydropower generation and relative to coal- or oil-generated power, the carbon footprint of hydropower is minute (but see below – it is not zero). On the other hand, the social and environmental consequences of damming rivers are huge. Although the decision as to whether or not to dam a river ought to be a trade-off between various competing advantages and disadvantages, nothing but economic (and hydropower) advantages have been considered in the vast majority of cases.

More than 10 000 km^3 of water is now stored behind the world's big dams. Looked at another way, this is more than five times the annual average volume of water flowing in all of the world's rivers. The total area flooded is equivalent to the size of California. More disturbing is the fact that much of the inundated land once boasted rich alluvial soils or virgin forests with high biological diversity. Furthermore, an article (Chao, 1995) in the journal ***Geophysical Research Letters*** suggests that the impoundment of these huge masses of water, over a timespan that is 'a blink of an eye' in geological terms, has even induced a '… slight but measurable impact on the speed at which the earth rotates, the tilt of its axis and the shape of its gravitational field.'

THE TROUBLE WITH DAMS

Mounting evidence suggests that the drive to construct more and more dams is often misguided. Dams may be offered as means of economic or human upliftment because they will increase production of electricity, or jobs, or fisheries, or irrigation (and hence food), or water supply, or because they will 'make the deserts bloom'. Yet a close examination of the economic, sociological and environmental effects of dams illustrates time and again that such benefits may be outweighed by the disadvantages, which may be catastrophic. To deal with them all would take a book like Patrick McCully's ***Silenced Rivers.*** Here we merely summarise some of his more interesting findings.

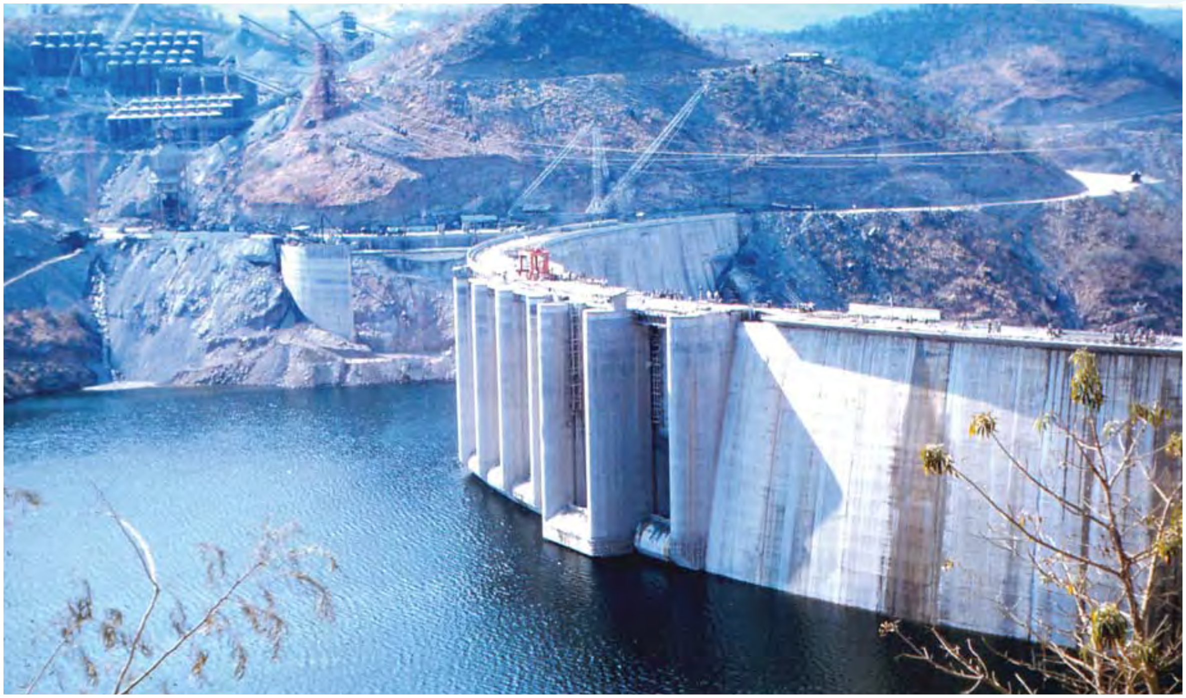
Dams are the main reason that 20% of the world's freshwater fish species are endangered. Dams have disrupted riverine migration routes, fragmented the habitats of fish, turned spawning grounds into lakes and greatly reduced the quantity of nourishing silts flowing onto nursery areas in floodplains, estuaries and the coastal zone. The irrigation schemes supposed to bring benefits from damming have led to problems such as over-watering, production of inappropriate water-hungry cash crops (like tobacco and cotton), waterlogged soils, and changes in water tables that may bring ancient salty and alkaline groundwaters to the surface of the soil, where they evaporate and make the land unfit for growing crops.

Often, and ironically, more fertile lands are lost under the waters of dams, or to the canal, road and pipeline infrastructure that is built to service them, than are gained through the implementation of irrigation schemes. Let us say that again: more fertile land is lost as a result of dams than is gained by the irrigation water they provide. One of the worst cases on record concerns the Bargi Dam on the Narmada River in India. This dam inundated 81 000 ha of farmland and forest, supposedly to irrigate 440 000 ha of crops. The dam was completed in 1986, but some seven years later it was irrigating only about 12 000 ha of land, less than one-seventh of the area lost to the reservoir. Another example from our own continent is the Aswan High Dam on the Nile River. One set of statistics will point to the enormous benefits to irrigation (and people) that this dam has provided. Another set will show that the area of irrigated land in Egypt has actually not changed since before the dam was constructed and that 100 000 ha of topsoil have been mined (for the manufacture of bricks) although topsoil is no longer replaced by the river because the life-giving silts of the Nile are now trapped upstream by the reservoir.

SOCIAL COSTS

Dams, particularly large ones, also incur social costs. It is conservatively estimated that more than 65 million people worldwide, often from politically weak minorities, have been forcibly removed from their homes as a result of dam construction. The Batonga of Kariba are but one such people. Thousands upon thousands of similarly dispossessed communities were often far more in harmony with their environments than are the huge irrigation schemes and agricultural systems that have replaced them. Large-scale forced removals have been reported from virtually every country where large dams have been built. Compensation for loss of land and homes has often been woefully inadequate. The vast majority of the dispossessed have melted into the cities while, in some cases at least, the wealthy now farm the abandoned areas.

In one notorious instance, the indigenous people who were earmarked to lose lands and homes as a result of the construction of the Chixoy Dam on the Rio Negro in Guatamala vigorously opposed the dam for over four years. The government retaliated by arranging the killing of two village representatives who presented the villagers' case, and later tortured and killed several hundred inhabitants of villages opposed to the dam. The World Bank, one of the funders of Chixoy, later reported that the resettlement plans for the people of the area were," …conceptually … seriously flawed". This having been said, it should be noted that in the last decade or two the World Bank has become far more responsible with regard to the social – and to some extent the environmental – consequences of the projects it finances.



Peter Seyffert

Kariba Dam between Zambia and Zimbabwe during construction in 1955.

ECONOMIC COSTS

Not only have human communities been inhumanely treated, but the benefits of large dams are often grossly exaggerated. Their costs are consistently underestimated. Referring to a hydroelectric scheme in Colombia, one wit wrote "If God had said 'Let there be Light' in Colombia, He would have run out of money for the rest of creation." Indeed, many poor and developing countries have spent vast amounts of money developing major power projects that either fail to produce the estimated amount of power (due to reservoir siltation, poor design or poor maintenance) or produce far more than is needed. The resulting debts incurred by such countries can be crippling; what is more, their meagre resources would have been far better spent on small-scale projects. In the case of Colombia, a third of that country's total public investment was consumed by the power-production industry in the 1990s and some 60% of that money has left the country to pay for services and goods produced in the developed world. Obviously there have been beneficiaries of this splurge of dam building but these have hardly ever been the local people.

Several additional features of large dams need to be explored. They include the contamination of reservoir waters by metals leached from drowned soils; the filling-up of reservoirs by silt; the catastrophic decline of riverine, floodplain and coastal fisheries; dam failure and ageing; and reservoir-induced seismic activity (RIS).

DAMS AND WATER QUALITY

Scientists have only recently become aware of the dangers of inundating large tracts of land bearing substantial quantities of heavy metals in the soils. Some metals are required in trace amounts by living organisms as components of enzymes and co-enzymes but are toxic at only slightly higher concentrations. Mercury in reservoirs has now become an issue in several parts of the world, from Finland to South Carolina and from northern Canada to Thailand. Mercury occurs naturally and more or less harmlessly in inorganic form in many soils. But as soon as the soils are inundated, bacterial action transforms the inorganic form to organic methyl mercury, which is extremely toxic, as well as accumulating through food chains.

In northern Canada, mercury levels in fish have increased six-fold in the reservoirs of the La Grande Rivière hydro power complex, part of the gigantic James Bay Project. In 1992, 64% of the indigenous Cree people, for whom fish are a major component of the diet, were reported to have blood-mercury levels far in excess of the recommended World Health Organisation limit.

In the San Joaquin Valley of California, the soils are rich in the essential trace element selenium, which in high concentrations is also toxic. Decades of irrigation of land in the Central Valley of California have led to the accumulation of selenium-rich leachates in rising saline water tables. The American Bureau of Reclamation planned to 'solve' the problem with a 250 km-long concrete drain to take the polluted water to San Francisco Bay. They got halfway when protesters halted the work. In 1978, the drain was ultimately diverted to the newly constructed Kesterson National Wildlife Refuge. In 1983, a group of biologists informed the media of the effects of the effluent on the reserve: birds were producing young with horrific deformities, among them, 'pretzel beaks', external stomachs, missing legs, exposed brains and warped wings. It took ten years and US$80 million to clean up the refuge. While the soils of the region still have naturally high levels of selenium, the problem is now recognised and irrigators and the public are learning how to deal with it.

DAMS AND SILTATION

As a river flows downstream, it weathers the rocks over which it flows, picking up minute particles of silt, clay, and sand. Some of these particles will become lodged between boulders or entrained in the sediment, but ultimately they will be washed to sea, land up on the ocean floor, and eventually become part of sedimentary rocks. When a barrier such as a dam is placed in the path of a river, this process ceases, and particles are moved donwstream only when the dam overtops or the sluices are opened.

Depending, then, on the geology of the rocks over which a river flows, greater or lesser quantities of sediment are trapped within the reservoir. In the long run, the capacity of the reservoir to store water is diminished until ultimately it ceases to act as a significant reservoir of water. The management of siltation in reservoirs is a matter of considerable importance because, after all, dams are very expensive to erect and need to perform the task for which they were erected in the first place. A less obvious consequence is an increase in erosion of the coastal zone, because beaches are starved of sediment.

A well known example of the effect of silt-trapping by a dam, this time a very large one, concerns the 221 m-high Hoover Dam on the Colorado River in the USA. In 1945, within 9 years of the closure of the dam, the river below the wall had cut down by 4 metres and had eroded 110 million m^3 of sediment from the first 145 km of river below the dam. This rendered bridge supports unstable, left irrigation systems high and dry, dropped water levels in wells and caused riparian vegetation to dry out and die. This would not have happened in the unmodified river because silt carried in the water would have been deposited along its length as current speeds increased and decreased seasonally.

A good-news story in a chapter like this one will almost invariably be about removal of dams. One of the largest river restoration projects in the USA was the restoration of the Elwha River in Washington State. Two badly conceived and constructed dams had been built on the river in the 1920s. They were removed for two main reasons. Firstly, the dams provided no fish ladders, so salmon disappeared from the river; secondly, the dams filled up so completely with silt that the river could no longer flow in its original bed. The restoration has taken many years but the Elwha River is beginning to look the way it once was.

Olympic National Park - Inset: Robert Ashworth / Wikimedia / CC BY 2.0

Reforestation taking place in the bed of the old Elwha River reservoir in Washington State, USA. (Inset shows the totally silted-up reservoir on the river)

One of South Africa's most sediment-filled dams is the Welbedacht, on the Caledon River in the Free State, which has lost more than 90% of its storage capacity due to siltation. In 2016, the CSIR estimated that nationally, about 10% of storage capacity has been lost, threatening water security, and therefore food security, ecosystems, and economic progress. At the time of writing, the South African Water Research Commission was developing a National Siltation Management Strategy for Large Dams (the NatSilt Programme – see link in the Reading List). The strategy includes improving catchment management by focusing on land-use practices and restoration, effectively attempting to treat the problem at the source. (As well as natural weathering processes, land clearance and soil erosion contribute significantly to sediment accumulation in dams.) Other management options include the construction of upstream 'check-dams' to aid in trapping sediments during flood events (although this means that yet another downstream stretch of river will be affected), and bypass schemes via tunnels or off-stream dams, as well as flushing or sluicing techniques. Sediment bypassing is not new in South Africa. More than 70 years ago, dams such as the Nagle, Henley and Shongweni in KwaZulu-Natal were designed with sediment bypass facilities. And currently, experts have recommended that such facilities be incorporated in the proposed Smithfield Dam in KwaZulu-Natal to help limit further coastal erosion.

DAMS AND THE COASTAL ZONE

An example of the important ways in which rivers affect the coastal zone comes from Namibia. The Epupa Hydro project, which has met implacable opposition from the Himba people who live in the area, will involve the construction of a large hydropower station on the Cunene River. Looking at the impacts of the proposed dam on the river, Rob Simmons and his colleagues noted that reducing river flow into the sea has serious implications for the future wellbeing of the coastal birds and turtles in the area. Most notably, the river water is warm, the mean monthly temperature lying between 18 and 30°C, because the river flows as it does through the Namib Desert. On entering the sea, the river forms a 270 km^2 warm-water plume that pushes deep into the very cold waters of the Benguela Upwelling Zone. A large dam could potentially decrease the temperature of the river, destroying this 'island' of tropical water in a very cold upwelling region and having disastrous consequences for two species of rare turtles for whom the mouth of the Cunene is the most southerly distribution point. The species concerned are the green turtle, ***Chelonia mydas***, and the soft-shelled turtle, ***Trionyx triunguis***. Further, the Cunene River mouth forms the second most species-rich coastal wetland for birds in Namibia and is an essential part of the Asian and European migratory bird 'flyway' to and from southern Africa. In this context, migratory waders would have to travel many hundreds of kilometres further south to find food and rest in the next coastal wetland in this exceptionally arid environment. Ronald Burmeister from Kubas, Namibia, kindly updated me on the situation with regard to the Epupa Dam: "The Epupa project has still not been realised and has effectively been shelved for its disruptive impact on Himba heritage sites. An alternative option is being pursued … but there is currently no clear indication as to when it will eventually take off." (The Epupa Dam should not be confused with the proposed Popa Dam, which would include a hydropower station on the nearby Okavango River.)

Hand Hillewaert / Wikimedia / CC BY-SA 3.0

The spectacular Epupa Falls on the Cunene River.

DAMS: FISHERIES, GREENHOUSE GASES AND AGEING

Any wall across a river acts as a barrier to the free movement of aquatic organisms and of the sediments that downstream areas and coastal seas require. In fact, the loss of riverine and coastal fisheries worldwide is possibly the single most important ecological and economic argument against large dams. Salmon are fish that spend much of their lives at sea but breed in rivers. Under natural conditions, each year the spawning fish migrate upriver in countless thousands. When dams block their passage, they cannot reach their traditional breeding sites in the cool upper reaches of rivers. Losses to the steelhead salmon fisheries in the Columbia River basin in the United States between 1960 and 1980 amounted to US$6.5 billion, while of the original 400 American Pacific salmon fisheries, only 214 remained. Of these, 169 are still endangered. Without a fish ladder to mount a dam wall, migratory fish are doomed to extinction but even fish ladders and other ways of navigating dam walls (fish lifts, capture-and-transport operations and so on), frequently do not work and only a fraction of the migrating animals survive to pass upstream. On the downstream run, salmon and other anadromous fish (fish that are born in fresh waters, mature in the ocean and return to spawn in the streams of their birth) in regulated rivers have to negotiate a reservoir or reservoirs and survive passage through turbines or release gates.

Similar stories can be told of economic and ecological damage elsewhere. For instance, the hilsa, an important food fish in the herring family, was deprived of 60% of its spawning grounds in the Indus River by Pakistan's Gulam Mahommed Dam and is now threatened by the Sardar Sarova Dam on the Narmada. The new dams on the Narmada have reduced the fishery and local dwellers on the banks and floodplain of the river downstream of the dams are struggling to survive.

It is not just migratory species whose numbers have declined. Estuarine and coastal fisheries rely on river water, nutrients and sediments delivered annually during natural floods. Recent estimates of the economic losses associated with losses of fisheries in the Black Sea, the Sea of Azov and the Caspian Sea as a result of river regulation amount to US$35 billion annually. After closure of the Aswan Dam on the Nile, the annual catches by the Egyptian sardine fishery in the southern Mediterranean fell from 18 000 to less than 1 000 tons. A reduction of 80% in discharge of water into the delta of the Indus River by dams in India and Pakistan has led to almost total destruction of 250 000 ha of mangrove swamps, once nurseries to teeming estuarine and coastal fisheries.

It is also not strictly true, as one brochure of the United States Department of Energy states, that "… hydropower plants produce no carbon dioxide … no air emissions at all". Although this may be close to the truth once the dam has been constructed (unless the reservoir becomes anaerobic and produces a lot of methane), we should not forget that construction of every dam produces greenhouse gases: earthmoving and other equipment consumes fossil fuels, as does the manufacture of concrete, steel, and turbines. Did you know that for every ton of concrete produced, half a ton of CO_2 is emitted and that production of cement is presently responsible for about 3% of anthropogenic CO_2 worldwide? When ecosystems are inundated by large masses of water, the normal fluxes of carbon into and out of the soils and wetlands are fundamentally altered. Tropical forests, for instance, normally store between 20 and 100 times as much carbon as farmlands do, and the fluxes of gases usually remain in balance as long as they remain undisturbed. When a forest is inundated, though, carbon fluxes alter as vegetation decays and CO_2 and methane are lost into the atmosphere.

In a detailed study in Brazil, Philip Fearnside (2001) looked at the effects of the giant Tucuruí and Balbina dams on carbon dioxide fluxes, calculating that within six years of closure of the wall, the Tucuruí dam had produced 9.45 million tons of CO_2 and 90 000 tons of methane, while Balbina had produced 23.75 million tons of CO_2 and 140 000 tons of methane. (Note that, molecule for molecule, the atmospheric effect of methane on global warming is about 60 times as great as that of CO_2.) Fearnside further estimated that Tucuruí Reservoir would have had about two-thirds the impact on global warming of an equivalent coal-fired power plant, but 50% more impact than a gas-fired power station, while Balbina had ".. 26 times more impact than an equivalent coal-fired power station". Emissions from reservoirs are both variable and difficult to measure, being dependent upon a myriad factors such as the type of soils and vegetation inundated, the mass of drowned material, the rate of reservoir filling, the temperature, and so on. Even though emissions of greenhouse gases may decline after the lake has stabilised (see below), the overall picture is not what many politicians and large-dam lobby groups would have us believe.What is more, declining rainfall means that the turbines are able to deliver electricity at only about 20% of design capacity. Ingeniously, the water surface of the Balbina Dam is currently being used as a floating solar farm, which will make up at least a little for the environmental disaster that is "the worst hydro plant in the world".

AGEING AND FAILING DAMS

Now we turn to the thorny problem of what to do with dams when they grow old. A great deal of concern has (rightly) been expressed about the decommissioning and regulation of nuclear power stations, which stimulated the formation of the International Atomic Energy Agency as a regulatory agency. However, no such equivalent exists to watch over the operation, maintenance and decommissioning of dams worldwide. Like humans, dams have finite lifespans. Furthermore, with the spate of dam-building over the past 50 years, a multitude of problems await us. Many hundreds of dams have already failed worldwide without loss of human life, but other failures have been catastrophic.

In Table 9.2 we list several dams whose failures have each resulted in the deaths of more than a thousand people. It is remarkable that the number of catastrophic dam failures has decreased in the last 40 years or so, the Brumadhino collapse in 2019 causing the greatest number of fatalities since the Machchu-2 overtopping in 1979.

***Table 9.2.* Some of the failing dams that have killed 1 000 people or more (modified from McCully, 1996 and internet sources).**

Locality	Height of wall (m)	Date	Cause	Casualties
Iruhaike, Japan	28	1868	overtopping	>1 000
South Fork, USA	22	1889	overtopping	2 209
Tigra, India	24	1917	overtopping	>1 000
Oros, Brazil	54	1960	overtopping	≈1 000
Panshet, India	54	1961	structural & overtopping	>1 000
Viaont, Italy	261	1963	overtopping	2 600
Banqiao, China*	118	1975	structural /overtopping	247 000
Machchu-2, India	26	1979	overtopping	>2 000
Brumadinho, Brazil	86	2019	collapse	270

** The structural failure of an upstream dam led to the overtopping of lower dams. In all, about 60 dams failed more or less simultaneously. Information about this tragedy has only recently become known in the West; see http://en.wikipedia.org/wiki/Banqiao_Dam for details.*

Table 9.2 gives the impression that overtopping, rather than structural failure, is the engineer's major nightmare. Certainly, overtopping can be disastrous. It is usually caused by poor management of a dam that is subjected to sudden flooding: the reservoir is not drawn down sufficiently prior to the rainy season and water flows in too fast, or spillways are blocked with debris. About a third of all failures have been due to structural or geological weaknesses, though. One estimate puts large-dam failure at between 8 and 25 large dams per decade, while another indicates that generally about 2.2% of small and 1.7% of large dams failed between 1900 and 1970. In China, though, a conservative estimate suggests that some 3 200 dams (4% of registered dams) failed between 1950 and 1990.

Dams fail for a variety of reasons. Overtopping usually places stresses well beyond the design capacities of sluices and dam walls; earthfill dams are particularly susceptible to this problem. Excluding acts of war, other causes for dam failure include poor foundations; weak and fractured rock supports; a process known as piping (internal erosion of the wall that causes it to slump); cost cutting and the use of substandard materials (the collapse of Zoeknog Dam on the Sand River in Mpumalanga in 1992 has been attributed to this); earthquake damage; old age; and shoddy maintenance.

Diego Baravelli / Wikimedia / CC BY-SA 4.0

Utter devastation downstream after the failure of the Brumadinho Dam in Brazil.

Without doubt, the worst case so far has been the Chinese disaster of 1975, although news of the event was suppressed by the Chinese government for twenty years. The Banqiao and Shimantan dams, built in the 1950s, stood across the Ro, a major tributary of the Yellow River. Both were built to withstand a once-in-a-thousand-year flood event. In August 1975, a freak typhoon swept across the region, delivering rainfall estimated to be likely to occur no more than once in every 2 000 years. As Banqiao filled, its operators discovered that the sluice gates were partially blocked by sediment. The water level rose to more than two metres above its designed safety level before the wall burst, liberating a deluge of 500 million m^3 of water that moved downstream at about 50 km an hour, engulfing towns and villages in its path. The wall of water hit the smaller Shimantan dam in its downstream flood, causing this dam to fail, too. Altogether, a further 62 dams in the area collapsed during the storm. Because these dams had been constructed, dykes and other forms of flood control (like dredging) had been neglected. Eleven days after Banqiao burst, 800 000 people were reportedly cut off from help and 350 000 had contracted diseases of one sort or another. Statistics on the final death toll will probably never be known with any certainty but conservative estimates put the figures at 85 000 killed immediately, and a further 143 000 killed by epidemics and famine. News of the disaster was published in 1995 by Human Rights Watch.

Near-misses are disturbingly common. In 1971, for instance, the 50-year-old Upper and Lower Van Norman dams near Los Angeles were subjected to a magnitude 6.5 earthquake whose epicentre was about 11 km away. The larger, lower dam was mercifully only half full and although the upper dam suffered severe damage, the lower dam held. Had it not done so, the ensuing flood would have overtopped the lower dam and threatened some 70 000 people in the San Fernando Valley. As it was, they were all evacuated because of fears of aftershocks.

In another notable near-miss in North America, the 216 m-high Glen Canyon Dam on the Colorado River came within 20 mm of an uncontrolled release during floods in June 1983. The flood, which would have been even larger than that caused by the collapse of the Banqiao and other dams in China during 1975, was prevented by shoring up the tops of the sluice gates with plywood while repairing spillway tunnels. On the other side of the globe, the full story of the 143-m-high earthfill Tarbala Dam in Pakistan has never been released but we do know that it came very close to devastating the populous Peshawar Valley. First, two of four tunnels used to control the rate of filling collapsed just after filling commenced, bringing down quite a chunk of the dam wall itself. After the basin was drained, engineers found that silt blanketed hundreds of sinkholes that had developed under the dam and now had to be plugged. After the dam had become fully operational, the force of water gouged a hole 50 m deep and 300 m long in one of the spillway chutes and caused parts of it to collapse. A year later the base of the spillways was similarly eroded and these began to move away from the dam wall. The cost of the dam rose from US$800 million to a total of US$1.5 billion by the time it finally came on stream.

Thomaschewski Fabienne / Wikimedia / CC BY-SA 4.0

The Glen Canyon Dam on the Colorado River almost failed after massive flooding upstream.

Quite clearly, large dams may be highly problematic and many are positively dangerous. In 1994, a review of dams in Georgia (formerly part of the USSR) by Canadian engineers revealed a shocking situation: the world's third-highest dam, Inguri, was "… in a rare state of dilapidation". The spillway was defective; only two of five groups of turbines worked and the turbine galleries were flooded by water leaking from the arch of the dam; no maintenance was being performed and staff operating the dam had not been paid for six months.

The identification of dams that should be decommissioned, and procedures to be used, are already in place in parts of the United States. The operators of dams have to meet licence requirements of the Federal Energy Regulation Commission if they are to continue to operate and, in fact, between 1989 and 2004, some 500 licences expired. New action groups such as the Hydropower Reform Coalition are calling not only for careful re-examination of licences but also for dam operators to pay into funds that will offset decommissioning costs from their own profits rather than having taxpayers foot yet another bill (since they often paid for the construction of the dam in the first place). Similar reviews are needed worldwide: many dams represent disasters that have found their places but merely await a time to happen.

Kariba is a case in point. It has been virtually incapacitated by ongoing drought, which on occasion has lowered the reservoir's volume to twelve per cent of its usual capacity. But if the reservoir is refilled, the dam faces the possibility of collapse. It was built in the late nineteen-fifties, and in the years since then, water flowing through the dam's six floodgates has carved a three-hundred-foot-deep pit, or plunge pool, at its base. The plunge pool extends to within a hundred and thirty feet of the dam's foundation; if it reaches the foundation, the dam will collapse. That seems hard to imagine now, with the reservoir at a record-low level. But the Zambezi River Basin, on which the dam sits, is the most susceptible of Africa's thirteen basins to exceptional droughts and floods, and climate change is intensifying both.

In the previous edition of ***Vanishing Waters*** (1998) Bryan wrote, "Undoubtedly the time will come, for as global warming accelerates, so the severity and unpredictability of floods will increase. As yet, Mozambique has escaped a major disaster on the floodplain of the Zambezi River downstream of Cahora Bassa Dam, but this area represents a potential disaster. Cahora Bassa dam has regulated the flow in the Zambezi for the last 35 years or so. Before the dam was built, people refrained from living on the floodplain because they knew that it would be flooded every year during the rainy season. Now a whole generation of people has grown up with no memory of those conditions, and large numbers of people are living on the floodplain that their grandparents shunned. Should heavy rains cause overtopping of the huge Cahora Bassa and Kariba dams, massive floods will cover the floodplain and, unless excellent flood-warning systems are in place, could devastate whole villages and kill many people." Bryan was right. The devastation caused by actual flooding and overtopping of Cahora Bassa is discussed in more detail on page 348.

RESERVOIRS AND EARTHQUAKES

One of the least known side effects of large dams is their propensity for triggering earthquakes. But how can dams cause earthquakes? The answer is the three-way relationship between mass, lubrication and the pattern of filling or drawdown of the reservoir. The volumes of water impounded (and hence the mass of water) can be truly vast. At full supply level, Kariba impounds nearly 180 billion tons, Aswan 168 billion tons, and Cahora Bassa, 63 billion tons, for instance. Such redistribution of mass occurs with extreme rapidity as a reservoir begins to fill behind a dam wall. The enormous mass, the rate at which the mass accumulates (during filling and re-filling) and the lubricating effects of water as it percolates through the rock faults below the new reservoir, combine to make the earth groan and writhe. The phenomenon is called reservoir-induced seismicity (RIS).

Table 9.3 lists data, culled from Patrick McCully's ***Silenced Rivers,*** on the most violent earthquakes known to have been caused by reservoirs. (Note: the open-ended Richter Scale is a logarithmic scale, in that every unit is an order of magnitude greater in strength than the preceding unit: e.g. an earthquake of magnitude 4.0 is 10 times stronger than one of magnitude 3.0, while one of magnitude 5.0 is 100 times greater than one of magnitude 3.0.)

"Large dams may be highly problematic and many are positively dangerous."

Table 9.3. **Cases of reservoir-induced seismicity greater than magnitude 5.5 on the Richter scale. (The time lapse between each reservoir starting to fill and the recorded RIS event(s) is noted in years; modified from McCully, 1996.)**

Dam	Height of wall m	Volume 10^6 m^3	Magnitude Richter scale	Time since filling (y)
Koyna (India)	103	2 780	6.3	5
Kariba (Zimbabwe/Zambia)	128	175 000	6.2	<5
Kremasta (Greece)	160	4 750	6.2	1
Xinfengjiang (China)	105	14 000	6.1	3
Srinakharin (Thailand)	140	17 745	5.9	6
Marathon (Greece)	67	41	5.7	9
Oroville (USA)	236	4 400	5.7	7
Aswan (Egypt)	111	164 000	5.6	7

There appears to be two types of RIS, rapid and delayed. Kariba, for instance, experienced low-level seismicity followed, as the reservoir reached full supply, by two major earthquakes (magnitude 6), which damaged the wall. Various other large dams were hit by earthquakes five or more years after filling. The Koyna Dam (India) triggered a swarm of micro-events, followed after 5 years by two major earthquakes (magnitudes 5.5, 6.3), the second killed 200 people and injuring more than a thousand.

More recent major earthquakes, including two in China – the massive 8.0 Sichuan earthquake in 2008 and a somewhat lesser one in 2013 – have been attributed at least in part to the presence of numerous dams in the region, including the very large Zipingpu dam. Really large earthquakes are probably triggered by the weight of dams situated on fault lines in tectonic plates. The latest dam-related earthquake in China seems to have been a 6.2 quake triggered by massive floods overfilling the Three Gorges Dam in 2021. For details of reservoirs and earthquakes, see Tosun (2015) and for details of early earthquakes associated with Lake Kariba, see Gough & Gough (1970).

What about the Katse Dam and the Lesotho Highlands Water Project? Well, in a matter of 18 months after Katse began to fill, there were 95 confirmed RIS events around the reservoir. The largest so far (magnitude 3.5 but still fairly minor) occurred in February 1996 and ripped a 1.7-km-long crack in the mountain just north of the dam wall and through the village of Mapeleng. (Indeed, villagers felt the first earth tremors less than three weeks after the reservoir began to fill). The villagers were naturally terrified, not least because the Basotho people of the Malibamatso Valley traditionally have a deep fear of water. One of their myths involves the great river serpent who swallows the foolhardy who venture too near the river banks. After nearly a year of complaints, those who wished to move away from the old village were rehoused higher up the mountain away from the lake.

Katse Reservoir is one of the deepest and most sinuous systems in the world; at well over 2 km above mean sea level, it is also one of the highest. A visit to the reservoir leaves one with an abiding impression of a very long, very heavy axe head with the blade burying itself in the valley floor. Katse Dam has been engineered to withstand a magnitude 6.5 earthquake, so the wall may withstand such a quake; but what about the offtake tower seated in the bed of the reservoir? Will that stand such shocks? And the transfer tunnels? One of the very disturbing features of the situation at Katse is the apparent disregard for the 'worst case' scenario. Bryan was informed by an engineer on site that "… we have done an all-fall-down scenario". The result? Should Katse Dam fail at full supply level, the wall of water surging down the Malibamatso Valley would completely destroy the town of Maletswa (Aliwal North), more than 220 km away, before rushing on to form a wall of water 5 metres high at the upper end of Lake Gariep on the middle Orange River. The destruction of towns and villages in the path of the flood would be horrible, and there are frightening implications for nearby cities in the Free State, KwaZulu-Natal and Gauteng. While numerous earthquakes

A satellite image of the sinuous reservoir behind the Katse Dam on the Malibamat'so River in Lesotho.

shook the Katse area during the filling phase, this seems to have settled down, and it is good to know that there have been no reports of earthquakes associated with the Mohale Dam.

THE CHANGE FROM RIVER TO RESERVOIR

THE UNSTABLE PHASE

Let us consider what happens to a river physically, chemically and biologically, when a dam wall is closed across it. As the waters begin to rise behind the barrier a remarkable series of interrelated events is set in train, altering the river and converting it into an artificial lake. The most obvious and immediate feature is the change in flow rate as the water slows and spreads. As it does so, its sediment-carrying capacity falls, and materials in suspension (clays, silt and sand particles eroded by the upstream reaches of the river, as well as organic particles) begin to settle out, large particles first, and then smaller and smaller grains as the velocity of the water decreases until it is essentially standing still. So the first change is usually a rapid increase in water clarity in the developing lake.

Of course, the water does not immediately become crystal clear in new reservoirs. In some it never does because the particulate matter carried by their rivers is so fine that it remains permanently in suspension in the new lake. Gariep and Vanderkloof dams on the Orange River are classic examples of lakes with water made permanently turbid by clay particles coming off the land. An increase in water clarity means an increase in the depth of light penetration which, together with a decreased (or non-existent) flow rate, allows enhanced photosynthetic activity by phytoplankton and later sometimes by rooted plants. The depth of the euphotic zone is increased, allowing light to penetrate deeper into the water column. At the same time, because the waters of the reservoir are static, the water column is warmed by sunlight so that temperatures rapidly begin to exceed those found in the river. The new lake is becoming very different from the original river.

Over and above these physical changes, major shifts take place in the chemistry of the water. As filling commences, the spreading waters begin to drown the vegetation and any organisms that cannot escape the flood. Microorganisms, grasses, trees, soil animals, a myriad insects, slow-moving vertebrates such as snakes and, in large reservoirs, large vertebrates, are trapped by the flood and die. Decomposition follows, and the tissues of most of the drowned organisms are rapidly mineralised to their chemical constituents, releasing nutrients, carbon dioxide and methane. The destruction may be awesome, particularly where the areas inundated by reservoirs are vast. Lake Volta, behind Akosombo Dam in Ghana, is not only Africa's largest artificially flooded area but the largest in the world (8 500 km^2). Lake Kariba (Zimbabwe/Zambia) inundated some 5 250 km^2, and Lake Cahora Bassa (Mozambique) 2 739 km^2, while Gariep, Vanderkloof, Pongolapoort and Vaal dams, all in South Africa, inundated 364, 139, 133, and 293 km^2, respectively.

It is at the stage when flood waters rise that the public sometimes becomes aware of the plight of large animals as they desperately attempt to flee the flood. On occasion, major rescue operations have been directed at the more spectacular game species. Operation Noah, which took place while Lake Kariba was filling during the late 1950s, was probably one of the most publicised of these events. Laudable as such exercises may be, however, such human responses typify common perceptions of what is worth saving. We submit that they are often inappropriate, for although they might serve to heighten general public awareness of conservation issues, they often divert attention from the other subtle and less spectacular, but far more important, events taking place within the inundated area. Indeed, the number of mammals saved by Operation Noah was minimal, but created far more interest than that devoted to the people who lost their lands and homes to the lake.

To give an idea of the quantities of biomass destroyed by reservoirs created for human use, Lake Manyame (Darwendale) in Zimbabwe was estimated to have drowned several hundred tonnes (dry mass) of termites alone, never mind the earthworms, spiders, lizards, roundworms, bacteria, fungi, thorn trees, grasses, daisies and mopane trees. The decomposing tissues of the billions of organisms killed in this way provide huge quantities of mineralised nutrients, which are subsequently used by aquatic plants, animals and microorganisms for their own growth. Additional nutrients enter the lake from the inundated soils, which in many instances are rich alluvial deposits from past natural flood events in the river. Physical and chemical conditions may fluctuate wildly for some time, depending on how long the reservoir takes to fill, the prevailing water temperature, the rate of release of water from the new lake, the quantities of nutrients made available from the drowned flora and fauna and inundated soils, and the rates at which the nutrients are released into the water column. It is this unstable phase at the beginning of the life of a new reservoir that humans emulate when natural freshwater systems are polluted with nutrients from domestic sewage or agricultural fertilisers.

So far we have concentrated on the physical and chemical features of the unstable phase: reduced flow and increased water clarity, temperature and nutrients. What of the biotic responses to these changes? The physical and chemical changes provide conditions that are favourable for very rapid plant growth, particularly of phytoplankton, which frequently blooms explosively. Such algal blooms may discolour the water, may be toxic (see Chapter 7) and, under the action of wind, may blow on to the shore, producing evil-smelling mounds of decaying material. It is also at this time that invasive alien floating plants such as Kariba weed (***Salvinia molesta***), water fern (***Azolla filiculoides***), water hyacinth (***Eichhornia crassipes***) and Nile lettuce (***Pistia stratiotes***) may exploit the increased nutrient supply, sometimes with disastrous consequences (see Chapter 8). Some readers will be familiar with the problems caused by water hyacinth and the bluegreen ***Microcystis*** in Lake Hartbeespoort near Pretoria.

The biotic changes associated with the unstable phase are not confined to the development of phytoplankton and the potential invasion by floating alien vegetation. The species that make up the various animal and plant communities are altered: specialised river-adapted species become extinct, a few more broadly-tolerant species found in the river will survive in the new lake and lake-tolerant species that were never seen in the original river will start to appear in the new lake. A rapid rise will occur in the number of individual organisms, followed by a new pattern of fluctuation in numbers but, after some time, the various biotic communities will stabilise in some new and steadier state. Thus extinction of certain species, and their replacement with others capable of rapid growth in the new conditions, are normal features of the early lake. Eventually, however, the reservoir will stabilise as nutrients become 'fixed' in new living tissues and are slowly lost, either in water released from the reservoir or by being immobilised in the sediments on the lake floor.

As long as the flow of water through the reservoir is not excessive, and the reservoir is sufficiently deep, the sun will cause heating of surface waters and stratification will ensue (see Chapter 3), with profound implications for the flora and fauna of the newly developing lake. Since the upper, warmer epilimnion and the lower, cooler hypolimnion cannot mix during the spring and summer growing periods, the nutrients cannot mix either. They will be trapped in the lower hypolimnion during spring and summer. The dead material is decomposed by microorganisms, depleting the hypolimnion of oxygen so that the water becomes hostile to most of the organisms living in the lake. In extreme conditions (in fact, fairly frequently in warm climates), decomposition of dead material at the bottom leads not only to complete exhaustion of the oxygen supply of the hypolimnion, but also to the production of large quantities of methane and of toxic hydrogen sulphide gas (H_2S). This is because aerobic bacteria (those reliant on oxygen) die and are replaced by anaerobic bacteria that continue the process of decomposition more slowly, extracting oxygen from chemicals such as sulphates (SO_4^{2-}) and generating sulphides. H_2S formed in the waters of the hypolimnion of Lake Kariba for at least the first seven years of its existence, preventing aerobes from using the hypolimnion because near the bottom they would die either of asphyxiation or of H_2S poisoning.

Probably the most extreme example of H_2S formation comes from Surinam in South America. The combination of vast areas of flooded virgin forest (1 500 km^2), the shallow depth of the reservoir and tropical temperatures caused emissions of massive amounts of hydrogen sulphide gas from the surface of the Brokopondo Reservoir. Emissions were so toxic that dam workers had to wear gas masks for the first two years after the reservoir began filling in 1964, while water released from the dam remained deoxygenated for up to 110 km below the wall, depriving the river of fish and local communities of drinking water. Of course, one of the oxidation products of H_2S is sulphuric acid, which is highly corrosive. In 1977, estimates of the repairs to the turbines necessitated by acid corrosion stood at US$4 million – some 7% of the total cost of the dam.

Mark Ahsmann / Wikimedia Free Documentation Licence

The Brokopondo reservoir in the Suriname rainforest; the decaying remains of thousands of dying trees contributed to anaerobic conditions for many years.

Of course humans may further disturb the normal cycle of stratification, nutrient depletion, overturn and nutrient replenishment by polluting the lake with domestic effluents or agricultural chemicals. By doing this we unwittingly add essential nutrients to the epilimnion, topping it up all the time and allowing the growth of organisms within the epilimnion right through the warmer periods of the year and sometimes even during winter. In these circumstances, therefore, organisms in the epilimnion simply grow and reproduce as if they had continual access to the nutrient store of the hypolimnion – in other words, as if stratification had not occurred.

The enriched conditions of the unstable phase will reduce slowly with time, but whenever the surface waters begin to warm, stratification will exert its influence on the biology of the system. It is during the unstable phase of the lake, when oxygen depletion or H_2S production is common, that some of the more distressing and visible problems of new reservoirs arise. Overturn may, in certain circumstances, cause the sudden release of H_2S-laden or oxygen-depleted hypolimnetic waters into the upper parts of the lake. This in turn may cause localised or even widespread fish kills, with shoals being simultaneously affected in different parts of the lake. So if fishes are to be introduced to a new lake as a food resource, it makes sense to wait until the lake has passed through the highly unstable period and is beginning to settle into its new cycle before making costly introductions. In this context, it is interesting to note that the first attempts to introduce the kapenta (also known as the Lake Tanganyika sardine, ***Limnothrissa miodon***) to Lake Kariba failed in the early 1960s. Some years later, however, the fish was successfully introduced, and kapenta now form the basis of a viable fishery. This leads to the next topic: the new lake as a new environment.

A meal of kapenta from Lake Kariba with a side dish of sadza (maize meal).

NEW BIOTOPES

The shoreline

Reservoirs are constructed for a variety of purposes, the production of hydroelectric power, irrigation, and the storage of potable water being the main ones. In each case, water must be drawn off at some stage, so water levels will inevitably fluctuate. Sometimes draw-off can be quite dramatic, causing huge areas of the shoreline to be exposed. South African droughts over the past few years have seen reservoirs such as the Gamka Dam in the Karoo dry completely (see image on page 14). Such massive decreases in volume are becoming common and are significant both aesthetically and biologically. In addition, managers of very large impoundments take cognisance of each rainy season and, prior to the rains, have to draw down the water level by a calculated amount in order to accommodate floods, whether or not this is environmentally sound. On a shorter timescale, the production of hydrolectric power requires water for the generators when power is needed, which may not (and almost always does not) take cognisance of the needs of the river. Similarly, the needs of farmers for water for irrigation are more often than not incompatible with the needs of the aquatic animals and plants of the reservoir or in the river below the dam.

What sort of effects are evident? First of all, there is the effect on the development of plant communities along the shoreline. Rooted plants are rarely found around our impoundments simply because they never get a chance to establish themselves: the water levels keep falling and rising with biologically unpredictable irregularity. This has profound effects upon the system, for it prevents the establishment of sheltered areas where fish fry can avoid predators, or the development of invertebrates that require plants for their own success. Secondly, shallow-water (littoral) communities of fish and invertebrates have difficulty in adapting to the fluctuating environment. The fish family Cichlidae (the 'tilapias' or bream), for instance, nest in shallow waters, while many invertebrates cannot move quickly enough to escape when water levels drop, so that both they and fish eggs may become stranded and dry out.

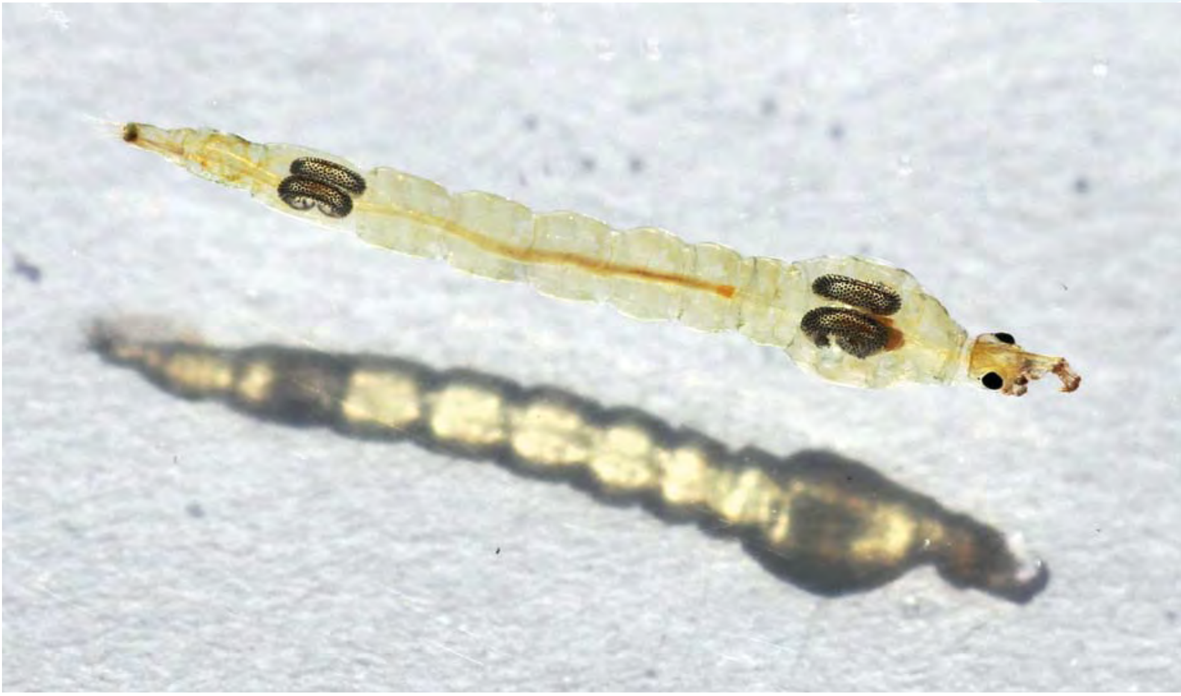
Some invertebrates can, however, take advantage of the fluctuating system. Athol McLachlan, working on Lake Kariba, showed that the larvae of certain midges (Chironomidae) migrate up or down the shoreline to follow the rising and falling water levels. As the water levels fall, so grasses develop on the moist, newly exposed shore, providing food for large grazing mammals. Rising waters drive these animals off the flooding shore, flood their dung and drown the grasses, thereby releasing nutrients into the water and enriching the water column along the shoreline. The system acts, in fact, as a highly productive artificial floodplain (see Chapter 5). Thus, not all changes are deleterious. Sensitive management is needed, however, to balance the requirements of impoundments as ecosystems with their use as water storages for industrial, agricultural, power-producing and domestic purposes.

The open water

As well as the fluctuating shorelines, which in reservoirs are often convoluted and extensive, the open waters of the lake form new biotopes ripe for exploitation. In the case of planktonic organisms, many of which have resistant resting phases and/or are very tiny, introduction to the new environment is a relatively simple process. The quiescent stages of bacteria and fungi, and zoo- and phytoplankton, are transported to the lake borne on the winds in dust, or on the feet or feathers, or in faeces, of water birds. Obviously, some will fail to become established but others will succeed in colonising the lake. Other species, originally in low numbers in the riverine environment but possessing adaptations that will allow their survival in lentic conditions, may live through the changes from river to lake and proliferate in the new system. Some species of fish fall into this group, exploiting the rapidly developing food reserves of the new reservoir and sometimes even forming the basis of new fisheries.

martinpel / 123RF

Lake Kariba in Zimbabwe.



Chaoborid larvae are known as phantom midges because they are planktonic and entirely transparent; they often dominate the zooplankton of reservoirs. The four dark spots on the upper specimen are air sacs of the larva; the lower image is its shadow.

We have already mentioned the early failure and the later successful introduction of kapenta to Lake Kariba. As we pointed out in Chapter 4, except in slow-flowing lower reaches, rivers do not normally develop planktonic communities, with the result that few predators of plankton have evolved in them. The kapenta, a plankton feeder, evolved in Lake Tanganyika, one of the great lakes of the African Rift Valley. When kapenta were introduced in the newly formed Lake Kariba, plankton communities were still slowly developing, so the fish did not have enough to eat, and a population didn't become established. Later, plankton communities expanded and could provide food for the fish, which now sustain a commercial fishery of some 25 000 t per year. A tiny fish (maximum 140 mm long), ***Limnothrissa*** is edible in its own right, converting plankton into valuable fish protein. In Lake Kariba, they also form a food source for the highly prized tigerfish, ***Hydrocyon vittatus***. Thus, the introduction of one species has led to the development of two lucrative fishing industries, one providing an income and much needed protein from traditional and commercial fishing methods, the other providing income and employment in the lucrative recreational fishing industry and its associated activities (manufacture of equipment, boating operations, tourism, hotels and so on).

Tigerfish, an angler's dream, but a small fish's nightmare.

Obviously, there is enormous potential for exploitation of new open-water environments created by the formation of reservoirs, farm dams and so on. Clearly, though, one must be careful to ensure that such introductions are not deleterious (see Chapter 8, for instance). The introduction to South Africa of three voracious North American fish (the large- and smallmouth bass, ***Micropterus dolomieui*** and ***M. salmoides***, and the bluegill sunfish, ***Lepomis macrochirus***) is a case in point. Being extremely hardy and tolerating a wide range of environmental conditions, these fish have devastated populations of indigenous fish in rivers, reservoirs and farm dams. Even the kapenta, once thought to be too puny to survive the turbulent passage through the hydroelectric turbines and sluice gates of Kariba Dam, have not only survived but have successfully invaded Lake Cahora Bassa in Mozambique, more than 200 km downstream. In this case, however, few people have complained, for its arrival in the reservoir has precluded the expense of artificial introductions of this lucrative fish stock.

The bottom substrata

Along with open water and new shorelines, new benthic habitats are formed when a dam wall closes. In Chapter 3 we explored the evolution of a new lake. Similar events occur in reservoirs. As we have seen, the flooded soils are leached, the vegetation is drowned and the bed of the lake slowly becomes covered in fine ooze as organisms in the water column complete their lifecycles, die and sink to the bottom, there offering their bodies for decomposition. The sediments in new reservoirs, though, are usually anaerobic and therefore unavailable to most organisms. As the reservoir slowly stabilises, however, midge larvae, oligochaete worms, roundworms and a myriad bacteria and fungi colonise the maturing sediments, feeding on the rich organic materials they store, as well as on the debris continually raining down from above.

One common substratum of the new reservoir is often overlooked: the drowned trees that were not cleared or burned before the floodwaters rose. These provide micro-environments for lake invertebrates and fish, and are frequently colonised by specialists that live on or in the drowned wood. The exposed parts also become roosts for water birds such as fish eagles and kingfishers, ducks and herons. Dragonfly larvae prowl the nooks and crannies of the drowned tree trunks and branches looking for prey, while adults rest on or flit between the tangle of dead branches that point their skeletal fingers to the sky. Many chironomid midge larvae build tubes of mud on tree surfaces and feed off particles in the surrounding water. Other insects, such as nymphs of the specialist mayfly, ***Povilla adusta,*** bore holes into the dead trunks of drowned trees. Slowly the trees are reduced and collapse, adding their tissues to the bottom muds. Often their decomposition is very slow: more than 50 years since Lake Kariba began to fill, the lake's shores still support dense stands of dead trees, apparently marching in upright, silent ranks into the water. It will take many decades more before the activities of insect burrowers and the ravages of storms eventually clear the lake of such obstructions.

EFFECTS OF DAMS ON THE RIVER DOWNSTREAM

We have seen that, in southern Africa, hardly a river exists that is not impounded by at least one dam. Indeed, most rivers now comprise cascades of reservoirs of varying sizes from source to the sea, or they are manipulated so as to receive water from, or donate it to, some other river (see below, *Inter-basin transfers of water*). The Orange-Vaal system is a good example. As well as the myriad small farm dams on its tributaries, the river is regulated by the giant Vaal Dam, the Vaal Barrage and the Bloemhof, Gariep and Vanderkloof dams. Through inter-basin transfers the Vaal already receives water

Jenny Day

Trees drowned by the rising waters of the new lake behind Theewaterskloof Dam in the Western Cape.

from a number of other river basins, including the Thukela in KwaZulu-Natal and the Katse and Mohale dams on the upper Orange River, which is called the Malibamat'so in Lesotho (see Chapter 1). No longer do rivers necessarily carry their own waters.

Human manipulation of rivers by reservoirs is known as 'river regulation'. As each reservoir has its own unique combination of biological, physical, chemical and hydrological characteristics, the effects on the receiving river are variable and complex, and so river regulation forms a sub-discipline of river ecology. In southern Africa during the 1970s and 1980s, ecological research on inland waters tended to concentrate on reservoirs, but at about that time an interest developed – mostly for management purposes – in the effects of reservoirs on the downstream reaches of rivers. This research informed the developing science of 'water allocation for Nature' (also known as e-flows, and in South Africa as 'Reserve determination') as river ecologists began to recognise the complex and sometimes devastating effects of dams on rivers. A journal, ***Regulated Rivers Research and Management*** was born in 1987. Recognition of South Africa's pivotal role in this work occurred in 2015, when Jackie King, who worked in the Freshwater Research Unit at UCT for many years, was awarded the Stockholm Water Prize (the 'Water Nobel Prize') for her work in this field.

Features of regulated rivers

The effects of dams on the downstream river depend largely on whether or not any water is released from the dam and, if it is released, whether it is released from near the surface (epilimnetic discharge) or near the bottom of the reservoir (hypolimnetic discharge). If no water is released, then the river above the dam becomes a lake (see Chapter 3 for features of lakes). The river below the dam may dry up completely upstream of the first tributary unless some water leaks from the dam wall or groundwater wells up into the stream bed from the below. If, on the other hand, water ***is*** discharged from the dam into the river downstream, then conditions in the river will depend on a number of factors, the most significant being the vertical position in the reservoir from which the water is released. Table 9.4 summarises some of those effects.

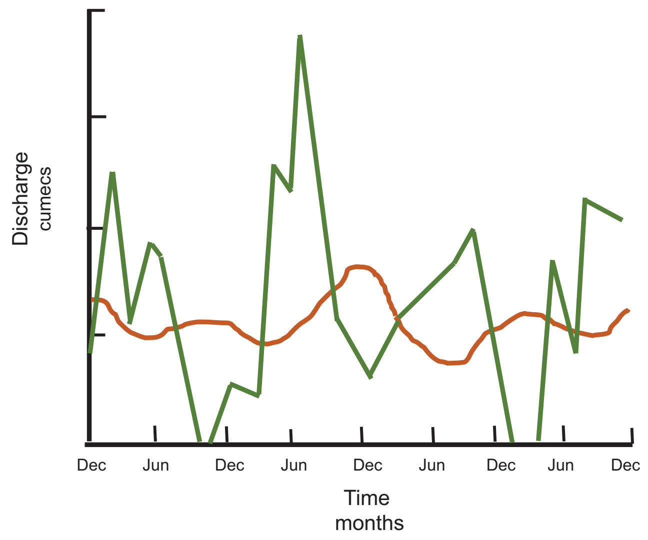
Table 9.4. **The most obvious effects of dams on downstream river reaches. 'Epilimnetic' refers to discharge of water from near the surface and 'hypolimnetic' to discharge from deep water.**

	epilimnetic discharge	*both*	*hypolimnetic discharge*
water quality		lower [DO]	
	higher temperature		lower temperature
	decreased turbidity		increased turbidity
	decreased TSS		increased TSS
	lower [nutrients]		higher [nutrients]
		higher [toxins]	
geomorphology		armouring	
hydrology		flow regime	
biota	increased plankton		little or no plankton
	food for filter-feeders		smothering by anoxic sediments

Flow, temperature and other physical effects

Most South African rivers are naturally seasonal systems with summer high and winter low flows in the summer rainfall regions of the centre and east of the country; winter high and summer low flows in the south-western winter rainfall region; and non-seasonal patterns in between. Unfortunately, although over aeons aquatic organisms have become adapted to these patterns, human use of water from reservoirs seldom follows any of these patterns. For instance, the generation of hydroelectric power, and therefore the discharge from power-producing dams such as Gariep, reaches a maximum in winter when the weather is cold, although the highest discharges in the unregulated Orange River used to occur in summer. Indeed, when hydroelectric power production is optimised, rivers are usually caused to flow in daily pulses, which are frequently inappropriate for riverine organisms going about their daily lives.

Another less obvious problem may also arise. Discharge in many southern African rivers is naturally variable, whereas the tendency of water managers is to remove this variability, either for operational convenience or for some specific purpose such as irrigation, or even in the mistaken belief that it is better for rivers to have more water in the dry season than nature provided them with. The graphic below neatly demonstrates the consequences of this 'smoothing' of flow. One can see that discharges in the unregulated river fluctuated wildly. The biota must obviously have been adapted to cope with these fluctuations. After regulation, though, the biota has to contend with flows that never totally cease and which very rarely give rise to a major flood. Thus, the peaks and troughs have been 'ironed out' by human manipulation. This may be convenient for humans, but is not necessarily so for river ecosystems and their organisms.



modified from Cambray et al., 1986

Natural (orange) and regulated (green) discharges in the Orange River below Lake Gariep.

The pattern of discharge below the Vaal-Hartz Diversion Weir is even odder. A peculiar regularity is superimposed on the relatively constant rate during the irrigating season. Why? The answer is that irrigation pumps tend to be in use during the day, and some are switched off by the few thoughtful irrigators at night. Thus, one can see nightly 'blips' in river flow during the working week. On weekends the irrigation pumps go off while the releases from the irrigation diversion scheme continue. The result is a massive elevation in river flow over each weekend during the irrigation season. This is not the sort of flow regime one might expect the biota of a river to be able to cope with. In the Western Cape, where most water is needed for irrigation in summer – when the rivers are at their lowest – a complete reversal may occur in the natural flow regime. Normal low summer flows are elevated in order to satisfy irrigators, but no regard is given to the rivers that are modified. In the case of the Berg River, summer flows have been elevated by as much as 4 500% in order to satisfy irrigation demand.

Readers will recall that lentic, or standing, waters, often become stratified in summer (page 83). The same is true, of course, for reservoirs. But now we have the situation where a lake (a reservoir, in this case) has a release point or points through which discharges may be manipulated. The height on a dam wall or in a dam at which discharge outlets are built is critical for determining what subsequently happens in the receiving river. Looking first at temperature, during summer, water released from the hypolimnion is nearly always cooler than river water, while water released from the epilimnion is often much warmer. Thus, discharges from the hypolimnion will depress the temperature of the water in a receiving river, while an epilimnetic discharge will elevate it, often quite dramatically. So? The vast majority of riverine organisms, be they bacteria, insects, worms, algae or fish (mammals, being warm-blooded, are exceptions), depend upon certain levels of ambient temperature to regulate their growth and reproduction, since the rate of all biochemical reactions doubles for every 10°C increase in temperature. Thus, a reduction in temperature as a result of releases of cold water from the hypolimnion of a reservoir will reduce rates of growth, and digestion of food and so on, and will lead to mis-timing of parts of the lifecycle. By the same token, elevation of temperatures from epilimnetic water will accelerate growth rates, perhaps also mistiming parts of the lifecycle. In other words, riverine foodchains and lifecycles may be disrupted because any change from the natural pattern may create biological 'confusion' so that the wrong thing occurs at the wrong time.

Chemical and biological impacts

Changes in oxygen concentration are less spectacular than those in flow and temperature because oxygen is rapidly absorbed by water as it is turbulently discharged from dams. Toxic gases like hydrogen sulphide can occasionally be problematic in hypolimnetic releases, though, but nutrient levels are important. Chemically, the hypolimnion is nutrient-rich in summer during stratification, while the epilimnion is nutrient-poor. So, there may be significant differences in the effects of releases of water from different depths in a reservoir. In the case of silt, however, unless water is drawn from very close to the bottom of the reservoir, where sediments may be resuspended, water discharged from dams tends to have less silt than in the natural river water. Interestingly, because discharges from dams usually take place at high velocities, water leaving a reservoir tends to have a 'capacity' for silt. The water is said to be 'silt hungry' and results almost universally in rapid erosion of the bed and banks downstream of the dam wall. Erosion of this type is often spectacular and is known as ***bed armouring:*** all loose fine particles are stripped from the river channel, frequently exposing bedrock and causing the banks to collapse for some distance downstream. Indeed, if engineers are not careful in their design, releases that fall close to a dam wall may undermine its base or its spillways and sluices, as occurred in the massive Tarbela Dam, the world's largest earth- and rock-filled structure. The Tarbela Dam, on the Indus River in Pakistan, stands almost 150 m high. When it was being constructed in 1974, engineers noticed huge cavities in the wall, and one of the tunnels collapsed. It was eventually fixed by the addition of a lot more concrete, and appears since then to be stable.

Of course, the epilimnion and hypolimnion differ biologically as well as physically and chemically. In summer, conditions in the epilimnion of a reservoir are conducive to the development of plankton, while those in the hypolimnion are not. Thus, epilimnetic releases are often laden with what is effectively fine particulate organic matter (FPOM) in the form of living plankton. Such releases into the river have major impacts on the structure of the natural biological communities. As described in Chapter 4, CPOM and FPOM vary along the river continuum in a predictable way and, as such, contribute to the structuring of the biological communities occurring down the length of the river. It is easy to see that, if we change the quantity or kind of particulate matter in a river's waters as a result of releases from a reservoir, we may significantly alter the types (and numbers) of organisms in the river for some distance downstream of the dam. For instance, where plankton is released into the river below the dam, filtering collectors proliferate, feeding on this new and rich source of food and altering the proportions of the different Functional Feeding Groups relative to the proportions found in the undisturbed river. Unfortunately for humans, the collectors that cash in on this largesse are frequently 'nuisance' or pest species. For instance, the larvae of blackflies (Simuliidae – see page 314), being collectors of fine particles, frequently occur in vast numbers below discharging dams. In summary, dams disrupt the river continuum in almost every respect, acting as discontinuities and upsetting the natural communities and processes that are found in systems undisturbed by human activities.

Dams as discontinuities

Of course, dams form barriers, resulting in discontinuities in the river continuum (see Chapter 4). Using the River Continuum Concept as a baseline, together with an idea called the Intermediate Disturbance Hypothesis (IDH), American river biologists James Ward and Jack Stanford developed a theoretical approach to river regulation that allowed a number of predictions to be made about the influences of dams on rivers. Their concept is known as the Serial Discontinuity Concept, or SDC.

Simply put, the IDH posits that species richness (number of species, as a measure of diversity) will be lowest where a system is subjected either to very small or very large physical disturbances (completely constant or entirely erratic flows, for instance), and highest where the system is subjected to intermediate levels of disturbance. 'Disturbance' may be human-induced but is often natural – floods or droughts or storms, for instance. Building on this, the SDC proposes that the longitudinal location of a dam on a river, and the depth in the reservoir from which downstream discharges are made, will determine the extent and the kinds of effects that the dam will have on its river. In addition, each feature that is altered by a dam will recover to 'normal' (i.e., to what it would have been if the dam were not there) at some point downstream. This approach is important because it can be tested in the field, and parts of it at least may allow amelioration of some of the more severe impacts of dams by informing the choice of site, the design of outlets and the operating rules.

DAM BUILDING IN SOUTH AFRICA

We have already noted the proliferation of reservoirs in South Africa. According to the Department of Water and Sanitation, about 520 major dams capture more than half of the mean annual runoff (MAR). In fact, all large- and medium-sized rivers of South Africa have been impounded. The largest structures have formidable storage capacities. For instance, Pongolapoort (KwaZulu-Natal) can store 2.5 x $10^9 m^3$ (billion cubic metres) at full supply, while Bloemhof and the Vaal Dam on the Vaal River can hold 1.3 and 2.2 x $10^9 m^3$, respectively. On the Orange River, the giant Vanderkloof dam stores 3.24 x $10^9 m^3$ and Gariep dam, 5.95 x $10^9 m^3$. The real giants of southern Africa store orders of magnitude more, though: Cahora Bassa in Mozambique has a capacity of about 70 x $10^9 m^3$, and Lake Kariba 180 x $10^9 m^3$.

The period from 1930 to the mid-1970s saw a particularly active phase of dam building, which has levelled off in the last decade or so. The reasons for this are not simply economic or environmental, because the rapidly growing human population still requires water, but because we have already used up most sites suitable for constructing dams. As the attention of engineers turns to more sensitive environments, such as the Palmiet and Olifants Rivers in the Western Cape, the Sabie and others in the Kruger National Park and the Cunene in Namibia, conservationists are becoming more vociferous in their objections to new water-supply projects that will damage the remaining relatively untouched rivers.

A further troubling issue about southern African reservoirs is that many are situated in areas with high evaporation rates (see Chapter 2) and unpredictable runoff. Table 9.5 lists the coefficient of variation – a measure of unpredictability – for river flow in various parts of the world. The great variability in rainfall and river flow in South Africa means that it is very difficult to predict how much rain will fall in any given period. As a result, engineers have been forced to build reservoirs with large storage capacities that can capture as much water as possible in case there is a drought the following year, or the year after that. Evaporative loss of water from reservoir surfaces can be much greater than rainfall, dams in arid areas often capturing water that has fallen as rain far upstream in the headwaters. Of course, such dams were seldom designed to allow any water to flow downstream, so many of these rivers cease to flow at all downstream of the dam.

Table 9.5 **Coefficient of variation of mean annual runoff for rivers in various regions. (Data from van Biljon & Visser, undated) These values are a little unfair to Australians, who consider themselves to be at least as badly off as we are in South Africa, because the well-watered land of New Zealand was included in one of the calculations and the other refers to the relatively mesic state of Victoria. We do not have a value for Australia alone. NB: these values are based on data series up to the 1990s so do not reflect the effects of climate change in the last two or three decades.**

Region	Coefficient of variation %
USA	38
Canada	20
Europe	22
Victoria (Australia)	53
Australia & New Zealand	50
Africa	23
Asia	27
South Africa	117

SOME EARLY RESEARCH ON RIVER REGULATION IN SOUTH AFRICA

Early evidence of the effects of impoundment on South African rivers was collected in the 1960s by Dr Mark Chutter, who investigated the Vaal-Hartz Diversion Weir in order to understand the reasons for plague outbreaks of the blackfly ***Simulium*** sp. (later named ***S. chutteri*** in his honour). The densities of the pest peaked when flow fluctuated most. It appeared that the larvae were better able to invade newly flooded areas than were their natural predators (mainly caddisfly larvae) and competitors (other blackfly species). As a result, huge populations (literally billions) of larvae persisted for up to 50 km below the weir. Swarms of the adult flies caused cattle to abort foetuses, to lose condition and production and, in some cases, to bleed to death, as described in Chapter 8.

The problem of plague populations of blackflies associated with river regulation became so serious that during the 1970s, Dr Ferdie de Moor undertook a doctoral study of the problem on the Vaal River. He found that regulated flows during winter allowed the maintenance of blackfly larvae through what would otherwise have been lean times, when the river would normally have dried up, so that densities were large enough in winter to kickstart a plague outbreak through rapid reproduction as temperatures increased in spring. As a result of this research, attempts have been made to control blackfly larvae by manipulating releases from dams to simulate natural fluctuations in the river so that large areas of the riverbed dry out. This has had a measure of success in the Vaal-Hartz area and also in the Orange River, illustrating how important it is to have detailed, research-based understanding of the interactions of regulated rivers and the organisms they support.

Of course, this type of research should have occurred before the dams were planned or constructed, particularly since warnings had been sounded at that stage. Even today the need for pre-impoundment studies is often glossed over even when these are essential for scientifically-based and sensible management of regulated rivers, and even when the research would cost a minute fraction of the capital costs of construction.

This last point was clearly made as long ago as 1970 by Mike Coke in KwaZulu-Natal. He gave a fascinating account of the effects of a 1 000 m^3/s flood released from the Pongolapoort Dam on the Phongolo River floodplain pans. The flood, deliberately released from the dam by managers, turned out to be inadequate, causing more problems than it alleviated. The biological functioning of the pans, and the migration and breeding requirements of the fish populations (and so of fisheries), are historically dependent upon the nature and regular occurrence of flooding. But the deliberately released flood from Pongolapoort did little to help in this regard because it was too steady and stopped too quickly. Indeed, reduction in flood height, together with mis-timing of flood releases, caused several major pans on the Phongolo River floodplain to dry out in 1969 and 1970. The fish populations had always relied on a regular flood to inundate the floodplain and to recharge the pans, providing large nursery areas for juvenile fish; as natural floodwaters receded, the newly spawned fish would slowly move back into the river. But when the floods were reduced, such recharge and flooding (and therefore fish spawning) did not occur or was considerably reduced. In the case of the artificial 1 000 m^3/s flood deliberately released from the dam soon after the artificial 'drought' of 1969-70 while the reservoir was filling, the upstream migration of the remaining fish occurred as expected. The flood was not as beneficial to the fish as it might have been, however, because it was a steady discharge quite different in character from the short, sharp floods once characteristic of the river – and to which the fish normally responded. Accordingly, and inevitably, the artificial flood simply filled the pans, inducing ripe spawning fish already in them to go back into the river before they had spawned. In other words, mature spawning fish were detrimentally affected by a flood that was designed to help them complete their natural reproductive cycles. Mike Coke noted that unless flood heights, intensities and timing from the dam matched normal, pre-regulation conditions, severe damage to the floodplain fisheries could be anticipated. In fact, the timing, intensity and duration of the flood were so abnormal as to be tantamount to a well-intentioned, but completely wasteful, use of the water stored in the dam. Obviously, the research and planning required to ameliorate the impacts of dams is neither easy nor cheap.

Shortly after Coke's reports were published (1973), a far-seeing article by Mark Chutter predicted that impoundment of rivers would cause accelerating perturbation of South African rivers.

He urged increased research into the effects of dams on rivers, pointing out that flow reversals, highly pulsed flows, flow constancy and rapid changes in flow rates were all manifestations of the same problem, and that without pre-impoundment information on natural river functioning, predictive studies would later be compromised. He was so right. (In contrast, at about that time a senior

A pan on the seasonal floodplain of the Phongolo River.

freshwater ecologist – who did not work on rivers – believed that we already knew as much as we needed to know about rivers, and recommended that research funds should not be allocated for research on them.)

The first research in South Africa on the thermal impacts of dams on rivers was performed in 1975 by Drs Pitchford and Visser, who measured water temperatures below Lake Gariep on the Orange River to try to predict the spread of bilharzia vector snails in the area. The research showed that releases from the dam caused temperature ranges in the regulated river to be reduced, relative to natural conditions, by as much as 7°C. Natural seasonal changes in river temperatures were delayed so that in winter they were higher than normal and in summer, lower than normal. Pitchford and Visser concluded that, in the Orange River at least, ***Biomphalaria pfeifferi*** and ***Bulinus*** (***Physopsis***) sp., vector snails of bilharzia, would probably find conditions more favourable for them than before, and that there was the possibility of transmission of bilharzia in summer. Fortunately, this finding has not been borne out: no incidence of the disease has yet been reported from the system although this may be due more to good fortune than to good planning.

DAMS IN SOUTHERN AFRICA: TWO CASE STUDIES

Rich Beilfuss

A rare image of the Cahora Bassa Dam under construction, situated in a remote part of Mozambique.

CAHORA BASSA

Only two studies have been carried out on 'pre-impoundment' conditions in southern African rivers: on Cahora Bassa on the Middle Zambezi in Mozambique, and the Epupa Scheme on the Cunene River in Namibia. Note the use of inverted commas on the word 'pre-impoundment', for even these studies came after the construction of other impoundments upstream on the same rivers: Kariba on the Middle Zambezi, some 200 km above Cahora Bassa, and Caluéque, Gové and five other dams in Angola, as well as the Ruacana diversion scheme on the Cunene in Namibia. We have chosen Cahora Bassa as a case study because extensive research was carried out on this system in order to allow prediction of the effects of the dam (and because Bryan was part of the team, so was very familiar with the findings). Studies were done on sediment loads, physical and chemical conditions, the population structure of zooplankton, phytoplankton and fish populations, the riverine and coastal fisheries, coastal processes and mangrove forests, as well as the impacts on the very important deltaic floodplain of the Lower Zambezi, and the Marromeu Game Reserve, its plant communities and its resident large mammal populations. Briefly, the predictions about the impacts of Cahora Bassa were that it would cause:

- a decline in coastal and riverine fisheries;
- alterations to the structure and functioning of mangrove communities;

- severe coastal erosion (already evident after Kariba started to fill in 1959);
- a gross reduction in sediment transport during floods;
- a decline in primary production, and alterations in vegetation community structure, with concomitant declines in populations of large mammals on the floodplain and in the Marromeu Game Reserve;
- alterations in vegetation dynamics on the floodplain, resulting in reduced flushing, choking of oxbow lakes and replacement of wetland grasslands by trees;
- a reversal of the flow regime;
- a loss in productivity for the floodplain recession agriculture practised by inhabitants of the floodplain;
- a transformation of a floodplain river into a degraded channel;
- the spread of the disease vectors of malaria and schistosomiasis and of floating alien plants such as ***Eichhornia crassipes, Salvinia molesta*** and ***Pistia stratiotes*** (see Chapter 8).

Despite the importance of the Zambezi River to southern Africa, very few of these predictions have subsequently been verified quantitatively, firstly because research interest immediately switched to the newly forming lake (the wall was closed in December 1974), and secondly because of the murderous civil war in Mozambique, which lasted for nearly 20 years. During that time, the dam was operated by the Portuguese (Mozambique had been a Portuguese colony) for production of hydropower. The water level in the reservoir was held constant with no compensation releases for 19 years; the last flood had occurred in 1978. Many of the predictions were supported by privately funded aerial surveys carried out by local conservators. In 1996, Bryan Davies, who had worked on the river before the dam wall was closed, managed to return to Cahora Bassa and the Lower Zambezi for a brief aerial and ground survey. This enabled a comparison of the pre-closure situation and an assessment of the predictions made two decades before.

Direct observations indicated the following:

- The mangroves of the delta had markedly receded, probably as a result of mistiming and altered intensity of floods, and of sediment depletion. Some 40 to 60% of the mangrove swamps had dried out and died back. There was evidence of only one period of recruitment of young trees since the dam had closed more than 20 years before.

- Major changes had occurred in the community structure of the floodplain vegetation, encroachment by trees being substantial. Because intense floods did not occur, meander trains and oxbows were choked with reeds and trees.

- Productive, flood-dependent grasslands were depleted of their grasses, the favoured food plants of herbivorous mammals. Large parts of the lower Marromeu were dry. (This effect was also reported for the Kafue Flats in Zambia, where the Kafue lechwe suffered deterioration in food quality as a result of the Itezhitezhi Dam.)

- Mammals, particularly the once-populous buffalo (over 78 000 head) virtually disappeared from the Marromeu and Zambezi deltas, possibly as a result of changes in food quality. This decline might have resulted from the deadly impact of the AK47 assault rifle as well as the dam, of course. As an aside, various species of large mammal are currently (early 2020s) being re-introduced to Marremeu.

- Waterfowl, as well as wattled and crowned cranes were rare to non-existent.

- Floodplain recession agriculture had declined.

- Vast, vegetated islands, some with substantial tree growth, had appeared in the old channel and, most disturbingly, large numbers of people had settled on the islands. Folk memory of the large river had virtually disappeared, and people had no idea that they were re living on a floodplain. In 2001, and again in 2008, extreme rainfall upstream led to the dam sluices being opened (in 2001 this was for the first time in years) and the dam wall overtopping, resulting in a massive flood coming down the river below the dam. The people living on the floodplain were washed away in their thousands and about 800 people died.)

- The erstwhile 'sand-bank' river, with one or two wide main channels and dense gallery forests on the banks of the floodable reaches, has been reduced to a series of down-cutting meanders: a flood-pulse-driven river has been transformed into a vast, braided, slow-flowing lake.

- Dense reeds, clear signs of regulation of flow, lined the new channels.
- At the time of the visit, the water in Cahora Bassa Gorge was bright green, either because of the discharge of phytoplankton from the reservoir, or because of the growth of phytoplankton as a response to the constant hypolimnetic discharge, or both.
- Erosion of the coastal zone was evident.
- Verbal reports indicated a) that the floodplain fisheries had declined and that people now lived on islands in the river in order to be nearer the water, which in places was several kilometres away from old riparian settlements and b) that the coastal prawn fisheries had collapsed soon after the closure of the dam and before the civil war intensified, possibly as a result of nutrient depletion through reduction in flood-mediated sediment transport to the coastal zone.

TSGT Cary Humphries / USAF

Flooding in Mozambique in 2000. The helicopter was provided by the US Airforce. The white object at the bottom right is a refuelling hose.

The delta at the Zambezi River mouth. Note how flat and low-lying the land is and how difficult it must be to escape a large and sudden flood.

These observations give us two immediate insights. The predictions made in the early 1970s were inaccurate but only in that they underestimated the degree of change to come (in all other respects they were correct); and that catastrophic geomorphological, ecological and social changes had been wrought in the 23 years since Cahora Bassa became operational. Even the word 'operational' is misleading. A visit to the dam wall in 1996 revealed that of the 2 075 MW of installed hydroelectric capacity (five turbines each generating 415 MW of power), three were out of commission, while one was generating 10 MW and the other 5 MW. It is safe to say that Cahora Bassa was a disastrous and inappropriate application of First World technology to a developing country that hardly needed it at the time although it is now fully functional and providing much-needed power to South Africa, who contributed finances for the building of the dam. A report by Richard Beilfuss and David dos Santos (2001) is the latest document that I have been able to find on the Zambezi floodplain in Mozambique – see reference list.

In the planning phase, Cahora Bassa was to be the largest hydroelectric power producer in Africa, projected to compete with the top five in the world. It was originally designed to generate 3870 MW, although the final capacity was reduced to 2 075 MW. It cost well over US$4 billion to build and an unknown amount to protect during the anti-colonial war, yet in 1991, some 17 years after it had been completed, it was reported to be supplying, intermittently, about 420 MW to South Africa.

The mismanagement of Cahora Bassa Dam is now in the history books. The original recommendations of the ecological team were that the reservoir be filled over a minimum of two years, allowing a continuing discharge to the river of 400–500 m^3/s in order to maintain the riverine biota. This recommendation was totally ignored: the volume released was slashed to a mere dribble – about 60 m^3 ***per day*** (less than the daily losses from a city water main) – and this may have been merely from leakage. Further, filling took place during the flood season, depriving the river of its peak summer flows. The gorge dried up, and the town of Tete had no drinking water. The lake then rapidly overfilled and very nearly overtopped due to heavy late-summer rains in Zimbabwe and Zambia, and all eight sluice gates (plus the five turbines) were opened as an emergency measure to lower the level of the reservoir by releasing the surplus water. (Indeed, one engineer confessed recently that the managers and engineers really did not know what would happen and ran as the dam wall began to shake!) This release caused a massive unseasonal flood of more than 14 500 m^3/s into the Lower Zambezi, the delta and the floodplain at a time when people were moving on to the floodplain to plant crops and large mammals were migrating there to feed on new growth.

Mozambique is still bedazzled by megadams. The latest news in the continued abuse of the Zambezi River is that Mozambique plans to sell Cahora Bassa Dam. ***Sell*** it? Yes, to provide some of the funds to build a new dam called Mphanda Nkuwa, to be situated about 60 km downstream of Cahora Bassa. This dam will have a design capacity of about 1 500 MW of power and will cost an estimated US$4 billion. It seems that Mozambique expected South Africa to agree to buy most of the power generated by Mphanda Nkuwa and, indeed, Mozambique cannot raise the finances for the dam without having a buyer for the power it will generate. Until very recently (2021), however, South Africa showed no interest in doing so. ***But*** South Africa is under considerable pressure to decommission its huge coal-fired power stations, and the cheapest replacements will be hydropower and natural gas from Mozambique. So, we have an interesting conundrum. Someone (X) buys Cahora Bassa dam and its generated power (but South Africa is financially crippled, so probably won't be the buyer). Mozambique builds the new power station and sells most of the power to South Africa, who can then decommission several coal-fired power stations. The environment, like us, wins some and loses some.

That is not the end of dam-building in Mozambique. Another dam, this time at Mapai on the Limpopo River, is budgeted at one billion dollars. The reservoir will store 6×10^9 m^3 of water and a power station will generate 75 MW, as well as enabling the irrigation of 250 000 hectares of land in this semi-arid part of the country, and assist in the control of flooding of the Limpopo River. Construction was said to start in March 2022, but no updates are available after that time of writing.

The first stone of the smaller Moamba-Major dam, on the lower Incomati River, was laid in 2014. Construction was financed by Brazil but financial scandals in that country resulted in that source of funding drying up. Mozambique then started unsuccessful negotiations with the Chinese but as of 2021, the World Bank has agreed to provided financing for the dam, which will soon (early 2023?) be under construction. Water from the dam will be used for domestic supply to Maputo, for some irrigation and for a modest amount of power generation.

THE BUFFALO AND PALMIET RIVERS

Both the Palmiet River in the Western Cape and the Buffalo River in the Eastern Cape are regulated by a series of dams down their lengths. In the late 1980s, the Palmiet was investigated by Barbara Gale, then a PhD student, and the late Bryan Davies of the Freshwater Research Unit at the University of Cape Town, and the Buffalo by Rob Palmer, then a PhD student, and the late Jay O'Keeffe of the Institute for Freshwater Studies at Rhodes University. The objective was to test the Serial Discontinuity Concept in order to provide information for the designers of new dams.

The Palmiet rises in the Hottentots-Holland mountains of the Western Cape. Except for a few small pine plantations, the catchment in the headwaters is covered by open-canopy Mountain Fynbos typical of the high-lying areas of the Western Cape. The river then flows through areas of intensive fruit farming and, before entering its estuary, through the Kogelberg Biosphere Reserve. It is a short river, only 74 km long, with clear, cool acid waters and peak flows in winter. Within 40 km of its source it is regulated by five reservoirs that are used mainly for irrigation but include a pumped-storage hydro-power scheme. In addition, water is abstracted in a loosely controlled manner for private irrigation and for supplying domestic water to local towns. Of these reservoirs, two bottom-release dams were studied.

One of the cascade of dams on the Palmiet River.

The Buffalo River rises in indigenous forest and then flows through agricultural land before entering the urban/industrial complex of King William's Town and Zwelitsha. A turbid, relatively warm, non-acidic river, with a shallow gradient and high flows in summer, the Buffalo is very different from the Palmiet. It is about 140 km long and its waters are impounded by four dams. Laing Reservoir, immediately below Zwelitsha, receives very poor-quality water. The lower reaches of the river are impounded at Bridle Drift, which supplies Mdantsane and East London. Sewage effluent from Mdantsane enters the river below this dam. The river is being exploited near to its sustainable limit, supplying 80% of the water requirements for a population of more than 800 000 people.

Dams regulating the upper reaches of both rivers had similar effects, despite differences in release patterns, while most chemical effects were small, and many recovered within 3 km of each dam. Lower-reach impoundments also had comparable effects but changes downstream were more pronounced. In addition, all impoundments on both rivers significantly depressed fluctuations in discharge.

These findings tend to contradict some aspects of the SDC, particularly regarding release patterns and the operation of dams. Not only do alterations to nutrient regimes occur below all dams, but the type of release (epilimnetic versus hypolimnetic), seems to be less important than the position of a dam along the length of the river. Major conclusions of the work were that, regarding design and location of dams on a river, specific research is needed for each river, and that particular attention needs to be paid to the effects on the river of the particular reach in which a dam might be located.

Another interesting conclusion concerned Laing Dam on the Buffalo River. The regulation of rivers by impoundments has traditionally been viewed by conservationists as necessarily detrimental to all rivers. While this is true for unperturbed systems, it is not always the case for rivers suffering from severe disturbance. The Buffalo River is a case in point. Although it is relatively undisturbed in its upper reaches, the river is grossly polluted further downstream. Laing Reservoir receives nutrient loads that are orders of magnitude higher than those found in natural rivers, so that this reservoir effectively acts as a giant settling tank, greatly reducing nutrient concentrations. It can therefore be viewed as a benefit to the river rather than as a drawback: it certainly provides protection for the lower reaches of the river from the worst of the upstream pollution. Indeed, the purification processes appear to be far more intense in the dam than they would be in a comparable stretch of flowing water. Other conclusions drawn from this work were that no effects were common to all six dams; that larger impoundments caused more intense impacts downstream than smaller ones did; and that hypolimnetic releases consistently reduced temperature ranges and increased both total suspended solids (TSS) loads and the concentrations of all nitrogenous compounds in the rivers below the dams.

RESET AND RECOVERY DISTANCES

The SDC posits that after some distance, physical, chemical and biological variables will return to the same magnitudes as those upstream of the disturbance. The distance from a disturbance to the point of complete 'recovery' to upstream conditions is termed the 'reset' or 'recovery' distance. In other words, if sufficient distance is available downstream of a disturbance, the processes in a river below a dam, for instance, will allow the system to recover from the effects of the dam. This component of the SDC is arguably its most significant contribution to the understanding of river regulation and to the sensible management of dams. An understanding of the relationship between recovery distance and the longitudinal position of a dam, and the type of discharge it allows, should assist in optimising the design of dams and operating rules to minimise detrimental effects on the river downstream. A corollary of the idea of 'reset distances' is worrying: short rivers (like the Palmiet) may be too short for recovery to occur. It is not just short rivers that should concern us, though. What of rivers with cascades of dams along their lengths (and such rivers are common features of dryland environments)? Rivers with cascades of dams are like chains of short rivers, in which there may be insufficient distance for recovery to occur.

HOW MUCH WATER DOES A RIVER NEED?

The preceding section leads us logically to a very important concept, that of the 'instream flow requirements' (IFRs, or e-flows) of rivers. (The term is sometimes referred to by water managers as 'minimum flow requirements' but we dislike the term because it implies both that rivers can be exploited and that they can adequately survive on a minimal amount of water.) In the last decade or so, progressive staff of the Department of Water Affairs and Forestry (DWAF, now Department of Water and Sanitation or DWS) have recognised that dams and other regulatory structures do have detrimental effects on rivers and that mitigatory measures have to be considered when designing operating rules. We are pleased to say that in South Africa all new water resource projects are subject to an IFR assessment, as required by the National Water Act (NWA), Act 38 of 1998. Technical details are discussed in Chapter 10 but here we take a brief look at the historical background to South Africa's adoption of the environmental aspects of the NWA. (Wetlands, estuaries and groundwater are also protected under the NWA but here we concentrate on rivers. Note that a more generic term than IFR is ***Environmental Water Allocations*** – EWAs – since the subject deals with wetlands as well as rivers.)

One frequently hears statements about '… all that water running wasted to the sea…', while the term 'surplus water' crops up in almost any discussions with water managers. It has frequently been pointed out by river biologists, though, that there is no such thing as surplus water for inland aquatic ecosystems. All the water occurring naturally in a wetland, or running in a wild river, is useful to the system – sometimes in subtle ways. Flood waters, for instance, scour out and flush away the accumulated debris of past months and years: the bigger the flood, the greater its ability to scour the bed and return it to some baseline condition. None of that water is 'wasted' and none is 'surplus'. Managers often seem to assume that the amount of water suggested as the IFR for a particular river is in fact all that the river needs to carry on functioning normally ***in perpetuo***. This is simply not so. The instream flow requirement of a river is a compromise between the full amount of water that would allow completely natural conditions to pertain, and the requirements of human users of water.

The whole business of water requirements for the natural environment really started in the 1980s, when a DWAF official, Dr Paul Roberts, recognised that 'water for nature' (essentially for maintaining open mouths for estuaries) was a legitimate use for some of the water in rivers that were being exploited by water managers. He suggested that water for "nature conservation" might amount to something like 11% of the mean annual runoff for the entire country, basing his figures mainly on the evaporative losses and flooding requirements of estuaries and lakes, but also taking into account the water needed for nature conservation areas, including rest camps, game watering and the maintenance of riverine habitats in reserves such as the Kruger National Park. The concept of 'water for nature' (Roberts 1983) has matured over the last few decades. Although it started as the vague recognition that systems like estuaries would cease to exist without adequate supplies of water, it has now reached a stage where the NWA formally recognises that rivers are the sources of water and that a certain amount of water is 'theirs' by right. Beyond that amount (the 'ecological reserve'), DWS still considers rivers (and their biotas) to be in competition for water with industrial, agricultural and domestic users. Of course, rivers are not actually users (merely requirers) of water; they are also the ***providers*** of that very water, the homes of riverine inhabitants and resources in their own right. It took South African ecologists decades to get that message across to water managers, by the way. Jackie King and Harrison Pienaar (2011) have written a fascinating book, ***Sustainable use of South Africa's inland waters***, on this topic. (See details in the section on Further Reading below.)

Problems arise with regard to the ecological reserve: assuming (and there is good evidence that this is true) that each river is unique, how much water does each require to prevent degradation of its biotopes and biotas? Further, since the removal of even a little water may cause degradation, how much degradation is permissible or desirable? South Africa's community of freshwater biologists commenced work on this issue with pioneering research by Dr Jackie King and Rebecca Tharme of the University of Cape Town's Freshwater Research Unit in the late 1980s. It soon became apparent not only that 11% of mean annual runoff was insufficient to maintain even basic river processes but that each river had specific needs depending upon its geographical position, its seasonal flow pattern, its biotic communities and its conservation importance. In other words, intensive site-specific knowledge is required before allocations can be made for any system. (We will return to this point in Chapter 10.) It seems that, for most rivers, at least 20% to 40% of 'virgin' (unaltered) runoff is required to maintain close-to-normal habitats and processes. This naturally causes disquiet amongst engineers and water managers, but the simple truth is that if rivers are not allowed the amount of water calculated to meet their environmental needs then they will become degraded and will no longer be in a position to provide the clean water that we expect from them. And what of estuaries? Virtually all rivers flow to the sea (remember that some rivers, like the Okavango, drain into internal basins and not into the sea), and most have regions where estuarine conditions prevail at their mouths. Almost anything and everything that humans do to a river's catchment is bound to influence its estuary. South Africa has a very limited number of estuaries and the mouths of many of these are naturally and periodically closed by wave action, being scoured out and opened by the river when it comes down in flood. Nutrient replenishment by river floods is a phenomenon not only of floodplains but also of some estuaries (in fact an estuary may be an integral part of a coastal floodplain: see Chapter 6). Furthermore, the seasonal input of nutrient-rich sediments into and through the estuary is often important for estuarine and coastal fisheries, since juveniles of many marine fish grow up in rich, sheltered estuarine waters. So it is clear that the regulation of a river and the subsequent manipulation of its flow regime can profoundly affect its estuary, both physically and biologically. The amount of water entering an estuary from the river influences the distance that sea water can penetrate upriver. This in turn influences the distribution of organisms in an estuary, because each species can tolerate a particular range of salt concentrations. By smoothing out the flood- and dry-season peaks, dams can influence the extent to which salt water intrudes into an estuary, pushing it downstream if the river is discharging strongly or, by reducing the total amount of river water, allowing it to penetrate far upstream. It is thus possible, by manipulating discharges from a dam, to alter the position and the extent of the river where fresh and salt waters mix.

Estuaries that are naturally closed for part of the year may not be too badly affected by dams if compensation water is allowed to mimic natural floods, causing the mouth to open at appropriate times of year. One of the great dangers of impounding a river, though, is that its estuary will become seasonally (or even permanently) blind. The consequences can be profound, particularly for some species of fish whose juveniles will no longer be able to enter the estuary. It is possible to provide artificial floods but their outcome is usually unpredictable: they might not be able to scour out the mouth and they probably could not be timed to allow entry of more than a small proportion of the juvenile fish looking for an estuary to grow up in.

MULTI-PURPOSE USES OF IMPOUNDMENTS

Reservoirs are expensive to build and, in some instances, they flood irreplaceable arable land. Rich alluvial floodplains lie beneath the waters of numerous impoundments. Some sort of cost-benefit assessment is usually made during the early planning phases of a dam, weighing losses against the long-term economic benefits to be gained from the construction of the dam. Or so it is to be hoped, although the evidence we discussed earlier is not always convincing. A recent study has shown, for instance, that of several hundred American water-development schemes, not a single one was truly cost-effective in the final analysis. Indeed, most created much greater losses than would have been incurred by leaving the river alone in the first place. None of the estimated benefits were met; the schemes were nearly always over budget and the ultimate economic returns in no way matched the projections made in the planning stages. We hope that this is not generally the case in South Africa.

Whatever the truth of the matter, though, South African dams have seldom been designed for more than one purpose, despite the fact that there is little sense in constructing expensive water-storage systems without optimising their uses. Since not many more dams can sensibly be constructed on our rivers, we should use those we already have for as many purposes as possible. Some reservoirs are used for recreation (e.g., for boating), some for angling, some for storing potable water, some for power production and some for storing irrigation water, but none is used for fisheries production (true for South Africa, but it is worth considering the example of Lake Kariba cited earlier). Furthermore, none is used for all of these purposes together. Admittedly, it is difficult to manage an artificial water-mass for recreation and for potable water supply simultaneously, but it is not impossible. The fact that not one South African reservoir is commercially fished is extraordinary. Why is it that, as all of these systems are artificial anyway, we do not treat some of them commercially, for example by using them for the production of protein in the form of fish? In other cases, we might even be able to reduce eutrophication problems by turning some of those nutrients into edible fish or other forms of consumable biomass.

Finally, most reservoirs in South Africa are deleterious for the river downstream and for its biota. Not only have the instream requirements of rivers been ignored until recently, but dam walls with multi-level offtake points have only been considered in the last couple of decades. The Berg River Dam in the Western Cape was the first to be built to the standards of the World Commission on Dams and the first designed to allow large discharges for environmental purposes. What is more, until 1992, only two dams – of the many hundreds in the whole country – had fishways (fish passes or fish ladders) to allow migratory species of fish to pass up and down the river to their feeding and spawning grounds. Today there are dozens of fishways across the country. Some work better than others because the design has to take into account the particular species of fish, as well as flow characteristics of the river concerned. Anton Bok and colleagues have provided a useful WRC-funded report on fishways in South Africa. This document describes where the current fish ladders are and how well they work, as well as providing detailed instructions for the design and building of a variety of different models. But for the thousands of other barriers across our rivers, rehabilitation and construction of adequate facilities would take decades and cost hundreds of millions of rands, even if the political will and finance were immediately available. In the meantime, the dams stand firm, preventing the passage of migratory fish. Perhaps worst of all, the majority of South African dams have no release valves and so water cannot pass through them. The only time that the rivers downstream of these dams receive water (other than from leaks in and around the walls, and from direct rainfall) is when floods overtop them. This type of design is mercifully on the way out, but funds are not available for the modification of old dams.

FARM DAMS: THE INFLUENCE OF SMALL-SCALE WATER HARVESTING ON RIVERS

In Chapter 2 we discussed the distribution of large dams in South Africa and indicated that many thousands of smaller barrages, farm dams and weirs act as barriers across virtually every watercourse in the country. In-channel dams harvest water in the stream itself, and in some cases, water is pumped from the stream for storage in off-channel dams. These structures constitute a badly neglected aspect of river regulation in South Africa. Although each is relatively small, farm dams together store a considerable amount of water, particularly in KwaZulu-Natal and the Western Cape (also see page 148).

Dana Grobler

A massive discharge of 200 m³/s from the Berg River Dam, during a pilot study as required by the operating rules for the dam.

flipflopnick / Wikimedia / CC BY-SA 3.0

A weir and fishway; note that there are various pathways that a fish could use.

The Western Cape System Analysis, commissioned by the Department of Water Affairs and Forestry in the 1990s, examined the water resources of the region in relation to local water demand. Part of that study used aerial photography to estimate the number of farm dams in the area (there are more than 4 000) and showed that more than 100 x10^6 m^3 of water (the equivalent of a large reservoir, by Western Cape standards) was stored by these structures. In fact, almost 80% of this amount is stored in about 20% of the dams. The data from the study were used to assist the development of models for water supply and demand in the Greater Cape Town Metropolitan Region. Also in the 1990s, James Adams (as an Honours student at UCT) examined farm dams, this time in a smaller-scale study on the distribution and hydrological impacts of small water storages on the Klein Berg River. He estimated that there were about 349 farm dams in the relatively small catchment of about 650 km^2. These dams can potentially store somewhere between 8.9 and 17.2 x 10^6 m^3 of water but most are drawn down to <10% of full supply by the end of the summer dry season. This means that, while they are refilling in early winter, some 25% of runoff to the rivers is delayed after the onset of the winter rains, on average by some six weeks. A similar delay occurs in spring and early summer, so that at the time when rivers would normally have little (or no) flow, they are provided with water from the dams. All of this occurs in an area where the biota is adapted to high flows in winter and low flows in summer. Interestingly, using computer simulations, Adams also showed that these effects were most marked during already stressful years of natural drought. It is clear that privately-owned storages like these have major implications for the regional development of water resources. Unless the effects of small storages are understood, and can be quantified, planners cannot calculate how much water will be available for larger developments designed for public supply.

Jenny Day

A small Western Cape farm dam, full at the end of winter.

The effects of cascades of small lakelets on the lifecycles, growth and feeding of riverine biotas can presently only be surmised. The extent to which they alter normal cycles of particulate material, living organisms, flow and nutrients must be considerable, but has still to be quantified. Some preliminary work has been done on farm dams in the south-western Cape, which is virtually without natural standing water in high summer. Farm dams therefore represent an entirely new kind of aquatic ecosystem: permanent lakelets that support phyto- and zooplankton of a kind not normally found in the area. Albert Froneman and Helen Davies, when MSc students in conservation biology at UCT, looked at the importance of farm dams for bird life and for biodiversity in the landscape. They showed that farm dams provide a significant type of habitat for aquatic organisms, particularly for wading and swimming birds. They also showed that artificial systems may provide benefits for some components of the biota, even if farm dams situated on watercourses are detrimental to rivers.

INTER-BASIN TRANSFERS OF WATER

The transfer of water from rivers with a perceived 'surplus' of water to those perceived to be in deficit is an increasingly frequent solution to human demands for water, particularly in arid and semi-arid areas. Ninety-eight percent of the water for the city of Cape Town, for instance, is brought from far outside its boundaries through inter-basin transfers (IBTs). Indeed, the city and its environs ran out of water well over 100 years ago and ever since then have depended on 'other people's' water. The same holds true in many parts of the world. Canada transfers a total of about $14x10^9 m^3$ of water per year, while in the People's Republic of China, proposals are afoot to transfer up 44.8 billion m^3 a year in the 'South-to-North Water Diversion Project' (see also chapter 1). In South Africa, as we pointed out in Chapter 1, water naturally flows away from the industrial heartland, Gauteng, and great efforts are being made to feed extra water into it via IBTs (see discussion on the Lesotho Highlands Water Project on page 29). Furthermore, many of the large storages elsewhere in the country collect water in areas where demand is low and move it to other catchments where demand is high.

Table 9.5 **Some data concerning the largest existing IBTs in South Africa (data from DWAF) and the Eastern National Water Carrier (ENWC) in Namibia.**

Donor system(s)	Recipient system(s)	Mean annual transfer x 10^6 m^3
Vaal	Crocodile	615
Vaal	Olifants	150
Komati	Olifants	111
Usutu	Olifants	81
Assegaai	Vaal	81
Thukela	Vaal	630
Great Fish	Sundays	200
Orange	Riet	189
Orange	Great Fish	643
Lesotho Highlands (tributaries of the Orange)	Vaal	≈2 000
ENWP: Kavango R and Omatako, Karstveld groundwater	Swakop	120

Table 9.5 lists the largest extant IBTs in South Africa and, for comparison, includes the two major trans-border schemes presently under construction. More than $3x10^9$ m^3 of water are presently transferred each year. This will rise to more than $5x10^9$ m^3/y when

the Lesotho Highlands Water Project is complete, and in fact the potential exists for transfers of up to 9 or 10 x10^9 m^3 a year. At that stage, IBTs will harness about 9% of the total MAR and will increasingly be used as tools for 'maximising hydrological diversity' (i.e. for optimising the use of available water resources) in South Africa. Ultimately, it is possible that a network of interconnections throughout all the countries of the subcontinent will transfer 'surplus' (in the management sense of the word) water at will to areas temporarily stricken by drought, rather as ESKOM currently tries to do with electricity. It would only be a matter of political resolve, and of funds, before such transfers could take place – if we were to allow them to.

THE EFFECTS OF IBTS ON AQUATIC ECOSYSTEMS

Because IBTs can occur both between rivers in separate basins and within the same basin (from a headwater stream to its lower reaches, for instance) our working definition of IBTs encompasses both types. It is taken from a paper published in 1992 by Bryan Davies in cooperation with Michael Meador of the United States Geological Survey and Martin Thoms of the University of Canberra. We define an IBT as constituting '… the transfer of water from one geographically distinct river catchment, or basin, to another, or from one river reach to another'.

If the RCC approaches reality, then all IBTs must cause disruptions to, or discontinuities in, the continuum. For example, transfer of cold headstream water to a warmer middle reach will affect the temperature of the receiving stream and recovery will occur at some distance downstream of the point of transfer. There may of course be a multiplying effect if other variables have synergistic effects. The same must be true for other characteristics such as nutrient concentrations and so on. If we now consider the implications of the SDC as well, additional insights can be gained. We know that impoundments act as discontinuities, altering a variety of riverine features, each of which recovers to a greater or lesser extent at some point downstream of the discontinuity. With IBTs, however, two rivers are involved, thereby making the problem even more complex. While it is easy to envisage the detrimental effects engendered by the loss of water on a donor system, most other impacts are likely to be system-specific. They are also likely to depend on the initial conditions and on the river reaches involved. Examples might include the improvement in water quality in a perturbed recipient river by release of high-quality water from a donor or the deleterious release of sediment-laden water from a middle-reach donor river to a clear headwater stream. It is pretty obvious that impacts will be greatest over time, and when water is removed from a donor reach very different in character from that of the recipient reach.

In addition, we are concerned not only about the likelihood of transfer of invasive species from system to system, but also of the reuniting of once-isolated indigenous populations. The geographical isolation of populations of a single species is the most common way in which animals speciate (increase the number of species by splitting of existing ones). Thus, IBTs can act as unwitting experiments in genetics, the once-separated populations mixing and interbreeding, altering unique gene pools and preventing speciation (and thus decreasing biodiversity). Indeed, although quantified data are not yet available there is anecdotal evidence for the transfer of four species of fish to the Great Fish River in the Eastern Cape from Lake Gariep on the Orange River via the Orange-Great Fish-Sundays River IBT, which has been operational for nearly 50 years.

A while ago Kate Snaddon of the Freshwater Research Unit at the University of Cape Town demonstrated and quantified the successful transfer of large numbers (hundreds of thousands) of individuals of living zooplankton and insect larvae from Theewaterskloof Reservoir on the Riviersonderend River in the Breede River system to the upper Berg River through the Berg River Siphon near Cape Town. During the dry summer period in the Western Cape, the siphon provides irrigation water to the Berg River, exceeding the natural summer flow in the river by anything up to about 4 500%. Disturbingly, algal exudates called geosmins, which impart a nasty plastic-like taste and odour to drinking water, are already coming through the tunnels in the Franschhoek Mountains to the Berg River, where they have tainted the flesh of rainbow trout being reared at a fish farm below the siphon. The successful translocation both of fish from the Orange and plankton from Theewaterskloof indicate that these organisms can withstand the extraordinary rigours of pressure valves, transfer tunnels and 'dumping' under high pressure. If they can survive, then so can parasites, competitors and invasive plants and animals.

Before the Berg River Dam was built there was an IBT providing summer irrigation flow; the spray in the distance is the irrigation water entering the river.

To complete this discussion on river regulation and IBTs, we have chosen three case studies. The first, the transfer of water from the Orange River to the Great Fish River, illustrates the importance of information developed prior to the construction of an IBT. The second (Namibia's Eastern National Water Carrier) and third (the Lesotho Highlands Water Project) highlight concerns surrounding the development of IBTs where sound ecological knowledge and sensibly applied impact assessments are lacking. The second example is the epitome of all that has been wrong with many southern African water-development schemes: an almost total neglect of ecological concerns, resulting in great harm to the environment. The third case study has implications for the future development of water-demand management strategies (see Chapter 10) and is also an example of earthquakes as side effects of large dams.

IBT CASE STUDIES

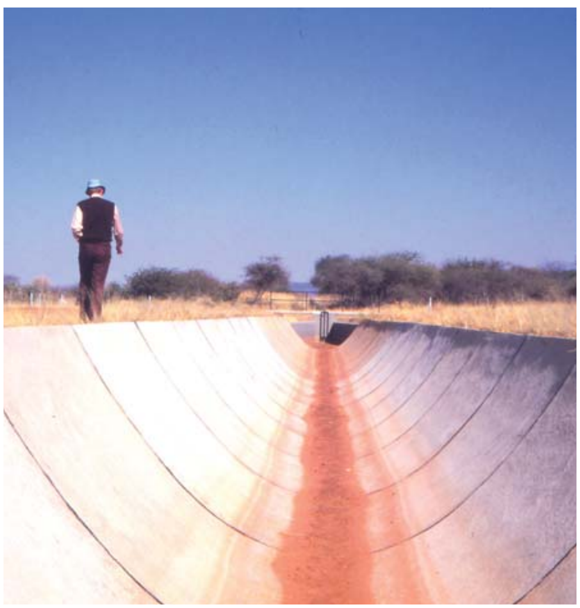
Great Fish River, Eastern Cape

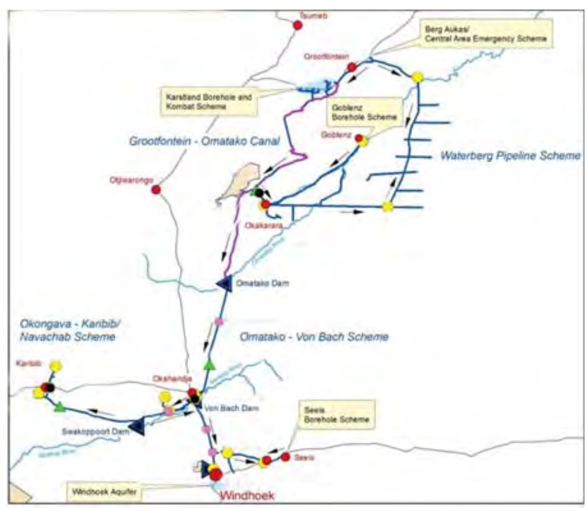
The only river in southern Africa on which at least some research was done prior to the construction of an IBT is the Great Fish River, part of the Orange-Great Fish-Sundays River Water Transfer Scheme (Table 9.5). The Great Fish River flows mainly through semi-arid ranch land in the Eastern Cape, and provides limited water for agriculture. In 1977, a tunnel was opened from the Orange River to provide the Teebus tributary of the Great Fish with 350 x 10^6 m^3 of high-quality irrigation water annually. In its natural state, the Great Fish was a seasonal river in which flow ceased between May and September of most years. Now it is perennial, and carries up to eight times as much water as it used to. The salinity (TDS usually >3 000 mg/L during low flows) that made the water virtually unusable for irrigation has now been greatly reduced by the inflow of purer Orange River water. In 1985, Jay O'Keeffe of Rhodes University and Ferdie de Moor of the Albany Museum in Makhanda, repeated a survey that had been carried out on the Great Fish River by Dr Marjorie Scott and colleagues during the early 1970s, before the IBT scheme had been put into place. O'Keeffe and de Moor found that while the number of taxa of invertebrates had changed little (from 41 taxa before the transfer, to 47 taxa after), the species composition had changed considerably, with only a third being collected in both surveys. Apart from the transfer of four species of fish to the Great Fish, the most striking change in the biota was the replacement of the dominant blackflies ***Simulium adersi*** and ***S. nigritarse*** by the pest species ***Simulium chutteri*** (see Chapter 8). These changes were attributed to the more permanent flow of the now-regulated Great Fish River, as well as to an increase in fast-flowing water, which the larvae of the pest species prefer.

The Eastern National Water Carrier, Namibia

The Eastern National Water Carrier (ENWC), is the largest IBT in Namibia. The scheme involves groundwater, several dams, three rivers (the Swakop, Omatako and Kavango) and, most controversially, the uncovered Grootfontein-Omatako Canal, which is open for 203 km of its 263 km length, and which is designed to carry 2–3 m^3/s of water. The final phase of the project, the canal linking the Omatako Dam with the Okavango River, has not been built and the main canal from the Omatako Dam to Windhoek still carries water only during floods. Most of the time the Omatako Dam is dry. During recent droughts a pipeline from Rundu to Grootfontein has again been considered for water supply to the centre of the country. Despite some initial public disquiet, the potential ecological impacts of the scheme were ignored, the only research being undertaken after construction was well under way and parts had already been completed (a familiar story). The belated research raised a number of serious concerns, which are discussed below.

Jenny Day





A dry section of the Eastern National Water Carrier canal: the shape explains why it is so difficult for animals to get out of the canal.

Transfer of fish from the Okavango River to more southerly drainage systems

The potential effects of the transfer of fish from the Omatako to the Swakop River was not considered, probably because of the ephemeral nature of these rivers. It is possible, though, that some species could survive the transfer from the Okavango River or its wetlands to the Omatako Dam, for instance.

Transmission of bilharzia

In theory, if water flows rapidly in the canals, host snails should be unable to establish themselves. The establishment of the snails in the reservoirs of the scheme seems to be inevitable, however.

The 'killer canal': effects on terrestrial animals

The open canal is a 200 km-long barrier to the migration of ground-dwelling animals, including large vertebrates. Large animals fall into it and, because of its semi-circular shape in cross section, they cannot get out again and so starve to death. When it carries water, the canal is the biggest insect trap in the world as insects are attracted by the water, fall in and are swept downstream. This is one of the most contentious, emotive and serious impacts of the scheme, and one that should have been obvious from the first. It has been estimated that more than 17 500 animals, mostly large mammals, are killed by falling into the (mostly dry) canal each year. This figure does not include reptiles or the myriad insects and other invertebrates that die and decompose in the canal. Between June 1985 and August 1986, a 65 km length of canal contained the bodies of 7 234 vertebrates. Some 28 species of mammal were recorded, including the rare pangolin, aardwolf and aardvark. Of the total, 57% were reptiles, 22% amphibians, 19% mammals and 2% birds. (Birds like the Cape vulture are obviously attracted to the dead and dying animals in the canal but they require a 'runway' to take off after feeding.)

Although the ideal solution would have been to cover the canal when its effects were recognised, the R30 million required was considered by planners to be "… too high at this stage to make such action a practicable solution …" In 1987, a number of experimental 'escape' structures were built into the canal but apparently are seldom used by panicking animals. In 1990, a stretch of canal 1.5 km long was covered as an experiment and has been a great success. Experimental barriers to prevent reptiles from falling in have also met with success. There is now a strong recommendation to cover the entire canal, but the cost has risen to R50 million and the authorities still consider this to be too big a price to pay. Small electrified fences, grids and sloping ramps have been incorporated in some parts, but have been far less effective than a complete cover. One can sympathise with the Namibian public: not only was the planning ecologically poor, and warnings blatantly ignored, but now they must pay to have the system modified at a greater cost than that initially rejected by the decision makers. (An ironic aspect of the canal is that IBTs usually break down barriers that isolate aquatic populations, thus reducing the likelihood of their being able to speciate. In this case, the canal acts as an artificial barrier to gene flow in terrestrial organisms that are unable to cross it and so it should, in theory at least, contribute to the potential for speciation in these taxa if it lasts long enough.)

Water quality

The concentrations of nutrients in water transferred from the Okavango ought to be relatively low but the mineralised products of decomposition of trapped animals, together with wind-blown material, may result in reduced water quality and increased algal growth.

Losses of water from the canal

Loss of water by evaporation amounts to between 2 250 and 3 000 mm a year for the region, while precipitation rarely exceeds 200 mm a year. Yet although concerns were expressed about how much water might be lost from the canal (not to mention from the surfaces of the storage reservoirs) by evaporation alone, original estimates were that "…such losses will be relatively insignificant …" Subsequent investigations have clearly shown that evaporative losses from the canal alone are close to 70%. Furthermore, hydrostatic pressure on the concrete-lined canal causes it to 'float' during periods of rainfall and so to crack at the base, leading to leakage of water.

Effects on groundwater in the Karstveld

A significant proportion of the water being transported in the canal is abstracted from massive natural aquifers in an area known as the Karstveld, in the vicinity of Grootfontein. After this resource was first exploited, early reports from local farmers suggested (hardly unexpectedly) that the water table was falling and that springs were drying up. As a result, research has been carried out for some years, monitoring the depth of the water table and the effects on vegetation, particularly trees. All that research such as this can show, however, is how great the effect is. Whenever water is abstracted from aquifers faster than it is recharged, the water table will fall, and ultimately the water supply will dry up. The only way to ensure that the resource is sustainable is to balance supply and demand and not to remove more water than is replaced by rainfall or by artificial means. This is hardly a difficult concept even for a seven-year-old.

The environmental effects of the ENWC are still becoming apparent. The lack of a full-scale ecological impact assessment (EIA) at the planning stage has led to public outcry (although it must be said that much of the planning took place before EIAs were legally required in Namibia). The scheme is still incomplete, though, and an EIA is presently under way of the proposed abstraction of some 3 m^3/s from the Okavango River, which drains into the Okavango swamps. The trans-border dimension of this development is likely to be interesting, because Botswana is very concerned about its effects on the Okavango Swamps, while the Okavango is one of the few major water resources for Namibia.

The Lesotho Highlands Water Project

(See also pages 28 and 332)

Lesotho, the 'mountain kingdom', is entirely surrounded by South Africa, and being small and mountainous, has very few natural assets. The one thing it does have in abundance is water, though, because South Africa's largest river, the Orange, arises in its mountains. South Africa, on the other hand, is much larger and is endowed with numerous natural assets from gold and diamonds to coal and valuable minerals, but it is an arid country. What is more, the industrial heartland of the country is perched in poorly watered highlands. As long ago as the 1950s, people realised that it would be good if South Africa could have some of Lesotho's water, and Lesotho could have some of South Africa's wealth. A deal was therefore struck and the Lesotho Highlands Water Project (LHWP) was born. A treaty was signed in 1987 and construction of the first dam, the Katse, began in 1989. The scheme was designed to transfer 2.2×10^9 m^3 of water a year from the Malibamat'so River, a major headwater tributary of the Orange River in Lesotho, to the Ash/ Liebenbergsvlei River, a tributary of the Vaal River rising in the Free State near the Golden Gate Highlands National Park. The water was to be, and is, used primarily for industrial and domestic purposes in Gauteng. Construction was phased, starting with the Katse Dam (completed in 1998) on the Malibamat'so River and the Mohale Dam (completed in 2003) across the Senqunyane River. The second phase consists of a third dam, the Polihale, which is under construction as of 2022. A third phase seems to be on hold. The cost of the Katse and Mohale dams and other construction work was about US$8 billion and of the Polihale will probably be another US$1.5 billion.

Obviously it has been enormously beneficial to Gauteng to have an assured supply of water, and to Lesotho both to have a steady income from the sale of water, and a steady supply of electricity from the dams. What are the down sides of the dams? As you might imagine, there are many.

Unbelievably, the sluice gates of Katse dam are built near the top of the wall (and there are ***none*** in the wall of Mohale Dam, other than a spillway) allowing no flow to the river except through spillage at full supply (which is likely to be a rare event, seeing that the water in the reservoir is meant to travel northwards to Gauteng rather than downstream). It is hard to believe that this is possible, but it is so. The compensation tunnels (tunnels allowing flow to the river below the wall) at Katse allow for an average release of only 0.75 m^3/s, a pathetic amount of water for a river of this size and magnificence. The dam will produce electricity for Lesotho, but a generating capacity of only 72 MW has been installed. This may satisfy Lesotho in the medium term, but with such a large project, in such a well-watered land, why not produce more and sell the rest? And why not investigate the use of the reservoirs for aquaculture?

One of the major criticisms of the project was an entire lack of environmental assessments in the early stages of the project (see the Master's thesis by Setenane Nkopane in the reading list). In the late 1990s the LHDA finally called for tenders to carry out proper instream flow assessments that would take two years or more and would provide proper information on the water requirements of the rivers themselves. It seems that ecologists and IFR practitioners at last managed to persuade the World Bank financiers, as well as the developers, that compensation water of <1 m^3/s of water (which was agreed in the original treaty between South Africa and Lesotho) was shockingly inadequate.

Even the human aspects were overlooked. Despite the fact that the Lesotho Highlands Development Authority (LHDA) undertook to move people at its own expense, and to compensate them for lost lands, homes, pasturage and gardens, virtually every family affected by the scheme complained that compensation was inadequate; tree seedlings had not been delivered; insulated stone homes had been replaced by thin metal huts utterly unsuited for the bitter winters of Lesotho; and supplies of replacement foods and fodders were inadequate and would only be provided for a limited time after the reservoir had filled. What is really disturbing is that villagers, once free of sexually transmitted diseases, soon suffered the scourges of syphilis, gonorrhoea and HIV/AIDS brought by thousands of migrant construction workers, prostitutes, and truckers. HIV, which was unknown in the area before construction started, soon infected one person in ten. The people of the Malibamat'so Valley have been exploited by our consumption of water in Gauteng.

The financial, social and environmental costs of the project are mind-boggling. Proper planning would have taken a minute fraction of the total cost and could have prevented embarrassing mistakes. For instance, it transpired that diamond mining rights existed in the basin to be inundated by the Katse Dam and that the foreign company holding those rights was prepared, well after construction has begun and money committed, to go to litigation to prevent inundation of the land. So, it seems that not even the legal aspects had been adequately researched. The dispute reared its head again in 2017. If you are interested, follow the very convoluted story at http://bit.ly/3HR4q8y

Furthermore, according to DWAF's old projections of water demand in the region controlled by the Johannesburg-based water utility Rand Water, the dam would have been needed by 2003. It turned out, however, that water from the dam would not have been needed before 2009–2012. Although Rand Water revised the estimates of water demand, DWAF went ahead with building the dam on schedule. Taking into account the revised estimates alone, building of the dam could be put off for 6 years even without instituting ***any*** water demand management (see Chapter 10); with it, building could be put off for 10 years at least. The financial burden of this enormous undertaking is so great that it would have been financially better for Rand Water (i.e. the taxpayers) to pay Lesotho all the money that they would obtain from the sale of water over this time, and to pay farmers in the area not to plant crops, than to have to pay off the capital costs (let alone running costs) of the dam 6–10 years before it was needed.

As one might expect, enormous projects like this present other challenges too. Ever since Katse Dam had begun filling there were earthquakes, and houses in several villages were destroyed, being replaced only years after the events. In the 1990s striking workers clashed with police and five workers were killed. In 1999, corrupt practices were discovered: various multinational companies were bribing senior LHWP officials; both officials and the companies were finally tried and found guilty in the early 2000s.

A final twist in the tail is related to the vagaries of climate change. In 2021, Gauteng received such good rains that their major storage dams, including those on the Vaal River, were full to overflowing and could not receive the water coming from Lesotho. Lesotho, on the other hand, needs water to flow from the dams to allow the turbines to produce the hydropower it relies on. As a result, 'excess' water was not retained in the dams. So, in effect, the dams were drawn down and the water flowed out to sea instead of into the dams of Gauteng. Of course, this is seen in engineering terms as "dumping it in the ocean" although we know that water flowing down a river is never wasted. This may have been the first time in years that an adequate amount of water had flowed down the Orange River to the sea. The url with details is http://bit.ly/3WY1qeI. Even the title of the article gives an interesting insight into the opinion of the writer of the piece.

In conclusion, dams of all sizes are fundamental to water management in South Africa and, of course, in other arid lands. We recognise the crucial role that dams play in evening out the un-evenness of water supply, particularly in todays' warming world. It is important to remember, though, that while dams may be necessary evils, they will always affect the rivers on which they are built, and seldom in a good way. Their effects can be moderated by sensible planning and sensitivity to the potential damage, of course.

Terraced fields in the highlands of Lesotho in winter.

READING LIST

Balon EK & AG Coche (eds) (1974) ***Lake Kariba: A man-made tropical ecosystem in Central Africa.*** W. Junk, The Hague, 767 pp.

Beilfuss R & C Brown (2010) Assessing environmental flow requirements and trade-offs for the Lower Zambezi River and Delta, Mozambique. ***International Journal of River Basin Management*** **8**: 127-138. DOI: 10.1080/15715121003714837

Böge V (2005) A glass half full or half empty? Resource politics in Sub-Saharan Africa. ***Hamburg African Studies*** **14:** 272-304

Bok A, P Kotze, R Heath & J Rossouw (2007) ***Guidelines for the planning, design and operation of fishways in South Africa***. South African Water Research Commission Report No. TT 287/07.

Bond WJ, N Coe, PBN Jackson & KH Rogers (1978) The limnology of Cabora Bassa, Mozambique, during its first year. ***Freshwater Biology*** **8**: 433–447

Brown CA & P Watson (2006) Decision support systems for environmental flows: Lessons from Southern Africa. ***International Journal of River Basin Management*** **5** (3): 1-10

Brown C, A Joubert, T Tlou, A Birkhead, G Marneweck, B Paxton & A Singh (2018) The Pongola Floodplain, South Africa; Part 2: Holistic environmental flows assessment. ***Water SA*** **44** http://dx.doi.org/10.4314/wsa.v44i4.22

Cambray JA & RA Jubb (1977) Dispersal of fishes via the Orange-Fish Tunnel. ***Journal of the Limnological Society of southern Africa* 3**: 33–35

Connell JH (1978) Diversity in tropical rain forests and coral reefs. ***Science* 199**: 1302–1310 (*The* seminal paper on the Intermediate Disturbance Hypothesis)

Davies BR (1975) Cabora Bassa hazards. ***Nature, London* 254**: 477–478

Davies BR (1986) The Zambezi River System. pp. 225–267 in: BR Davies & KF Walker (eds.) ***The ecology of river systems. Monographiae Biologicae* 60**. Dr W. Junk, Dordrecht. 793 pp.

Davies BR, MC Thoms & M Meador (1992) Viewpoint: An assessment of the ecological impacts of inter-basin water transfers and their threats to river basin integrity and conservation. ***Aquatic Conservation: Marine and Freshwater Ecosystems* 2**: 325–349

Fearnside, PM 2001. Environmental impacts of Brazil's Tucuruí Dam: Unlearned lessons for hydroelectric development in Amazonia. ***Environmental Management* 27**: 377-396

Hartnady CJH (1985). Uplift, faulting, seismicity, thermal spring and possible incipient volcanic activity in the Lesotho-Natal region, SE Africa: The Quathlamba Hotspot Hypothesis. ***Tectonics* 4**: 371–377

Heeg J & CM Breen (1982) ***Man and the Pongolo Floodplain***. South African National Scientific Programmes Report 56. Council for Scientific and Industrial Research, Pretoria. 117 pp.

King JM, JH O'Keeffe, S Pollard RE Tharme & D Weeks (1996) ***Assessment of environmental water requirements for selected South African rivers: problems and possible approaches.*** South African Water Research Commission Report No. KV 72/95

King JM & H Pienaar (eds) (2011) ***Sustainable use of South Africa's inland waters.*** South African Water Research Commission, Report No. TT491/11

McLachlan AJ (1970) Some effects of annual fluctuations in water level on the larval chironomid community of Lake Kariba. ***Journal of Animal Ecology* 39**: 79–90

McCully P (1996) ***Silenced Rivers: The ecology and politics of large dams.*** ZED Books, London and New Jersey. 350 pp.

Nkopane S (1997) ***An evaluation of environmental impact assessment procedure in the Lesotho Highlands Water Project: Phase 1.*** MSc thesis, University of Cape Town

O'Keeffe JH, BA Byren, BR Davies & RW Palmer (1990) The effects of impoundment on the physico-chemistry of two southern African river systems. ***Regulated Rivers: Research and Management* 5**: 97–110

Phelines RF, MM Coke & SM Nicol (1973) Some biological consequences of the damming of the Pongola River. Pp. 175–191 ***in***: ***Commission Internationale des Grands Barrages,*** Eleventh Congress, Madrid.

Pitchford RJ & PS Visser (1975) The effect of large dams on river water temperature below the dams, with special reference to Bilharzia and the Verwoerd Dam. ***South African Journal of Science* 71**: 212-213

Roberts CPR (1983) Environmental constraints on water resources development. ***Proceedings of the South African Institute of Civil Engineers* 1**: 16–23.

Scudder T (1972) Ecological bottlenecks and the development of the Kariba Lake basin. ***In***: MT Farrar & JP Milton (eds) ***The Careless Technology: Ecology and International Development***. Doubleday, New York.

Snaddon CD, MJ Wishart & BR Davies (2008) Some implications of inter-basin water transfers for river ecosystem functioning and water resources management in southern Africa. ***Aquatic Ecosystem Health & Management* 1**: 159-182

Tosun H (2015) Reservoirs and earthquakes. Chapter 7 in: A Moustafa (ed.), ***Earthquake Engineering***. Intech Open publishers www.intechopen.com DOI:10.5772/59372

Ward JV & JA Stanford (1983) The serial discontinuity concept of lotic ecosystems. Pp. 29–42 ***in:*** TD Fontain & SM Bartell (eds) ***Dynamics of Lotic Ecosystems.*** Ann Arbor Science Publishers, Michigan, USA

Ward JV & JA Stanford (1983) The intermediate disturbance hypothesis: an explanation for biotic diversity patterns in lotic ecosystems. Pp. 347–356 ***in***: TD Fontaine & SM Bartell (eds) ***Dynamics of Lotic Ecosystems.*** Ann Arbor Science Publishers, Michigan, USA.

WEBSITES (LAST ACCESSED NOVEMBER 2022)

Balbino Dam
https://www.fastcompany.com/40444039/this-dam-has-been-a-disaster-can-turning-it-into-a-solar-plant-save-it

Banquiao Dam failure
http://en.wikipedia.org/wiki/Banqiao_Dam

Elwha River restoration
https://www.usgs.gov/programs/coastal-and-marine-hazards-and-resources-program/science/elwha-river-restoration-project

https://en.wikipedia.org/wiki/Elwha_Dam

ENWC
https://namibian.org/news/nature-and-environment/water-supply

Global dam tracker: useful up-to-date data
https://www.energypolicy.columbia.edu/sites/default/files/pictures/GlobalDams_CGEP_2018.pdf

IBTs in southern Africa
file:///C:/Users/User/Downloads/Bookchapter24-HandbookofDrought.pdf

Lesotho Highlands Water Project
https://archive.internationalrivers.org/resources/a-brief-history-of-africa%E2%80%99s-largest-water-project-3664

https://archive.internationalrivers.org/resources/lesotho-highlands-water-project-what-went-wrong-4060

https://www.afdb.org/sites/default/files/documents/environmental-and-social-assessments/esia_summary_for_lesotho_highland_water_project_ii_-polihali_reservoir_associated_infrastructure.pdf

Limpopo River
https://www.limpopo.riverawarenesskit.org/

Namibian water supply
https://www.wikiwand.com/en/Water_supply_and_sanitation_in_Namibia

Nyami Nyami, the God of the Zambezi River
https://www.victoriafalls-guide.net/african-mythology.html

Silt control in reservoirs
https://infrastructurenews.co.za/2021/08/03/increasing-dam-storage-capacity-through-the-natsilt-programme/]

Water as a resource in southern Africa
https://books.google.co.za/

markdescande/123RF

The Calitzdorp Dam, peeking out in the distance, was constructed more than a century ago. South Africa has a number of dams that are more than 100 years old.

CHAPTER TEN

Siempreverde22 / 123RF

Managing water for people

Some, for all, forever

SA Department of Water Affairs and Sanitation slogan

THE CASE FOR THE CONSERVATION OF WATER

We are rapidly running out of water in South Africa. The situation arises party because of climate change but mostly because the hugely increasing human population of southern Africa requires more and more water. Many of South Africa's water-resource problems stem from ingrained attitudes, although the droughts that have recently afflicted most of the subcontinent are making many of us think twice before leaving the tap running. This is a Good Thing because if we want to protect human wellbeing, our ecosystems and our economy, we have to develop new ways of thinking about water and how we use it.

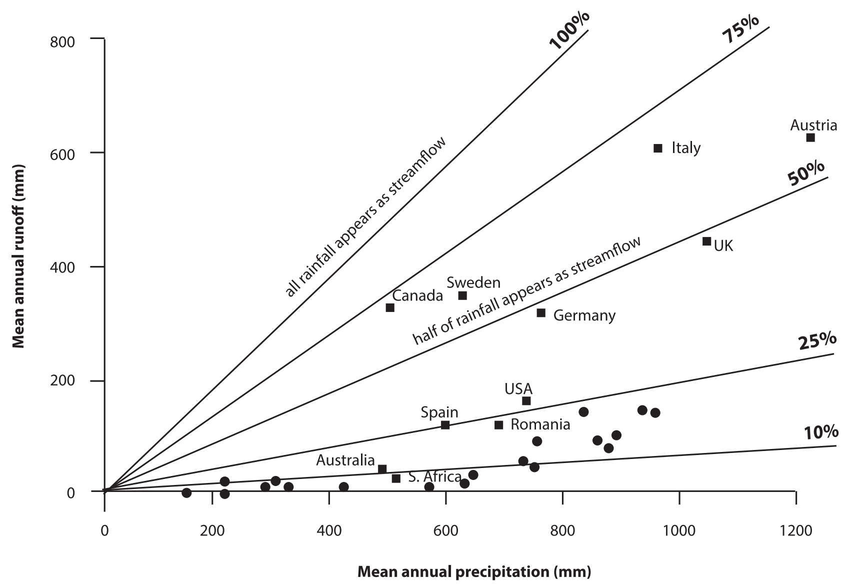
You may be old enough to remember how a few days before Christmas 1995, an almost-miraculous series of deluges boosted the Vaal Dam from a very dangerous low of 14% of capacity, to 110% – and spilling – so that Gauteng was let off the hook of enforcing water restrictions. Do you remember the terrible droughts in the old Natal and Transvaal in the early 1980s? Maybe you don't, but you almost certainly remember Cape Town nearly running out of water just a few years ago, and the horrible pictures of empty dams and dying cattle. As of November 2022, Gqeberha (Port Elizabeth) has virtually reached Day Zero. We are certainly living through warmer summers, bigger floods and deeper droughts and yet we still seem to be unable to learn from experience. As soon as a drought breaks, the dams fill and those irritatingly inconvenient water restrictions are lifted, the slogans evaporate like water from a pond on a hot summer's day, the garden hoses go on again, the car is washed and the gutters fill with soapy water. The fuss dies away and the problem is conveniently poured into the swimming pool, or down the drain, for another few years. Unfortunately, at the same time our memories of drought fade and we become careless with water once more.

The collective human memory is remarkably short. To most of us, the idea of conserving water, of paying a realistic price for it, of using it sparingly and of installing water-saving devices,

1 m^3 = a thousand litres	= 1 kilolitre = 1 ton
a half-full bathtub contains about 100 litres	
103 m^3 = a million litres	= 1 megalitre (ML)
an Olympic swimming pool contains about 2 500m^3	
106 m^3 = a million m^3 = 1 Mm^3	= 1 gigalitre
before the 2015/17 drought, Cape Town used about 1 million m^3 per day	
109 m^3 = a billion m^3	= 1km^3 = 1 teralitre
South Africa uses about 16 km^3 per year	

seems unnecessary if not economically senseless. It is certainly a downright nuisance. After all, rain comes sooner or later and is provided free of charge by nature, isn't it? Why should anyone be forced to pay for it? Of course, water itself is free. But the provision of water conveniently through a tap is a very costly business. We are generally unaware of this because we do not presently pay the real costs of the water we consume. As a case in point, the provision of water for Gauteng from the Lesotho Highlands Water Project has already cost tens of billions of rands (see Chapter 9 and below), but this will not come from the people of that province alone. Instead, it will be lifted from the wallets of every tax-paying South African.

More fundamental than the cost of water is its scarcity, though. The plain facts are that there are very few rivers left to dam or divert, there always seems to be a drought in some part of the land, and there are too many people competing for too little water. A glance at the figure shows us that South Africa is teetering on the brink of permanent drought – the stage at which the resource simply cannot provide for further increases in demand.



The relationship between mean annual runoff (y axis) and mean annual rainfall (x axis) for selected countries around the world (squares). South Africa's primary drainage regions are plotted as dots (modified from Alexander, 1995).

Let us briefly revisit some harsh realities:

- South Africa has close to the lowest conversion of rainfall to usable runoff from rivers of all countries in the world (e.g., South Africa 8.6%, Australia 9.8%, Canada 66%).
- South Africa has a surface area of the order of 1 220 000 km^2, of which about one-sixth (roughly the area of the United Kingdom) has no significant surface runoff. The only water available here is groundwater, and most of that is brackish.
- In comparison with world average rainfall, estimated at something like 860 mm/y, the mean annual rainfall of South Africa

fluctuates around 475 mm/y (see page 43). This results in a mean annual runoff of 50–60 billion cubic metres (50–60 km^3), which is roughly four times the volume of Lake Kariba. If spread over the entire country, this water would form a layer less than 50 mm deep.

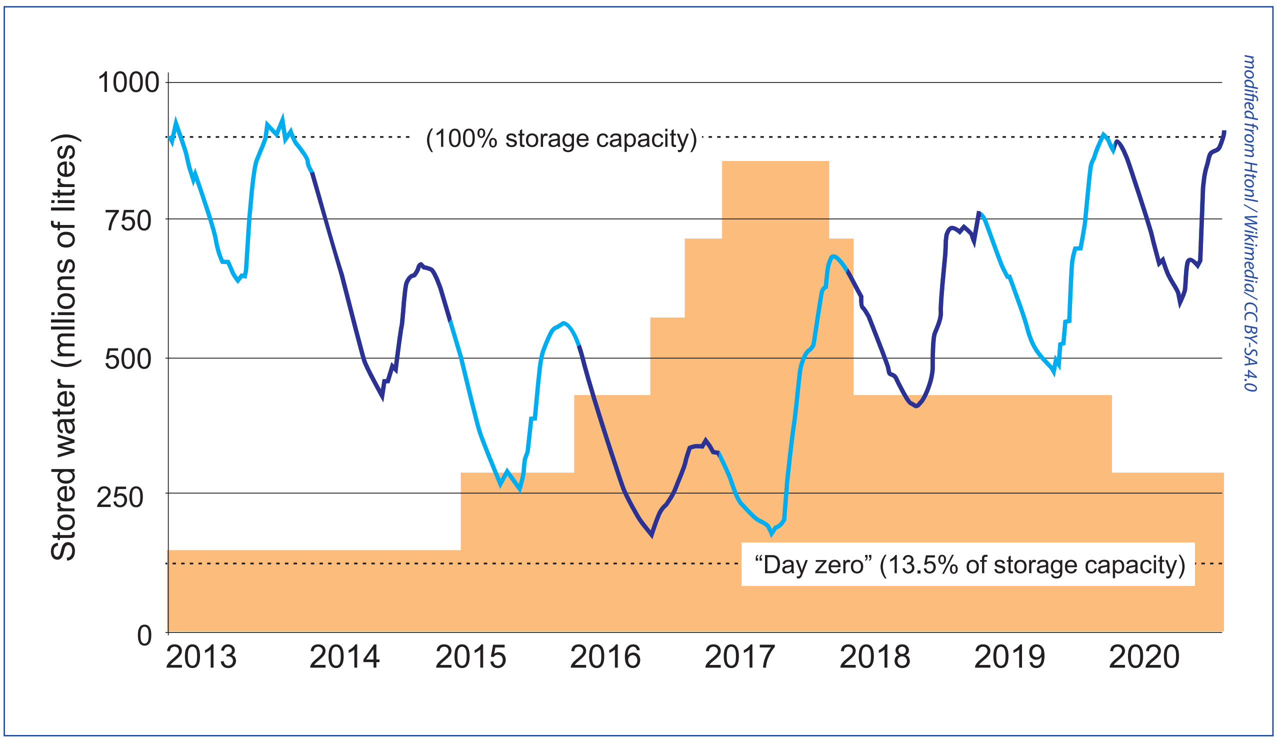
- Of the rain that does fall, about half is caught and stored in dams, while about 8% returns to the sea in rivers and the rest disappears as evaporation, evapotranspiration and infiltration into the ground.

- DWS estimates South Africa's exploitable surface water to be about 49 x 10^9 m^3/y and groundwater another 10 x 10^9 m^3/y; South Africa currently uses about 580 x 10^9 m^3 (= 580 x 10^6 m^3) a year.

- The demand for water is increasing exponentially. To keep up with demand, as many dams were built between 1971 and 2000 as the number built by the twelve generations of European settlers between 1652 and 1970.

- If total surface water resources were to be combined with the lowest rate of population growth and the total exploitation of groundwater, permanent drought in South Africa might be postponed until 2040, at best. In reality, extensive exploitation of ground water is probably not feasible due to the lack of large aquifers (but see information on the Table Mountain Aquifer on page 61), the dependence of farmers on groundwater in many areas, poor water quality and the very slow rate of recharge, which is usually no more than about 2% of annual rainfall.

- All predictions of water-demand assume that both demand and supply are roughly evenly distributed around the country. This is not the case.



The volume of water stored in Cape Town's six major storage dams from 2013 to 2021, based on City of Cape Town data. Orange panels represent levels of water restrictions.

Virtually all parts of the country have experienced unprecedented drought over the last decade or so. Droughts have been part of the South African landscape for as long as there have been people, but the current frequency and depth of drought are something new. Granted, the South African population is growing rapidly, but it is climate change, and not just increased demand, that has been causing us such trouble recently. The figure on page 373 is a water manager's nightmare, for it shows that Cape Town rainfall over not just one, but two, years was the lowest on record. It is common knowledge that Cape Town almost reached 'Day Zero', the day on which the City would have been unable to provide any water for its citizens. Cape Town is not alone. In South Africa, there have been devastating droughts in KwaZulu-Natal, in the centre of the country, and now in the Eastern Cape. Southern Africa is not alone. Australia and the western USA, particularly California, have been, or currently are, in dire straits.

On the other hand, there is some relatively good news about the general public's increased access to water. The values in parentheses below are those cited in the previous edition of this book. Current values are for about 2020. According to DWS, some 4 million (12 to 14 million) South Africans do not have access to safe drinking water and some 5 million (21 million) have inadequate sanitation; 9 000 (50 000) children die every year from diarrhoeal infections. South Africa's population increases by about half a million (a million) people every year.

As Carl Sagan noted, average life expectancy was 20–30 years during pre-agricultural times. It rose to about 40 years in 1870 and then accelerated from 50 years in 1915, through 60 in 1930 to 70 in 1955. In the more developed countries of the world, it is now approaching 80 years and demographers suggest that the first person to live to 200 years of age has already been born. (In other words, the population is growing in size and a greater proportion of the population is also getting older). Although ecologically the land may be able to cope with a countrywide increase in the human population of this magnitude, can water supply be stretched to accommodate huge numbers of people? Furthermore, the proportion of people living in cities is expected to rise to 80% by 2050 (currently about 60%), thereby placing enormous pressures on our urban environments and on the rivers that supply them – and us – with water. This issue is discussed further in Chapter 11.

The question then arises – is this urbanisation sustainable? In the sense used by, for instance, the International Union for the Conservation of Nature (IUCN), 'sustainability' suggests the idea of the indefinite restraint of human consumption within the compass of available resources. In many quarters, though, this concept has become confused and twisted to refer to sustainable ***economic*** growth rather than sustenance of natural ecosystems and communities. In 1996, South Africa's then Minister of Finance, Trevor Manuel, released a policy document described as 'non-negotiable' and setting out a target for economic growth of 6% a year. (Well, that ***was*** 25 years ago!) In contrast, Manfred Max Neef, the so-called 'barefoot economist' from South America, has shown that such growth of national and global economies is environmentally nonsensical. Resources, even renewable ones, are finite and cannot sustain indefinite growth. (See Chapter 11.)

The cry of conservationists to conserve water is not only a practical one but also carries an essential message: our limited resources must be carefully husbanded and wisely used. But how can we do this, and can it be done without continuing the devastation of our remaining natural or semi-natural aquatic ecosystems? It would be simplistic to suggest that the answer is easy, or even that it is truly soluble using conventional sources of water like rivers and ground water. Only a limited number of solutions lies open to us. The first is establishing a human population of a size that does not stretch natural resources beyond their limits. (Control of population size would be difficult to achieve in a practical and morally defensible fashion.) Other solutions lie in our attitudes and our lifestyles. We must help ourselves by nurturing a culture of conservation, by reducing consumption, by putting the brakes on economic growth as far as we can, by recycling, by education and by a humbler and wiser approach to the wonders of our planet. This chapter deals specifically with water-related issues, but Chapter 11 is written with these wider ideas in mind.

WHO USES THE WATER?

We all do, of course. When the world's population was about six billion (1999), we humans used approximately 3 240 km^3 of water every year. The more fortunate of us use it personally and directly (by turning on the tap, flushing a toilet cistern and so on), and some we use indirectly when we purchase a motor car, a laptop a newspaper, or a kilogram of tomatoes, the production of which consumes water. In absolute terms, though, we should have no difficulty in finding enough water for our needs. After all, two-thirds of the earth's surface is covered by water, the most abundant substance we know (page 40). The problem, of course, is that most of the water is stored in the oceans and too salty to use, or in the polar icecaps and therefore inaccessible. It is technically feasible, although expensive, to extract fresh water from the sea by desalination, while early experiments are already underway to determine the feasibility of melting icebergs. Later in this chapter we will have more to say about the use of these unconventional sources of water, and whether or not it is possible to balance the conflicts of supply and demand. In the meantime, let us consider who uses water, and in what quantities.

INDUSTRIAL USE

We examine the industrial use of water first because, if asked which sector of the economy consumes the most water in South Africa, most people would probably point to the mines and to power stations and other industries. They would be wrong, though. Industry comes a distant second in the water-consumption stakes, using only about 12% of the total amount consumed in South Africa; mines use about a quarter of this total, or 3%. Industries use water as a solvent, a coolant, a dust-settler and a cleanser and even as a means of transport (coal transported by pipeline, for instance). Some industrial processes are very costly of water. For instance, about 150 m^3 of water are used in the production of a single ton of steel. What is more, very little of the water used in most industrial processes is actually used up: most is polluted and returned to source.

Some industries are particularly thirsty. For instance, 20 years ago the Secunda industrial complex, which produces fuel from coal, consumed a staggering 240 Mm^3 of water a day in the production of petrol and other (mainly pharmaceutical) by-products. Many industries have become far more responsible in their use of water, though, and today Secunda uses about 134 Mm^3 a year – little more than half of what it used in 1995.

Yale Centre for British Ar/ CC0.10

Industrial landscape, painting by Thomas Austen Brown.

Jenny Day

View over the Cape Flats from the University of Cape Town, cooling tower in the distance releasing steam into the chilly winter morning.

SASOL plant, Secunda, polluting the air but using less water than it used to.

AGRICULTURAL USE OF WATER

Unquestionably, farmers are the main users of water in South Africa. It was estimated in 1983 that about 73% of the total amount of water used in the entire country went to irrigation and stock-watering, although this decreased to about 69% in 1997 and about 60% in 2022. Since four-fifths of all water required by humans is used for agriculture of one sort or another, it is interesting to realise that South African farmers are more water-efficient than some in other countries, particularly those using flood-irrigation of fields. Nonetheless, consumption of even 60% of the total is too high, especially when we consider that the agricultural sector actually contributes only about 5% to the economy of South Africa although, of course, its contribution to human welfare is unquestioned. We might well ask why water is not used more efficiently, but, in fairness, we must point out that to change the method of irrigating can be expensive.

Various websites list the amount of water required to produce a certain quantity of each of a number of items. The methods of calculation vary, as do the units – everything from the number of cubic metres of water required to produce a kilogram (see next page), to litres of water required to produce a pot (of tea) or gallons to produce a single beef burger. So be careful when trying to compare data from different websites.

About 150 m^3 of water are used in the production of a single ton of steel.

***Table 10.1.* The quantity of water required to produce various items.**

Produce	m^3 of water required to produce 1 kg
lettuce	0.2
tomatoes	0.2
melon	0.3
broccoli	0.4
orange juice	0.8
corn (maize)	1.0
oats	1.6
barley	1.8
dry timber	2.0
brown rice	2.1
sugar	2.2
white rice	3.3
eggs	4.0
soybeans	4.0
chicken	5.5
almonds	10.7
butter	17.2
beef	24–110*

It also takes about 450 m^3 of water to manufacture a small car and 0.13 m^3 to make a bicycle

**The variation is probably explained by differences in climate, breed of animal, age of slaughtering, source of feed, etc.*

We should never lose sight of the fact that farmers grow these products because we as consumers are prepared to buy and consume them. After all, about 33 m^3 of water are required every day to produce food sufficient to keep one adult on a daily diet of 2 500 calories.

Virtual water

The water involved in the production of these items is often known as 'virtual' or 'embedded' or 'hidden' water. It has little to do with the amount of water literally in an item, but the amount of water needed to produce it. If we take this into account in our personal 'water budgets', a different picture emerges. In the UK, for instance, average daily water use is about 150 litres but if the virtual water embedded in every item is used, the quantity rises to 3 400 litres a day (a 2 300% increase), food production accounting for about two-thirds of this, and industrial goods a third.

Irrigation

Although it all started in neolithic times some ten thousand years ago, when farming first began, modern irrigation-driven monocultural agriculture is probably the single most environmentally devastating development in the recent history of our species. This might seem like an exaggeration, but think of a tract of land anywhere outside of a game reserve, and what comes to mind? Probably what you see is a land covered with mielie fields or vines or wheat or pine trees. If you see natural vegetation in South Africa, it is probably because the land is too dry or too mountainous to sustain agriculture and too far from a river to be easily irrigated. And yet not only is irrigation farming expensive of water, but it can also be downright detrimental to the land and to aquatic ecosystems. In fact, throughout the world as much land is lost through irrigation farming (by waterlogging or salinisation) as is newly put under irrigation every year. What is more, in developing countries it is nearly always true that the few wealthiest farmers pocket more than half of the profits from farming newly irrigated land.

At first sight, and in monetary terms, spray irrigation is the cheapest form of irrigation. The long-term realities are far from comforting, though. Firstly, spray irrigation is only about 30% efficient in arid and semi-arid environments, where a lot of water is lost by evaporation. This means that less than a third of the water sprayed onto a field is used by the plants, the rest being lost to the atmosphere. Secondly, irrigation results in salinisation of soils in many parts of southern Africa (see page 245). Here it is enough to say that, in arid areas, the rate of salinisation is generally proportional to the amount of water used in irrigation. In addition, excessive irrigation can raise local water tables. If the groundwater is naturally brackish, it will accelerate damage to crops when it rises to the surface. Thirdly, excessive irrigation combined with poor ploughing practices contributes enormously to erosion. The good news is that a lot of farmers now use shade netting or growing tunnels, or clear alien vegetation, so that they can cultivate high-value cash crops (e.g. blueberries) with high water demands. These systems are as water-efficient as possible but do create apparently sterile agro-industrial landscapes.

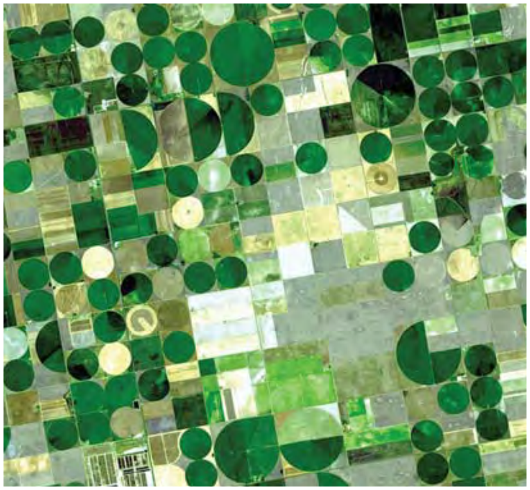
From an agrichemical point of view, many South African soils are low in nutrients (which is not surprising, since the land is old, and the good, rich topsoil is constantly being lost by erosion), so they are enriched by the addition of fertilisers to allow crops to grow satisfactorily. When excess nutrients from fertilisers reach rivers, they may cause eutrophication. And modern agriculture is almost defined by stands of single-species crops (monocultures). As soon as dense, single-species stands occur, pest insects and fungi proliferate as vast fields of a single species of plant encourage the uncontrolled multiplication of a small number of species of pests that compete with farmers for their crops. The farmer usually reacts by using pesticides, but unless care is taken to use exactly the right quantity, the excess pesticide or its residues, as well as excess nutrients, will land up in local aquatic ecosystems (see Chapter 7).

Jenny Day

Cattle are thirsty creatures, even these Kenyan beauties.

Aqua Mechanical / CC BY 2.0

A tractor spraying pesticides in Utah, USA.



United States Geological Survey, courtesy NASA

Not abstract art, but centre-pivot irrigation of hundreds of fields in Kansas; plots are 800 or 1 600 m across and the water comes from the Ogalalla Aquifer (see chapter 1).

Taking all these factors together, it is clear that extensive irrigation can have seriously detrimental effects environmentally, economically and socially. But it is also clear that crops have to have water in order to grow. Ironically, in the wetter parts of the country irrigation is not often needed and the irrigation water is not particularly salty, so that traditional methods of spray – or channel-irrigation can do little harm other than wasting water. In drier areas, though, alternative methods of agriculture and unconventional but more suitable crops should be seriously considered. The more arid the area the more sensitively it ought to be farmed, if at all. This brings us back to the issue of virtual water. We need to ask why particular crops are grown where they are, given that some are much less thirsty than others. The answer is usually that "this crop has ***always*** been planted here", or the crop provides the most valuable financial return (if one doesn't take into account the cost of the water and to the environment). Both of these reasons are valid but where water is scarce, the thirstiness of the crop also needs to be factored in. Cotton and sugarcane are two very valuable crops, but both need a lot of water, while olives, beans, melons, potatoes, squash, millet and many other crops are able to thrive on much less water. We can see a time in the future when farmers may be constrained in what they can plant, either because water becomes too expensive, or because agricultural authorities dictate that certain crops can be grown only in areas where sufficient rain falls to make irrigation unnecessary. The easiest way to do that will simply be not to provide irrigation water, of course.

DOMESTIC USE OF WATER

A little more than half of the remaining 15% of water consumed in South Africa (after agricultural and industrial needs are met) is used domestically for washing, cooking, watering the garden, cleaning the car, filling the swimming pool, flushing the toilet, and so on. Strangely, South Africans on average use about 230 litres of water a day, which is above the world average of 173 litres a day (and should have been greatly reduced by the droughts experienced in so much of the country) (Ngobeni & Breitenbach 2021). At first sight the average person seems to require a surprisingly small proportion of all the water used – until one asks why agriculture and industry seem to use so much. The answer, of course, is that those sectors supply that 'average person' with commodities such as food and drink, a car, a house, appliances, eating utensils, furniture, newspapers, clothes, and so on.

In other words, almost everything we use, do, eat, sit on, cook

'Automatic' handwashing station, Uganda.

with, read, and play with involves the consumption of water. It should be clear, though, at least for those living in the 'drought belt', that the amount of water one uses follows a corollary of Parkinson's Law: the more there is, the more one will use. The converse is also true, though: one can make do with much less water than normal if not much is available. Anyone who has travelled in really arid areas will know that this is so, especially if they have had to carry the water on their backs or heads. Table 10.2 shows that the amount of water used in the home depends firstly on availability and secondly on standard of living: a high standard of living is virtually equivalent to a low outlay of labour for mundane tasks such as washing clothes and dishes – and even oneself.

***Table 10.2*. The relationship between domestic water consumption, water availability and standard of living. (These figures are based both on requirements of single individuals and of a family of four, because the amount of water used by gardens, swimming pools, dishwashers, and so on, is almost independent of the number of people sharing facilities.)**

Water consumption	Litres per person per day	Litres per household per day
Absolute minimum consonant with health (drinking, cooking, washing hands; nearest source 15 km away, no transport)	3	12
Nearest source 1 km away, with no transport (any washing done at water source)	5	20
Water in village or water-tank near house*	10	40
House with tap and shower only	50	200
Full sanitation (bath and toilet); no garden	175	700
Full 'mod. cons.', including dishwasher, washing machine; no garden		1 150
Full 'mod. cons.', including garden and swimming pool		1 550

**The South African National Water Act assigns 25 litres per person per day for 'basic human needs' but this does not provide for nutritional needs such as watering a vegetable garden or keeping a sheep, a goat or a cow.*

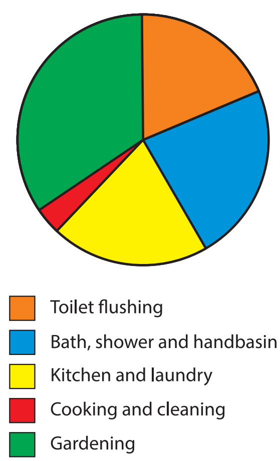
Domestic servants once filled the role of hewers of wood and drawers of water, and later of washers of clothes and dishes, and removers of nightsoil. But they are now selling their labour more dearly, so other means are being found to avoid labour-intensive occupations. Machines are the obvious answer and those who can afford washing machines and dishwashers can also afford the concomitantly higher costs of water and electricity required to run them. When we wrote the previous edition of this book, we stated that there was very little incentive in South Africa for manufacturers to make their machines more efficient. Happily, this has changed and today efficiency of water and electricity use are major selling points of washing machines and dishwashers. As the cost of electricity and water continue to soar, we can expect manufacturers to make even greater efforts to produce energy-efficient appliances.

That ultimate showcase of a high standard of living is a large garden with a lawn and swimming pool, but these are the biggest consumers of 'domestic' water. In the United States, lawns and gardens are the greatest consumers of fuels (for lawnmowers, leaf blowers, weed eaters, etc.), pesticides, fertilisers and water. Cities like Los Angeles and Phoenix have reduced the great rivers of the West to saline trickles, and yet the homes of Beverly Hills are surrounded by emerald lawns. But this is rather a matter of the pot calling the kettle black. According to the City of Cape Town, at least until recently, fully half of the water consumed domestically went on keeping the lawn green and the water-hungry bedding plants from Europe flowering brightly.

Zigzig20s / CC BY-SA 3.0

California is in the deepest drought in history but the lawns of Beverly Hills are still green.

The pie chart to the right illustrates how water is used in an average middle-income Cape Town home. By comparison with water consumption in cities in general, the results are shocking: some 64% of the scarce, expensively-treated potable water consumed in the home is either sprayed onto the garden for thirsty exotic plants (35%), or is flushed around the U-bend of the toilet (29%). Most of the remainder goes on bathing (20%), laundry and dishwashing (13%), while drinking and cooking consume only some 3% of the total.



Despite the lessons of the last great drought, Capetonians still use nearly half of their water on their gardens.

WATER LOSSES

Water losses account for most of the rest of the water 'consumed' in South Africa. Stored water may be lost in a number of ways. Particularly problematic in our dry climate is loss through evaporation from the surfaces of reservoirs. A while ago, Arthur Chapman and Hugo Mäaren of the Water Research Commission and John Carter of DWAF estimated that, given that registered dams in South Africa probably cover a total area of a little more than 3 000 km^2, evaporative losses would be of the order of 930 million m^3/y. Obviously, the geographic positions of the dams are of vital importance since the rates of evaporation of water vary enormously across southern Africa (see page 44).

Equally problematic is the fact that city water mains and pipelines are often old (in older cities like Cape Town, some are even unmapped) and leaks can be considerable. Water that is unaccounted for (leaks, theft, etc.) is now called, somewhat euphemistically, 'non-revenue water' and is calculated as the difference between the amount provided by a utility and the amount that can be billed. In 1982 known leakages and unaccounted-for losses in the Cape Town municipal area were 14% (nearly 12 million m^3), while revised estimates in the late 2010s put the value at about 30%. In Nairobi it is thought to exceed 40%. Recent figures for the Ethekweni Municipality, which services Durban and surroundings, indicate that non-revenue losses exceed 56%, of which 11% is due to theft and the rest to leaking pipes. As of November 2022, this costs the municipality about R5 million per day. At the same time, infrastructure is so badly maintained that sewage leaks are continuous, and the municipality does not have the money to repair the sewers. And it seems from the outside that no-one is doing anything to solve the problem, which does seem to have a fairly simple solution: fix the leaks, save money, and then fix the sewers.

The problem is not solely African. A report from the now-privatised water utility companies throughout the UK recorded a loss of about 25% of all water supplied to consumers. To put this in context: if these losses were to be recouped, there would be no need to build a single storage dam in the UK for the next 45 years. (As a footnote, it is interesting that the rainy climate in the UK was such that storage reservoirs tended to be very small, often holding enough water for no more than a week or two. With the advent of climate change, bringing considerable increases in temperature as well as longer dry periods, today these reservoirs are often too small and new ones need to be constructed.)

The huge losses of non-revenue water in South Africa lead us to the conclusion that a quarter of all reservoirs and inter-basin transfers would be unnecessary right now if we would (or could) plug the leaks. Initially expensive as it may be, tracing and plugging leaks will be a significant and necessary means of saving water. But it goes even further than this. Do you have a slowly dripping tap, a washer that slowly oozes water, or a cistern that permanently overflows almost imperceptibly by day and becomes an irritating noise that keeps you awake at night? Fixing leaks around the house is a good way to start saving on your water bill and, ultimately, to conserving a river for just a little longer. It is to be hoped that sooner or later there will be a significant reduction in the number of dysfunctional municipalities in this country, and that effective water management will once more become a mayoral priority. Every so often there is a news item about another newly elected mayor taking his or her 'service delivery' responsibilities seriously, though. We needn't lose hope as long as there are people like that in positions where they can make a difference.

Lani van Vuuren

A spectacular municipal pipe burst in a Pretoria suburb.

WHERE CAN WE GET MORE WATER FROM?

Given that we need to make use of as much water from as many sources as possible, let us examine the sources conventionally available to us and see to what extent exploitation of each is possible, economically feasible and desirable. We cannot emphasise too strongly that these three factors have to be considered hand in hand. Given unlimited finances, for example, it should be technically possible to provide unlimited fresh water by desalination, and yet the environmental cost would be high.

THE ATMOSPHERE: CAN WE ENHANCE RAINFALL?

The atmosphere of our planet holds some 400 thousand million km^3 (400×10^9 km^3) of water. It can theoretically be forced to give up a part of its moisture in a number of ways. For example, hygroscopic (moisture-loving) chemicals saturate themselves with water quite readily; cooled air will drop its moisture as the dew-point is reached; fine meshes can trap fog; and if 'seeded' with chemicals, clouds may drop their moisture as rain.

Lani van Vuuren

Fog harvesting nets at a school in Venda.

The energy involved in extracting moisture from hygroscopic chemicals or by refrigerating huge volumes of air presently makes these sources of water a matter of science fiction. On the other hand, fog- or cloud-meshes work well in mountainous regions and deserts where fogs occur regularly, although they sometimes cannot be used close to the sea where the air is salt-laden (see page 390, capture of mist). Another way in which humans can exploit atmospheric water is by manipulating clouds to force rain to fall. This has been done as a measure of desperation in South Africa by seeding clouds with finely-divided particles of silver nitrate or other salts delivered to clouds by high-tech aircraft during times of drought. Using such techniques, Israeli meteorologists claim to have increased rainfall in some areas of their country by 15%. Oddly, despite very limited successes, fully 18% of the annual research budget of South Africa's Water Research Commission has at times gone into studies on cloud seeding (various techniques have even been patented through the organisation – see the chapter on hydrology in the ***WRC@50*** volume). Success has so far been limited and the technique is fraught with difficulties. For instance, one might question the ethics of forcing a cloud to drop its moisture in one place rather than another. Even if it should become technically simple to do, cloud seeding will always be a cause for complaint by the farmers who claims that had the clouds been left alone, they would have dropped their rain on their lands, not on their neighbours'. This has, indeed, happened in the Nelspruit area, where complaints forced the researchers to shift their attentions northwards to Tzaneen. Furthermore, who is to deny similar complaints from neighbouring countries? Secondly, even if a cloud is successfully seeded it is almost impossible to guess where the rain will actually fall. This means that it is difficult to measure the amount of rain that falls, or its conversion to useable runoff for humans. It is particularly difficult to estimate what the actual increase in rainfall is in comparison with what ***might*** have fallen if no manipulation had taken place. Because of these difficulties, the funding of research into cloud seeding by the WRC ceased in 1996. Since humans have always had a tendency to carry their technological advances far ahead of their understanding of the consequences of their actions (for instance the effect of chloro-fluoro-carbons [CFCs] on the ozone layer), we must hope that any further intentional tampering with the weather will not become technically feasible for a very long time. So much for conventional methods of obtaining water from the atmosphere.

SURFACE WATERS

What about more water from rivers and lakes? As we have already seen, natural wetlands and lakes in this country contain insignificant quantities of water and the rivers are pretty much dammed already. Of course, we could take the last few drops of Orange River water that still reach the sea (and we are not far from doing just that). In fact, we could dam up all the rest of the rivers in southern Africa and have no water at all running to the sea. Indeed, if the rhetoric we hear from some farmers, water managers, economists and politicians were to be heeded, that is exactly what should happen. But all these measures would still not be enough to supply the needs of the growing population in the long term.

GROUNDWATER

The only other conventional source of water is groundwater. Think of a farming scene almost anywhere in southern Africa and your mind will conjure up a windmill (the geohydrologists' preferred term is wind pump) clanking in the dry air. These pumps are signs of boreholes sucking water out of the ground to irrigate an often-parched land. A number of small towns in the Karoo also rely entirely on groundwater, while many private householders in towns use groundwater for watering their gardens, even during water restrictions. Cities such as Cape Town prefer householders to use groundwater during these times to prevent them from selfishly using the shrinking resources needed for domestic supply, on the understanding that eventually rain will replenish the groundwater.

We have already mentioned (page 61) that South Africa can exploit about 19 000 Mm^3 of usable groundwater annually (in comparison with about 12 500 Mm^3 of surface water). Given that requirements will remain roughly constant in some farming areas, this water can probably be considered as a perpetually renewable resource that will dwindle slowly over time as a result of climate change. Groundwater that may have accumulated over vast periods is usually referred to as 'fossil water'. Examples of the short-sighted use of 'fossil' groundwater are described in Chapter 1.

When exploiting groundwater we must consider where it comes from, where it is stored and where it would naturally be going to. Much of the information in the following paragraphs is based on an article by G. Gardner in an issue of ***World Watch*** for 1995.

dpreezg / 123RF

A series of windmills (more accurately, wind pumps) on the R63 between Victoria West and Loxton.

Jenny Day

Water spouting from a borehole. If the aquifer is under pressure, groundwater will come to the surface without being pumped.

Firstly, groundwater may be too brackish to use, either because it has infiltrated through salty soils, or because the rock formations in which it is held are themselves saline. Secondly, just because a borehole produces fresh water at first does not guarantee that all its water will be fresh. Fresh water floats on top of salty water because it is less dense: use up the fresh water on top and you may just find that as you lower the bore-head, the water becomes unfit for irrigation or drinking. This has happened in some of the coastal towns in Namibia and on the south coast of South Africa. Thirdly, it is very easy to inadvertently pollute underground waters. This has happened in Britain, where excessive use of nitrates and pesticides by farmers led, in 1992, to more than 10 million Britons being supplied with drinking water well below the standards agreed to by the European Union (***New Scientist*** 24 July, 1993). Lastly, although groundwater may be suitable for use by thinly scattered populations, it is not easy to extract in quantities sufficient for urban use.

Accordingly, groundwater seldom contributes more than a small proportion of the total water required for cities in mesic areas where surface water resources are available. For example, some of the suburbs of Cape Town overlie the Cape Flats aquifer, which is estimated to have an annual recharge rate of about 18 x 10^6 m^3/y. In the previous edition of this book, we said, "It is to be hoped that the notion of recharging this aquifer with purified sewage effluent, with its high nutrient levels, has been dismissed." Well, you see, some of this water was satisfactorily exploited during the catastrophic drought of 2017-18 and so today the City of Cape Town is developing a system for recharging the aquifer using purified effluent from a nearby wastewater treatment plant. Well. One can sympathise with the City for wanting to do everything possible to prevent another Day Zero, and the City's water resources managers are monitoring the water quality in the aquifer very carefully but the jury is still out on the use of effluents for drinking water generally (see the section on contaminants of emerging concern on page 266). Interestingly, it seems that the major role of the recharged water will be to act as a "curtain", preventing seawater intrusion when the water table drops, but the recharged water will no doubt also be used as potable water during droughts.

A great deal of research is currently focusing on many aspects of groundwater research in South Africa, and maps of groundwater quality and quantity are available for the whole country. The enormous Table Mountain Group aquifers underlying the sandstones of the south coast are discussed on page 61 and the acidification of the large dolomitic aquifers on the Reef on page 236. The chapter on groundwater in the recent WRC publication ***WRC@50*** is a useful summary of South African work on groundwater.

UNCONVENTIONAL SOURCES OF WATER

Icebergs

There is more fresh water on this planet in solid form than in liquid and gaseous forms put together, and so we need to consider the possibility of using icebergs as sources of fresh water. The potential supply is vast, and icebergs are constantly melting and thus disappearing anyway (1 250 km^3 of ice is 'calved' as icebergs each year), so that the exploitation of this resource would have to be on a massive scale to have any serious environmental consequences at source, as long as calved icebergs (those already broken away from the mother ice shelf) are used. Whatever their origin, there would be difficult technical and economic problems to overcome in using this great supply of fresh water, though. For instance, the ice in icebergs suitable for towing to our shores would have to be liquefied, stored and transported inland. Each of these processes would be costly, so this potential source of water would be far from environmentally or economically impact-free. So is this just a crazy notion? Not entirely. The first conference on using water from icebergs was held in 1977, so the idea has been around for some time. More recently, a feasibility study was undertaken aboard the German research vessel RV ***Polarstern.*** A small berg was wrapped in plastic and and left at sea for some months to see if the water quality decreased (which it didn't). The link to the article is in the reading list at the end of the chapter. There is also a story, perhaps apocryphal, of a wealthy Middle Eastern country towing a small 'growler' into the Persian Gulf for use at a particularly large celebration; we have not been able to verify that story. But there really was a proposal (see Reading List) by a company from the UAE to tow an iceberg from the region of Australian-administered Heard Island to the Middle East, ***via*** either Perth in Australia, or Cape Town, in 2020. The Australians are wondering about environmental impact assessments, and the fact that the Antarctic treaty prohibits mining south of 60°S, although the proposers note that icebergs were excluded from the Treaty. I have been unable to find out if the proposed project ever got off the ground, as it were.

Uwe Kils & Wiska Bodo, Wikimedia /GNU FDL

An iceberg is a lot bigger than it seems. This remarkable image was made from two separate photos, one taken from above the surface and the other from below.

DESALINATION

Water from the sea is undrinkable because it contains large quantities of salt (35 g/L, in fact). Many inland waters, particularly groundwaters, are also unusable, even at a salt content as low as 1–2 g/L. If we could get rid of the salt from seawater, from underground water, from salinised surface waters and even from sewage effluents, then we would have a virtually unlimited supply of fresh water both near the sea and inland. The process of desalination, first patented in 1869, will do this because it is simply the process of removing salts from water. Although desalination has been used on board ship for many decades, very few large-scale land-based desalination plants have existed worldwide until very recently. Exceptions are in the Middle East, where about half of the world's desalinated water is generated. (These nations can afford to depend on desalination because they are wealthy.) But desalination is expensive (Table 10.3). Towns like Lüderitz in Namibia depended largely on distilled sea water for several decades, until much cheaper but limited reserves of fresh underground water were discovered nearby in the late 1960s. Because of the general perception that there would always be enough fresh water to go around, for many years desalination was not seriously considered in South Africa as a viable means of providing fresh water in bulk. This attitude has changed, and desalination is on the list of available water resources for most municipalities today.

Mirco1 / 123RF

The quaint town of Lüderitz on the coast of southern Namibia. Mean annual rainfall is 17 mm.

Table 10.3 **Approximate cost in Rand per kilolitre (m^3) of domestic water from different sources (from WWF 2018, http://bit.ly/3HtUfFK) .**

Raw surface water	1 - 4
Water released by alien clearing	6 - 15
New groundwater resource	15
Re-use of treated wastewater	10 – 20
Large-scale, permanent desalination plant	10 - 22
Smaller-scale short-term ('package') desalination plant	34 - 44

How does desalination work? The most practical ways are by distillation, by freezing, by the use of membranes in the processes of reverse osmosis and electrodialysis, and by means of ion-exchange resins. Some methods are more suitable for the removal of salt from seawater and others for the treatment of brackish water, but all are now technically feasible and small plants of most types are in operation in various parts of the world. All desalination processes suffer from a series of similar drawbacks, however. Firstly, the equipment is costly. Secondly, desalination plants require very large amounts of energy to drive them. Thirdly, because the by-products are salts, parts become clogged or corroded and need regular maintenance and replacement. Fourthly, the concentrated waste brines must be discarded somewhere. Fifthly, and a fact that is seldom mentioned in discussions on desalination, toxic biocides and anti-fouling agents are needed to keep the membranes unclogged in membrane-based desalination. Together, these disadvantages mean that, although desalination may be a sensible option under certain circumstances, water obtained in this way is not cheap – either economically or environmentally. Regarding energy requirements, a while ago it was estimated that a plant large enough to supply Cape Town with the water it needed up to the year 2020 would have required a nuclear power station the size of Koeberg I, or a network of coal- or oil-fired power stations. Currently, though, the most suitable renewable energy resources are being investigated along with the latest desalination technologies.

A major issue with regard to building large desalination plants during drought conditions is that droughts do not go on forever (well, not yet they don't). Because these plants are so expensive to run, many municipalities have had to 'mothball' the plants during times of adequate rainfall. Even here, a snag arises: because of the fragile nature of the membranes, the plants need to be maintained even when they are not being used, so are not cost-free. This is one of the reasons for Cape Town relying on small plants during the drought but not (yet) investing in large plants.

According to WWF (bit.ly/3HtUfFK), Mossel Bay has a desalination plant capable of producing 15 million litres of potable water per day but on standby when local dams are full. The Knysna municipality plant, capable of producing 2 million litres per day, is used at the discretion of the municipality (i.e. mostly during the enormous influx of tourists during the December holidays). Plettenberg Bay (Bitou municipality) has an operational desalination plant producing 2 million litres per day. Two desalination plants in the Ndlambe municipality, at the Bushman's River Mouth and Cannon Rocks, produce 1.8 and 0.75 million litres per day respectively and in 2018 were producing at full capacity.

In summary, desalination can theoretically provide virtually unlimited water, but the cost in economic and environmental terms is considerable. Nevertheless, this is undoubtedly the most feasible way of providing significant quantities of water in the future and desalinated water is already forming an integral part of the water resources of South Africa. The recent paper by Taahira Goga and colleagues (Goga et al 2019) on the use of renewable energy sources for desalination plants is exciting, because reducing the use of fossil-fuel energy would benefit both for the desalination process and the natural environment.

Capture of mist

In the Atacama Desert in Chile, reputedly the driest place on Earth, fogs known as ***camanchacas*** regularly drift in from the Pacific Ocean. After seven years of intensive research by a group of Canadian and Chilean scientists, these fogs can now be harvested. The scientists string double-layered polypropylene nets on poles facing the fog-bearing winds. The nets yield about 4 litres of water per square metre of mesh and the array of nets provides 11 000 litres of water a day for 350 people who previously relied on water trucked to them from 80 km away. Similar cost-effective projects are underway in very arid regions around the world, from Peru and India to Yemen and, surprisingly, the Philippines – where, despite tropical monsoons, mountain springs frequently dry up in the long dry season. Recent experiments in Oman have yielded as much as 50 litres m^{-2} of mesh. Once set up, the system costs virtually nothing to maintain and there is no waste to dispose of (except, of course, from the processes involved in the production of the meshes in the first place). There is every reason to suppose that such technologies can rapidly and cost-effectively be used in small communities in southern Africa where coastal or mountain fogs are regularly generated. The coast of Namibia seems ideal.

Solar stills

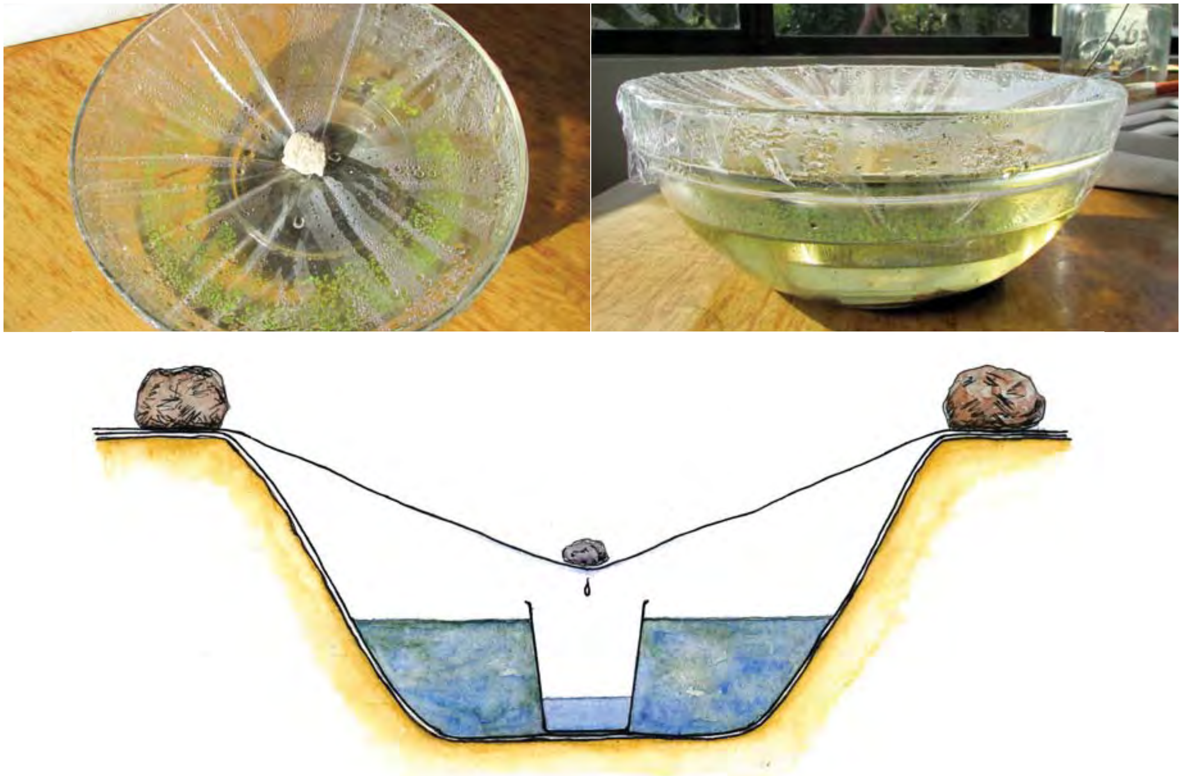
Thanks to his hyperactivity, his wise use of the media, his high profile and the solid and sound advisory team that he gathered around him, as Minister for Water Affairs the late Prof Kader Asmal elevated the South African Department of Water Affairs and Forestry, the backwater of ministries, to regular talk-show status. As a result, many people working in the media became interested in water-related topics. A media event involving solar stills (***Cape Argus*** May 13, 1996) demonstrated how one person's actions can make a difference. The report cited the case of a farmer in Bushmanland who, worried about his minimal water supply, wrote a letter to the WRC in Pretoria. This letter was faxed from the WRC to the University of Stellenbosch, where it elicited a rapid response. Aware of the invention of a cheap and remarkably effective solar still in the United States, researchers persuaded the inventor to part not just with designs for the still, but with two fully operational units that were imported immediately.

The McCracken Solar Still is a very simple device for providing clean water. It can be as complex as a rectangular structure that can be raised off the ground on bricks or oil drums, and produces 8–10 litres of solar-distilled water per day: not much, maybe, but sufficient to keep a small family going with safe, potable water. Or it can be as simple as a bowl partly filled with the liquid to be 'distilled' and covered with a flexible plastic membrane. Furthermore, it can use almost anything 'watery', no matter what state it is in, for it distils water from the liquid (even salty water or urine) using heat from the sun. The University of Stellenbosch's Institute for Polymer Research has investigated the most suitable plastic sheeting to use because it must be resistant to both heat and ultraviolet radiation. The greatest advantage is, of course, that the still requires no power source other than the sun. It is reputed to have a life of about 20 years, is virtually maintenance-free and, because of heat it has stored, continues to work even after dark. Surprisingly this low-tech and inexpensive device seems not to have become popular in the decades since we reported on it in the previous edition of ***Vanishing Waters***.

Veolia/ WRC archives

An aerial view of the Windhoek water reclamation plant and Goreangab Dam. The Namibian facility, the first plant of its kind in the world, was established in 1968.

Jenny Day



The principle of a solar still is quite simple.

Recycling of sewage effluent

Windhoek is world famous for subsisting substantially on recycled water, and there is no intrinsic reason why this should not occur everywhere in southern Africa. We have probably all heard that the water entering the sea from the River Thames will have been recycled at least seven times since it fell as rain. The explanation is simple: each town along the river extracts and uses water, which is then partially purified before being returned to the river, from which the next town downstream abstracts its water. So, you can see how it is that the water in the River Thames, for instance, is on average filtered through some seven pairs of human kidneys by the time it reaches the sea. Admittedly the rivers of Western Europe tend to have much stronger flows than South African rivers do, because they receive more rain, but the point still holds: people regularly use water that has passed through other peoples' kidneys and, as long as it is adequately purified between users, there is no reason to doubt its safety. Certainly, recycling has been the order of the day for some areas of South Africa, even if the practice has not been given that name. Water in the Gauteng region has been recycled for years, in that purified sewage effluent runs into the Vaal Barrage (Loch Vaal) via the Klip River. (Return flow to Loch Vaal represents about 45% of the water supplied to the Gauteng region.) From the barrage, the water is pumped to the Vereeniging Purification Works where, courtesy of Rand Water, it is made suitable for the next day's cup of tea.

A river is the best – and cheapest – recycling system.

In South Africa, we have been backward in fully developing recycling techniques because of public reluctance, official reluctance, rejection based on religious beliefs in some cultures and, most of all, because there has always been another river to dam. It is becoming quite clear, though, that recycling on a large scale will have to take place in order to slow down the increasing demand for water. Having read this far, however, you will be wise to the fact that in the management of water resources, nothing is ever simple: no magic nostrums will remove the water-supply problem at the flick of a wand. What is the trouble with recycling, then? It is not so much a problem as a matter of simple arithmetic. Water for recycling must obviously start off as sewage, or sewage effluent, or otherwise contaminated water. It must be purified (as all sewage is), then it must be scrubbed of harmful chemicals and pathogenic organisms like bacteria, fungi and the eggs of parasites, stored, and finally piped to the consumer. At each stage a good proportion of the water is lost, either in flushing out wastes or through evaporation. In fact, even efficient systems can only replenish about a quarter to a third of the water they receive as sewage. So, we simply cannot exist on recycled water alone. In fact, calculations for the Western Cape show that recycling the bulk of sewage water in this region, at an efficiency of 25%, will only reduce the projected increase in demand by a quarter. We would be going backwards three times as fast every year if we were to rely solely on recycled water. What is more, each time water is recycled it becomes saltier because it has been subjected to a certain amount of evaporation during the purification process. So, it is always necessary to add some 'new' water to the old if it is to be used for drinking. Despite these problems, recycling is a vital component in the battle for the conservation and wise use of water.

Perhaps a few general words on the treatment and use of wastewater (in other words, sewage) are appropriate here. Local authorities receive sewage from many sources. Domestic waste is, oddly, much easier to purify than is industrial waste, which contains such nasties as heavy metals, insecticide residues, mineral acids and organic solvents that kill off the bacteria and fungi that decompose the organic wastes in the sewage plant. Thus, if sewage from domestic and industrial sources arrives at a purification plant all mixed up, then it is very difficult to clean. On the other hand, we receive through our taps water which is much purer than it really needs to be for normal household purposes and, in most cases, vastly purer than it needs to be for industrial purposes. From an environmental point of view, though, recycling of used water is extremely valuable. It may be expensive to recycle effluent but remember that the water that becomes effluent comes from rivers that can scarce afford the loss of water in the first place. Furthermore, the rivers that receive regular effluents from wastewater treatment plants are also degraded by receiving water that is almost certainly rich in nutrients and other chemicals (see page 203). So, while it is expensive to treat effluents for reuse, the practice does address the real environmental costs of using water and producing effluents.

In effect, we are using very expensive, extra-high-quality water for a multitude of purposes, polluting only some of it with noxious substances, and discarding all of it into the same sewage systems, thus making it difficult to purify and to recycle. In an ideal world, we would have separate supplies of water of different qualities for different purposes, as well as separate sewage systems for domestic and industrial wastes. This would result in an easier and cheaper recycling task. Furthermore, some of the resulting water could then be added to lower-quality water supplies, which could be recycled and mixed with still-lower-quality water and so on. In other words, both the supply and the purification of water could be made much more efficient if the only criterion was reducing the demand for water. It would obviously be impossibly expensive to put such a scheme into effect in existing built-up areas, but the separation of industrial and domestic sewage is already beginning to occur in some newly developing places. Planners of new industrial and urban areas would do well to consider this issue because the cost of water is going to rise further and further, particularly when desalination becomes essential. (In fact, they may ultimately have no choice in the matter.) Right now, though, while thousands of new homes are being built, few attempts are being made to address the issue.

The current National Water Act (see chapter 10) requires that some industrial water-users treat their effluent before discharging it into the sewerage system. Environmental audits by some users of large volumes of water have shown that, considering the cost involved in the required on-site purification procedures, it is economically sensible to purify the water just that much more in order to be able to recycle it within the factory or mine, thus saving on water consumption and on the subsequent water bill. Large industrial plants are showing that they can indeed cut down enormously on water consumption. For example, an African Explosives and Chemicals Industries (AECI) plant at Sasolburg has developed an efficient on-site water-recycling plant, while the giant oil-from-coal plants, SASOL II and III, have 'nil effluent discharges', being able to recycle water from every part of the plants, because they have found this to be cheaper than cleaning used water to 'effluent standards'. ESKOM was able to reduce the amount of cooling water used in its power stations by 50% between 1963 and 1978, and its newer plants use only an eighth as much water per kW-h of electricity produced as the older plants do.

On the other hand, not all industrial plants are large enough, use enough water or produce dirty enough effluent to warrant the very heavy financial outlays necessary to recycle their own wastes. They do, however, have the opportunity to use recycled or purified sewage effluent, 193 million m^3 of which was used by industry and agriculture in South Africa in 1980. (Data on quantities currently used do not seem to be available, perhaps related to the dysfunctionality of many wastewater treatment plants.) Oddly, a few years ago a survey of a number of industries showed that most were not interested in using cheaper, poorer-quality water. It turned out that water represented less than 1% of the expenditure of most industries so that there was little incentive for saving. This will change once they have to pay the real cost for water (see the sections on, a paradigm shift and South African Water law).

Industries can make far better use of recycled or partly purified water than householders can because many industrial processes do not require water of high quality. So, it looks as if it will be necessary to hike the cost of pure water to industry by a very considerable amount in order to persuade them to take in low-cost recycled water. As we pointed out earlier, we should remember that industry is responsible for consuming huge amounts of water because we, as buyers, demand their products and the cost of water is still a relatively trivial component of their overheads.

As a final consideration regarding recycling, with a little care and investment, all water supplied to the home can be used twice: for a primary purpose like washing or bathing, and secondarily as 'grey water' for flushing the toilet or for watering the garden. Unless one is prepared to carry large numbers of buckets of water, it is necessary to have a tank or a system of pipes and small pumps to facilitate this form of domestic recycling. It is not very expensive to fit such a system so if you want to make a difference, this form of recycling can be really useful. A word of caution to Namibians and others living in very arid regions, though: check to see if your local authority will permit you to use such a system. In Windhoek, for instance, the municipality needs every drop of used water for its recycling plants and does not look kindly on residents who squander that precious resource, dirty water, on their gardens.

NATURE-BASED SOLUTIONS

A few years ago we would not have thought of writing about a topic like alien vegetation in a book about inland waters, but today it makes perfect sense. We have already noted the invasion of large tracts of South Africa by alien plants (see Chapter 8). One of the main reasons for disliking these aliens is that invasive alien plants such as Australian acacias and European pines are generally 'thirstier' than native plants, taking up and transpiring far more water than an equivalent biomass of native plants would. This means that dense stands of alien trees massively increase loss of water from mountain catchments where, deep underground, much of our water is stored. (As an aside, the commercially afforested areas of South Africa are populated by monocultures of alien European and Australian trees. We are effectively causing our mountains to export their valuable water in the form of floorboards and paper, which can be neither drunk nor used for irrigation or industrial purposes. There's that virtual water again.)

Mountain catchment areas in South Africa are protected under the Mountain Catchment Areas Act 63 of 1970. This protection is vital because although these catchments constitute only 9% of the surface area of the Western Cape, they provide 60% of the water generated in the province. Given the acute shortage of water in South Africa, any reduction caused by the invasion of alien plants (and the concomitant loss of native ones naturally adapted to our climatic conditions) is of concern. What is more, a survey of the Kogelberg Reserve in the Palmiet Valley near Cape Town showed that alien vegetation had spread from a cover of about 5% in the 1930s to about 40% in the 1980s. The study estimated that if the invasion were not controlled the aliens would cover 80% of the area within the next 50 years and would reduce the water yield to Cape Town by some 30%. But read on.

WORKING FOR WATER: A GOOD NEWS STORY

Some 25 years ago Guy Preston, then of the Department of Environmental and Geographical Sciences at UCT, discussed with Kader Asmal, then Minister of Water Affairs, the issue of water consumption by alien trees. The outcome of this discussion was a remarkable government-funded scheme that came to be known as ***Working for Water***. The idea was a simple but clever case of killing two birds with one stone. Alien trees needed to be cleared in order to increase streamflow in infested catchments. Unemployment was high. Unemployed people could be trained to do the clearing. Thus, Working for Water (WfW) was born and between its inception in 1995, and 2017, the programme cleared more than 3 million hectares of invasive alien plants, providing jobs and training to approximately 300 000 people from among the most marginalised sectors of society per annum. Of these, 54% were women. As of 2017, the scheme has created around 50 000 jobs every year, and has expanded its focus to target economic support for the most disenfranchised: well over half its workers are underprivileged women, and the programme has ambitious quotas for young people, disabled individuals, and those living with HIV/AIDS. As well as jobs, WfW provides employees with education and training, health and reproductive care, rehabilitation for convicted criminals, childcare services, HIV/AIDS awareness courses, and savings programmes. Oh, and water? It has been estimated that the clearing of invasive alien plants from riverbanks alone between 1997 and 2006 increased streamflow by nearly 46 million m^3 per annum. With a total annual budget of more than R400 million WfW is the largest single poverty relief and public works programme

DWAF

Highly skilled Working for Water employees clear alien trees from sheer cliffs.

in the country. It's amazing what a little lateral thinking can do, backed by political will. And with regard to the Kogelberg Biosphere Reserve, the Working for Water programme has reduced the area invaded by aliens from 40% to 20%.

WORKING FOR WETLANDS

The success of WfW lead to a copycat scheme, Working for Wetlands, in 2004. The model is the same, but the target is rehabilitation of degraded wetlands throughout the country. Between 2004 and 2017, the programme has invested nearly a billion Rand in the rehabilitation of over 1 300 wetlands.

About 27 000 job opportunities have been created in the process, generating over 2.59 million 'person days' of work as well as nearly 250 000 person days of vocational and life-skills training. At the time of writing, more than 120 wetlands were rehabilitated a year across all provinces.

Both programmes have their critics, and the work done is not always as successful as it might be. In fact, a major criticism has been that there has been insufficient monitoring of the results of the interventions so that new innovations in techniques are not often developed or applied. Despite these justified criticisms, we can be really proud of both

DWAF

Working for Wetlands employees clearing hyacinth.

programmes, which have had enormously positive effects on water saving, alien removal, wetlands rehabilitation and social upliftment. There are doubtless high-tech methods of clearing alien vegetation that are more efficient than human labour, but a trade-off has been made that includes social benefits at the expense of high-tech efficiency.

WATER FUNDS

The international organisation The Nature Conservancy (TNC) is instituting what they call *Water Funds* in many cities around the world. These are "organisations that design and enhance financial and governance mechanisms which unite public, private and civil society stakeholders around the common goal of contributing to water security through nature-based solutions and sustainable watershed management" (TNC 2018).

The business case of The Greater Cape Town Water Fund (GCTWF), launched in 2018, showed that investments in nature-based solutions, including controlling invasive alien plants and rehabilitating wetlands, can gain 55 million m^3 a year within five years – equivalent to two months of Cape Town's current supply needs – and 100 million m^3 a year within 30 years. You will notice that the principle is the same as that employed by WfW but WfW is a national initiative and cannot provide adequate service to individual cities, hence the GCTWF.

A PARADIGM SHIFT – FROM 'WATER SUPPLY MANAGEMENT' TO 'WATER DEMAND MANAGEMENT'

In 1986 we predicted that, within a few years, permanent drought would prevail in South Africa. We trust that in this latest book we have already reiterated that point sufficiently, for our prediction turned out to be horribly close to the truth. At that time, we argued for the immediate implementation of a public education programme and the initiation of demand-management strategies (although we did not know that fancy term at the time), including realistic water-pricing tariffs, throughout South Africa. Either our arguments were not cogent enough or the people who might have heeded them did not read them. Whatever the reason, they were missed, and while millions of South Africans still did not have clean, safe drinking water or adequate sanitation, the 'supply-side' philosophy continued in response to ever-increasing demands for more water. The higher the demand, the more new water storages were provided. But supply simply cannot match demand because, as we have demonstrated, there is an absolute limit to the amount of water that can be taken from our rivers and aquifers. What is more, in many cases those limits have already been reached.

It comes as a surprise to most South Africans when they learn that we all rely on 'other people's water' through networks of reservoirs and inter-basin water transfers crisscrossing the country. The Gauteng region alone relies on nine rivers, while Cape Town takes most of its water from four, all well outside its borders (see figure on the top right), and has done so for more than a century. But the provision of more large reservoirs, inter-basin transfers and other high-tech solutions simply cannot be the only way to go, for unless over-consumption is curbed, our aquatic systems – our very life-support systems – will collapse under the twin burdens of pollution and abstraction of water. Moreover, we are running out of good new dam sites and, when once the LHWP is complete, also out of large rivers that will allow inter-basin transfers of water. (The Congo River seems to have an inexhaustible supply but getting water from there to here – more than 3 500 km as the crow flies – would be challenging, and very expensive.)

The Nature Conservancy

Cape Town water supply is not a simple matter; dotted lines represent pipelines and tunnels.

The institution of the National Water Conservation Campaign in 1995 was a necessary attempt to change from 'supply management' (supplying water because it would be nice for the consumer to have as much as he or she wants) and to implement 'water-demand management' (WDM), or the tailoring of demand (how much water the consumer wants) to supply (how much there is to go around). Water demand management is not just about detection of leaks and control of losses, though – it is multi-faceted. The essentials for optimal water-demand management are the following:

- education programmes, both in and out of schools;
- municipalities providing appropriate examples by reducing water consumption;
- a review of water-payment and water-use patterns in collective dwellings;
- the installation of prepaid meters and the introduction

of realistic tariff structures (including capital, running and environmental costs: the real cost of water);

- tax incentives for the installation of drip irrigation systems, xeri-scaped gardens and so on;
- adoption of a 'carrot and stick' approach to water savings by tariff reductions, rebates to rates, and other forms of inducement for the installation of water-savings devices.

We must remember that water demand management, like water supply management, involves costs, although we are sure that these will be far less of a financial burden all round than those incurred through yet more water schemes. It certainly appears to us to be the only rational approach.

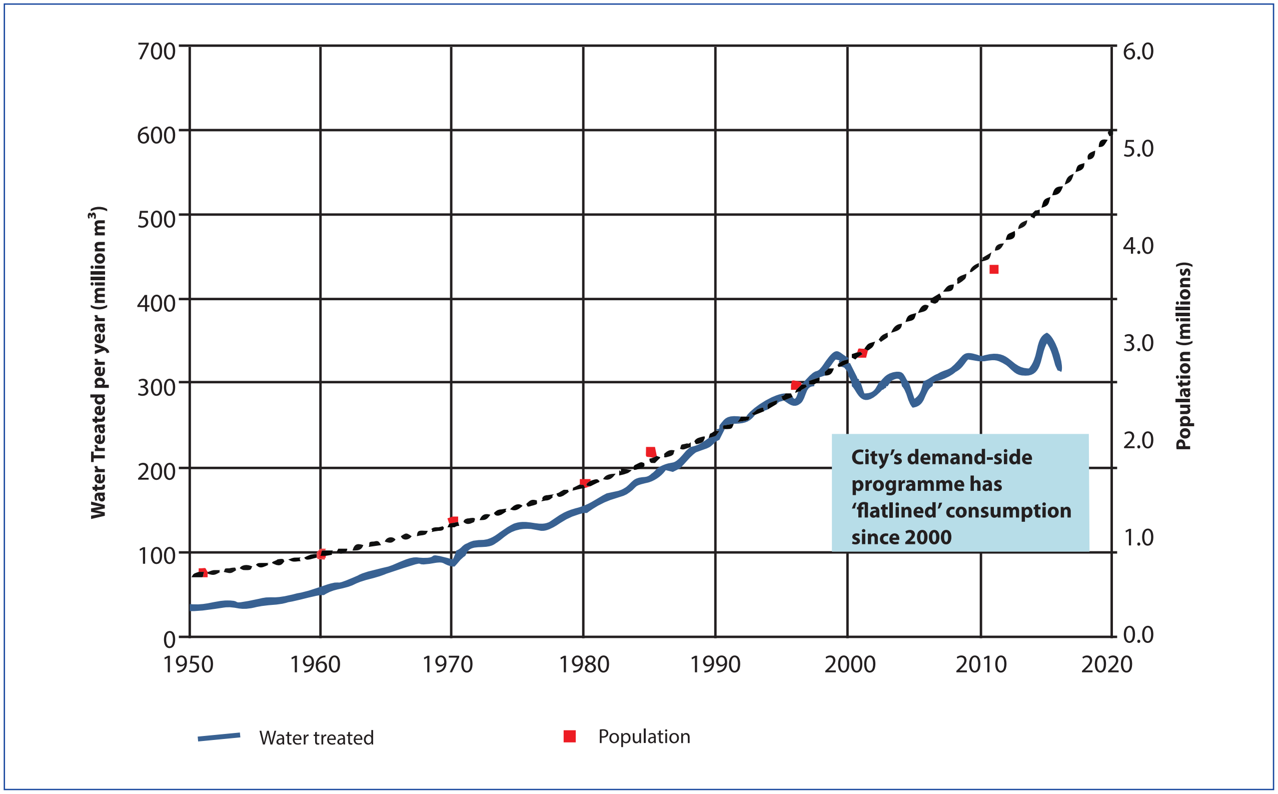
URBAN WATER RESILIENCE: PERSPECTIVES FROM SOCIETY

Wholehearted acceptance by the public is necessary for the success of any campaign to institute demand-management. In South Africa, the need to save water became conflated in the minds of a large sector of the public with political notions of the redistribution of resources. Although the major droughts of the last few years have convinced a large part of the population that drought is real and not political, some remain to be convinced. Ernst Conradie and his colleagues, writing in the volume ***Towards the blue-green city: building urban water resilience*** (2021), ask "What are the underlying weaknesses of civil society that may cause us to fail to respond to escalating water shortages? What makes it difficult for us to get our own act together?" They, too, note that a number of groups in civil society view water scarcity as a matter of unequal distribution and not, in the first place, a limit imposed by nature. Civil society therefore tends to attribute a lack of access to water to poor governance, management and unequal distribution, and political ill-will. Sometimes they are right. If WDM is to work properly, though, the populace needs to be shown that this is not the case, and that can be done only by exemplary water management and appropriate – and all-important – communication with the public.

With regard to public participation, a few examples are worth examining. One concerns a change in the law of the State of Massachusetts in the 1980s. Continued expansion of the city of Boston brought confrontation with people in catchments well outside the city (this will no doubt also happen in South Africa sooner or later). Wanting more and more water, Boston built water transfer schemes until the public of the hinterland had had enough of 'water theft'. Active lobbying led to a review of patterns of local water consumption and an assessment of water-supply vs water-demand management which, in turn, led to a change in state and local laws. Boston has now reduced its water requirements so significantly that new supply projects are not envisaged for some time. What is more, the law now requires that, before the expenditure of public funds is authorised for a new water scheme, a community must demonstrate both that its need for a new water-development project is based on sound calculations, and that a sound and active water-demand management strategy is in place. In other words, the onus of proof is placed on the consumers rather than on unwilling suppliers. The argument is no longer accepted that a city must be allowed to grow regardless of the consequences for smaller communities.

A local example concerns construction of the Berg River Dam (the last major new dam to be built in South Africa). When plans were under discussion, Kader Asmal assured us that it would not be built unless Cape Town could be shown to be implementing WDM. Somehow the engineers seemed to be unaware of this promise, and went ahead with plans for the dam. I (Jenny) wrote to Prof Asmal and reminded him of his promise. He kept it, and it was only after Cape Town ***did*** in fact institute WDM that the dam was allowed to go ahead. Cape Town later became so successful in WDM that it won the ***C40 Cities Award*** in recognition of its Water Conservation and Demand-Management Programme at the Paris Climate Conference (COP21) in 2015.

> "The Gauteng region relies on nine rivers, while Cape Town takes most of its water from four, all well outside its borders."



This remarkable graph (blue line) shows how the City of Cape Town's water-demand programme succeeded in reducing water consumption despite an ever-increasing population. It was this reduction that cushioned the City from reaching Day Zero during the 2016-17 drought. Dotted line is population. Map provided by the City of Cape Town.

CONFLICT AND RESOLUTION: MANAGEMENT AS A PARTNERSHIP

The supply-side approach to water management has, over the years, frequently led to conflict between those managing the resource and those speaking on behalf of ecosystems depending on it. Precious years were lost by 'top-down' management, largely by engineers trained to subdue rather than nurture 'nature' and the confrontational attitude of environmentalists frustrated and alienated by this kind of approach. It has been only relatively recently (since the 1980s) that both sides have woken up to the fact that, by joining forces, at least some ecological and economic conflicts related to the management of water resources can be resolved through negotiation. A valuable partnership, with mutual respect and many shared experiences, has now grown between water managers and ecologists in South Africa. This relationship was greatly envied by water scientists in many other parts of the world where in many cases relationships are still fundamentally confrontational rather than co-operative.

SOME ETHICAL CONSIDERATIONS

A number of issues seem frequently to be overlooked. Firstly, without a healthy, functional environment, people cannot survive. Ecosystems sustain us and if we do not nurture them, then we might as well turn up our collective toes as a nation, if not as a species. So, any strategy to provide water for all must have sustainability of the environment as a fundamental construct.

Secondly, the environmental costs of water-supply developments have traditionally been regarded as too nebulous to be considered when new developments are being planned. Although it is difficult to place a monetary cost on 'the environment', this is another issue that has to be addressed. Resource economics and environmental economics are two burgeoning disciplines, and in fact we have far too few resource economists in the water field in this country. If anyone out there is looking for a challenging but vitally important career in water, think about training as an environmental economist. Or an environmental lawyer – we have far too few of them, too.

Thirdly, it makes more sense to heavily tax those who over-consume and who pollute, rather than further taxing the remainder of the populace, many of whom are already heavily taxed. Hit those who waste and hit them where it hurts: in their wallets. The 'polluter-pays' principle is one of the principles upon which the National Water Act is based but unless the payment is seriously painful, those who can afford to waste and pollute will continue to do so.

The latest development in the field of water management at a national scale is a new National Water Resources Agency proposed by DWS. Faced with "potentially crippling water shortages", and the need to spend at least R900 billion on water infrastructure by 2030, it is clear that 'business as usual' will not be sufficient, given particularly that the Department of Water and Sanitation has been seriously dysfunctional for some years. The new utility will be created by combining the Department's Water Trading Entity and the Trans Caledon Tunnel Authority, or TCTA, and could be operational by 2023. This seems to be a very sensible proposal, although similar ones have been rejected by Parliament in the past. Mike Muller, once Director-General of the Department of Water Affairs, notes rather drily that, "Now that there is a track record of successful public management by Trans Caledon Tunnel Authority and evidence of the dire consequences of a decade of muddled management in the Department of Water and Sanitation, the agency may have a better chance of success."

One somewhat bothersome aspect of the proposed bill, though, is that the private operation of water facilities will be considered. In many cases throughout the world, the privatisation of water utilities has been disastrous, particularly with regard to water supply to the very poor.

WATER SAVINGS – HOW YOU CAN MAKE A DIFFERENCE

I think that by now, most of you are already very conscious of the need to save water. This section is written with the others of you in mind. Let us start by looking at some of the ways in which each of us can make a difference. Consider the following statistics on the use of water around the home (Table 10.4).

Table 10.4 **Consumption of water around the home. (Daily consumption is calculated as litres per person and annual consumption is calculated as m^3/y for a family of five; data from DWAF brochure, *Water, Precious Water*.)**

Activity	Daily consumption litres	Annual consumption m^3
Bath	120	219
Shower	75	137
Toilet (5 flushes per person @ 11 litres per flush)	55	100
Kettle		32
Car wash with hose, one car once a week		6.5
Dishwasher once a day	150	55
Leaking tap, 50 drops a minute	5	1.8
Washing machine (3 times a week @150 litres)		23
Swimming pool, uncovered, evaporation		50
Approximate total		620

It has been estimated, by the way, that the biggest ***wastes of water*** in a household are from 1) the dishwasher; 2) waiting for hot water from the cistern; 3) leaking toilets; 4) high-flow showerheads; 5) the washing machine; and 6) the kitchen sink. When we wrote the previous edition of this book, automatically flushing urinals were also a major waste of water. It was calculated that a single urinal flushed about 1 300 m^3 of water a year. Not being in a position to do the research myself, I asked various friends to update me on urinals in Cape Town and they reported that at least since the drought, there are very few automatically flushing urinals. Most are triggered by an infra-red sensor, and some are even waterless. These use a fluid that is lighter than urine and so traps any odour. It is really interesting how the drought brought so many people and institutions to their senses.

WATER-SAVINGS IN THE HOUSE

Do you clean your teeth (at least twice a day) as follows? You turn on the tap, then fumble for the toothbrush and toothpaste, take the top off the tube, load your toothbrush and then wet the brush – all with the tap running? Or do you load your toothbrush with paste and only then turn on the tap briefly to wet the brush, subsequently using water only to rinse? It takes an awareness, a consciousness of the effects of one's actions, to alter a lifetime of bad habits. Conscious behaviour is about appreciating the consequences of our actions: the conservative use of water could save a river and avoid the worst consequences of another disastrous drought.

Simple changes in habit can make an enormous difference. For instance, washing up dishes in batches rather than one by one or, if you use a dishwasher, setting it for a short cycle instead of a long one, can save as much as 100 litres a day. A family of four showering instead of bathing can save another 300 or 400 litres a day. Collectively, that amounts to saving half a ton of water per household per day. And when we consider that families living in drought-stricken Cape Town were able to manage, albeit uncomfortably, on 400 litres or less per household per day, it becomes clear that most of us normally use water with little thought as to where it comes from or how much there is to go around.

TOILETS AND TAPS

On average, a full flush from a toilet consumes approximately 10 litres of water, but many old cisterns have a capacity of 11–12 litres or more, while some modern ones hold 9 litres. Find out what yours is and, if you do not have cash immediately available to get a smaller cistern, fill a plastic cooldrink bottle (1- or 2-litres, depending on how big the cistern is), lift off the lid and place the water-filled bottle into the cistern with the lid tightly closed. This is a cheap and easy way to reduce the volume of water that can be flushed. A 1-litre bottle displaces about 1 litre of water so your cistern will use that amount less on each flush. About 4 million people in Cape Town use flush toilets at home or at work, or both. With at least five flushes a day and a cistern with a capacity of 10 litres, this amounts to 50 litres of water per person per day just to flush away waste. A smaller cistern will pay dividends in terms of your water bill, and it will help to save a river, somewhere. Better yet, install a dual-flush cistern, which will give you, at the push of a button, the choice between a small flush (usually about 3 litres) to dispose of liquid waste and a larger flush (7 litres) for effectively removing solids.

There is also the problem of leaks from toilet cisterns. To find out if your cistern is leaking, place a small piece of toilet paper on the back of the pan. If it becomes sodden in a minute or two, you have a leak. This can cause a loss of up to 4 000 litres of water per day, or a staggering 1.46 million litres (1 460 m^3) a year – the equivalent of 24 urban swimming pools. Fix your leaks. If in doubt, call a plumber: the cost will soon be offset by a reduced water bill, particularly as water tariffs are escalating rapidly. If you are handy around the house, then before you call the plumber, have a look on Youtube for some of the many useful videos on household plumbing.

A simple device that reduces the amount of water used from taps is the tap aerator. This is relatively cheap and easy to install and produces a diffuse flow instead of a jet of water. An aerator with a built-in 'flip switch' can save up to 75% of water coming out of a tap and its switch can be conveniently used when cleaning teeth, washing vegetables, rinsing dishes, shaving, and so on.

Toilet-lid sinks or basins are beginning to be marketed in South Africa. Water used in the basin can be redirected to a small sink installed on the lid of the cistern. This water can either be used, instead of fresh water, to wash your hands after using the toilet or, with a little modification, can be directed into the cistern. This is perfectly safe re-use of water, if it is treated with a biocide like household bleach. It just takes a little work. Such devices are not always easy to install, particularly in old properties with old plumbing systems. In large households, the volume of water from the basin is often too great for the cistern to cope, but for a small family, or in a new home, they are very useful.

BATHS AND SHOWERS

Low-flow showerheads are sensible, cheap devices that are easy to install. Because they expel water in a fine spray, they reduce the amount of water used for showering by approximately 50 litres per person per day, virtually without affecting the 'feeling' of a good shower. A small switch on the head allows the jet of water to be turned off temporarily so that it is possible to wet oneself, turn off the water, soap oneself and turn the jet on again without having to readjust the flow. These shower heads can demonstrably effect considerable water savings in the house, and can be fitted to standard shower heads. Why bath at all, in fact? Baths are extraordinarily wasteful of water (see Table 10.4), so why not fit a low-flow shower head over the bath and pipe the wastewater into a tank for 'grey' (used) water. Finally, google '2-minute shower songs' for songs that last exactly two minutes – just long enough for a shower.

SAVING WATER IN THE GARDEN

Until recently, and when significant water restrictions were not in place, almost half of the water used domestically in Cape Town was sprayed onto the garden. (It may be that cities in summer rainfall areas use less because Cape Town gardens do suffer from naturally imposed summer drought.) Do you spend hours spraying your garden with a hosepipe? Rule number one: don't install a microjet system instead. Rule number two: don't water during the heat of the day or in a high wind, because you will be throwing away water, almost literally.

You may have a xeriscaped (drought-resistant) garden, one with some of the hardy and beautiful plants that can survive with little or no watering. Or maybe you are beginning to think that such a garden is a great idea. If water savings can be effective in the house, they can be just as effective in the garden. Across the drier parts of the country, farmsteads and cottages are fringed by rainwater tanks, often covered in creepers, and certainly adding to the atmosphere and architecture of rural landscapes. Sleepy ***dorps*** in the Karoo are almost bursting with them and many Cape Town households now have at least one JoJo tank in the garden. In fact, quite a few householders pride themselves on having drought-proofed their gardens by planting wisely and employing rainwater harvesting devices on roofs and even on other hardened surfaces. In fact, there is no reason (other than space and affordability) why each South African household, rural or urban, should not have at least one rainwater tank collecting water from the roof.

These days, there is a wide variety of shapes and materials to choose from and all that is needed is the will, and perhaps some subsidy or tax reduction from the government, to set the trend. It would certainly be a more cost-effective approach to water harvesting than most large dams are and, what is more, although rainwater tanks cannot catch every drop from the roof, they lose very little water by evaporation. In most of South Africa, a roof area of 100 m^2 can provide 50 m^3 of water a year, enough for 150 litres a day. Obviously, a tank holding this amount of water would be large and unsightly in a suburban garden, but much of it could be sunk into the ground if the property were large enough. And 150 litres a day is enough to nurse a garden of xerophytes (drought-resistant plants), even through a drought.

A water-wise garden can look lush and colourful.

If irrigation is needed, then drip-irrigation and microjet systems are conservative of water. Coupled with establishing indigenous plants, the removal of alien vegetation and xeriscaping your garden, they can significantly reduce water consumption. Microjet spraying systems are relatively cheap and very easy to install and come with nozzles providing different delivery rates so that sunny and shaded beds can be simultaneously, but differentially, watered. A recent American invention is even more effective: soaker hoses. These are ordinary rubber or plastic garden hoses with small holes in them. You can easily make them out of an old hose by drilling a series of holes about 5 mm in diameter into it. Attach one end to the tap using everyday connectors and plug the other end with a hose cap so that water doesn't leak out of it. The hose can be buried a few millimetres into the soil, or left on the surface. Experiment to find out how often the tap needs to be run to keep the soil permanently damp.

In a similar way, it is amazing what one can do for special plants, or for special areas of the garden, using old plastic bottles or clay jars. An unfired clay jar, if filled with water and buried to its neck next to a favourite plant or in a vegetable bed (check the level of water regularly with a dipstick), will, like the soaker hose, slowly release water to the soil through its open pores. 'Grey' water from the bathroom can even be used as a refill. And that unwanted plastic bottle? Perforate the surface of the bottle with a big sewing needle. Cut the bottom off and 'plant' the bottle upside down next to your valued clivia, where it will leak water in the same way as the unfired clay pot or the soaker hose.

Mulch collected from dead plants and scattered on the soil will reduce evaporation and keep the plants' roots cool at the same time.

Then, of course, there is mulching. It is amazing how many green plastic bags filled with branches, prunings, cuttings, dead leaves and grass clippings are hauled off to the dump after a day's gardening. Why is this material removed with such great care and then laboriously bagged and donated to the municipality? It can be used for compost for the garden or for mulch, or for both. Mulching simply copies nature and involves leaving dead material on the soil surface, or in fact adding to it. When a leaf falls off a tree, it decomposes and returns its nutrients to the soil in the vicinity of the tree, not of a rubbish dump. In this way, soil is made continuously, and nutrients are recycled locally. The same is true of mulch, but even more important in the context of this book is that mulch causes water loss through evaporation from the soil to be significantly reduced. What is more, the micro-environments created by mulch lead to enormous diversification of micro-organisms, insects and other arthropods and worms, all providing food for one another, turning and aerating the soil and providing food for garden delights such as birds. If you don't fancy chopping small branches and twigs by hand, you could purchase a mulching machine, which will probably soon pay for itself in the form of reduced water use.

All of this brings us to the use of 'grey' water. Recycling water is not just the responsibility of local municipalities, it can be done by everyone, especially if municipalities are not investing in recycling as official policy. 'Grey' water lost through the bathplug or the discharge of a washing machine or shower to the sewers can be effectively re-used. We have already discussed the potential of minor replumbing of bathroom basin wastes directly to toilet cisterns and cistern-lid sinks, but there are larger steps to take. Some are very simple and some a little more complex and expensive, but all are worth it. The bath 'Torpedo' has been on the market for a couple of years now and is very simple. It comprises a simple UV-protected plastic device that couples the drain from the bath to the garden hose and relies on gravity to feed water to the garden. Once fitted, all you have to do is move the spray attached to the hosepipe. Other slightly more complex devices are also available.

What about the swimming pool? Table 10.4 shows that the average-sized urban swimming pool (60–80 m^3 in capacity) loses about 50 m^3 of water through evaporation every year. There are easy and cost-effective remedies for such losses. First, cover it when it is not in use (if there are young children in your house or neighbourhood, the pool should be covered anyway, whenever you are not in attendance.) Covers may comprise fine-meshed netting or continuous plastic sheeting, both of which will greatly reduce evaporation. Secondly, replumb your roof guttering downpipes to feed the pool with rainwater during summer. If you are worried about leaves and other material entering the pool in this way, this will happen anyway when the wind blows (which is why most pools have some kind of 'Kreepie Krauly' cleaner), or you could trap such material using a mesh of chicken-wire over the outlet to the downpipe: simple but effective.

MUNICIPAL WATER SAVINGS

Of course, the responsibility for saving water cannot be placed solely on the doorstep of private householders. Cities should be in the vanguard since council employees are responsible for water supply within the city and also for metering, tariff-setting, leak-detection and repair, and billing.

REGULATIONS, BYLAWS AND TARIFFS

Cities can have an enormous impact on water conservation in the design of houses, factories and offices, and in developing appropriate policies for dealing with the acquisition, distribution and disposal of water. Local bylaws can become important tools for water conservation: guidelines for design can be laid down, fines for non-compliance can be set and collected, building regulations can be tightened, and so on. Local authorities can also tighten up on the behaviour patterns of the public, as well as on their own behaviour. For instance, the use of certain types of garden-watering equipment might be banned between specified hours of the day (when the greatest evaporative water losses occur). Secondly, local authorities urgently need to reconsider policies concerning their own gardens, parklands, road verges, and so on. How many of these facilities are planted to display the advantages of water-wise gardens? Has your local authority banned automatically flushing urinals? Does it produce useful media releases and other information about saving water? Does it allow for prepaid metering of water? If not, why not? And what about informative water bills that show things like the monthly rainfall and evaporation rates, how full the dams are, the likely implementation of water restrictions, and so on?

Despite the obvious need to save water in urban areas, there are some unexpected consequences of particularly intensive savings. On the one hand, the less water we use, the less will land up in the sewage works and thus less will be available for recycling. Obviously, it is more efficient to save water directly, but we must not expect the sums to balance if we include both recycling at the sewage works and reduced household consumption. On the other hand, when householders lower their consumption of water, they pay less. But in most cases the local authority still has to pay a fixed minimum sum per annum for the water it receives, usually from DWS, so that some authorities may land up losing quite heavily financially. And then because less water is being used there is a reduction in the amount of wastewater being produced so that the operator of the sewage works is faced with a smaller volume of more concentrated 'liquor' for his (or rarely, her) plant to deal with. In really bad times the sewage microorganisms simply cannot cope and the entire system collapses. The toxic and foul-smelling untreated sewage then ends up in the river. Once again, things are not as simple as they seem.

Finally, local authorities have to make vital decisions about how much we should pay for the water we use. One of the tenets of the South Africa's National Water Act is that a certain minimum amount of water (for 'basic human needs') must be provided free of charge to each person as a 'lifeline'. (The allocation is currently 25 litres per person per day.) Is 25 litres a day a reasonable amount? Well, it is sufficient for drinking, cooking and washing, but not much more. During the Cape Town drought, households were restricted to 400 litres per day, which meant minimal showering, much reduced use of washing machines and dishwaters, half-empty swimming pools and dead gardens. People learnt (or were reminded of the days when washing happened on a Monday, and ironing on a Tuesday) that it is not necessary to wash one's clothes or use the dishwasher every day.

To curb excessive use of water, and to regain the costs incurred in supplying water, most municipalities charge for water on a sliding scale. The cost of water for Capetonians (Table 10.5) is interesting. Those households identified as 'indigent' pay nothing at all, even if their consumption is above the minimal 6m^3 per month. For regular free-standing households, consumption up to 35 m^3 a month is relatively low – up to R38 per m^3 – but above 35 m^3, the cost jumps to R83.43 per m^3. Of course although this amount seems horrendous to everyday citizens, it is probably no more than a minor annoyance to the very wealthy, some of whom comply rigorously with the City's water restrictions, while others don't. That is where neighbour begins to spy on neighbour, and old quarrels can be settled – not an edifying situation, but understandable to anyone who had to allow their garden to die because they did behave responsibly.

10.5. An illustration of a sliding scale of water tariffs, in this case, in the City of Cape Town.

City of Cape Town

Residential Water Tariffs (Domestic Full and Domestic Cluster)		
Water Steps (1kl = 1000 litres)	**Level 0 (2021/22)** until 30/06/2022 **Rands (incl VAT)**	**Level 0 (2022/23)** From 1/07/2022 **Rands (incl VAT)**
Step 1 (0 ≤ 6kl)	R18.23 (free for indigent households)	R19.42 (free for indigent households)
Step 2 (>6 ≤ 10.5kl)	R25.06 (free for indigent households)	R26.69 (free for indigent households)
Step 3 (>10.5 ≤ 35kl)	R34.05	R36.27 (free for indigent households)
Step 4 (>35kl)	R62.84	R66.93 (free for indigent households)

Residential Sanitation Tariffs (Domestic Full and Domestic Cluster)		
Water Steps (1kl = 1000 litres)	**Level 0 (2021/22)** until 30/06/2022 **Rands (incl VAT)**	**Level 0 (2022/23)** From 1/07/2022 **Rands (incl VAT)**
Step 1 (0 ≤ 4.2kl)	R16.03 (free for indigent households)	R17.07 (free for indigent households)
Step 2 (>4.2 ≤ 7.35kl)	R22.02 (free for indigent households)	R23.45 (free for indigent households)
Step 3 (>7.35 ≤ 24.5kl)	R30.93	R32.94 (free for indigent households)
Step 4 (>24.5 ≤ 35kl)	R48.64	R51.81 (free for indigent households)

** Sanitation charged to a maximum of 35kl*

Domestic Full = Stand-alone houses

Domestic Cluster = Flats, sectional title units, cluster developments and gated villages

WATER-DEMAND MANAGEMENT (WDM)

WDM is a very effective way of reducing domestic water consumption. The previous edition of this book listed the water tariffs for Hermanus, which was the first municipality in South Africa to implement water-demand management in the 1990s. The town's water department had applied to the central government for a new dam and the answer was 'no', so the town decided to implement WDM. Among other things, the price of water was drastically increased. The block tariff from 6 to 10 m^3 was 70 cents per m^3 (not a typo) and the highest, for consumption of >100 m^3, was R10 per m^3. According to those tariffs, a consumption of 125 m^3 per month would have cost R707.00, while the cost of the same amount of water in Cape Town would have been R188.25. Clearly the high cost of water was one of the main ways in which Hermanus was able to reduce water consumption. (There had been an intensive public participation process, by the way, and the majority of Hermanus's citizens had agreed that the municipality should proceed with implementing WDM, including a large increase in the cost of water). Of course, there were many who raised howls of protest, and public meetings saw vociferous debates, but eventually the majority prevailed and WDM was instituted.) Water consumption dropped by 30%.

Themba Gumbo noted in 2005 that Windhoek, Bulawayo and Hermanus had achieved considerable success in implementing WDM programmes, and that all three cities had been able to reduce non-revenue water to <20%, whilst cities (Johannesburg, Maputo, Maseru, Lusaka and Mutare) that had been less successful could not account for 40–60% of the water introduced into the distribution system. Cape Town's WDM programme was hugely successful, to the extent that the City won the ***C40 Cities Award*** in recognition of its water conservation and demand-management programme at the Paris Climate Conference (COP21) in 2015.

SAVINGS BY INDUSTRY

'Where thar's muck thar's brass' is the quaint way in which a Yorkshireman might indicate that money (brass) can be made from 'muck' (dirt – pronounced "mook") – and he would be right. Mining, milling and refining are examples of wealth-generating industries that use large quantities of water and are major polluters. Some mining processes produce the most horrible cocktails of acids and heavy metals, together with cyanides, while effluents from some coal mines are so acid that they render water positively dangerous to go near – around Witbank, for instance. Of even more concern is the fact that many mining operations on the Witwatersrand punch their way through groundwater-laden dolomites, and in the process pollute water that could be used for human consumption. The steel mills run by ISCOR can deliver mixtures of cadmium, arsenic, lead, tin, copper, iron, antimony and other toxic materials as well as acids and phenols to the environment. Chapter 7 deals with pollutants in more detail.

How does one control this type of pollution? The answer is 'with difficulty', although the 'polluter pays' principle does help: an industry that pollutes a resource must pay accordingly. The principle is sound in the sense that particularly dirty processes will be cleaned eventually if the financial incentive is strong enough. The extra costs incurred, either in fines or in the development of cleaner processes and their installation, are passed on to the consumer. And of course, there is always the possibility that irretrievable damage will have been done before the financial penalties are stringent enough to enforce a clean-up. These issues are exacerbated in South Africa by failing municipalities and the shocking state of infrastructure in most of our wastewater treatment works.

We have already talked about the use of recycled water, but there is no sensible reason that we can see that many industries cannot be supplied with 'grey' water. The expense of purification is avoided and processes such as cooling are little affected. With careful planning, the medium- and long-term saving of water should be significant although short-term costs might increase (laying of dedicated pipelines, for instance). Finally, of course, there is the simple expedient of supplying water at a more realistic cost. Sliding scales can be implemented for industry, as they can for domestic water, while special tariffs can be introduced to force savings.

FRACKING

Fracking is one of those subjects that raises a great deal of heat. Briefly, fracking is the fracturing of rocks deep underground in order to extract methane, the fossil hydrocarbon gas stored there. The process is very disruptive in many ways and in the Karoo, where various fossil-fuel companies have exploration rights, water is a major concern. Karoo residents have two major concerns. The Karoo is, as you know, a very arid area, which means that there is no surface water available for the fracking process. Groundwater would have to be used. Farmers in the area already use groundwater for all their water requirements and they are concerned that frackers would both use and contaminate the little water they have.

The other major concern with regard to water is that the fluids used in the fracking process contain some very nasty chemicals indeed (although the fracking companies will tell you otherwise). Accidental spills of fracking fluid, on the ground or under it, could cause major contamination of the groundwater used by both the farmers and the towns in the area. The CSIR produced a detailed report on fracking for shale gas in the Karoo in 2016. Relevant links are provided in the section of Further Reading. By the way, shortly after this report was produced, OPEC dropped the price of fossil fuels to such an extent that potential fracking companies postponed further prospecting until further notice. With the oil price once more soaring in 2022, we can expect further prospecting to go ahead in the Karoo.

WATER SAVINGS IN AGRICULTURE

The proportion of water used annually for irrigation has fallen from more than 70% in the 1980s, to less than 60% today (2022). As the price of water increases, and availability decreases, farmers are becoming much more efficient at saving water than they were in the 1980s. Many of them use the most water-efficient varieties of food crops and the most efficient irrigation methods, avoiding spray irrigation in favour of drip- or microject methods where possible. These methods aren't always viable, though. Drip irrigation is useless on coarse soils that do not hold water, for the water runs straight through the soil and does not spread out in the root zone. And wheatfields, which grow small individual plants and are ploughed annually, cannot have a network of pipes that would be ripped up by ploughs and threshers; wheat farmers use huge rotating centre-pivot irrigators instead. As we have mentioned above, in the future some farmers will be forced to grow crops based on the amount of water they consume. Especially as global warming continues, and mean annual rainfall reduces by as much as 35% over much of the country, this may well become a matter of survival.

Lani van Vuuren

Centre pivot irrigation at Vaalharts, the country's largest irrigation scheme.

WATER AND ENVIRONMENTAL LAWS IN SOUTH AFRICA

AN HISTORICAL PERSPECTIVE ON WATER MANAGEMENT

Through historical accident, South Africans inherited the first legislation on water from the Dutch settlers who arrived in this country in the seventeenth century. Interestingly, the Dutch in turn inherited their laws from the Romans. Now much of Italy, where Roman law was developed, is dry, so their laws would probably have suited conditions in South Africa very well. The Dutch, on the other hand, have always suffered from an excess of water in their country. Unfortunately for us, much of the original Roman law was lost while most of the remaining (and inappropriate) Dutch components were imported to South Africa. In those days, the Dutch state had no need to control watercourses other than for navigational purposes, and under what came to be known as Roman-Dutch law in South Africa, watercourses became privately owned, placing the onus on the private landowner to deal with any excessive quantities of water on his property.

Thus, in our water-stressed country we had the iniquitous situation where, depending upon their title deeds, landowners could own not only the banks but even the bed of a river, together with the water in and below it. With a number of landowners in a single river catchment it does not take much imagination to realise what that means for the rational management of a river. In the case of the Liesbeek River, a small stream that runs through the 'leafy' (read 'wealthy') suburbs of Cape Town, 'ownership' of the banks (and sometimes of the bed) led to unbridled private activity. For instance, a number of residents with properties abutting the river in its upper catchment altered its course to suit their own purposes –a nice extension to the garden or extending the banks to allow the installation of a tennis court, for example. In addition, because the river (and the Liesbeek is not the only one) runs through a number of suburbs, different byelaws applied to different activities along different reaches. Neither local nor national legislation effectively managed the river, the only active management activities being the construction of canals and holding ponds allowing flood waters to leave the city as fast, as efficiently and (apparently) as cost-effectively as possible.

Roman Dutch law was also inadequate as far as aquatic ecosystems are concerned because, among other things, it distinguishes between 'private' and 'public' water. Water extracted from a borehole under one's property, or running in a stream whose banks one owns, is 'private' water and therefore an aspect of property rights. All other water is 'public'. The right to use water for irrigation was only vaguely outlined, since even watering garden vegetables may be regarded as an act of irrigation. One of the many deficiencies in the Act, was control over groundwater, in that the Act consistently ignored the interlinkages between freshwater systems. Fortunately, we no longer have to understand that complex and peculiar piece of legislation because it was one of the first laws to be replaced under the new political dispensation in the mid-1990s.

SOUTH AFRICA'S NATIONAL WATER ACT 38 OF 1998

In 1995, an intense interactive process was set in train by the Minister, Kader Asmal, who, recognising the shortcomings and inequities of the Act then in force, decided to set matters right by rewriting the Water Act. Hundreds of people were involved in dozens of consultative meetings, workshops and conferences. Initially a set of 28 principles were identified upon which the new Water Act would be based. These principles fall into six major categories: legal aspects; the water cycle; priorities for resource management; approaches to resource management; the institutions governing water supply and distribution; and services.

The first category contains four principles governing ***the ownership of water as a resource.*** The most significant is the recognition that there should be no ownership of water (except by the State) and that basic human and environmental needs should be met. Thus, ownership of riparian land no longer includes the right to own or even use water. This notion departs very significantly from the tenets of the old Water Act and is a fundamental step towards collective stewardship, rather than private exploitation, of water and aquatic ecosystems.

Two principles relate to the ***water cycle***: the recognition that '…evaporation, clouds, and rainfall are linked to underground water, rivers, lakes, wetlands and the sea, and … the basic hydrological unit is the catchment'. To have this principle underpin the new laws is a major victory for conservation and the environment because it forces acceptance of the fact that, as providers of a resource that humans cannot do without, aquatic ecosystems have their own water requirements that must be catered for, regardless of perceived human needs. Furthermore, consideration of all water down to and including the coastal zone means that estuarine and coastal processes and requirements are recognised.

The third category, concerning priorities in the ***management of water resources,*** deals with access to water as a resource by humans and natural environments. The first of these recognises that the exploitation of water in all its aspects (quality, quantity and reliability of supply) must be sustainable in the long term. The next two principles concern the 'water reserve': water for maintenance of human wellbeing (currently 25 litres per person per day), and water required for the sustainable maintenance of rivers, wetlands, estuaries and aquifers. This means that long-term sustainable use of aquatic ecosystems is a matter of policy. This is a fundamental departure from the old Water Act. Effectively, '… the water required to meet the basic human needs … and the needs of the environment shall be identified as 'the Reserve' and shall enjoy priority of use by right.' Finally, South Africa's obligations to neighbouring countries are recognised. The other principles are important but not in our context, so we will not discuss them here.

The final National Water Act (the National Water Act 38 of 1998) is a remarkable piece of legislation for many reasons. It was the first in the world to specify the environment as the source, and therefore in a way the custodian, of water. It was the first to require water to be managed in such a way as to ensure the sustainability of 'the resource' (rivers, wetlands, estuaries and groundwater). It did away with the notion of private water, making the State the custodian of all water. It required that aquatic ecosystems be managed by catchment (and not according to political boundaries) and therefore provided for the establishment of Catchment Management Agencies (CMAs). Last, but definitely not least, aquatic ecologists were encouraged to contribute to and debate the Principles on which the Act was based, and even to be represented in discussions on the drafting of the Bill.

Other legislation involved in ecosystem protection and conservation is discussed in Chapter 11, as is the implementation of the National Water Act.

READING LIST

Cock J & E Kock (eds.) (1991) ***Going green: People, politics and the environment in South Africa.*** Oxford University Press, Cape Town. 262 pp.

Conradie EM, J Fackethal, R Gallant, JJ Hasselaar, D Jalajel, R Mash, J Matenda & C Pearson (2021) Urban water resilience: perspectives from civil society. Pp 168-198 ***in:*** LL Swatuk, G Brill, C Bűchner-Marais, K Carden, E Conradie, JA Day, J Fatch, J Fell, M Hara & B Ncube (eds) ***Towards the Blue-Green City: Building urban water resilience.*** Water Research Commission Report No. SP 153/21

Day B, J Day, E Day, R Palmer, K Reinecke, K Rowntree & C Thirion (2021) The WRC and rivers, reservoirs and the Reserve. Pp 172-193 ***in:*** JA Day, BE Day & J Reizenberg (eds) (2021). ***WRC @50: Celebrating a half-century of excellence***. Water Research Commission Report No. SP 148/21

Department of Water Affairs (1986) ***Management of the Water Resources of the Republic of South Africa.*** Pretoria. [The 'Red Book']

Day JA (2009) Rivers and wetlands Pp 842-867 ***in:*** HA Strydom & ND King (eds) ***Fuggle & Rabie's environmental management in South Africa.*** 2nd ed. Juta, Cape Town. 1135 pp.

Day J, G Cleaver-Christie, E Day & L Stafford (2021) Water and the natural environment: biodiversity and urban water management. Pp 24-45 ***in***: LL Swatuk, G Brill, C Bűchner-Marais, K Carden, E Conradie, JA Day, J Fatch, J Fell, M Hara & B Ncube (eds) ***Towards the Blue-Green City: Building Urban Water Resilience.*** Water Research Commission Report No. SP 153/21

Day JA, BE Day & J Reizenberg (eds) (2021) ***WRC@50: Celebrating a half-century of excellence***. Water Research Commission Report No. SP 148/21,

Department of Water Affairs and Forestry, 1993. ***Western Cape System Analysis, Summary Document.*** With the City Engineer's Department, Cape Town, Ninham Shand Consulting Engineers and BKS Incorporated, Pretoria.

Department of Water Affairs and Forestry, 1995. ***You and your water rights: South African water law review – A call for Public Response***. Government Printers, Pretoria. 30 pp.

Fuggle RF, GR Preston, MR Sowman, N Robins, R Short, SA Grindley, RC Hill, RB Stauth, JP Raimondo, SM Fowkes, SB Lane, JA Barker & J Glazewski (1992) ***The Integrated Environmental Management Procedure.*** 6 volumes. Department of Environment Affairs, Pretoria.

Fuggle RF & MA Rabie (1992) ***Environmental Management in South Africa.*** Juta, Cape Town. 823 pp.

Gardner G (1995) From oasis to mirage: the aquifers that won't replenish. ***World Watch*** May/June 1995: 30–36.

Goga T, E Friedrich & CA Buckley (2019) Environmental life cycle assessment for potable water production – a case study of seawater desalination and mine-water reclamation in South Africa. ***Water SA*** **45** http://dx.doi.org/10.17159/wsa/2019.v45.i4.7552

Gumbo B (2004) The status of water demand management in selected cities of southern Africa. ***Physics and Chemistry of the Earth*** **29:** 1225-1231 https://www.sciencedirect.com/science/article/pii/S1474706504001913?via%3Dihub

Jacobson PJ, KM Jacobson & MK Seely (1995) ***Ephemeral rivers and their catchments. sustaining people and development in Western Namibia.*** Desert Research Foundation of Namibia and Namibian Department of Water Affairs. Windhoek. 160 pp.

Jewitt G (2021) Hydrology. pp 28-47 ***in:*** Day JA, Day BE & Reizenberg J (eds) (2021). ***WRC @50: Celebrating a half-century of excellence***. Water Research Commission Report No. SP 148/21

King ND, HA Strijdom & PF Retief (3rd ed.) (2018) ***Fuggle & Rabie's environmental management in South Africa,*** Juta, Cape Town. 1387 pp

Lumbwe C, J Michalow, A Tugendhaft & K Hofman K (2015) Reducing diarrhoea deaths in South Africa: costs and effects of scaling up essential interventions to prevent and treat diarrhoea in under-five children. ***BMC Public Health*** **15**: 394. doi: 10.1186/s12889-015-1689-2

Machingura J, J Coetzee, B Day, J Day, D Hay, P Skelton, C Thirion & M Uys (2021) The evolution of ecosystem research – from biodiversity to bioassessment. Pp 142-171 ***in***: JA Day, BE Day & J Reizenberg (eds) ***WRC@50: Celebrating a half-century of excellence***. Water Research Commission Report No. SP 148/21

Mather GK & DE Terblanche (1992) Cloud physics experiments with artificially produced hygroscopic nuclei. Proceedings of the 11th International Conference on Clouds and Precipitation, Montreal. ***American Meteorological Society.*** 147–150.

Ngobeni V & MC Breitenbach (2021) Production and scale efficiency of South African water utilities: the case of water boards. ***Water Policy*** 23: 862 DOI:10.2166/WP.2021.055

O'Keeffe JH, M Uys & MN Bruton (1992) ***Freshwater systems.*** pp 277–315 in R.F. Fuggle and M.A. Rabie (eds), ***Environmental management in South Africa.*** Juta, Cape Town. 823 pp.

Palmer Development Group, 1994. ***Water and sanitation handbook for community leaders (urban and peri-urban areas).*** South African Water Research Commission Report no. TT68/95: 1–31.

Pearce F (1993) Fogs yield drinking water in the desert. ***New Scientist*** 16 October: 19.

Postel S (1993) ***The Last Oasis: Facing water scarcity***. Earthscan, London.

Preston GR, N Robins & RF Fuggle (1992) ***Integrated environmental management.*** pp. 748–761 in: R. Fuggle & MA Rabie (eds), ***Environmental management in South Africa.*** Juta, Cape Town. 823 pp.

Quick AJR (1995) Issues facing water resources managers and scientists in a rapidly growing coastal city: Cape Town, South Africa. ***South African Journal of Science* 91**:175–183.

Ramutsindela, M & D Mickler (eds) (2020) ***Africa and the Sustainable Development Goals***. Cham: Springer.

SA Water Law Review Panel, 1996. ***Fundamental principles and objectives for a new water law in South Africa. Report to the Minister of Water Affairs and Forestry.*** Government Printers, Pretoria. 33 pp.

Saunders J (1997) Proposed water demand management strategy for Greater Cape Town. ***Civil Engineering*** January: 15–17.

Schemenauer RS & P Cereceda (1994) Fog collection's role in water planning for developing countries. ***Natural Resources Forum* 18**: 91–100.

Sonnendecker PW, HL Marais & E Adu-Awuku (2020) ***Performance of a simple basin solar still under the South African climate: a baseline study*** Water Research Commission Report No. 2727/1/20

Swatuk LL, G Brill, C Bűchner-Marais, K Carden, E Conradie, JA Day, J Fatch, J Fell, M Hara & B Ncube (eds) ***Towards the Blue-Green City: Building urban water resilience.*** Water Research Commission Report No. SP 153/21

Turner KR, K Naidoo, JG Theron, JG Theron & J Broodryk J (2015) ***Investigation into the cost and operation of southern African desalination and water re-use plants. Vol. 2. Current Status of desalination and water reuse in Southern Africa.*** Water Research Commission Report No. TT 637/15

WEBSITES (LAST VISITED NOVEMBER 2022)

Cape Town water crisis
http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/Towards%20a%20blue%20green%20city_final%20web.pdf

https://www.capetownmagazine.com/innovative-water-savings-ways

Desalination
https://www.wwf.org.za/?24281/wednesday-water-file-07

Farming in arid regions
https://people.umass.edu/psoil370/Syllabus-files/Dryland_Farming__Crops_&_Tech_for_Arid_Regions.pdf

Fracking
https://seasgd.csir.co.za/

https://seasgd.csir.co.za/wp-content/uploads/2016/11/Ch-5_Water_13Nov2016_LR.pdf

http://awsassets.wwf.org.za/downloads/wwf_shale_gas_report.pdf

Future issues
https://unfoundation.org/blog/post/five-global-issues-to-watch-in-2021/

Proposed National Water Resources Agency
https://businesstech.co.za/news/energy/573048/south-africa-plans-new-state-water-utility/#:~:text=South%20Africa%20has%20begun%20the,off%20potentially%20crippling%20water%20shortages

South African demographics (excellent data)
https://en.wikipedia.org/wiki/Demographics_of_South_Africa

South African water issues
https://www.businesslive.co.za/bd/opinion/2022-03-03-mike-muller-there-are-no-water-supply-backlogs-just-difficult-decisions/

The Nature Conservancy
https://www.nature.org/content/dam/tnc/nature/en/documents/NBSWhitePaper.pdf

Virtual water
https://waterfootprint.org/en/water-footprint/national-water-footprint/virtual-water-trade/

https://www.thegreenage.co.uk/what-is-embedded-water/

Water crisis in Libya
https://www.deswater.com/DWT_articles/vol_167_papers/167_2019_351.pdf

Water use in Cape Town pre-drought
https://greencape.co.za/assets/Sector-files/water/Water-conservation-and-demand-management-WCDM/Viljoen-City-of-Cape-Town-residential-water-consumption-trend-analysis-2014-15-2016.pdf

Wheat production in Saudi Arabia
https://www.world-grain.com/articles/15070-saudi-arabias-wheat-production-falls

Use of fog and mist
https://www.wrc.org.za/wp-content/uploads/mdocs/TT%20632-15.pdf

Use of icebergs
https://www.freedrinkingwater.com/water_quality/quality1/13-08-icebergs-for-drinking-water.htm#:~:text=Even%20though%20icebergs%20are%20floating,risks%20associated%20with%20moving%20them.

Water crisis in North Africa and the Middle East
https://www.downtoearth.org.in/news/water/a-worsening-water-crisis-in-north-africa-and-the-middle-east-58585.

Working for Water
https://www.greeneconomycoalition.org/news-and-resources/working-for-water-in-south-africa

http://kogelberg-botsoc.co.za/Blog/index.php/2018/10/22/the-aliens-drank-our-water/

Working for Wetlands
https://www.dffe.gov.za/projectsprogrammes/workingfowetlands

https://www.dffe.gov.za/sites/default/files/docs/publications/workingforwetlands2021.pdf

World Resources Institute
https://www.wri.org/

WRC@50
http://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/WRC50%20celebration%20book_final.pdf


borgogniels / 123RF

CHAPTER ELEVEN

Udokies / 123RF

Managing water for the environment: conservation and planet management

In nature there are neither rewards nor punishments – there are only consequences.

Robert G Ingersoll, Lectures and Essays, Some Reasons Why

INTRODUCTION

This chapter is new and has largely been written by Jenny with a few sections cannibalised from the 1998 edition that Bryan and I wrote together. I have no doubt, though, that Bryan would have agreed with most of what I have to say.

So far in this book we have looked at the different kinds of aquatic ecosystems, the ways they function, and the ways in which human activities have affected them. In this chapter I first discuss the issue of ecosystem conservation, starting by showing the values of ecosystems to humans as an argument in favour of conservation. I then examine the technicalities of conservation, the importance of genetic evidence in conservation strategies, and provide a couple of South African case studies. Next, we look at South African legislation that deals with ecosystem conservation and with river management – including environmental water allocations – with a brief detour into climate change. The last part of the chapter deviates from a strictly aquatic perspective, recognising that many aspects of ecosystem degradation are universal, and that the fundamental approaches to solutions must also be universal.

THE CASE FOR ECOSYSTEM CONSERVATION: ECOSYSTEM SERVICES

If we expect people to take the issue of conservation seriously, we need to show the ways in which natural environments are important for our survival on this planet. If we also want politicians to include environmental considerations in their policies, we need to provide as much evidence as possible about the monetary value of functioning ecosystems. So let us first look at the services provided by wetlands and rivers, and then see the extent to which it is possible to attach monetary values to these services.

The term 'ecosystem services' (ESs) was coined in the 1980s to refer to both the tangible and the intangible benefits that we humans receive from 'nature'. During a UNESCO-funded project on the assessment of ecosystems (the Millennium Ecosystem Assessment – MEA – and see page 451), ESs were divided into a number of classes – provisioning, regulating, supporting and cultural services – although the edges between the classes are blurred and the classification seems to me to be an unnecessary complication. In the following account we will concentrate on services provided by aquatic ecosystems, although many are common to all sorts of ecosystems.

Provisioning services refer to material 'goods', such as

- food and spices, including fodder for livestock
- fuel and energy: wood, dung, peat
- materials such as wood and bamboo used for building, furniture-making and weaving
- naturally-occurring pharmaceuticals, vitamins and other chemicals
- clean water.

'Provisioning' services: A) reed houses on floating reed islands, Lake Titicaca; B) a crop of cranberries grown in a wetland; C) artisanal fishery: kapenta drying in the sun on the shore of Lake Kariba.

Aquatic ecosystems provide **clean water**, for instance, because microbes such as bacteria and fungi decompose and mineralise organic waste, leaving the water pure and drinkable. Of course, microbes are unable to process many toxins, so if microbes are eliminated from water because of the presence of toxins, organic waste will not be processed either.

Less obviously, aquatic ecosystems also provide some important **nutritional supplements**, including PUFAs. PUFAs are poly-unsaturated fatty acids, found in the aisles of pharmacies as **ω**-3 & -6 (omega-3 and omega-6) fatty acids. PUFAs constitute nearly 16% of the weight of the human brain and are especially important in the developing foetus. Many cannot be manufactured by the human body but have to be consumed in the diet. Certain PUFAs are found in fish oil (e.g. salmon oil) and a variety of terrestrial plants but unicellular algae are the only ***direct*** manufacturers of the most essential PUFAs. (Salmon get theirs from their diets too.)

Regulating services are those that control natural processes such as the climate, the concentrations of atmospheric gases, and the decomposition of organic remains. Wetlands are particularly important in regulating the chemistry of the particulate matter and the water flowing into them. Wetland plants are generally effective in flood control, while the plants and soils together act as filters, retaining particulate material (including pathogenic bacteria), and taking up nutrients.

Because flood waters are retained by wetland vegetation, wetlands are also important areas for recharge of aquifers: water held back by the vegetation filters slowly into the soil and from there into the underlying aquifer. The best illustration of the value of wetlands in regulating water quality is the fact that constructed wetlands are now commonly employed to purify waste streams, especially in small towns.


Jenny Day

*Dense stands of reeds such as papyrus (*Cyperus papyrus*) dampen the force of floodwaters.*

A bee covered in pollen grains, some of which will be rubbed off her body and onto the stigma of the next flower she visits.

Supporting services is a rather odd term that essentially refers to any natural processes that cannot easily be tucked neatly into either 'provisioning' or 'regulating' services. In fact, they include everything from pollination and biogeochemical cycling to the production of soil, oxygen and photosynthetic products. Although these services ae often dismissed in a few words (as they are here), they are crucial for life on Earth, and would be extremely difficult to replace should they cease for some reason.

A case in point is pollination. This is a terrestrial issue, but reductions in pollinators are of universal concern, as well as illustrating yet again the effects that humans are having on the planet. The number of bees is declining worldwide. In fact, Johanne Brunet has indicated that the number of ***species*** of bees has declined by 40% in the UK, and 60% in the Netherlands (https://bit.ly/41qOQIt). The reasons for this decline are still being investigated, but almost certainly involve loss and degradation of habitat, climate change, bee parasites, and exposure to agrichemicals (see page 263). Christian Lippert and colleagues (Lippert 2021) estimated pollination services in Germany to be worth €3.8 billion annually, and globally of the order of US$ one trillion a year. They further estimate that total loss of pollinators would reduce global GDP by 1-2%. (Just think of all the plants pollinated by bees: virtually all soft and deciduous fruits, and hundreds of others.

Cultural services, while less crucial to human physical wellbeing, are often completely irreplaceable. They include spiritual, intellectual, recreational and scientific values. They are also the most difficult to value in monetary terms because they are intangible.

Other services that are less easy to classify include the provision of transport routes for humans in the form of waterways, both rivers and lakes. And with regard to transport, rivers don't only transport people and fish. They also provide an important service in delivering nutrients and sediments to the coastal zone. Ocean waters are generally very nutrient-poor, so nutrients coming off the land ***via*** rivers are crucial for sustaining coastal-zone fisheries, coral reefs, and so on. In fact, declines in coastal fisheries can often be attributed to rivers being dammed and no longer providing significant concentrations of nutrients to the ocean. Similarly, ocean currents often sweep sediments away from the coast towards the deep sea. Sediments coming downstream into estuaries and from there to the sea, provide the particles that make up sand banks in the estuary, and beaches on the coast. Large storms some years ago resulted in huge washaways of beach sand in KwaZulu-Natal, destabilising beachfront properties and destroying recreational beaches. Dams on several rivers were implicated in these losses.

THE ECONOMIC VALUE OF ECOSYSTEM SERVICES

The strange – but understandable – thing is that no-one has yet worked out the actual monetary value of most of the services that the Earth's rivers and wetlands provide. This is a very tricky thing to do, for various reasons, including needing to reach agreement on the data and methods to use. The first brave people to attempt to get a rough global figure were Bob Costanza, Professor of Ecological Economics at the Institute for Global Prosperity at University College London, and his colleagues. They estimated in 1997 the mean annual value of wetlands to be around US$14.79 per hectare per year and of rivers and lakes, US$ 8.50. Multiplying by the surface area covered by each type of ecosystem, the total global value of the goods and services provided by wetlands was US$ 4.9 trillion per year, and by rivers and lakes, US$1.7 trillion. Those are big numbers, and even bigger when one realises that these authors calculated the total annual world 'gross national product' to be about US$ 18 trillion. Table 11.1 shows some values calculated by Costanza and his team for the late 1990s.

Table 11.1 **Value of the world's ecosystem services and natural capital (Costanza *et al.* 1997, 2014).**

	value/ha US$/ha/y		global value US$/y	
	1997	2014	1997	2014
Forest	969	3 800	4.7×10^{12}	16.2×10^{12}
Wetlands	14 785	140 417	4.9×10^{12}	26.4×10^{12}
Lakes and rivers	8 498	12 512	1.7×10^{12}	2.5×10^{12}
Total			**33.3×10^{12}**	**125×10^{12}**

This all looks very impressive to a mere ecologist, but my resource economist colleague Prof Tony Leiman advises caution. He notes that "the basic flaw in the approach is that 'value' is subjective, in that it is based on how much people want something, but it also has an objective component, in that it depends on how much they are able to pay. If GDP is US$18 trillion, and people have to spend on all manner of other things too, then their willingness and ability to pay for wetland services simply cannot be as much as US$4.9 trillion. [These authors have] them paying more than double what they earn, and this for only one resource." The take-home message is that we should not base too much faith in the numbers provided in Costanza's paper, although it does point out that natural aquatic ecosystems are incalculably valuable.

In 2014, Costanza and colleagues wrote another paper, providing an updated estimate of the global value of ecosystem services. In 1997, they had estimated the global value to have averaged about US$33 trillion/year. Using the same methods as in the 1997 paper, but with updated data, they estimated total global ecosystem services in 2011 to be between about US$125 and $145 trillion a year. Using both of these values, they estimated the loss of ESs from 1997 to 2011 to be between $4.3 and $20.2 trillion/year, depending on which unit values they used. They attributed these losses mostly to land-use changes. The most valuable ecosystems were coral reefs, worth US$350 000 per hectare per year, based mainly on their value for climate control, erosion control, waste treatment, and tourism.

The World Annual 'GDP' was estimated at that time to be about half this: US$ $75 \times 10^{12}\,y^{-1}$, suggesting that ecosystem services contribute more than twice as much to human well-being as global GDP does. Even if the values are exaggerated, the data in this paper do confirm our suspicions that human activities are continuing to erode the ability of the natural world to provide ecosystem services.

On a much smaller local scale, in her Master's thesis in 2009, Katie Lannas compared the value of wetland goods and services for two local communities, one in Cape Town and the other in Lesotho. The Mfuleni wetland in Cape Town is somewhat degraded, largely man-made, and surrounded by informal housing. The wetland in Lesotho, Letseng-a-Letsie, is larger, close to pristine, and situated in the highlands of Lesotho. Katie found that the annual value of wetland goods and services to the users was

Mfuleni wetland	US$1 765 /ha/year
Letseng-la-Letsie (Lesotho)	US$ 220 /ha/year

and the average annual household income from the wetlands was

Mfuleni wetland	US$2 003 /year
Letseng-a-Letsie	US$66 /year

It is salutary to think of even degraded wetlands as being of greater value to local communities that the pristine ones we more affluent people cherish.

The Mfuleni wetland in Khayelitsha, Cape Town.

Letseng La Letsie wetland, Lesotho.

Kirsten Schuyt and Luke Brander (2004) have written a useful document entitled ***The Economic Values of the World's Wetlands*** for WWF, https://bit.ly/3X8x7T0.

MAINTAINING WATER QUALITY AS AN ECOSYSTEM SERVICE

In chapter 7 we looked at the water quality requirements of aquatic organisms themselves. Another issue of far greater importance to humans is the beneficial effects that riverine organisms have on water quality. It has been said that once upon a time a drop of water entering many a European river would have passed through the kidneys of several people before reaching the sea (a figure of seven times is often quoted for the River Thames where it runs through London). This was only possible because each time it was used, the water was returned to the river, where the living organisms cleansed it by decomposing the nutrient-rich organic waste it had received. As we know, aquatic organisms, particularly the detritivores and microbes, break down complex organic matter into simpler molecules and ultimately into their constituent parts: carbon dioxide, water and inorganic substances like nitrogen and phosphorus. In this way, aquatic ecosystems provide a free service to human beings. The same processes of decomposition and nutrient recycling, using some of the same species of microbes, are harnessed at great expense in wastewater treatment plants, which are necessary because humans produce more organic waste than natural aquatic ecosystems can cope with. This cleansing process, whether in a stream or lake or in a wastewater treatment plant, is impossible where toxic substances change the chemical nature of the water, killing even those organisms that are hardy enough to withstand gross organic pollution and initiate the cleansing process. Equally, if rivers are altered physically so that organisms cannot live in them, they will act merely as channels for transporting water but will be unable to cleanse it. Thus, careful management of aquatic ecosystems is financially beneficial as well as ethically appropriate.

alexeyfedoren / 123RF

The River Thames, a natural purifier of water if influent pollution loads are not too high.

PAYMENT FOR ECOSYSTEM SERVICES?

One way to reduce or eliminate degradation of natural ecosystems is to pay for them to be left alone. We with our relatively wealthy western approach to life often find it hard to understand why so many ecosystems become degraded. Why, for instance, do They burn thousands of hectares of rain forest, replacing them with subsistence agriculture, when we all know that this is a Bad Thing? Sometimes the answer is simple greed on the behalf of developers. Often, though, the reason is economic on the part of small subsistence farmers. As an example, Mexican forests, estimated to be worth at least US$4 billion a year, are still being obliterated at an alarming rate. To a local ***camposino***, the presence of forest is of no value, while the money coming in from the felling of trees for timber certainly is. If a way could be found to recompense the camposinos, they would be better off that they currently are. What if they were also to be trained as forestry managers, so that some sustainable exploitation of the forest could take place? Obviously if we want to pay a fair wage to the new forestry managers, we need to know the value of the resource that they are not exploiting. So that is but one reason for evaluating the monetary value of ecosystem services. I thank Tony Leiman for additional insights into the point of view of the camposino.

Tony says, "Objectively there are a few problems:

- a) poorly defined property rights (if he owned the forest, he might use it more carefully; but he figures that if he doesn't cut down the trees, somebody else will);
- b) his time horizon is short: is there enough incentive to sustainably harvest a patch of forest rather than mine it – how long do these trees take to grow? The optimal rotation rate for tropical hardwoods it may be over 100 years;
- c) the institutional issue: although the private benefits that he sees may be much less than the social benefits that the forest provides, any payment for those social benefits is unlikely to filter down to the poor bloke who is considering clearing the forest."

The opposite seems to be happening with regard to catchment management in South Africa. Catchment Management Agencies (CMAs) were to be established under the 1998 National Water Act, and two are already in existence (see chapter 10). It seems that while they are currently funded by DWS, the expectation is that CMAs will eventually be self-funded by the sale of water in their areas. This seems to be a brilliant solution to the question of "who pays for the CMAs to exist?" but has a fundamental flaw from an environmental point of view. If a CMA is to be financially sound, it has to sell as much water as possible. This means that during droughts, income will plummet. Worse, though, is that it will not be in the interests of the CMA to reduce consumption and save water, flying in the face of the need to retain as much water as possible in its natural habitat – rivers and wetlands. The fraught story of CMAs in South Africa is picked up again later in this chapter.

OVERVIEW / Wikimedia / CC BY 2.0

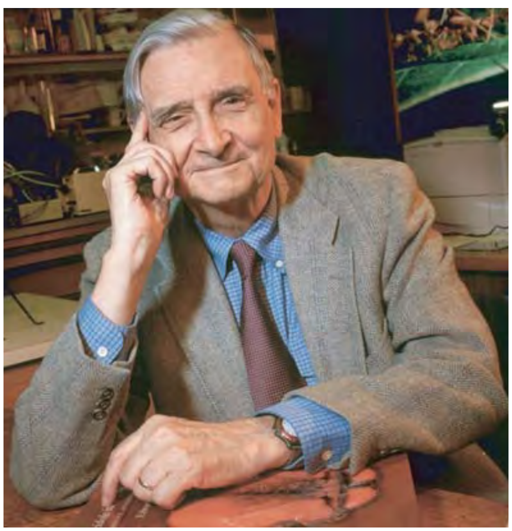
Deforestation in Rondonia, Brazil; swathes are cut into the forest, leaving strips of apparently undamaged trees.

WHY DOES BIODIVERSITY MATTER?

> … loss of genetic and species diversity by the destruction of natural habitats …is the folly our descendants are least likely to forgive us.
>
> *EO Wilson*

Why is there such emphasis on maintaining the Earth's species and ecosystems? After all, the world would probably continue in much the same way as it does with far fewer species than currently exist. The discussion on ecosystem services earlier in this chapter describes the value of biodiverse ecosystems but doesn't explain why we should try to prevent the extinction of every species. The late Ed Wilson, a premier American biodiversity scientist, clearly understood the importance of biodiversity. He said, beautifully,

> This is the assembly of life that took a billion years to evolve. It has eaten the storms – folded them into its genes – and created the world that created us. It holds the world steady.
>
> *EO Wilson 2001*



Jim Harrison / Wikimedia / CC BY 2.5

Ed Wilson, one of the great ecologists of the twentieth century.

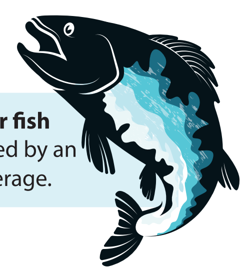
But it took Wilson a couple of books (e.g. ***The future of Life,*** 2001) to explain why. The most fundamental reason, in my opinion, is an ethical one. We as sentient beings should respect the immense beauty and complexity of every life form, regardless of its effect on our own lives. The precept ***if you can't fix it, don't break it*** seems to apply here. Beyond ethics, though, we do need to abide by the precautionary principle. This principle is explained in various verbose definitions but perhaps some trite common sayings do it best: better safe than sorry; first do no harm; if you don't know what you are doing, don't do it. More formally, when an activity may harm human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically. We humans can't (yet) create species, and we certainly can't re-create extinct species, so we should be very careful not to destroy them. Extinction is irreversible.

CONSERVATION OF RIVERS AND WETLANDS

> *... the standard paradox of the twentieth century: our tools are better than we are, and grow better faster than we do. They suffice to crack the atom, to command the tides. But they do not suffice for the oldest task in human history: to live on a piece of land without spoiling it.*
>
> *Aldo Leopold Sand County Almanac, 1949*

Freshwater ecosystems are some of the most threatened and degraded ecosystems on Earth. An IUCN report in 2021 (https://www.iucn.org/news/water/202102/one-third-freshwater-fish-face-extinction-warns-new-report) notes an 83% collapse in populations of freshwater species, the catastrophic decline in populations of large freshwater fish such as catfish by 94%, and the loss of 30% of freshwater ecosystems, all since 1970. In UK waters, the sturgeon and the burbot have vanished, salmon are disappearing, and the European eel remains critically endangered. Although freshwater habitats are said to have more species of animal per square kilometre than dry land or oceans, they are losing species to extinction two or three times faster.

Migratory freshwater fish populations have declined by an estimated **76%** on average.



*Ukraine valued the burbot (*Lota lota*) enough to put its image on a postage stamp.*

Despite these horrendous statistics, freshwater ecosystems worldwide are accorded less protection than their terrestrial and marine counterparts. In the EU, for instance, over the last few years freshwater systems as a whole have received only 3.2% of the total amount of funding set aside for the environment.

David Tickner and numerous colleagues wrote a paper in 2020 calling for an 'emergency recovery plan' for freshwater ecosystems. They identified six priority actions for reversing the trend towards the continual decline in freshwater ecosystems and the species that inhabit them. These actions are accelerating implementation of environmental flows; improving water quality; protecting and restoring critical habitats; managing the exploitation of freshwater ecosystem resources, especially species and riverine aggregates; preventing and controlling invasion by alien species; and safeguarding and restoring river connectivity. Sounds easy when put like that, doesn't it? Unfortunately, the authors are silent on potential sources of funding for these activities in less affluent parts of the world, including almost every single country in Africa.

Conservation science, which incorporates both conservation biology and conservation ecology, studies organisms and ecosystems in order to find ways of maintaining biological diversity and ecosystem integrity or 'health'. The practice of environmental conservation ('nature conservation') uses the data generated by conservation scientists to find ways to protect the environment and the natural resources it provides. On the one hand, the aim is to protect or conserve biodiversity from individual species to whole biomes, and on the other, to include individual humans and organisations as well as government agencies, in the practice of conservation.

Once upon a time, formal Nature Conservation was almost entirely confined to the protection of individual species, usually terrestrial, nearly always big, sometimes hairy, and often cuddly. The idea was to exclude humans from protected areas and even to remove them in order to delineate a nature reserve. People who had lived in equilibrium with wildlife became criminals when they continued to hunt ('poach') their traditional prey. It soon became clear that simply putting a fence around an area and excluding people did not necessarily save the target species. Today things are usually different, however. It is understood that conservation of habitat is key to conserving species as well as the wider environment. Many conservation areas include local communities, who may be involved in managing the area, including granting of hunting licences and bag limits for the locals themselves.

Because natural resources, including land, are often in short supply, a major task of conservation biologists is to decide how much of a certain vegetation type, or geological formation, exists, and what proportion of this needs to be protected if the biodiversity of the area is to be maintained in perpetuity. They will take into account issues like connectivity across migration routes, or requirements for pollination, and then set up targets for conservation, such as 10% or X hectares of a particular landform or vegetation type. In short, they set minimum, quantitative requirements ('targets') for biodiversity conservation, these values usually being based on scientific best judgement. Of course when once the targets have been agreed upon, the next trick has to be to "sell" these suggested target values to the landowner, who may be a private individual but is usually a provincial or national government.

A good example of a really successful exercise in formal conservation planning concerns the CAPE programme. The Cape Floristic Realm (CFR), which is situated entirely in the southernmost parts of South Africa, is the smallest and most biodiverse of the World's six floral kingdoms. According to SANBI, "CAPE is a 20-year partnership of government and civil society aimed at conserving and restoring the biodiversity of the CFR and the adjacent marine environment, while delivering significant benefits to the people of the region." It started with very generous funding from the Global Environmental Facility, a division of the World Bank, and has since been funded by a variety of donors. Crucially, from a biodiversity point of view, the CAPE programme resulted in the formal establishment of three megareserves: CapeNature's Cederberg Wilderness Area, the Cape Agulhas National Park and the Baviaanskloof cluster of formal protected areas, as well as a number of smaller Biosphere Reserves. (https://bit.ly/40B31KQ and https://bit.ly/3l5yLXY)

We've all heard,
"There is no Planet B"
So what do you plan on doing
When we lose Planet A?"

Kate Day

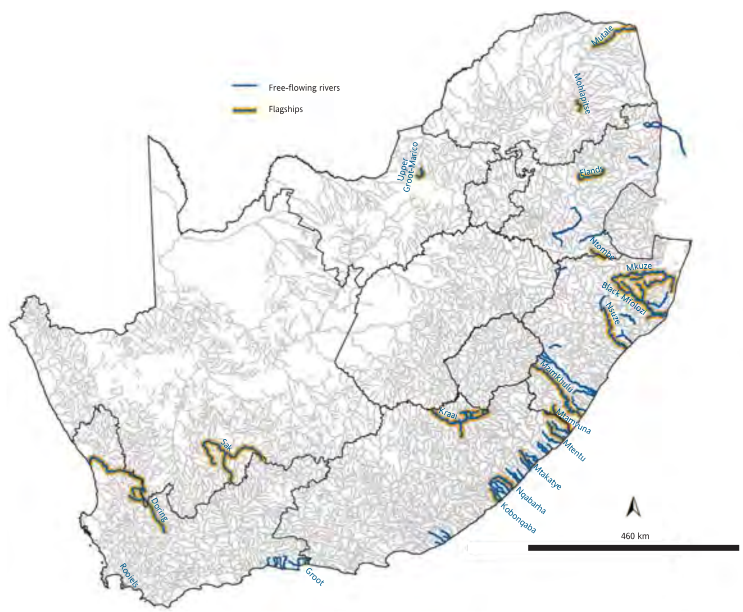
The three mega-reserves created as a result of the CAPE project include rivers: A) The Rondegat River in the Cederberg; B) the Kouga River in the Baviaanskloof; and C) wetlands: Soetendalsvlei on the Agulhas Plain.

You may be wondering why no aquatic ecosystems were mentioned in the discussion of the CAPE programme. The answer is, because aquatic ecosystems are not mentioned in the CAPE landscapes initiative. Diekie van Nieuwenhuizen and other members of the Freshwater Research Unit (now defunct) at UCT produced some really useful material that contributed to the decisions as to where the megareserves should be located, but the decision was made (as it so often is) that rivers and wetlands could be accommodated within the megareserves to be demarcated and did not need to be named specifically. In a way this is true, but it does not explain why important aquatic ecosystems were not specified. It is because the integration of freshwater biodiversity priorities in systematic conservation planning is a major challenge, as noted by Mao Amis and colleagues (Amis 2009) in a paper on this very point. Maintaining upstream–downstream connectivity and the influence of catchments on freshwater ecosystem integrity are some of the issues that make it difficult to reconcile terrestrial and freshwater conservation planning. (In short, rivers are long and thin, may stretch for long distances, and may flow through very degraded areas.) As a result, most conservation assessments are biased towards terrestrial systems without adequate incorporation of information on rivers and wetlands.

As we mention elsewhere in this book, there is little formal and legal protection for individual rivers, wetlands or estuaries in South Africa. As a result, SANBI, together with the WRC and a number of other South African organisations, produced a series of maps of National Freshwater Ecosystem Priority Areas – NFEPAs. The data for these maps, which are available at https://www.fosaf.org.za/documents/SANBI/fish-priority-areas.pdf, were identified through a process of systematic biodiversity planning based on a range of criteria:

- representative river, wetland and estuary ecosystem types
- representative free-flowing rivers (of which there are exceedingly few)
- water supply areas with high water yield and high groundwater recharge;
- connected systems;
- threatened fish species and associated migration corridors.

WRC archives



South Africa's last remaining free-flowing (blue) and flagship (yellow) rivers.

FEPAs were identified if they overlapped with any free-flowing river, or priority estuaries identified in the National Biodiversity Assessment 2011, or Department of Environmental Affairs' focus areas for expansion of protected areas. River and wetland condition was assessed on the basis of various DWAF databases as well as expert knowledge and natural land-cover data, the presence of wetland clusters, and known hotspots for fish conservation. While many of these FEPAs have still not been ground-truthed, they represent an enormous amount of work and are a valuable step in our understanding of the conservation status of our freshwater ecosystems. They are widely used in environmental impact assessments and also as tools for expanding and consolidating South

Africa's protected area network. A simplified document on the entire project can be found at http://biodiversityadvisor.sanbi.org/wp-content/uploads/2016/07/NFEPA-Presentation-for-Policy-Audience-2011.pdf .

CASE STUDIES ON SOUTH AFRICAN RIVERS

Below are two case studies on South African rivers chosen because they illustrate important aspects of the management and conservation of rivers in South Africa.

PALMIET RIVER

The Palmiet River is a typical Western Cape blackwater river, experiencing winter rainfall and summer drought. Its mainstem is 74 km long and its catchment area about 500 km^2 in extent. In its middle reaches it flows through deciduous fruit orchards and in its lower reaches it is part of the Kogelberg Biosphere Reserve. Its estuary is small and sandy and closes temporarily in some years. The river has five dams along its length, three providing water for agricultural and urban use, and two being linked to form a small hydropower-producing pumped-storage scheme, which also delivers some water to the City of Cape Town. Famously, during the intense drought of 2017-2018, farmers of the Groenland Irrigation Board donated 16 million m^3 of their water, which they would otherwise have used for irrigating, to the City, thus helping to avert Day Zero. Who knows – it may have been just that amount of water that prevented the dreaded day from dawning. This example of ***ubuntu*** is not adequately advertised. The lower reaches of the river flow through the Kogelberg Biosphere Reserve. It is the floristic heart of the CFR, hosting approximately 1 600 plant species, 150 of which are endemic to the area and characteristic of the Fynbos biome. All in all, this is a special place on the Earth's surface. The Palmiet River is also discussed on pages 352-354.

The Palmiet River was the subject of the first major confrontation between environmental and engineering interests in South Africa. The late 1970s saw the first stirrings of 'green' attitudes. The proposal by the Department of Water Affairs (DWA) to construct a major dam on the river, virtually within sight of the estuary, and in the very heart of the Kogelberg, caused a rumpus. It was at about the time that Paul Roberts of DWA had first mooted the idea that it might be worth considering providing a small amount of water (11% of virgin flow) for 'nature conservation' because a recent drought had had severe consequences for the Kruger National Park, and because it was becoming clear that estuaries required at least some river water flowing into them to prevent them from closing (and lots of people like fishing in estuaries). So, a Palmiet River Ministerial Advisory Committee was set up by DWA, and a variety of stakeholders invited to a number of meetings. To cut a very long story short, the decision was made to allow the construction of the pumped-storage scheme, which had already been on the cards, but to shelve the idea of the massive dam. In hindsight, this was a remarkable decision, given that the dam would have taken care of Cape Town's water supply problems for decades. Although the idea has not disappeared completely, it seems to me that the river may be safe for a long time before another large dam is proposed. The niggling feeling at the back of my mind, though, is – as always with these matters – that while environmentalists have to keep fighting the same battles over and over with each new generation of developers, the developers only have to win once, and the river will have been lost forever, or at least until at some future date the dam is demolished.

The Palmiet River should have pride of place in conservation circles because the threat of the development of its water caused the first major outcry by environmentalists, and resulted in the first official concern on the part of DWAF in relation to a specific environmental issue. The subsequent meetings brought together hardened foes in the form of ecologists and conservationists on the one hand, and engineers and planners on the other. The initial contacts were uncomfortable for everyone concerned but negotiation and listening to other peoples' points of view taught us all some salutary lessons. DWA, as well as the CSIR, organised a number of workshops to thrash out the water requirements for a number of rivers for which dams had been planned. In good workshop style, these were held out of town so participants were more or less forced to get together socially after hours. (There were no cellphones then.) After a few beers had been drunk, implacable foes became friendly and eventually began to trust each other. Engineers and planners on the one hand, and environmentalists and ecologists on the other, will probably always have different points of view, but at least we now all acknowledge that the other's point of view might be valid. The environment can only benefit from these remarkably changed attitudes. In fact, the South African approach to water management was the envy of water managers and ecologists in the rest of the world for many years. Not only that, but it was this relationship of trust that allowed the remarkable new National Water Act to be developed in the late 1990s (see chapter 10).


Abu Shawka / Wikimedia / CC0 1.0

The Kogelberg Biosphere Reserve.

THE BERG RIVER

The Berg River, which rises in the same mountains as the Palmiet, is considerably bigger. It flows northward for a distance of nearly 300 km before turning westward to its estuary and the coast. The catchment is 7 715 km² in area. The upper reaches are very mountainous but land in its middle reaches is mainly used for cultivation of grapes and deciduous fruits. Dryland grain and sheep farming predominate in the drier areas further downstream. Six dams occur on the main stem but only a single tributary, the Twenty-four Rivers, remains more or less undisturbed.

Way back in the 1950s, the late Arthur Harrison and colleagues wrote a series of seminal papers on the Berg River, its biology and the degree of pollution to which it was subjected, even in those days. The main paper (Harrison & Elsworth 1958) was one of the first anywhere in the world to provide a detailed description of a river – in those days, 'limnology' was largely about lakes, and rivers got very little attention from limnologists. The indignities suffered by the Berg River include salinisation from irrigation return flows; nutrient enrichment from agricultural runoff; return flows from wastewater treatment plants; effluents from industries and wine farms; effluents from trout farms; invasion by alien aquatic and riparian organisms; and development on the banks of informal settlements, with their attendant problems of pollution. On top of all of this (and in fact designed to mitigate against these effects), an IBT in the upper reaches brought water from various other sources into the upper reaches of the river in summer.

Jenny Day

The Berg River before damming.

Daniel Saaiman / Wikimedia / CC BY-SA 4.0

The Berg River Dam from the air.

Proposals for a dam on the Berg River go back to the 1960s but detailed environmental and social impact studies, and public participation processes, were undertaken during 1996 and 1997, building on the South African experience in planning for water-resource developments. The project was given the go-ahead by the Department of Environmental Affairs and Tourism in 1999 and in April 2002, the Cabinet approved the construction of a 68 m-high dam on condition that the City of Cape Town instituted significant water-demand management. The City complied. Construction began in July 2004 and the dam was closed in July 2007. It filled a year ahead of expectation, because 2007 was a very rainy year.

The Berg River Dam was the first dam in South Africa, and probably one of the first in the world, to be designed, constructed, and operated in accordance with the guidelines of the World Commission on Dams (WCD). Looking at the dates involved, however, we can see that the design was completed ***before*** that Commission presented its report in 2000. The experience of designing the Berg River Dam thus influenced the work of the Commission, rather than the other way around. It is worthwhile pausing to consider the WCD, which was instituted by the World Bank, but entirely independent of that organisation. The WCD was instituted in 1997, specifically to produce guidelines for the design and operation of large dams. The South African influence is obvious. Prof Kader Asmal, then Minister for Water Affairs, chaired the commission and the final report was presented by Nelson Mandela. It is heart-warming to think that the early tussles at the Palmiet River Ministerial Advisory Committee in the late 1970s (see above), and the experiences of DWA and ecologists in attempting to understand the water requirements of rivers, had such far-reaching consequences: involvement in the writing of the National Water Act in 1998 (see page 410), and subsequently the elevation of our Minister to the Chair of the WCD.

Back to the Berg River Dam: it was completed on time and within budget (R1.5 billion). It is of great significance in the region. The Berg River basin generates only about 3% of the country's water resources but it produces about 12% of the Western Cape Province's regional domestic product, mostly in the form of wine grapes and deciduous fruits. Moreover, the outlet works of the dam have been designed for a peak release of an enormous discharge of 200 m^3 per second, simulating a 1:2-year flood. The dam is the first in South Africa where provision has been made for realistic flood releases for environmental purposes and is all the more remarkable because constructing outlet works adequate for releasing this huge discharge increased the cost of the dam by >R16 million and the cost in 2007 of releasing water equivalent to a single 1:2-year flood was about R2 million.

Is there a fly in this soothing ointment? Unfortunately, there is: inadequate implementation of the operating rules for this, and very many other, dams in the country. The operator of each dam where discharges can be controlled (i.e. those with sluice-gates that allow water to be released from the dam) are provided with a set of 'operating rules', which tell the operator when to, and how much, water to be released every day, every week or every season. These rules are not always well thought out and even if they are, the operators often do not abide by them. It seems ludicrous that enormous amounts of money and effort are spent in designing and building the most environmentally friendly dams possible, only to have their discharges inadequately managed. An image of the dam discharging 200 cumecs appears on page 357.

CONSERVATION OF TEMPORARY WETLANDS

Basins holding temporary waters are often small, usually endorheic, and may lack significant vegetal cover. For these reasons, most are probably not significantly able to do any of those things that appeal to humans as the 'functions' or 'roles' of wetlands in the landscape. Thus, they are unlikely to be able to purify water to any useful extent, or to diminish the force of floods. And relative to larger, permanent wetlands, temporary waters are not particularly rich in species. As a result, in much of the world, and certainly in southern Africa, they are probably the most neglected and threatened of all ecosystems, terrestrial or aquatic. On the other hand, they certainly store water, even if only for a short time. This is of major significance, particularly in arid regions, because the stored water may attract vast numbers of birds and other vertebrates, often from great distances away. The migrations of birds such as flamingoes and pelicans along the south-western coast of southern Africa, from Cape Town to southern Angola, is dictated by the availability of water in temporary pans like Etosha Pan, while the great pans of the Northern Cape support tens of thousands of ducks and waders during infrequent periods of inundation. Temporary waters of all sizes are also used as sources of drinking water by wild game and stock animals alike, as well as being crucibles of biodiversity of the small and unusual.

Jenny Day

The enormous Makgadikgadi Pan from the air. The blue area in the middle of the image is water, which is not often seen in the pan.

The conservation status of temporary wetlands in southern Africa varies from good to non-existent. A few of the larger pans, like Etosha Pan in Namibia and small sections of the Makgadikgadi pan system in Botswana, are protected in national parks, as are numerous small ones in the south of the Hwange National Park in Zimbabwe and in the Namib Naukluft National Park (which includes Sossusvlei) in Namibia. In South Africa, Barbers Pan is specifically protected as a provincial nature reserve. (These days, Barbers Pan dries out infrequently, apparently because Jan Smuts arranged for the diversion of the Harts River to ensure that the pan always had water in it.) The new Meerkat National Park in the Karoo also includes a few pans, and smaller ones in the extreme north-west of the province fall within the Kalahari-Gemsbok National Park. Many of the smaller pans in the Free State are on privately owned farms and some are relatively intact. A couple of the larger ones are mined for salt, ploughed, and used to grow crops, or otherwise modified.

The systems under greatest threat are those in and around towns and cities. In the environs of Cape Town, for instance, much of the southern suburbs covers an area of uncertain drainage. It must once have been covered by small depressions that filled in winter because the names of so many of the old erven (plots) end in 'vlei': for example, Bamboesvlei, Varkvlei, Rietvlei, Tumbleweed Vlei, Swartvlei and Groenvlei. Of particular concern is the fact that virtually all of these small systems have now disappeared. Only remnants still exist and there is little reason to hope that they will be conserved. Some years ago, a developer 'moved' (i.e. destroyed) Blouvlei, one of the last remaining temporary wetlands of any size, replacing it by new ***perennial*** wetlands created at Century City. That was the end of the aquatic fauna of one of the last remaining temporary wetlands on the Cape Flats. Habitat loss is by no means confined to the south-western Cape, however: several anostracan localities in the Gauteng, Mpumalanga, North West, Eastern Cape and KwaZulu-Natal are known also to have been destroyed.

Ironically, temporary wetlands are threatened even by well-meaning but ill-informed planners and managers who consider that permanent waters are somehow 'better' than temporary ones. Not far north of Cape Town, for instance, plans were made to mine a thick deposit of gypsum underlying a seasonal salt pan. The mining company, which was relatively 'green', commissioned an environmental impact assessment. Its executives were surprised that wetland ecologists resisted the suggestion that the pan be deepened to form a permanent, rather than a seasonal, pan. They were quite unaware that an entirely different suite of organisms would become established there, or that the endangered temporary-pool fauna would have one less place in which to live.

Some years ago, Koen Martens and Ferdie de Moor, two colleagues of ours, wrote a short paper for the ***South African Journal of Science,*** describing a very similar situation. A bird hide was erected near a temporary pool at a nature reserve near Grahamstown. To encourage birds to visit throughout the year, the pool was made permanent. As should have become clear from what we have said above, the temporary pool fauna, including a new species of fairy shrimp, were completely eliminated because most temporary pool animals simply cannot survive in permanent systems. It may well be that ***Rhinobranchipus martensi*** became extinct even before it was described as a new species. That's a real shame.

Andresdewet / Wikimedia / CC BY-SA 3.0

A canal development in Cape Town. The canals and perennial wetlands are entirely different from Blouvlei, the temporary wetland that they were designed to replace.

FORMAL CONSERVATION OF SOUTH AFRICA'S ESTUARIES

Formal conservation is no better for estuaries than for rivers and wetlands. While the Groenrivier Estuary is protected as part of the newly formed (2019) Namaqua National Park Marine Protected Area (MPA) and the mouth of the Thukela River as part of the uThukela Banks MPA, estuary-specific protected areas do not exist in South Africa.

As Alan Whitfield points out in his book on estuarine fish communities (see reading list), the concept of Marine Protected Areas (MPAs) is very well established in South Africa. The objectives of MPAs are to protect spawning fish stocks; to enhance recruitment of fish species to surrounding depleted areas; to conserve biodiversity; to act as an 'insurance' against the failure of other stock management techniques; and to simplify policing and law enforcement, amongst others. Yet there are no 'Estuarine Protected Areas'. Given our extensive knowledge of the nursery role of estuaries in terms of coastal and riverine fish stocks, and of the maintenance of the biological diversity of entire estuarine biotic communities, it is astonishing that our estuaries are not provided with the kind of protection seen in MPAs. No doubt the same argument is used here as for rivers and wetlands: if the general area around an estuary has been declared an NPA, there will be adequate protection and no specific action needs to be taken for the estuary itself. That is a specious argument, as it is for conservation of rivers and wetlands.

chrisvanlennephoto / 123rf

The mouth of the Thukela River between Durban and Richard's Bay.

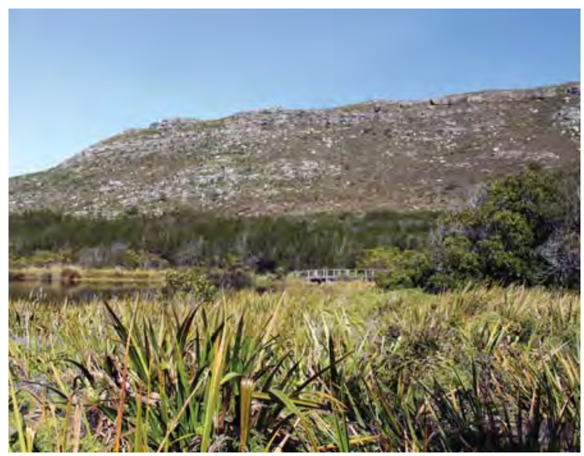
RESTORATION, REHABILITATION, REWILDING, RE-CREATION …

Another aspect of ecosystem conservation concerns the restoration of damaged and degraded systems, returning them to some previous, closer-to-natural condition. In some cases, the intention is to do no more than re-establish ecosystem functions, in others to improve recreational facilities or aesthetic appeal, and in others to re-create a system as close to the original as possible. In yet other cases, entirely new systems, usually wetlands, are constructed for a variety of purposes. Here is a brief discussion on some of the kinds of restoration projects that are undertaken. As is often the case, scientists take common words and give them more precise meanings than we are used to. What is more, not everyone working in the field agrees with the definitions, so be aware that the descriptions below will certainly be challenged by some people. Generally, in the following discussion the term 'wetland' is used in the wider sense to include rivers.

The US EPA defines wetland **restoration** as " … the manipulation of a former or degraded wetland's physical, chemical, or biological characteristics to return its natural functions." Restoration includes "… **re-establishment**, the rebuilding a former wetland; and **rehabilitation**, repairing the functions of a degraded wetland" (US EPA, 2007). Most writers tend to use the word "restoration" to mean returning a river or wetland to a condition as close as possible to the way it was before human interference (which obviously requires a good understanding of what that condition was). The implication is that a restored river or wetland will regain its original functioning. For more information on rehabilitation of rivers in South Africa, see the WRC-funded document on river rehabiltation by Liz Day and colleagues (see reading list).

Rewilding is a relatively new term that implies re-establishment of ***some*** biodiversity and ecosystem functioning that may be quite different from that which was originally present. In contrast to restoration, rewilding is less concerned with re-establishing taxa that were once present and more concerned with restoration (there is that word again) of ecological functions. Rewilding is commonly undertaken by citizen action groups rather than ecosystem managers and for this and other reasons is often somewhat controversial: the managers feel that the actions are not 'scientifically' sound, while the would-be restorers often feel that nothing will be done to improve a clearly damaged wetland or river unless they do it themselves. The estuary of the Silvermine River near Fish Hoek provides a good example of managers and locals working together. It seems that the mouth area was wide and sandy with a sinuous, braided stream that moved along the shoreline depending on the amount of rainfall and wind-blown sand. For years, as a result of an entirely inadequate road bridge built acros the river very close to the sea, the estuary was no more than a reed-choked channel. It is currently being rewilded. See link to an article by Kim Kruyshaar in the list of websites at the end of this chapter. One can see why this development might be controversial. In the minds of purists, the current system is nothing like the original; in the minds of local enthusiasts it is a huge improvement on the reed beds of the recent past, and even on the original condition, which was a wind-blown stretch of sand.

greenaudits.co.za



flowcomm / Flickr / CC BY 2.0

An aerial view of the Silvermine estuary in 1940 (left) and the Silvermine river and estuary today (right).

Establishment – creation of entirely new wetlands – is a common practice in many parts of the world, and for several reasons. Apart from rice paddies, probably the greatest surface area of artificial wetlands is given over to wetlands constructed for water treatment. 'Constructed' or 'treatment' wetlands are widely used for treatment of raw or partially treated sewage and other waste effluents. They are designed specifically for the purpose of improving water quality, so biodiversity and aesthetic appeal are not important aspects of their construction. In contrast, in some parts of the world wetlands are created as replacements for wetlands lost to other human activities such as urban development. This "no net loss" principle (see page 182) requires that the newly created wetlands provide the same functions and services as those that have been destroyed. As we have mentioned, many wetland taxa are not particularly 'fussy' about the origin of the system in which they live as long as environmental conditions are suitable for survival, so the new wetlands often perform the job that they were created for – for instance as habitat for ducks in parts of the USA where duck hunters may even fund their creation.

In all restoration work – indeed in management of all aquatic ecosystems – the fundamental question that has to be asked is, "What do we want to manage ***for***? What do we want the system to be like (when we have finished manipulating it)? If these questions are carefully considered, then different degrees of rehabilitation will be suitable for different systems.

CONSERVATION OF FRESHWATER TAXA

While the trend today is to conserve ecosystems with their inhabitants, rather than the inhabitants themselves, there are cases where conservation of taxa becomes important. Once again, the south-western Cape provides a good illustration of what we mean. The terrestrial landscape in the region is very ancient, having existed as dry land for probably 400 million years or more. The landscape is also deeply dissected, with high mountains and small rivers running in steep valleys. The headwaters of the rivers have probably been separated from each other for many millions of years, so the populations of animals, from fish to amphipods and crabs, have led isolated existences in all this time. Not surprisingly, then, there is a great deal of cryptic genetic diversity in many of these groups. What do we mean by 'cryptic genetic diversity'? Well, often the species within a group (take amphipods as an example) are almost inseparable morphologically (i.e. to look at) but are genetically very distinct. So while a casual glance might suggest that there may be half a dozen species of the amphipod family Paramelitidae in our streams, genetic studies show that there are at least 26 species in three genera. And it is also not surprising that many of them are confined to extremely narrow ranges – often a single reach of a single mountain stream.

Similar findings have been made for virtually every aquatic group of western Cape animals that has been examined genetically. These include crabs, isopods, net-winged midges, stoneflies, dragonflies and fishes. In each case, the group is much more genetically diverse than would appear from a superficial examination of its morphology, and in almost all cases the genetically separate groups have very distinct and narrow distribution ranges, usually being confined to the rivers of a single catchment.

The Buffalo River in the Eastern Cape offers a different perspective: the remarkable number of species of a single taxon in a single river. Rob Palmer, then at Rhodes University, studied the blackflies (Simuliidae) of the Buffalo River, recording a total of 20 species. Five are widespread, two are confined to torrents, six occur in the foothill-stony-run zone of the middle reaches of the river, and seven are rare. In each case, the structure of the feeding fans (these species are filter-feeders in fast-flowing water: see page 218) is adapted to the specific habitat conditions in which the species was recorded. Rob's work adds further support to the concerns about declining species richness: it is, or was, high in many rivers of South Africa, and it may already be too late to get a good idea of the original degree of biodiversity in rivers subject to anthropogenic stresses.

A similar situation is found in the fishes of the region. Relative to other comparable parts of the world, the South African freshwater fish fauna as a whole consists of rather few species – 106 valid species and eighteen genetic lineages, according to fish expert Albert Chakona and colleagues from the South African Institute for Aquatic Biodiversity (SAIAB) in Makhanda. Chakona ***et al*** (2022) recently carried out an assessment of the extinction risk of each species, concluding that " … 45 (36%) of South Africa's freshwater fish taxa are threatened (7 Critically Endangered, 25 Endangered, 13 Vulnerable). Of the remaining taxa, 17 (14%) are listed as Near Threatened, 57 (46%) are Least Concern and five (4%) are Data Deficient. More than 60% of the endemic taxa are threatened".

In the 1998 edition of this book we suggested that there were about 22 species of freshwater fishes in the CFR. Today we have about 26 valid species and 15 genetic lineages ('candidate species' waiting to be described). Of course, this is not because a whole lot of new species had magically evolved, but because genetic studies showed up sibling species that look very similar but are genetically distinct. It is horrific that two-thirds of the 26 species that have already been described are threatened with extinction.

Jeremy Shelton

The near-threatened Clanwilliam sawfin, Pseudobarbus serra, *found only in a few tributaries of the upper Olifants River in the Western Cape.*

Jeremy Shelton

The endangered giant redfin, Pseudobarbus skeltoni, *found in only three localities in the Breede River system.*

For an excellent account of the fish fauna of the region the reader is referred to the chapter by Dean Impson and colleagues in CapeNature's ***State of Biodiversity Report 2017*** (see reading list: the entire report is a source of excellent information on the province's biodiversity). In summary, the fishes of the CFR represent a huge and fragile pocket of biodiversity that requires particular care. This is a difficult challenge, however, because the four horsemen of the freshwater apocalypse – habitat destruction, alien species, pollution and water abstraction – are strong and difficult to vanquish.

It is not only the small and fragile that are threatened by these four horsemen. Historically, the **larger aquatic vertebrates** of South African rivers, particularly crocodiles (***Crocodylus niloticus***) and hippos (***Hippopotamus amphibius***), were relatively widespread. From the journals of early European travellers, we know that hippos once thrived throughout South Africa, wherever suitable habitat occurred, even as far west as Verlorenvlei. (Indeed, not only hippos were abundant in that system: rhinoceros, elephant, lion and a variety of grazing and browsing antelope were common too.). Crocodiles occurred as far south as East London. Simply because of their size, and the amount of biomass tied up in them, we can assume that these species are important components of aquatic ecosystems. Our knowledge of this aspect of their biology is poor, though.

Dalton Gibbs

Two of the resident hippos in Rondevlei in Cape Town.

Hippos in the perennial rivers of the Kruger National Park have been recorded at densities of 2-8 animals per kilometre of river length. Since these very large animals graze on land, but spend most of the day in water, they import allochthonous organic material to the aquatic environment because, although they spray their dung over vegetation, they do so near water. (As the Kikuyu folk tale goes, they spray their dung in this way so that the Good Lord N'gai, the creator of all creatures, can ensure that they are not eating fish because if they were, fish bones would appear in their dung. Why they may not eat fish is not explained.) Their large bulk, and their propensity for wallowing, play a role in maintaining pools and channels in rivers and wetlands. In the Okavango, for instance, much water is channelled through hippo paths. Indeed, hippos seem to be major forces determining the nature of the aquatic systems in which they live. For instance, rivers that have lost their hippos may also have lost many of the pools in which fish and invertebrates would thrive. It is a pity that we have so little real information on these gigantic animals and the effects that they have on their environments.

Densities of between 1 and 11 crocodiles per kilometre of river length – a considerable population – have been recorded in the perennial rivers of the Kruger National Park. This large vertebrate is another that should be studied (with great caution) not least because crocodiles, too, redistribute organic material and nutrients, albeit of animal origin. The proportion of organic material and nutrients moved around by hippos and crocodiles must be particularly significant in small, isolated wetlands and floodplain pans. One assumes, then, that the dynamics of nutrient cycling must be noticeably different in those systems that have lost their large vertebrates.

In 2008, large numbers of crocodiles and sharptooth catfish (***Clarias gariepinus)*** in the Olifants Gorge of the Kruger National Park died from a strange disease called pansteatitis. (A small Indian crocodile, the endangered gharial, has also been affected in Sri Lanka.) Until recently the cause of this disease, which is also known to affect cats, dogs and fish, was entirely unknown. The main symptom is a hardening and yellowing of the fatty tissue, resulting in the affected animals becoming stiffened and unable to move properly, eventually dying of starvation. A recent investigation into the disease in cats suggests that the cause may be infection by a bacterium of the genus ***Mycobacterium,*** but this seems not to be the case with the Kruger National Park crocs.

A remarkable team of veterinarians, toxicologists, conservators and biologists investigated the outbreak of pansteatitis in Kruger National Park and seem to have come up with the answer, which had puzzled vets for years. After investigating all sorts of potential causes, the team thinks that the best explanation so far is accumulation of excess quantities of unsaturated fatty acids. This upsets fatty-acid metabolism, resulting in the production of fats with very high melting points. And what caused this? The culprit seems to be the silver carp, ***Hypophthalmichthys molitrix***, a phytoplankton feeder that contains large quantities of PUFAs**.** Native to China, the silver carp was intentionally introduced into Lake Massingir in Mozambique to form the basis of a fishery. The wall of the dam forming Lake Massingir was raised in 2007, however, causing water to back up into the Olifants Gorge and bringing the carp with it. The carp form dense mating shoals, which are fed upon by both catfish and crocs. There we have it: another of the apocalyptic horsemen rides again! This fascinating story is detailed in
http://www.saeon.ac.za/enewsleter-archives/2014/february2014/doc02

David Huchzermeyer

A crocodile that died of pansteatitis in the Kruger National Park.

PRACTICAL AQUATIC ECOSYSTEM CONSERVATION IN SOUTH AFRICA

If we are to understand the possibilities and realities of conserving wetlands and rivers, we need to look at the relevant legislation: the National Water Act, and the National Environmental Management Act and its subsidiaries.

THE NATIONAL WATER ACT

We have already looked in some detail at the provisions of the NWA (chapter 10). When it was promulgated, aquatic ecologists were excited about the fact that rivers, wetlands and estuaries would be afforded significant protection. In fact, a careful reading of the Act shows that aquatic ecosystems are protected only with regard to sustainability for provision of water for human use, and nothing else. This was something of a blow but other legislation soon followed that ***is*** designed to protect aquatic ecosystems – sort of.

THE NATIONAL ENVIRONMENT MANAGEMENT ACT (NEMA) AND ITS SUBSIDIARIES

The Constitution of the Republic of South Africa (1996) sets out the right to an environment that is not harmful to health or wellbeing and calls on the government to take legislative and other actions to prevent pollution and ecological degradation; to promote conservation; to secure ecologically sustainable development; and to use natural resources while promoting justifiable economic and social development.

The **National Environmental Management Act** no. 107 of 1998 (NEMA) has various subsidiary Acts, two of which are of interest to us here. The first is NEM:BA (the National Environmental Management: **Biodiversity** Act No. 10 of 2004) and the second is NEM:PAA (the National Environmental Management**: Protected Areas** Act No. 57 of 2003). The first provides for "the protection of species and ecosystems that warrant protection" and deals also with alien species as threats to (native) biodiversity. The second provides for a national framework for the declaration and management of protected areas, as well as giving effect to the government's commitments to international agreements such as the Convention on Biological Diversity (CBD) and the Ramsar Convention.

The Ramsar Convention

The Ramsar Convention on Wetlands of International Importance Especially as Waterfowl Habitat is an international treaty for the conservation and sustainable use of wetlands. It is also known as the Convention on Wetlands. It is named after the city of Ramsar in Iran, where the convention was signed in 1971. It is the only international treaty that focuses specifically on wetlands. See details in Chapter 5.

What do these pieces of legislation actually do to protect rivers and wetlands? In essence, any aquatic ecosystems within protected areas (National or Provincial Nature Reserves or Parks, for instance) are protected from development, but others are not, unless they fall under the 1984 **Conservation of Agricultural Resources Act** (CARA: Act 43 of 1983). Weirdly, this is the only blanket legislation protecting wetlands from damage or obliteration, and it applies only to those on agricultural land. While landowners are charged by NEMA with "duty of care", requiring that they "must take reasonable measures to prevent, minimise and rectify environmental degradation on their properties", rivers and wetlands are not specifically mentioned. In other words, if a wetland doesn't fall under CARA or NEM:PAA, it is not protected by law. One of the major reasons for the development of the NFEPA maps (see page 430) was to highlight those that need to be protected against development or other forms of degradation in the light of the lack of appropriate legislation. (Note that the water itself is protected under the NWA).

If a river or wetland does fall within an area covered by current legislation, **the Green Scorpions** can be contacted and asked to investigate violations of the law. The Green Scorpions, who are members of the Department of Environmental Affairs' Environmental Management Inspectorate, are government officials from national, provincial and local government, including Parks authorities, who are responsible for compliance and enforcement activities with environmental legislation. A recent example concerned sewage spills into Zeekoevlei as a result of overflows from the City's sewers. When the sewage had not been satisfactorily been dealt with by the City's Sanitation Branch, the Provincial Green Scorpions were called in and provided the City with what is called a "pre-directive" requiring certain mitigatory actions to be taken by the City.

In the Western Cape you can contact the Green Scorpions online at Law.enforcement@westerncape.gov.za and throughout South Africa you can call the Environment Agency incident hotline on 0800 80 70 60 (24-hour service).

One other useful piece of legislation, the **Mountain Catchment Areas Act** 63 of 1970, provides for "the conservation, use, management and control of land situated in mountain catchment areas". It was essentially designed to protect what are today called 'Strategic Water Source Areas', although water is not specifically mentioned in the Act. It seems that this Act has become redundant, although it is still on the books. Presumably the Department of Environmental Affairs considers that other more recent legislation covers the same ground.

The Convention on Biological Diversity
The Convention on Biological Diversity, known informally as the CBD or the Biodiversity Convention, has three main goals: the conservation of biological diversity; the sustainable use of its components; and the fair and equitable sharing of benefits arising from genetic resources. South Africa's most recent report (2014) can be found at https://bit.ly/3HwNXoland a description of the Convention at http://bit.ly/3JM3pA1

IMPLEMENTATION OF THE NATIONAL WATER ACT

An outline of relevant sections of the NWA can be found in chapter 10. Here we look briefly at the way 'reserve determination' is assessed and implemented in South Africa. A more detailed treatment can be found at DWS (2017).

When water is to be abstracted from a river, whether by pipeline or by damming, a decision has to be made as to how much water can be removed, and when during the annual hydrological cycle this should take place. DWS calls the water remaining in the river "The Ecological Reserve" or just "The Reserve", and it is this that is calculated during DWS's "Reserve-determination" studies. Let us take as an example the assessment of the Reserve for a river that is about to be dammed. Firstly, the Management Class needs to be ascertained – is the river in 'good', 'fair', 'poor' or 'unacceptable' condition? This will determine the condition to be aimed for when the river has been dammed. Usually a number of scenarios are identified and a major aim of the entire procedure is to decide which scenario will be the best compromise between water for abstraction and water for the river, remembering that ***at the very minumum*** the river must remain in a sustainable condition (whatever that means!).

Using standard methods, aspects of the following are calculated or otherwise assessed:

- hydrology & hydraulics (quantity and timing of water required for each scenario)
- relationship between discharge and water chemistry / water quality
- relationship between discharge and geomorphology (habitat availability)
- relationship between discharge and vegetation (mostly riparian vegetation)
- relationship between discharge and the biota (usually fish and invertebrates).

In other words, the idea is to estimate the quantity, quality and timing of water (i.e. 'the Reserve') that will be adequate for maintaining habitat (depth & area), supporting the biota (including riparian vegetation) and sustaining human riparian dwellers. Various scenarios are examined, and a final decision made on the amount, timing and quality of the Reserve that will best provide the desired state of the future river. DWS officials then calculate the amount of water already allocated to users, grant new licenses if there is any 'spare' water (i.e. over and above the amount already allocated plus the Reserve) and prepare operating rules for the timing and quantities of water to be released from the new dam. Theoretically a monitoring system is then put in place to follow the effects of the reserve allocation both to ensure that the allocation is doing what the experts thought it would do, and to provide data for future reserve allocations elsewhere. (See a discussion on the River Health Programme on page 447 below.)

Dana Grobler

Surveying a river as part of an e-flows assessment.

South African aquatic scientists have been at the forefront of developing methods for calculating e-Flows (Environmental Water Allocations) for rivers. One of the first, developed primarily by Jackie King of the Freshwater Research Unit at UCT, is known as the Building Block Methodology (King et al 1998). More recently, the world-acclaimed method ingeniously called DRIFT (Downstream Response to Imposed Flow Transformations) has been used in numerous IFR assessments of rivers. I quote from the DRIFT website (https://www.drift-eflows.com/about-drift/):

"DRIFT is an internationally recognised EFlows decision support system (a software model) that has been developed over 20 years …To date it has been used in over 50 projects in 20 countries on 3 continents. … DRIFT can provide detailed and transparent predictions of how ecosystems will change under different water development scenarios or other management influences. It is a tool for synthesising data, global literature, expert opinion and local knowledge in a structured and explicit process to determine the ecological, social and economic implications of proposed developments or scenarios on a river system."

Several South African scientists have been involved in the development of DRIFT, most significantly biologists Jackie King and Cate Brown, and statistician Alison Joubert, of the Cape Town consulting company Southern Waters, and hydrologist Denis Hughes of Rhodes University.

Despite having more than 20 years' experience in reserve allocations, compliance with the NWA has followed a rocky road. Many water allocations have been implemented only partially, if at all. The reasons are complex (see Barbara Schreiner's analysis at https://www.water-alternatives.org/index.php/allabs/211-a6-2-8/file) and include the fact that the NWA was extremely ambitious, the Department of Water Affairs had insufficient technical expertise, and that political will was lacking. The Department has also been singularly unenthusiastic about the establishment of Catchment Management Agencies (CMAs), as required by the NWA. The 19 original CMAs have been reduced to nine (Limpopo, Olifants (Mpumalanga), Inkomati-Usutu, Phongolo-Umzimkulu, Vaal, Orange, Mzimvubu-Tsitsikamma, Breede-Gouritz and Berg-Olifants (Western Cape), and of these only two have been properly established: the Breede-Gouritz and the Inkomati-Usutu. One reason for the extreme tardiness in establishing CMAs seems to be an ideological one: reluctance on the part of the ruling party to relinquish hold on 'the provinces'. In fact, in 2017 there was an attempt to reduce water management to a single CMA, but this idea did not last long. (More than that, over the years there have been attempts by various senior DWA officials to repeal whole sections of the NWA. They have not succeeded – yet.) Victor Munnik, Richard Meissner and colleagues have written about this issue in Munnik (2020).

A further omission on the part of the Department has been the establishment or maintenance of monitoring programmes. The Resources Quality Information System, which can be found at https://www.dws.gov.za/iwqs/report.aspx, mentions four National Monitoring Programmes (MPs): the national Eutrophic, Chemical, Microbial and Aquatic Ecosystem Health MPs. In 1971 an instruction came from senior DWA management in response to the SCOPE report on global environmental monitoring: "Environmental pollution has become an international problem. However, trends in the effects of this pollution and advance warning of the approach of dangerous and possibly i[r]reversible situations, will have to be based on a sound national monitoring programme. It is in our own interest, as well as being an international obligation, that we should establish this as soon as possible" (Alexander 1972). As a result, the Department of Water Affairs established an invaluable chemical and hydrological programme for monthly monitoring of more than 1 000 sampling points, mostly at gauging stations on rivers. A much reduced number of sites is currently monitored but DWS's analytical laboratory at Roodeplaat Dam has lost its accreditation and results emanating from it may therefore not be trustworthy. I am delighted to hear from Mike Silberbauer, who was a stalwart in the Roodeplaat lab for many years, that "the laboratories … are going through the long and expensive process of accreditation again". Mike pays tribute to "dedicated analytical chemists with years of training who know what must be done but don't have the resources to do it. Early in the crisis, some even bought reagents out of their own pockets, because the supply chain was unable to supply. That was unsustainable, especially when it came to procuring analytical instruments."

The National Aquatic Ecosystem Health Monitoring Programme ought to include wetland, estuarine and riverine monitoring programmes. The estuaries programme was established in 2016 and currently monitors about 30 estuaries. Most monitoring is being done in Western Cape by local authorities (e.g. Mossel Bay, Overstrand, Berg River) in collaboration with the WC Provincial government. I am delighted to report that, after many years, DWS has at last begun to institute a Wetlands Monitoring Programme. On the other hand, the official website dealing with DWS monitoring programmes, https://www.dws.gov.za/iwqs/report.aspx, shows very few entries in the last decade or more – an indication of the total dysfunctionality of DSW in the environmental field.

In this regard we should mention the River Health Programme (RHP). The RHP was instituted by DWA in 1994. It was an extensive biomonitoring programme that used in-stream and riparian biotas (fish, invertebrates, vegetation) to reflect the ecosystem integrity or 'health' of rivers. The programme, which was championed by Helen Dallas and Dirk Roux, was very successful and provided information that allowed an excellent understanding of the extent to which rivers were being degraded, or were able to maintain their integrity, thoughout the country. Colourful and self-explanatory State of Rivers reports (https://www.dws.gov.za/iwqs/rhp/state_of_rivers.aspx) were produced for many of our rivers, and an excellent database was developed to store the data. Like so many other DWA-led developments, the RHP was allowed to decline. In most cases ownership was passed to provincial nature conservation agencies, many of which had neither the funds nor the expertise to carry the programme forward: https://www.dws.gov.za/iwqs/rhp/rhp_background.aspx. In 2014 the RHP was dismantled, at least partly because there was insufficient funding to update the database. After a hiatus of some years, the database has been imported into the Freshwater Biodiversity Information System (FBIS - https://freshwaterbiodiversity.org/), while a reduced RHP has been reinvigorated as the national River Eco-status Monitoring Programme (REMP). A single Annual Report for the REMP was produced for 2017-18: https://bit.ly/3X8FIKS .

Jenny Day

Some of the excellent State of River reports that emanated from the River Health Programme.

CLIMATE CHANGE

So far, we haven't said much about climate change. While the nutcases deny that there is such a thing, or that it is 'natural' (so we don't need to worry??), there is no doubt that the world is warming rapidly. The United-Nations-sponsored Intergovernmental Panel on Climate Change (IPCC) (https://www.ipcc.ch/) warned in 1990 that the greenhouse threat was real, that the world had already warmed by 0.5°C over the past century, and that the 1980s was the warmest decade on record. As were the 1990s and 2000s and 2010s.

We can cite hundreds of examples of the effects of a warming climate but perhaps the Oxfam website https://www.oxfam.org/en/5-natural-disasters-beg-climate-action provides one of the most succinct analyses. They note the following

- The number of climate-related disasters has tripled in the last 30 years.
- Between 2006 and 2016, the rate of sea-level rise was 2.5 times faster than it had been for almost all of the twentieth century.
- More than 20 million people a year are forced from their homes by the effects of climate change.
- The United Nations Environment Programme (UNEP) estimates that adapting to climate change and coping with damages will cost developing countries US$140-300 billion per year by 2030.

In terms of climatic extremes, we have seen 'the worst drought in living memory' in at least three regions of the subcontinent during the past 20 years. The intensity and frequency of the El Niño effect (greater-than-average warming of parts of the Pacific Ocean) has caused floods and droughts in California, Peru and Chile, and southern Africa. The floods in Durban in 2022 were the worst on record and killed more than 500 people. Devastating droughts have afflicted Australia, accompanied by enormous forest fires both there and in California. We have already alluded to the terrible drought in Cape Town in 2017-18. Hurricane Andrew was labelled the worst storm of the century after it ripped through most of southern Florida in 1992, causing loss of life and billions of dollars' worth of damage. Severe late winters seem to be becoming the norm in North America and Europe. Viewing all of these events in the light of long-term trends in warming show that as warming continues, so do the frequency and magnitude of climate catastrophes.

So if global warming is a fact of future life, and if climate changes are anticipated, what will happen here? The answer is that we do not know the details. Although climate modellers attempting to model the world's climate do not agree on details, almost all of them suggest that in the mid-latitudes of the southern hemisphere (that's us), the land will become drier and warmer. So we have to be prepared to deal with warmer summers and less rainfall on top of increases in population. If we can handle all of these, then we will be taking the first tentative steps along the high road towards planetary healing. If we do not, then catastrophe almost

Groundup

Sisa Nukinakile empties water out of his home during floods in Cape Town in 2019.

certainly awaits us around the next bend in the low road. A number of South African climate scientists have been very much involved in research related to climate change and contributed significantly to the first part of the Sixth Assessment Report, ***Climate Change 2021: The Physical Science Basis***, which was released in February 2022: https://bit.ly/3DH4i9h.

Despite the excellent science that goes into the IPCC reports, climate-change denial still exists. Today it is less about individual citizens misunderstanding the science, deliberately or out of ignorance, and more about corporate greed. Just before the 2021 IPCC Conference of the Parties (CoP) in Scotland, Greenpeace was able to show leaked documents proving that several countries, among them Brazil, Argentina, Australia, Japan, Saudi Arabia and OPEC, were attempting to dilute the documents to be presented by the Panel. Meat-producing countries such as Argentina and Brazil tried to suppress statements promoting plant-based diets and curbing meat and dairy consumption.

At the same time, a coalition of meat industry associations has pushed for a boost in global meat consumption and promotion of intensive livestock farming despite its environmental footprint. It strikes me that the blame game is not helpful here, though. Yes, a reduction in meat production in general would assist in reducing methane emissions but we aren't about to slaughter all the wild ungulates on the planet because they also produce methane. At the same time, the unethical behaviour of many countries and organisations attempting to draw attention away from the real issues is despicable. (In passing, it is very interesting to see the way in which several oil companies are apparently realigning themselves with regard to climate issues. Their motives are unclear but given their histories, it will take a lot before they are trusted in any environmental discussions. See links in the reading list.

CLIMATE CHANGE AND AQUATIC ECOSYSTEMS

We know that climate change will involve higher temperatures, changes in rainfall patterns, and increased magnitudes and predictability of extreme events such as floods, droughts and wildfires. That's on land. What can we expect in inland waters like rivers and wetlands? Of course, water temperatures will increase and rainfall patterns will change, but what will this mean for the organisms that live in these systems? At worst, extreme floods and droughts will eliminate fishes and invertebrates from their native habitats, and sometimes cause their extinction. Many species can tolerate only small changes in temperature, and they, too, will be displaced from the habitats that they currently occupy. If they can move into cooler waters, by moving upstream, for instance, they may survive. If there are no cooler places, they won't. It has been suggested, for instance, that tropical species may be at greatest risk. This doesn't immediately make sense, in that tropical species are – of course – adapted to warm waters. The problem, though, is that many of them have remarkably narrow temperature tolerance ranges because temperatures in the tropics do not vary very much seasonally. In more temperate regions, even fairly small changes in the timing and magnitude of rainfall, together with increased temperatures, will disrupt lifecycles.

Many aquatic animals use changes in temperature and hydroperiod (flow rate in rivers) as cues for breeding or migrating. If the cues are modified as a result of climate change, then lifecycles may also be modified. Those species with the greatest sensitivity to change will be the most vulnerable. So as the world continues to warm, we can expect to see the extinction of many aquatic taxa, or at best, changes in distribution patterns of those species that can disperse to other more suitable places to live.

In South Africa, Helen Dallas's group at the Freshwater Research Centre in Cape Town is doing some excellent work on the effects of temperature on local freshwater fishes and invertebrates. Helen was probably the first in the country to deploy thermometers in numerous streams in order to gain some understanding of daily, seasonal and annual temperatures. She and her students have since assessed the temperature tolerances of a number of species, and her colleague Nick Rivers-Moore has modelled the likely effects of a number of climate-change scenarios on those species. This sort of detailed work will become more and more valuable as rivers continue to get warmer. It may be, for instance, that in at least a few rivers, dam releases could be adjusted to provide sufficiently cool waters for particularly vulnerable species.

The wire hanging down in the middle of the picture (circled in red) carries a series of tiny thermal probes used to capture a record of water temperature.

Let me end the discussion on climate change by introducing Peter Willis, who writes engagingly but with a hard-hitting message. He had this to say in a recent article in *The Daily Maverick (*http://bit.ly/3x1KFVF):

- After 200 years of digging down into the bowels of the Earth and repeatedly poking the sleeping dragon of an energy balance that had given us a relatively benign planetary climate interlude … we find the dragon is now wide awake and starting to throw its weight around in search of a new, much less civilisation-friendly equilibrium. Given what we know about tipping points and feedback loops in the global climate system, our chances of now coaxing the dragon back to its lair and singing it back to sleep must be zero.

His conclusion is that we can't put the dragon back to sleep and that the climate has been altered "effectively forever and without the means to control what we have set in motion" even if we attempt to reduce the effects as far as we are able.

PLANETARY MATTERS

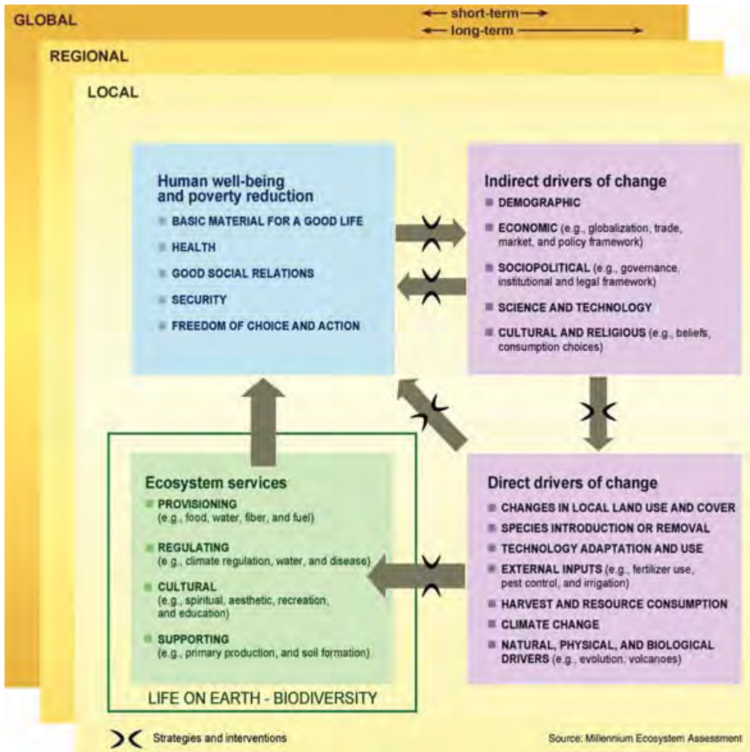
> This pendent World, in bigness as a star
> Of smallest magnitude close by the moon.
>
> *John Milton, Paradise Lost*

Up to now we have concentrated on what we might call 'water matters'. It has become clear that our rivers and wetlands, and indeed water itself, are under threat from the four apocalyptic horsemen: pollution, habitat destruction, loss of water and other resources, and alien invaders. It is likely that we could vanquish all the horsemen in some rivers or wetlands, but the possibility of reducing all of them to manageable proportions everywhere on Earth seems to be impossible. I have been wondering if this really is so, and if so, why; or if there may be ways out of the dilemma. Furthermore, these apocalyptic horsemen do not confine themselves to the aquatic realm: they are just as real and just as threatening on land. The rest of this chapter, then, takes a step back and looks at the environmental issues at the level of the entire biosphere.

The biosphere is the thin skin of the Earth within which we and our fellow-travellers exist, from the depths of the oceans to the edge of space.

Before we go any further, I want to mention one of my pet hates: the idea that we need to "save the planet". Of course, we don't need to do any such thing. If Earth were sentient, I have no doubt that it would view us pesky humans as an itchy rash on its skin. We are not destroying the Earth: we are making it uninhabitable for ourselves and the organisms that share the planet with us. *That* is what we need to deal with.

Millennium Ecosystem Assessment



An example of the issues addressed in the Millennium Ecosystem Assessment dealing with biodiversity and human well-being.

The Millennium Ecosystem Assessment (MEA) was a United Nations project designed to assess the consequences of ecosystem changes for human well-being. It was initiated in 2001 because previous studies noted that many of the Earth's major ecosystems were in decline, and yet significant information about ecosystem functioning was not available. The objectives of the MEA were firstly to assess the consequences of ecosystem changes, and secondly to establish a scientific basis for ways to conserve ecosystems in order for them to continue to contribute to human well-being.

In the following discussion the MEA website is quoted extensively. (https://www.millenniumassessment.org/en/index.html. A good summary of the results can be found at https://bit.ly/3E9kBvV).

The assessment resulted in four main findings:

- "Over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, … result[ing] in a substantial and largely irreversible loss in the diversity of life on Earth.

- "The changes that have been made to ecosystems

… will substantially diminish the benefits that future generations obtain from ecosystems.

- "The degradation of ecosystem services could grow significantly worse during the first half of this [21st] century and is a barrier to achieving the Millennium Development Goals.

- "The challenge of reversing the degradation of ecosystems while meeting increasing demands for their services can be partially met … but involve significant changes in policies, institutions and practices, that are not currently under way."

The authors offered the following warnings too.

- "At the heart of this report is a stark warning. Human activity is putting such strain on the natural functions of Earth that the ability of the planet's ecosystems to sustain future generations can no longer be taken for granted.

- "Protecting and improving our future well-being requires wiser and less destructive use of natural assets. This in turn involves major changes in the way we make and implement decisions.

- "Above all, protection of these assets can no longer be seen as an optional extra to be considered once more pressing concerns such as wealth creation or national security have been dealt with."

Peter Willis (***Daily Maverick*** 18.10.2021***)*** puts it bluntly: "…our relentless consumption of finite resources and pollution of our life-supporting ecosystems … support the view that we could right now be living through the peak of our civilisation cycle; … There are clear signs that the Earth systems that support life are close to the limits of their functionality."

A critique of the Millennium report, while largely positive, does mention two important gaps: there is no explicit statement that the solutions to the problem are a matter not of more scientific information, but of political will; and that a significant driver of the degradation alluded to in the report is material throughput [use of resources] driven by economic growth. The MEA serves as a useful introduction to the last thread in this book: appropriate management of Planet Earth.

WICKED PROBLEMS IN PLANETARY MANAGEMENT

Wicked problems are not just hard to solve. They are 'wicked' because traditional processes can't resolve them. Wicked problems are so-called because they have innumerable causes, are hard to describe, and don't have a 'right' answer. A fancier word is 'intransigent'. In the following pages we will look at some environmental problems that seem to be wicked, see which ones really are, and ask how we can attempt to tame them. (I thank John C. Camillus for a clear explanation of wickedness: https://hbr.org/2008/05/strategy-as-a-wicked-problem).

All of the following are wicked environmental problems that have to be solved if we are to maintain a functional biosphere into the future.

- the poverty spiral
- population growth
- depletion of resources
- economic growth

We have already looked briefly at climate change, which is probably the wickedest of all.

Now let us look at each of the other phenomena and see if 'solving' any of them is possible and, if it is, whether it may assist in alleviating the crisis.

WICKET PROBLEM 1: THE HUMAN CONDITION: POVERTY, WEALTH AND 'HAPPINESS'

If poverty significantly explains why the environment is in the mess that it is, then one of the ways of improving planet management is by improving the lot of the poor. Worldwide, how well are we succeeding in reducing poverty and improving 'the human condition'? We know that South Africa has one of the world's largest income gaps between the very poor and the super-rich. We also know that poverty goes hand in hand with environmental degradation, in that if one is very poor, one has little ability to choose how and where to find clean water, food, clothing and shelter for oneself and one's family. Poverty is more than just a lack of money, though. It is hunger, high mortality rates, conflicts, a lack of education and health services, and a bleak future for billions of men, women and children.

Poverty undoubtedly causes people to put pressure on the environment. Deforestation is a case in point. Poor farmers will slash and burn a small patch of forest to make room for fields that they can till. Tropical soils are often very low in nutrients, so just a few years later the crops begin to fail and, not having access to fertilisers, the farmer moves on, burning another small patch of forest. She doesn't get much from the land, but she has nowhere else to go, unless it is into the city, where – although she doesn't know it – life will be even harder than it is in the forest. Even though it is unquestionable that rural poverty is a cause of local environmental degradation, this is not really true with regard to urban poverty. Urban poverty may result in horrendously degraded slum environments, but these are confined in areal extent. In contrast, the wealthy are indirectly responsible for massive consumption of natural resources, from luxury foods and fossil fuels to the rare-earth elements used in the latest electronic devices.

One of the nastiest things about poverty is that it is self-perpetuating. If people do not have enough to eat, their ability to learn at school and to survive diseases is compromised. They seldom have access to adequate healthcare or birth control. Poor education reduces the likelihood of finding an

A small farm hewn out of the forest in Nagaland, India; after a couple of years the soil will become less productive and another plot will have to be carved out of the forest.

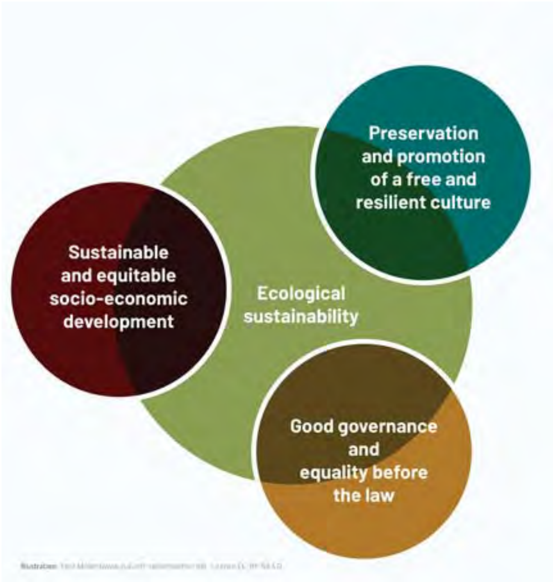
adequately paying job, so they are stuck in poverty, and so will their children be. Poor living conditions include unsanitary waste disposal and poor water quality, resulting in a greater disease burden from infectious diseases and environmental pollutants. This catalogue of misery is often referred to as the Poverty Spiral, in that the poor are often likely to get poorer from generation to generation.

With little in the way of insurance against environmental catastrophes, the poor – particularly the rural poor – are helpless against events such as floods and droughts, or plagues of pest insects, or climate change. In many parts of the world, as the population of poverty-stricken people increases, so resources such as wood for fuel and building decrease. The city is seen as the place where all these ills will disappear. The percentage of the human population living in cities is currently (2022) about 57% but as the world population increases, the percentage of people living in cities is expected to rise to 68% by 2050 (UN Department of Economic and Social Affairs 2018).

To what extent is money necessary for human wellbeing? And for human happiness? Perhaps instead we should ask about human contentment, happiness being that uncommon feeling of euphoria that comes over us when the world seems to be a particularly good place. What, then, do we need for our wellbeing? Clean water and nutritious food, obviously; shelter from the elements; health; education; sufficient money to provide for all these things, with a little to spare. Equal opportunities, contentment, and access to the 'stuff' of modern life, from electricity to smartphones, are nice to have but life can go on without them. In 2010, Daniel Kahneman and Angus Deaton from Princeton University carried out a famous study looking at the relationship between happiness and income in the US. While the traditional assumption by economists was that absolute income level is what determines individual well-being, Kahneman and Deaton found that beyond an income level of about US\$75 000 a year, contentment, or the feeling of well-being, flattens out. It does depend on the base from which we start, though. In a country such as Malawi, where the average salary is <US\$400 a year, an increase to US\$4 000 would probably be life-changing and would increase contentment enormously. In the US, on the other hand, where there is so much more to spend one's money on, and where 'keeping up with the Joneses' is important to many people, more recent studies have shown that contentment continues to rise linearly to a point considerably above the US\$75 000 per year estimated by Kahneman & Deaton: https://www.pnas.org/doi/10.1073/pnas.2016976118. The increased 'cost of contentment' seems to relate to Torstein Veblen's notions of conspicuous consumption and conspicuous leisure, which relate far more to modern life, where so much can be purchased, than earlier times when there was less to buy and fewer places to go.

Finally, I can't leave this section without paying tribute to Bhutan, a tiny Buddhist nation situated in the high Himalayas. Because of their Buddhist faith, Bhutanese consider environmental conservation to be a way of life, as evidenced by the fact that Bhutan is the only carbon-negative country in the world. Bhutan relies not on GDP but on GNH – Gross National Happiness – in policy-making and governance. 'Happiness' is calculated according to a complex set of indicators.

The Taktsang Monastery in Bhutan.

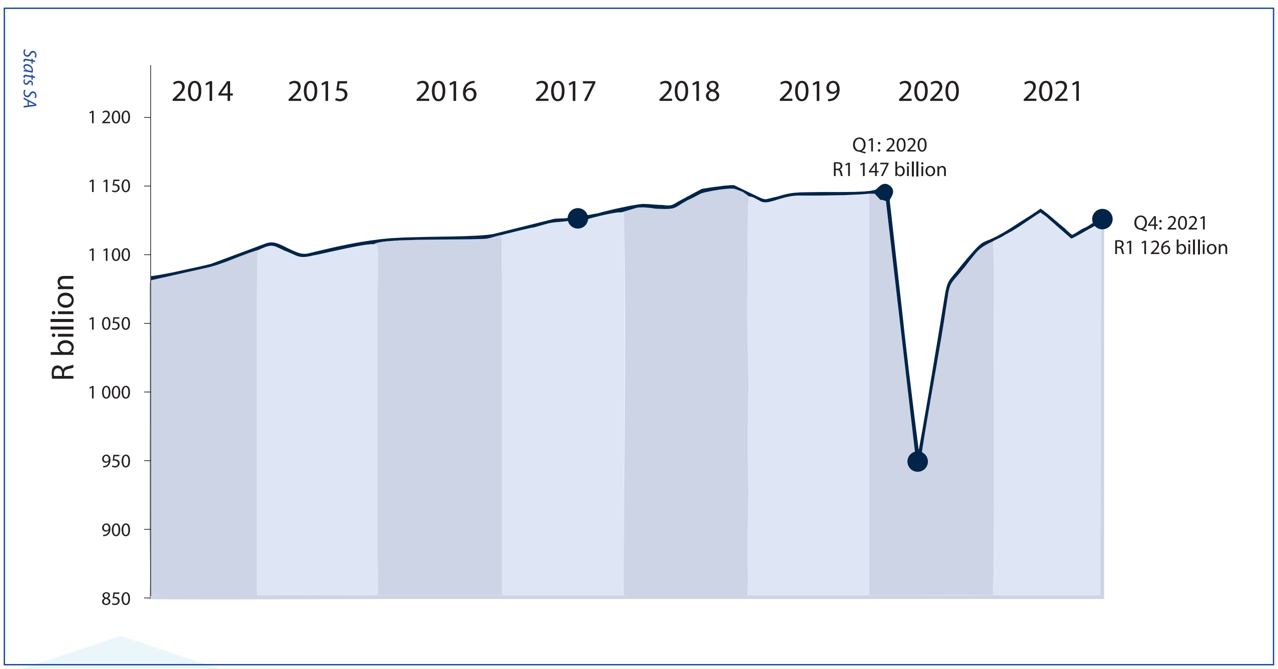


Bhutan's four Pillars of Gross Happiness; note the indicators are based on ecological sustainability.

Poverty affects most people in the world. In 2005, 71% of the world's population lived on an income of less than US $10 a day. Is it possible to reduce poverty? Can unbridled economic growth pull the poor out of the poverty spiral? In the 1980s, for every US$100 added to the economy, US$2.20 found its way to the very poor (living below World Bank's Absolute Poverty line). In the 1990s, this declined to 60c. In other words, for the poor to get less poor, the rich must get much richer (and how will they do it, other than by exploiting more resources?). In fact, the world's 2 153 billionaires have more wealth than the 4.6 billion people who make up 60% of the planet's population. The 22 richest men on the planet have more wealth than all the women in Africa. If the richest one percent paid just 0.5% extra tax on their wealth over the next 10 years this would equal the investment needed to create 117 million jobs in sectors such as elderly and childcare, education and health: https://www.oxfam.org/en/press-releases/worlds-billionaires-have-more-wealth-46-billion-people. Tony Leiman, my resource economist reviewer, points out that these Oxfam statistics are ***technically*** controversial because, for instance, most of the very wealthy pay virtually no tax, and much of the wealth of the rich is in shares, so if they tried to sell them the prices would collapse. Hmm – the principle of the richest each paying a small proportion of his or her wealth still seems like a sensible and viable option to me. The neoliberal notion that corporate greed is how the world works (or should work) seems to mean that politicians are entirely unwilling to increase taxes to the very wealthy (***why***?). It seems to me that if a political party in the USA had the courage, and sufficient votes, it could essentially end extreme poverty throughout the world in the blink of an eye.

How much money might be needed to end extreme poverty globally? Jeffrey Sachs in his 2005 book, ***The end to poverty,*** estimated the annual cost of eliminating extreme poverty (daily income <US$1.25 at the time) would be about US$175 billion per year for 20 years – less than 1% of the combined income of world's richest countries, and about a quarter of the annual USA spending on defence. When he wrote his book in 2005, Sachs considered that this could be achieved by the year 2025 thanks to investment in local farms to boost capital and productivity; education for both children and adults; enhancing access to health services; and leveraging renewable energy resources. A basic income grant (BIG) would be another way to distribute funds to the poor. Although it is a great idea, the fiscal authorities in South Africa feel that a BIG capable making a real difference is presently unaffordable and would sabotage the economy if they tried it. Maybe it would have been feasible in the absence of state capture.

It seems that extreme poverty ***is*** decreasing, though, if we look at the percentage of people living on <US$1.90 per day (the post-2015 measure of extreme poverty). Recent estimates indicate that in 2015, this was 10% of the world's population, compared with 16% in 2010 and 36% in 1990. Although a greater proportion of the world population is better off today, there are still nearly a billion people living in abject poverty. Why has the proportion dropped? It seems that people living in relatively well-off countries have benefitted from improved healthcare, education and employment, while those living in countries with very low average incomes are stuck in the poverty mire (see the figure below). Here is one of the wicked problems mentioned above. For extreme poverty to be eliminated, the countries in which the very poor live need to increase GDP. Increased economic growth puts pressure on natural resources and the habitability of the planet for humans. Of course, that magical US$175 billion per year for 20 years would be a far better solution for all of us if it actually means that people would thereafter be financially



The South African economy as GDP, showing the effects of Covid-19.

independent. And we should not lose sight of the fact that the vast majority of the world's population would still be very poor indeed, even with an income of US$2 a day.

To revisit the question posed at the beginning of this section*: is poverty a major driver of environmental degradation*? it seems that the answer is, not really. The extremely poor do cause environmental degradation but this tends to be local and most significant in slums in large cities. It is the wealthy who are able to cause the greatest and least reversible environmental damage.

What about the size of the human population, then?

WICKED PROBLEM 2: THE SIZE OF THE HUMAN POPULATION

Cities

Ever since the development of societies, humans have inexorably progressed, spurred by available technologies, from stone spearheads, copper cutting edges and iron implements to silicon chips and carbon fibres. Early humans were probably nomadic pastoralists, later settling in hamlets and villages, and still later in towns and cities. Amazingly, between 1950 and 1990 the world's urban population exploded from 200 million people to 2 billion. Already, some 15 cities contain more than 20 million people each, the largest being Guǎngzhōu with 65 million, followed by Tokyo with 41 million.

We have created vast conurbations for the benefit of a single species, whose wastes cannot adequately be treated and whose needs for resources have to be fed at enormous ecological and social costs. Food webs now encompass the planet: jet-lagged oysters and strawberries are transported by air between major cities; seasick sheep and cattle sail the high seas; road-trains hurtle down highways with loads of refrigerated meat and ice cream, mieliemeal, sugar, plastics and furniture; and rivers are disgorged into filtration plants. In sum, the ecological footprints of cities have global effects. Cities also consume vast quantities of water and energy, as well as producing untold quantities of waste, the global effects of which are only now being recognised (see Chapter 7).

To what extent is the rapidly growing human population causing environmental degradation? And how much worse will this get in the future? According to the Worldometer (https://www.worldometers.info/) the world population was 7 940 073 067 at 6pm on 13 April 2022, as I write this, and had increased by 168 099 people today. Of course, the 'ticking timebomb' shown by the Worldometer can't possibly be accurate, but the rate of growth is close enough to reality to be extremely scary.

Demographics (the study of human population numbers) is fascinating and bewildering. A few years ago, there was good reason to believe that population numbers would continue to increase to some point at which overcrowding would result in wars and starvation. The good news is that this is unlikely to happen. The fertility rate (number of live births per woman) worldwide fell from 4.7 babies in 1970-75 to 2.6 in 2005-10, 2.5 in 2017 and 2.44 in 2021 and the rate has continued to decline every year since 2018. Researchers at the University of Washington's Institute for Health Metrics and Evaluation predict that it will fall below 1.7 by 2100. As a result, the number of people on the planet is expected to peak at 9.7 billion around 2064, before falling to 8.8 billion by the end of the century. That is still a lot more people than the Earth currently supports.

According to the BBC (https://www.bbc.com/news/health-53409521), "Falling fertility rates mean nearly every country could have shrinking populations by the end of the century. And 23 nations – including Spain and Japan – are expected to see their populations halve by 2100." Well, this is good news – isn't it? Yes, from the point of view of the load on the planet but very definitely bad from the point of view of countries experiencing declining populations. As birth rates decrease, a greater and greater proportion of the population ages, in that an increasingly larger proportion of people reach retirement age and become dependent on a declining number of economically active people. As the BBC notes, "Countries will also age dramatically, with as many people turning 80 as there are being born." A consequence is that the age of retirement will need to increase. France, for instance, is trying with difficulty to raise the retirement age from 62 to 65. (As an aside, it has been said that the first person who will reach the age of 200 has already been born!)

Why should birth rates be declining so rapidly? The main reason is to do with women's changing roles. Economic opportunities, social norms and advances in reproductive health allow women to have a choice about the number of children they will have. Furthermore, once upon a time the more children a woman had, the more insurance she had against poverty in old age, particularly since it was unlikely that all her children would reach adulthood. Today there are old-age pensions in most advanced countries, and one or two well educated children are more likely to provide benefits to their aged parents than several poorly educated ones. Nonetheless not all women have those opportunities. The UN recently noted that roughly 350 million women in the poorest countries did not want their last child, but did not have the means to prevent the pregnancy either because they did not have access to any means of birth control or were prevented by their partners from using it. Creating a sustainable population is as much about boosting women's status as it is about reducing consumption of resources.

These demographic numbers make so many ideas stand on their heads. Countries will begin to compete for immigrants. Retirement ages will have to increase. The number of dependent elderly people will increase while the number of able-bodied potential carers will decline. What is more, if population numbers settle at a new low, the rate of consumption of natural resources will slow down. When global fertility rates fall below 2.1 (replacement rate) and remain there, however, population numbers will ultimately crash.

Why has fertility rate declined so dramatically? If growth rates in so many countries are expected to decrease dramatically, why is it that the human population will continue to grow for at least the next 50 years? Well, the answer is twofold. On the one hand young women being born now will continue to reproduce for the next 30 years or more. On the other hand, there is Africa. Fertility rates in many African countries are still very high: 6.8 for Niger, 6.0 for Somalia, 5.8 for Mali, for instance. The population of sub-Saharan Africa is expected to treble, to more than three billion people, by 2100. And according to the BBC report, at that stage Nigeria will become the world's second most populous country, with a population of about 790 million.

South Africa is likely to remain a middle-of-the-road country. The fertility rate is currently about 2.4 children per woman (and therefore above replacement rate) but the country's growth rate is only 1.24%, which means that population growth is slowing down. Tony Leiman comments: "our problem right now is that population growth still outweighs economic growth, so GDP per capita is declining. It grew by 7% in the six years from January 2014 to December 2019 (before Covid) and is still well down on where it was" (See Figure on page 456).

WICKED PROBLEM 3: DEPLETION OF RESOURCES

"The reason we seem to have everything is that we are using up what our children and grand-children should expect to inherit."

Gus Speth, American lawyer & activist

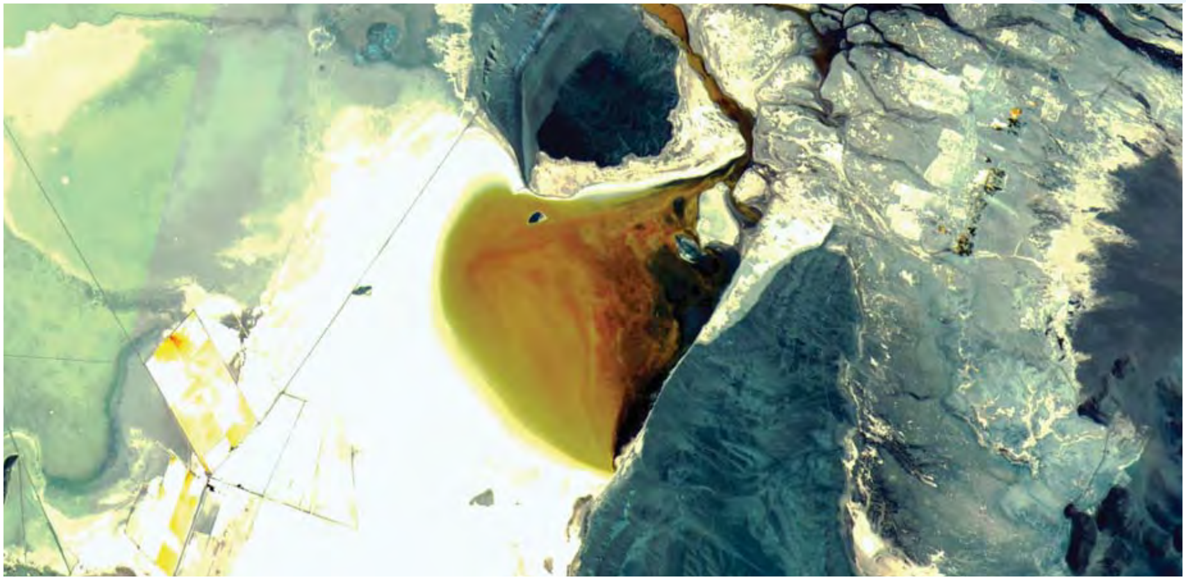
"Instead of supposing that we should continue to reduce the resources of the planet in support of humankind, we shall increasingly need to mobilise the resources of human-kind in support of the planet."

Norman Myers: ecologist, UK

We all know that fossil fuels have been depleted to the extent that one day there will not be enough for human needs. While the quantities of fossil fuels themselves are limited, we are learning to replace them with renewable sources of energy. Sources of energy, then, are not intrinsically of concern. Several elements are, though.

In chapter 7 we described the depletion of **phosphate** reserves and showed that this phenomenon is largely related to the peculiar chemical characteristics of phosphorus. A reduction in availability of P is already providing the first hard evidence that resources are not infinite. Other elements are likely to follow. Elements cannot be broken down under normal conditions on Earth, so of course in each case we are not using up the elements as much as diluting them – by scattering fertilizers on fields, for instance, or enclosing rare metals in cell phones – to the extent that they are not easily recoverable in useful quantities.

Lithium is used extensively in lithium-cobalt batteries: batteries for cell phones and laptops, but more significantly for electric cars. Production of lithium has increased more than three-fold over the last couple of years and is expected to increase even faster as electric cars (EVs – electric vehicles) replace petrol-driven ones. Globally, reserves of Li are estimated to be about 165 times the production volume in 2018. Simplistically, this means that at 2018 rates, supplies could last for another 165 years, but of course the quantities being mined are increasing rapidly from year to year, as EVs become more common. It is estimated that lithium batteries


Argentina Coordenação de Terra / INPE / Wikimedia / CC BY-SA 2.0

Extracting minerals is seldom environmentally friendly. Here, lithium mining in Argentina involves evaporation of Li-containing brine (the orange-brown lake).


Julien Harneis / Wikimedia / CC BY-SA 2.0

About 30% of cobalt produced in the DRC is by artisans working under dangerous and difficult conditions.

will not be replaced in bulk by other, more efficient, ones for at least another 10-20 years. Lithium batteries can be recycled but the process is expensive so it is still cheaper to mine new sources.

As we might imagine, **cobalt,** a component of lithium-cobalt batteries, is also in short supply. In fact, a lack of cobalt is said to be the greatest threat to an adequate supply of EV (electric vehicle) batteries in the near future. Because cobalt is abundant in certain rocks in the deep oceans, deep-sea mining may be necessary to increase the supply, which means that Co is not absolutely in short supply. The bulk of Co ore is currently being mined in the DRC, which is an uncertain source.

Within a day of writing about lithium and cobalt, I just happened across an article about this very topic. (https://www.pv-magazine.com/2022/03/26/the-weekend-read-sodium-ion-batteries-go-mainstream/) It seems that battery technology is changing at an amazing rate, and among other things, the search is on for batteries that use neither lithium nor cobalt. One of the new types relies instead on sodium, which is abundant throughout the Earth, not least in sea water.

The EU has a list of 'critical raw materials', which includes the elements antimony, barium, beryllium, bismuth, boron, cobalt, gallium, germanium, hafnium, indium, magnesium, niobium, platinum-group metals, scandium, strontium, tantalum, titanium, rare earth elements, tungsten and vanadium. Twelve elements were included in the list in 2012, and twenty in 2020. These are considered to be "raw materials for which there are no viable substitutes with current technologies, which most consumer countries are dependent on importing, and whose supply is dominated by one or a few producers".

Rare-earth elements (REEs) are used in smart phones, digital cameras, computer hard disks, fluorescent and light-emitting-diode (LED) lights, flat screen televisions, computer monitors, and electronic displays. There are seventeen of them, including scandium, yttrium, and others that most of us have never heard of. Until the electronic revolution, these REEs were no more than chemical curiosities but they now play a major role in our technological world. The word 'rare' really does apply to several of them. South Africa mines a few of them but the largest producer is China. Realising how keen the rest of the world is on obtaining these elements, the Chinese government has begun to reduce the quantity of the REEs that it allows to be produced and exported, although it also had to import some. At the same time, China is buying mines, mostly in the Democratic Republic of Congo, which has the richest deposits of many of the elements mentioned above. Much closer to home, a mine at Steenkampskraal in the far north of the Western Cape is said to have the Earth's richest deposit of a number of REEs (neodymium, used for lasers; praseodymium; dysprosium, used for flat-screen TVs; and terbium). The mine was operated many years ago by Anglo American and then abandoned, presumably before the resurgence of interest in REEs but is now being reopened under new management.

Depletion of resources does look like a wicked problem, doesn't it? In fact, it may become a major stumbling block to further technological developments because, as we know from primary school chemistry, elements cannot be manufactured. They can be recycled, however, and at the very least we have to develop effective, automatic processes for extracting these diminishing elements at the end of the lives of our electronic devices. So far, the world hasn't been doing very well in this regard. Ten years ago, Europe alone was producing about 12 million tons of metallic wastes a year, and recycling very little. We simply have to look at our devices in a more critical light. We do not need to have a new and fancier one every year, even though it is cool to do so. It is a fact that wicked manufacturers (in the old sense of the word) deliberately design electronic devices to become obsolete after just a few months. And they tend to view repair as a barrier to future profits. Not only are these attitudes despicable, but they also have to be changed if we are not to run out of the resources we need to manufacture them in the first place. Governments will have to take responsibility for forcing manufacturers both to stop planned obsolescence and to make components of electronic devices recycleable.

In summary, a number of natural resources, from fossil fuels to phosphorus and electronic components, are running out. (My resource economist friend says, though, that there is little market evidence to suggest that any of our natural resources are running low in that real prices show no sustained rising trend.) It is the responsibility of all of us to deal with these problems. We as citizens need to be more frugal in our purchases, keep our devices for longer, and recycle them responsibly. Manufacturers need, by force if necessary, to abandon the despicable practice of planned obsolescence and to design devices that are easy to recycle. And governments need to have the courage and fortitude to tackle the offending corporates. Of course, this won't be easy, but if it were easy, it wouldn't be a wicked problem. It will be interesting to see if USA politicians ever have the courage and fortitude have to force Apple to behave in a more ethical way. Apple currently claims to be a champion of the environment (https://www.apple.com/environment/) but they have a long way to go to convince me that this is more than just window dressing.

WICKED PROBLEM 4: UNBRIDLED ECONOMIC GROWTH

In his 1995 book, ***Conservation: replacing quantity with quality as a goal for global management,*** Carl F. Jordan states, 'The first chapter in the Old Testament of the Christian Bible contains the seeds of the fundamental split that has divided conservationists throughout the ages into two opposing camps:

> And God blessed them, and God said unto them, Be fruitful and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth'.
>
> *Genesis 1:28*

Jordan posits that one camp has interpreted the word 'dominion' as a metaphor for 'ownership', where organisms and resources '… serve no purpose or value other than to serve humankind'. The other camp, according to Jordan, interprets 'dominion' to mean 'stewardship', where humankind has a responsibility to preserve the wellbeing of all living things in so far as they '…have an intrinsic value that exists apart from any use they may have for people.' He says, "We need to move towards an age of enlightenment where we recognise that all living species on planet Earth, including humans, form the web of life [and] by breaking the strands of the web, we are in danger of destroying that which supports us and every other living organism along with us."

The late John Cairns, an aquatic scientist from the USA, had a slightly different take on the dichotomy. He said, "Toward the end of this century, two new cultures have emerged with dramatically different views of the relationship that ***Homo sapiens*** has with natural systems. The 'environmentalists' believe that humans are a part of natural systems and depend on them to keep the planet habitable. The 'exemptionalists' believe that intelligence, creativity and technology can free human society from the biophysical laws of nature that restrict other species."

In a similar vein, the economist Kenneth Boulding distinguished between a 'cowboy economy', the cowboy "being symbolic of the illimitable plains and also associated with reckless, exploitative, romantic, and violent behaviour" and the 'spaceman economy', in which "the earth has become a single spaceship, without unlimited reservoirs of anything". (Boulding should be better known than he is. As long ago as 1966 he wrote "… economists continue to think and act as if production, consumption, throughput, and the GNP were the sufficient and adequate measure of economic success". If you are interested in resource economics, have a look at his 1966 paper listed under Further Reading).

Essentially, Jordan, Cairns and Boulding have identified two world views. 'Exemptionalists' or 'owners' or 'cowboys' consider themselves to be answerable to no-one, least of all future generations, and to be exempt from natural laws: they can fix any problems that arise because of their actions (and can recognise them as problems before they become insoluble). They suffer from a surfeit of hubris, which is probably best defined as an overwhelming arrogance. The 'environmentalists' or 'spacemen' are less optimistic, and more realistic. I make no apology for being at the 'environmentalist' end of the spectrum. It may be that as a biologist, rather than an economist, I am particularly aware of the our human species stretching through time; to me, not ensuring a liveable Earth for future generations is unthinkable.

As a biologist, too, I am aware of the fragility of life and the ease with which we could cause irreversible damage to Spaceship Earth. In fact, some evolutionary biologists quite seriously believe that our intelligence will lead to our extinction. If John Cairn's exemptionalists cannot find technical solutions to all of the problems that we have been discussing, then the human species, and indeed all of the species in the biosphere, face the very real likelihood of extinction. Perhaps that is why Elon Musk is so serious about finding ways to colonise Mars.

WHAT DOES THIS MEAN FOR THE ENVIRONMENT?

> "Science and technology are what we can do; morality is what we agree we should or should not do."
>
> *EO Wilson, The Future of Life (1992)*

Writing in the magazine ***Resurgence,*** John Seymour has described Western humans as living in "the Age of Plunder" (http://thehessiansack.blogspot.com/2012/06/age-of-healing-by-john-seymour.html). Put simply, planet Earth cannot support unbridled growth and uncontrolled consumption for ever. The word ***planet*** means ***wanderer:*** a lonely unit in the vastness of the cosmos, stubbornly orbiting its sun, which itself is also a wanderer hurtling along the margins of a vast disc-shaped galaxy. In the words of Carl Sagan, the earth is '… a pale blue dot'. In 1990, the Voyager spacecraft, some 5 billion kilometres away from earth and on the verge of leaving our solar system for ever, sent back images of earth that were just that: a small blue dot. Our earth is our only home and the only source of everything we need for survival. The helter-skelter rush for profits takes no notice of what it is doing to the biosphere. Nor does the measure of Gross Domestic Product (GDP) indicate the extent to which the natural resource base is damaged or destroyed in achieving that growth. Kenneth Boulding's cowboys need to take to the spaceship.

What governments need to do

John Cairns considers there to be "…no clearcut ways to reconcile economic growth with the measures needed to curb environmental degradation [and] stretch dwindling natural resources. There is no doubt that the global financial system has to be restructured if we are to have a chance of regaining environmental integrity. Norman Myers says we need 'a seismic shift in thinking', and this is going to be hard to do because it is another wicked problem. Effective leadership will be crucial but that, too, occurs more as a matter of serendipity than of choice. (Serendipity is the occurrence of beneficial events by chance.) The most important issues that governments need to tackle are restructuring the global financial system (which would have to be a global initiative) and controlling the causes and effects of climate change. Only slightly less urgent are the need to protect and restore key ecosystems such as tropical forests, if necessary by paying for the ecosystem services they provide, and promoting 'green' energy. There is more than enough money in the large multinational corporations to pay for all of this as long as governments have the courage to increase taxation of the very wealthy, both people and corporations.

THE WICKEDEST PROBLEM OF ALL

Gus Speth has the ability to condense complex issues into simple words. The following perspective goes to the heart of the environmetal crisis.

> "I used to think that the top environmental problems were biodiversity loss, ecosystem collapse and climate change. I thought that thirty years of good science could address these problems.
>
> I was wrong.
>
> The top environmental problems are selfishness, greed and apathy, and to deal with these we need a cultural and spiritual transformation.
>
> And we scientists don't know how to do that."
>
> *Hear Gus Speth's podcast at https://earthcharter.org/podcasts/gus-speth/*

More than fifty years ago, in 1970, Dr TC Robertson wrote of South Africa: " … a new philosophy is needed: water resources can no longer be exploited primarily for the people and their industries; people have to be regulated for the sake of the efficient use of the water resources. Until this inter-relationship of man, wealth and water – the demographic-economic-ecological pattern – is understood, the Golden Age of Water Conservation, man's ultimate hope of survival, will not have dawned."

The ultimate question is, what can we actually do? Are governments and neoliberalism together too powerful to change until it is too late? We have overwhelming evidence that the biosphere is in trouble, and many people do subscribe to a philosophy that recognises the need for a new mindset. We need to rethink the economic growth model: give capitalism a chance to do what is supposed to be able to do without raping the biosphere and impoverishing the majority of mankind. We need to do simpler, personal, things like reconfiguring our diets (moving down the food chain; reducing our carbon footprints; reducing our water footprints), becoming more frugal, and thinking locally, not globally. But, as an editorial in ***New Scientist*** says, "… personal carbon virtue and collective environmentalism are futile as long as our economic system is built on the assumption of growth. … The science tells us that if we are serious about saving Earth, we must reshape our economy."

TOWARDS A CONSERVATION ETHIC

This book attempts to address the pressing issues surrounding over-consumption of water, pollution, human manipulation of aquatic ecosystems, and the resulting pressures placed upon those ecosystems. Throughout, we have stressed the fact that water is a renewable resource but that it is renewable only if it is allowed to be so. We have also stressed the role that the individual can play in alleviating the water crisis and using water wisely. But none of this is of any use unless we all develop a water-conservation ethic – and not all of us are prepared to do so. In a radio interview during the 2017 drought in Cape Town, the host was talking about having showers for no longer than two minutes. One caller informed us that he saw no reason to curtail his showers and that as a matter of principle he would continue to shower for ten minutes every day. This was at a time when citizens were doing everything in their power to save water. His attitude was despicable: it is nobody's right to squander scarce resources that everyone should have access to. The question is, how do we instil such an ethic in our citizens? Ernst Conradie and colleagues (2021), in a chapter on ***Urban water resilience: perspectives from civil society***, discuss this very issue. They note (p. 194) that "Organisations in civil society can play a vital role in cultivating … a sense of responsibility by strengthening the moral fabric of society. …some aspects [of water use] fall within the locus of control of every household." Dealing specifically with water, they emphasise the role of households (families, parents) in "… cultivating the virtue of frugality and avoiding the vice of wasting potable water; cultivating the virtue of care and avoiding the vice of polluting fresh water …" The same principles apply whether we are talking about water or any other aspect of planet management.

Tony Leiman makes the important point that speaks to Gus Speth's comment on selfishness. "If the caller had been a farmer using his own water, knowing that when he ran out he would have nothing, his own approach would have been different; but he was used to using ***public*** water, an almost free good, that he purchased at low prices as and when needed. He was competing with other consumers to have access to it, not competing against himself. If everyone in Cape Town had been allocated a finite supply of water and told, "When your allocation is gone, that's it, you get no more, we will turn off your mains connection", people would have been economising a lot earlier, and lot more consistently.

We need to talk more openly and passionately about treading more lightly on the Earth – reducing our ecological footprints both as individuals and as society. We also need to have discussions about rights and responsibilities. The new South African government in 1996 promulgated the South African Constitution (Constitution of the Republic of South Africa, Act 108 of 1996). Chapter 2, the Bill of Rights, states that "This Bill of Rights is a cornerstone of democracy in South Africa. It enshrines the rights of all people in our country and affirms the democratic values of human dignity, equality and freedom." But it says not a word about the responsibilities that should go with those rights. (https://www.justice.gov.za/legislation/constitution/saconstitution-web-eng.pdf). Surely the Constitution should be the place where people are informed that their rights are not unlimited? Surely the much-vaunted matric subject ***Life Orientation*** should deal with these issues of civic responsibilities? They should become so entrenched in the psyche of every person in the country that this discussion should not be necessary. I would add ignorance to Gus Speth's list of "selfishness, greed and apathy" as the causes of our global environmental problems. We should be educated about these problems at school, at home, in the workplace, and in everyday life. Then there will be no excuse for the country, and indeed the world, to continue down this dangerous path.

THE GOOD NEWS

All need not be gloom and doom if each of us makes conscious choices about what and how much we consume – indeed, about how we live our lives. Strong leadership is needed, though, and currently this is not coming from the political sphere, where powerful leaders who should know better seem to be more concerned with denying scientific evidence than facing the problematic future of the biosphere.

It seems, then, that we need to turn to the young. Everyone knows the name of Greta Thunberg, the young Swedish climate activist. As well as advertising the frightening predictions about a warming world, she has become a remarkable role model for young people. She has come to represent the younger generation (GEN-Z) and to show them that they, too, can be heard and can make a difference. It tells us something unsettling about the world we live in, though, when a young person with no education in science has more influence on environmental matters than well-known and respected scientists. Although in many ways the social media are a curse, and even a threat to the mental stability of young teens, cell phones are really important tools in disseminating information about this, and other, worldwide events. Had it not been for social media, we would have heard about Greta only in an occasional newspaper or TV report, and she would have been "that crazy Swedish girl". With social media, everyone on any of the social media platforms knows who she is and what her message is. Of course, not everyone is impressed by her. Those environmental dummies Vladimir Putin and Donald Trump have distinguished themselves by dismissing her and her work. Trump tweeted that she should "work on her anger management problem" and Putin described her as a "kind but poorly informed teenager". Which tells us a lot more about them than about her.

Of course, activism has to be transformed into action on the part of the authorities, but 'green' movements all over the world are causing governments to take notice and even to re-visit some of their economic and environmental policies. This has had some interesting consequences. For example, until recently the UK government forbade the cultivation of genetically modified (GM) crops because of public pressure. (The reasons for the public attitude towards GMOs were not always logical, or scientifically valid, but the government did take notice.)

Closer to home, the South African government is finally recognising the need to cut down on the use of coal for electricity generation. This country has massive coal reserves and about 77% of our primary energy needs are provided by coal (two-thirds for electricity generation and a third for Sasol's oil-from-coal plant), the rest coming from local renewables and imported hydropower from Mozambique. Any move away from coal has political implications because a large number of small coal mines has sprung up in Mpumalanga, enriching their owners and providing jobs for locals. Reducing the use of coal will cost votes, even if jobs can be created by situating some of the proposed wind and solar plants in the same area. Nonetheless, at COP26 in Glasgow, the South African delegation announced that we are to receive US$8.5 bn to help end our reliance on coal. The loan, mostly from the World Bank, can be repaid as carbon reduction. It will be used to decommission six of the most polluting coal-fired power stations as well as to increase power production from renewables. That is all good news but there is – you've guessed it – a downside. South Africa is wanting to buy a good deal more power from Mozambique, who is therefore planning to build yet another large hydropower dam on the Zambezi to provide for the additional requirements from South Africa. Let us hope that our own e-flows experts will be asked to design the best possible releases from the dam to cause as little further damage as possible to the great Zambezi River.

NASA

If you look carefully you will see the Earth, our only home, as a pale blue dot photographed by the spacecraft Voyager 1 on February 14, 1990, just 34 minutes before its cameras were shut off for ever.

READING LIST

African Journal of Aquatic Science (2022) SPECIAL MEDAL ISSUE: Perspectives on Protecting African Freshwater Ecosystems in the Anthropocene. Vol. **47**

Amis MA, MC Rouget, MD Lotter, JA DAY and others (2009) Integrating freshwater and terrestrial priorities in conservation planning. ***Biological Conservation*** **142** doi:10.1016/j.biocon.2009.04.021

Baxter AJ & BR Davies (1994). Palaeoecological insights for the conservation of aquatic ecosystems in dryland environments: a case study of the Verlorenvlei system, South Africa. ***Aquatic Conservation: Marine and Freshwater Ecosystems*** **4**: 255–271

Boulding E (1966) The economics of the Coming Spaceship Earth Pp 3-14 ***in:*** H. Jarrett (ed.) ***Environmental Quality in a Growing Economy, Resources for the Future***, Johns Hopkins University Press http://arachnid.biosci.utexas.edu/courses/thoc/readings/boulding_spaceshipearth.pdf

Brunet J (2019) Pollinator decline: implications for food security & environment. ***Scientia*** blog ***https://www.scientia.global/pollinator-decline-implications-for-food-securityenvironment/***

Cairns J Jr (1999) The diminished charge on the intellectual electric fence ***The Social Contract*** **9**: 145-151

Chakona A, G Gouws, WT Kadye, MS Jordaan & ER Swartz (2019) Reconstruction of the historical distribution ranges of imperilled stream fishes from a global endemic hotspot based on molecular data: implications for conservation of threatened taxa. ***Aquatic Conservation: Marine and Freshwater Ecosystems*** **30:** 1–15

Conradie C, J Fackenthal, R Gallant, JJ Hasselaar, D Jalajel, R Mash, J Matenda & C Pearson (2021) ***Urban water resilience: perspectives from civil society***. Pp 168-198 ***in***: L Swatuk & 10 co-editors ***Towards the blue-green city: Building urban water resilience***. South African Water Research Commission Report no. SP 153/21

Costanza R & 12 co-authors (1997) Value of the world's ecosystem services and natural capital ***Nature*** **387**: 253-260.

Costanza R, R Groot, P Sutton, S van der Ploeg, SJ Anderson, I Kubiszewski, S Farber & RK Turner (2014) Changes in the global value of ecosystem services ***Global Environmental Change*** **26**: 152-158

Crookes DJ & JN Blignaut (2019) Investing in natural capital and national security: A comparative review of restoration projects in South Africa ***Heliyon*** **5** e01765 doi: 10.1016/j.heliyon.2019.e01765

Dallas HF & N Rivers-Moore (2014) Ecological consequences of global climate change for freshwater ecosystems in South Africa. ***South African Journal of Science*** **110**: 48-58.

Dallas HF & NA Rivers-Moore (2022) A protocol and tools for setting environmental water temperature guidelines for perennial rivers in South Africa. ***African Journal of Aquatic Science***. https://doi.org/10.2989/16085914.2021.1982673

Dallas HF, JM Shelton, T Sutton, D Tri Cuptura, M Kajee & N Job (2021) Development of a freshwater biodiversity information system for evaluating long-term change in rivers in South Africa. ***African Journal of Aquatic Sciences*** **47** doi.org/10.2989/16085914.2021.1982672

Day JA, G Cleaver-Christie, EG Day & L Stafford (2021). Water and the natural environment: biodiversity and urban water management. Pp. 24-45 ***in***: L Swatik and 10 co-editors, ***Towards the blue-green city: Building urban water resilience.*** South African Water Research Commission Report no. SP 153/21

Day E, M Rountree & H King (2016) ***The developoment of a comprehensive manual for river rehabilitation in South Africa.*** South African Water Research Commission Report no. TT 646/15

Driver A, JL Nel, K Snaddon, K Murray, DJ Roux, L Hill, ER Swartz, J Manuel & N Funke (2011) ***Atlas of freshwater ecosystem priority areas in South Africa to support sustainable development of water resources*** South African Water Research Commission Report no. 1801/1/11 du Toit JT & N Pettorelli (2019) The differences between rewilding and restoring an ecologically degraded landscape. ***Journal Of Applied Ecology* 56:** 2467–2471

DWS Department of Water & Sanitation (2017). ***Development of procedures to operationalise Resource Directed Measures. Main Report.*** Prepared by: Rivers for Africa eFlows Consulting (Pty) Ltd. Report no RDM/WE/00/CON/ORDM/0117

Grantham J (2012) Be persuasive. Be brave. Be arrested (if necessary). ***Nature* 491:** 303 https://www.nature.com/articles/491303a

Harrison AD (1958) Hydrobiological studies on the Great Berg River, Western Cape Province. Part IV. The effects of organic pollution on parts of the Great Berg River system and of the Kromme Stream, Stellenbosch. ***Transactions of the Royal Society of South Africa* 35**: 299–329.

Harrison AD & JF Elsworth (1958) Hydrobiological studies on the Great Berg River, Western Cape Province. Part I. General description, chemical studies and main features of the flora and fauna. ***Transactions of the Royal Society of South Africa* 35:** 125-172.

Harwood A, S Johnson, B Richter, A Locke, X Yu & D Tickner (2017) ***Listen to the river: Lessons from a global review of environmental flow success stories***, WWF-UK, Woking, UK

Impson D, R van der Walt & MS Jordaan (2017) ***Freshwater Fish.*** pp 103-124 ***in*** Turner, AA (ed.) Western Cape Province State of Biodiversity. Cape Nature Scientific Services, Stellenbosch, South Africa https://www.capenature.co.za/uploads/files/Resources/State-of-Biodiversity-Western-Cape-2017.pdf

Jordan CF (1995) ***Conservation: replacing quantity with quality as a goal for global management.*** Wiley. 374pp.

Kahneman D & A Deaton (2010) High income improves evaluation of life but not emotional well-being. ***PNAS* 107** (38): 16489-16493 https://doi.org/10.1073/pnas.1011492107

Lippert C, A Feuerbacher & M Narjes (2021) Revisiting the economic valuation of agricultural losses due to large-scale changes in pollinator populations. ***Ecological Economics* 180**: 106860 https://www.sciencedirect.com/science/article/pii/S0921800920300793

Mishan EJ (1967) ***The costs of economic growth***, Staples Press, London

Munnik V (2020) ***The reluctant roll-out of Catchment Management Agencies: Assessing the key risks and consequences of delays in finalising institutional arrangements for decentralised water resource management*** South African Water Research Commission Report No. 2943/1/20

Nel JL, KM Murray, AM Maherry and others (2011) ***Technical Report for the National Freshwater Ecosystem Priority Areas project.*** South African Water Research Commission, Pretoria Report No. 1801/2/11

Nel JL, D Le Maitre, DJ Roux, C Colvin, JS Smith, LB Smith Adao, A Maherry & N Sitas (2017) Strategic water source areas for urban water security: Making the connection between protecting ecosystems and benefiting from their services. ***Ecosystem Services* 28:** 251-259. https://www.sciencedirect.com/science/article/pii/S0921800920300793

Nordhaus WJ & J Tobin (1972) Is ***Growth Obsolete? The Measurement of Economic and Social Performance 5: Economic Growth***. National Bureau for Economic Research, USA
https://www.nber.org/books-and-chapters/economic-research-retrospect-and-prospect-volume-5-economic-growth

Paterson AR (2009) Guidelines for protected areas legislation: South Africa. IUCN-EPLP No. 81
https://www.iucn.org/downloads/south_africa.pdf

Retief FP, ND King & HA Strydom (2018) ***Fuggle & Rabie's Environmental management in South Africa***, 3rd ed. Juta, Cape Town

Sachs J (2005) ***The end to poverty.*** Penguin books 448 pp

Schreiner RB (2013) Viewpoint - Why has the south African National Water Act been so difficult to implement? ***Water Alternatives* 6**: 239-245

Schuyt K & L Brander (2004) ***The economic values of the world's wetlands*** WWF Gland, Switzerland

Shelton JS, O Weyl, A Chakona, B Ellender, K Esler, D Impson, J Jordaan, S Marr, T Ngobela, BR Paxton, J van der Walt & HF Dallas (2018). Vulnerability of Cape Fold Ecoregion freshwater fishes to climate change and other human impacts. ***Aquatic Conservation: Marine and Freshwater Ecosystems* 28**: 68-77. DOI: 10.1002/aqc.2849

Silberbauer M (2019) Internet-based applications for interrogating 50 years of data from the South African national water quality monitoring network. ***Hydrological Sciences Journal* 65**: 726-734

Stafford L, D Shemie, T Kroeger, T Baker & C Apse C (2019) ***The Greater Cape Town Water Fund; assessing the return on investment for ecological infrastructure restoration, Business Case March 2019*** The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/GCTWF-Business-Case-April-2019.pdf

Swatuk LA, G Brill, C Büchner-Marais, K Carden, E Conradie, J Day, J Fatch, J Fell, M Hara & B Ncube (eds) (2021) ***Towards the blue-green city: Building urban water resilience***. South African Water Research Commission Report no. SP 153/21,

Tharme RE & JM King (1998) ***Development of the building block methodology for instream flow assessments.*** South African Water Research Commission Report no. 567/1/98

Tickner D, JJ Opperman, R Abell and others (2020) Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. ***BioScience* 70:** 330–342 https://doi.org/10.1093/biosci/biaa002

Wishart MJ, BR Davies & BA Stewart (2002) ***Examining catchments as functional units for the conservation of riverine biota and maintenance of biodiversity.*** South African Water Research Commission Report no. 975/1/02

van Wilgen BW, RM Cowling & CJ Burgers (1996) Valuation of ecosystem services: a case study from the fynbos, South Africa. ***BioScience* 46:** 184–189.

Walmsley JJ (1995) Market forces and the management of water for the environment. ***Water SA* 21**: 43–50.

Wilson EO (2001) ***The future of Life*** Alfred A Knopf Publishers, New York

Williams DR, A Balmford & DS Wilcove (2020) The past and future role of conservation science in saving biodiversity ***Conservation Letters* 13**: https://doi.org/10.1111/conl.12720

INTERNET SOURCES LAST SOURCED ON 29.11.2022

Berg River Dam
https://en.wikipedia.org/wiki/Berg_River_Dam

Bill of Rights
https://www.justice.gov.za/legislation/constitution/saconstitution-web-eng.pdf.

CAPE programme
https://www.sanbi.org/biodiversity/science-into-policy-action/mainstreaming-biodiversity/ cape-programme/

Climate change
https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

https://mg.co.za/environment/2021-10-21-greenpeace-investigation-exposes-countries-trying-to-dilute-climate-report/

https://unearthed.greenpeace.org/2021/10/21/leaked-climate-lobbying-ipcc-glasgow/

https://www.ipcc.ch/

https://www.oxfam.org/en/5-natural-disasters-beg-climate-action

https://www.iol.co.za/news/environment/major-climate-catastrophes-in-store-for-south-africa-latest-ipcc-report-4bb20f70-db67-4636-af20-90cef5884252.

https://www.dailymaverick.co.za/article/2021-10-18-on-death-and-the-climate-crisis-we-have-woken-the-dragon-and-the-adults-have-left-the-room/

https://www.bbc.com/news/world-europe-49918719

Coal
https://www.bbc.com/news/world-africa-59135169

https://www.washingtonpost.com/climate-environment/2021/10/31/south-africa-has-one-most-coal-intensive-economies-world-can-it-change/

Ecosystems & ecosystem services
www.GreenFacts.org/ecosystems

http://www.parliament.uk/documents/post/postpn281.pdf

https://www.iucn.org/news/water/202002/emergency-recovery-plan-could-halt-catastrophic-collapse-worlds-freshwater-biodiversity

Environmental Law
https://uk.practicallaw.thomsonreuters.com/4-502-7865?transitionType=Default&contextData=(sc.Default)&firstPage=true

https://www.gov.za/documents/national-environmental-compliance-and-enforcement-report-2019-20-13-nov-2020-0000

Estuaries of theCape, Palmiet
file:///C:/Users/User/Downloads/Estuaries%20of%20the%20Cape_37.pdf

Extinction
https://www.iucn.org/news/water/202102/one-third-freshwater-fish-face-extinction-warns-new-report

FBIS (Freshwater Biodiversity Information System)
https://freshwaterbiodiversity.org/

https://www.dws.gov.za/iwqs/rhp/state_of_rivers/annual/State_of_Water_2017_2018_hydro_year_updated_FINAL_2019_10_11_web.pdf

Happiness
https://ophi.org.uk/policy/gross-national-happiness-index/

https://www.pnas.org/doi/10.1073/pnas.2016976118.

http://www.princeton.edu/main/news/archive/S15/15/09S18/index.xml?section=topstories

IPCC contribution
https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/South%20Africa%20First/South%20Africa.pdf

IUCN
https://www.iucn.org/about

Millennium Assessment
https://www.millenniumassessment.org/documents/document.766.aspx.pdf

National Water Resources Agency
https://businesstech.co.za/news/energy/573048/south-africa-plans-new-state-water-utility/#:~:text=South%20Africa%20has%20begun%20the,off%20potentially%20crippling%20water%20shortages

Natural resources

Cobalt
https://frontiergroup.org/blogs/blog/fg/first-step-combatting-cobalt-shortages-stop-throwing-it-out

Critical elements
https://en.wikipedia.org/wiki/List_of_elements_facing_shortage

Lithium mining
https://www.volkswagenag.com/en/news/stories/2020/03/lithium-mining-what-you-should-know-about-the-contentious-issue.html

Planned obsolescence
https://uspirg.org/blogs/blog/usp/introducing-junked-design

Rare earth elements
file:///C:/Users/User/Downloads/TheRareEarthElements-AnIntroduction-2016.pdf

https://www.steenkampskraal.com/

NFEPAs
https://www.fosaf.org.za/documents/SANBI/fish-priority-areas.pdf

http://biodiversityadvisor.sanbi.org/wp-content/uploads/2016/07/NFEPA-Presentation-for-Policy-Audience-2011.pdf

Oil companies
https://www.nytimes.com/2021/05/26/business/royal-dutch-shell-climate-change.html

https://www.shell.com/media/news-and-media-releases/2021/shell-accelerates-drive-for-net-zero-emissions-with-customer-first-strategy.html

https://corporate.exxonmobil.com/News/Newsroom/News-releases/2022/0118_ExxonMobil-announces-ambition-for-net-zero-greenhouse-gas-emissions-by-2050#:~:text=Initial%20steps%20to%20achieve%20net,ExxonMobil%20with%20additional%20investment%20opportunities.

Pansteatitis
http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1019-91282012000100019

https://www.wrc.org.za/wp-content/uploads/mdocs/KV%20299-12.pdf

Population growth rate
https://www.macrotrends.net/countries/ZAF/south-africa/population-growth-rate

www.greenpeace.org/africa

Poverty
https://www.un.org/en/global-issues/ending-poverty#:~:text=There%20has%20been%20marked%20progress,poverty%20is%20within%20our%20reach.

https://www.oxfam.org/en/press-releases/worlds-billionaires-have-more-wealth-46-billion-people.

Restoration
https://www.epa.gov/wetlands/basic-information-about-wetland-restoration-and-protection.

Rewilding
https://en.wikipedia.org/wiki/Rewilding_(conservation_biology)

River Health Programme
https://www.dws.gov.za/iwqs/rhp/state_of_rivers.aspx

https://www.dws.gov.za/iwqs/rhp/rhp_background.aspx

State of the Rivers Report, Palmiet River
https://www.dws.gov.za/iwqs/rhp/state_of_rivers/state_of_diep_03/WC_diep_sor_A4.pdf

Socio-economic benefits of ecosystems
http://www.acdi.uct.ac.za/socio-economic-benefits-ecological-infrastructure-sebei

http://thehessiansack.blogspot.com/2012/06/age-of-healing-by-john-seymour.html

South Africa Climate & Development Initiative
http://www.acdi.uct.ac.za/socio-economic-benefits-ecological-infrastructure-sebei

The Nature Conservancy
https://afr100.org/content/nature-conservancy

Wildlife Society South Africa
https://wessa.org.za/

WWF SA
https://www.wwf.org.za/

World population growth
https://upload.wikimedia.org/wikipedia/commons/5/51/World_population_growth%2C_1700-2100%2C_2019_revision.png

https://www.bbc.com/news/health-53409521

Working for Wetlands
https://www.dffe.gov.za/projectsprogrammes/workingfowetlands#:~:text=The%201984%20Conservation%20of%20Agricultural,in%20force%20to%20this%20day

The river in my youth
(Kate Day and Francois Theron)

I spent weekends by the river in my youth
Days when we would swim
Miles paddled in a canoe.
The fish that we caught seemed to be limitless.

In my daughter's days, the river was a home
She would swim for a while, until her eyes began to burn
If the water level was high enough, she could paddle in my old canoe
She might sometimes catch a fish.

My grand-daughter goes to River Museum every weekend
She looks at old pictures of people swimming
She sits in a canoe to have her photo taken
(It used to be mine)
And she stares at skeletons of fish.

Ironic, isn't it?

These museum floors used to be flowing.
The wood used to be water.
The skeletons once had happy lives.
And my grand-daughter could have been just like me.

wandelguides / 123RF

CHAPTER TWELVE

Jenny Day

You and water: studying inland waters

> Is ditchwater dull? Naturalists with microscopes have told me that it teems with quiet fun.
>
> *GK Chesterton, The Spice of Life*

STUDYING INLAND WATERS CAN BE COOL

Having circumvented the political mismanagement of the last few years, it is time to put the environment back where it should be: uppermost in everybody's mind. We need a sound environmental understanding if we are to manage our rivers and wetlands appropriately for human wellbeing and for the wellbeing of the systems themselves. The study of natural environments is not just simply an esoteric pursuit carried out by academics in ivory towers. Getting wet and muddy, and sometimes cold and uncomfortable, is a physically and spiritually satisfying pursuit but it is also of practical value.

In this final chapter we introduce you to some methods for examining our inland waters and the plants and animals that live in them. We hope that what we have to say will help you the teacher, the school class, the natural history group or simply the concerned citizen, to expand your horizons by finding out something yourselves about aquatic ecosystems. Armed with information you have generated, you will be in a stronger position to defend the conservation of aquatic systems and the water that they depend on.

The study of inland waters ***is*** fun. We enjoyed it collectively for the best part of a century (although it is hard to believe that it has been this long). To be legitimately in the field in the middle of a summer's day when other poor academics are facing a computer screen or a class full of students who would rather be out surfing (or, these days, on their phones) is one of the blessings of being an ecologist. To be knee-deep in a beautiful mountain stream, to mess about in a boat on a vlei or an estuary or a wide, deep lowland river, and to know that you are ***working*** certainly adds to the enjoyment of life.

The information in this chapter is detailed enough to allow systematic sampling of a water body but even those of you who would just like to indulge in a little natural history should find it of some use. In addition, we provide lists of potential projects, ranging from some that are fairly challenging to others suitable for school classes or home activities.

> To business that we love we rise betimes, And go to't with delight.
>
> *William Shakespeare, Antony and Cleopatra*

Ezemvelo KZN Wildlife

Netting for fish, Ndumo Game Reserve: hot, muddy and wonderful.

Whatever your standpoint, the first thing is to decide what questions you want to ask. Then design the way in which you will go about answering them. This may seem obvious, but unless questions are sufficiently clear, it is easy to enter a world of data-rich confusion. When scientific questions are not clear, experimental designs are often flawed. So, think carefully before you act. Some questions can be addressed fairly simply, but others may be beyond your immediate resources. If you merely want to get to know some of the organisms that live in your local river or vlei, for instance, you will probably be very successful and thoroughly enjoy the exercise. The recommended guides to the identification of organisms (see reading list), together with readily available kits for simple chemical analyses and 'bug dials' (see later) for assessing the status of animal life in our inland waters, will take you a long way. On the other hand, detailed studies of pollution will be beyond the capabilities and resources of anyone without access to a professional chemical laboratory.

Perhaps the most successful student projects are those designed to examine invertebrates coupled with a limited number of environmental variables from two or three sites on a river or in a wetland. And in general, the best approach is to tackle only one (or maybe two) sites in a day. Be well prepared, with all the equipment you need and be sure that you collect biological and environmental data concurrently. Back In the lab, often on a later occasion, invertebrates can be sorted from the accompanying detritus and identified. It is often useful to have one group of students involved in the analysis of the biological samples, another of the water samples and another, the environmental data. Indeed, one of the pleasures of working on natural systems such as rivers or wetlands is that students with different skills and interests can all be involved. Those with practical skills can make equipment; those with a historical interest can find out about the history of the wetland and its catchment; geography students can be involved in drawing maps and in looking at flow patterns and aspects of geomorphology, while biology students can collect and identify the animals and plants. Those interested in physical science can perform the chemical and physical analyses, while those who enjoy mathematics can work up the data; artistically inclined students can illustrate the final report and those with good language skills can be responsible for writing up the result. Inspired teachers have gone as far as to get their drama, dance and music students to present a play about 'their' river or wetland. In our experience as teachers, students usually respond very positively to group work of this kind, especially if it has the added bonus of being 'relevant'. Many a school has shamed local authorities into action by producing a well-designed and carefully executed project with an environmental theme. This is what good teaching is all about: enthusing students with different interests and abilities, helping them to learn by cooperation, and showing them that what they do can make a difference.

Streams with stony beds, and wetlands with submerged plants, are the most suitable for study because invertebrates in these areas are usually common and they are also large enough to see with the naked eye. Large lakes and big rivers are more difficult, and not only because sampling them usually requires the use of a boat. Their beds are sandy or muddy and do not normally contain many different invertebrate taxa; while they may support a great biomass of zoo- and phytoplankton, the individual organisms are usually so tiny that it is really not possible to identify them without the aid of a good microscope. Indeed, one of the disadvantages of studying many freshwater invertebrates is that they are small and cannot be identified without at least a hand lens. If possible, try to have at least one or two dissecting microscopes available for practical work on the organisms.

SOME BASIC EQUIPMENT AND BIOLOGICAL SAMPLING METHODS

Many groups of animals and plants inhabiting our inland waters can easily be collected by hand. If you are simply interested in seeing what animals are present, then turning over stones, logs and twigs in a riverbed, or along the margins of a lake or wetland, will reveal all manner of small invertebrates that can be gently brushed or hand-picked into a tray on the bank, All you need is a small scrubbing brush or toothbrush, a pair of fine tweezers, a bulb pipette (such as an eye-dropper) and a shallow white plastic tray to put the specimens in for viewing (a drip-tray for pot plants works well, although a two-litre ice cream container will do). And don't forget a pair of strong wellies or waders. Wherever you collect, please make sure that you replace (same way up as before you moved them) any stones, logs, and so on that you have examined. Respect these little lives and don't destroy their homes.

Denise Schael

Wetland invertebrates collected in a single haul.

The simplest equipment for a happy day's collecting: tweezers, bulb pipette, nail brush and a small white sorting tray.

Please also remember that bilharzia is rife in many parts of South Africa (see page 306). If you are working in a bilharzial area, protect your hands with gloves and never allow water to splash onto your skin. If you suspect that bilharzial parasites may be present at your study site, carry a tightly sealed bottle of methylated spirits with you. To prevent infection by cercariae, if you get water onto your skin, dab on a little meths using cotton wool.

COLLECTING SAMPLES OF INVERTEBRATES

Because they are small, most aquatic invertebrates are collected with nets of one sort or another. Larger specimens such as crabs may also be collected by means of baited or unbaited traps. So-called 'macroinvertebrates' are generally considered to be those that can be collected by a fairly coarse (usually 1 mm) mesh. Such a mesh will catch larger individuals of most riverine invertebrates. To include even first-instar larvae, though, one usually uses an 80µm-meshed net, which is also commonly used for freshwater zooplankton (25µm nets for phytoplankton). It is best to use the largest mesh that will serve your purpose because the finer the net, the more easily it becomes clogged and the harder it is to sort the ***goggas*** from the accompanying gunge.

The box sampler

Semi-quantitative samples from riverbeds can be obtained with an easily-made box sampler, which consists of a topless and bottomless metal frame covered by netting on three sides, a tapered net on the fourth side, and a skirt of rubber flaps below. The tapered net has a collecting bottle at the end. It is best if the bottle can be unscrewed from the net. Such arrangements are not normally available commercially but a glance at the image should allow you to make one yourself. The bottom of the collecting jar consists of fine mesh (usually 80 µm), allowing water to flow through while retaining organisms in the jar. For some purposes, a mesh of 1 mm is adequate but if you want to include very early instars of insects, for instance, 80 µm is best. The box is placed firmly on the cobble bed of a stream with the face containing the collecting jar at the downstream end. The operator removes large stones before washing and lightly scrubbing the remaining stones to dislodge any organisms into the net. The gravel inside the box is then stirred so that benthic animals are dislodged and also swept by the current into the jar.

Jenny Day

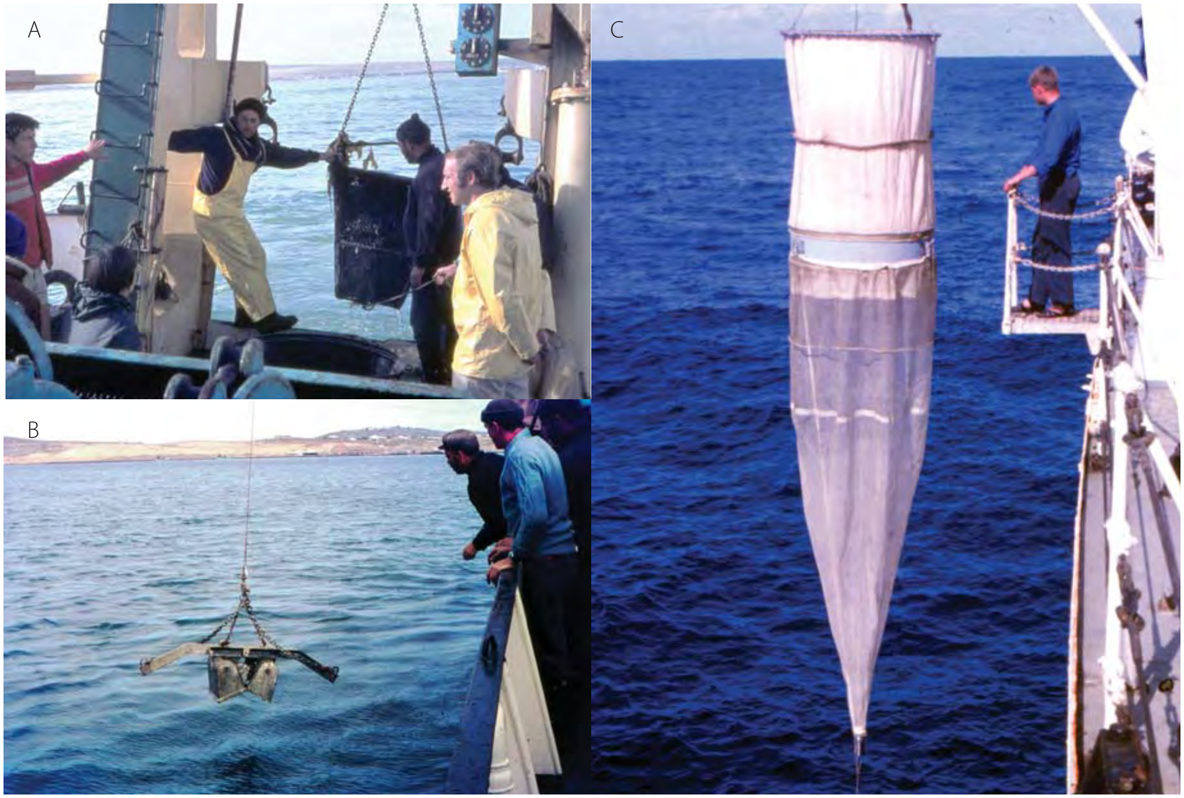
Jenny Day

Jenny Day

A) A net suitable for collecting invertebrates in shallow wetlands; the handle is about 75 cm long; B) The end of the net showing the removable collection jar, 9 cm in diameter, covered with plankton mesh; C) smaller nets: the one on the left is made from a 'knee-high' pantihose on an aquarium net; the one of the right is used for really shallow water, and is made from 80 µm plankton netting.

A simple hand-net can be made from a ring of wire from an old coat hanger, while the feet of pantihose make excellent nets for sweeping invertebrates from submerged vegetation or for filtering plankton from open expanses of water. Ensure that the net is fine enough to retain tiny animals; pantihose mesh is probably the best size that is easily available, and will retain even fairly small zooplanktonic animals. Some stream animals live on or under stones, logs or twigs, while amphipods and worms are found in gravel, and pond skaters and whirligig beetles on the water surface. Lifting stones and woody debris, and stirring the gravelly bottom, will disturb the animals living there. These can be caught in a handnet as the flow of water sweeps them downstream.

More sophisticated equipment, including plankton nets, grabs and dredges that can be operated from a boat, may be needed for sampling less accessible habitats. Several specialised companies manufacture equipment of this sort for large research vessels but are sometimes prepared to make smaller models that can be deployed from a small boat on a lake. Nets for sampling zooplankton usually have a mesh size of about 80 µm and for phytoplankton, whose cells are much smaller, about 45 µm.



Jenny Day

Peter Zoutendyk

Peter Zoutendyk

A dredge (A), a grab (B) and a plankton net (C) used in oceanographic work. Similar but smaller devices are often used in lakes.

A grab, when lowered from a boat, 'bites' the sediment when the jaws close, thereby trapping sediment and the invertebrates living on and in it. Grabs usually have very strong closing mechanisms, so one must be very careful not to lose one's fingers by accidentally setting off the closing mechanism – each of us knows a person to whom this has happened. Further, grabs can be frustrating devices: a small twig or stone caught in the jaws when they close will allow the escape of most or all of the sample by the time you have hauled it to the surface – most irritating on a cold and windy day in an open boat. Once at the surface, the grab is emptied into a bucket and the contents carefully washed out. Together with the grab, you will need a set of sieves of different mesh sizes through which the collected sediment can be washed. Again, you should ensure that the smallest sieve has a mesh fine enough to retain the organisms you are interested in while allowing the bulk of the unwanted sediment to pass through.

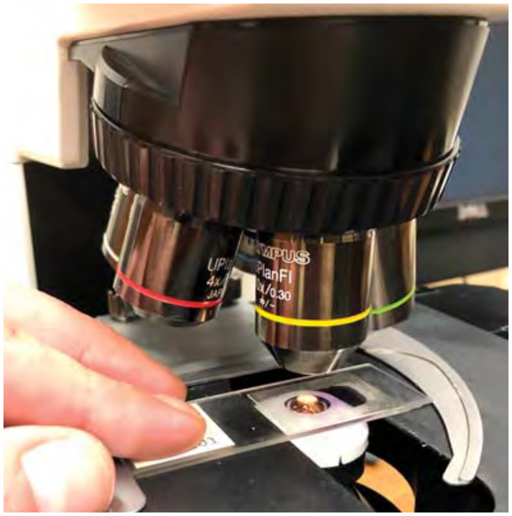
A dredge is a device that can be dragged along the bed to collect surface-dwelling creatures. It needs to be heavy enough to bite a couple of centimeters into the sediment, but light enough to handle on deck. Dredges are commonly used in the marine environment but less so in lakes and wetlands.

IN THE LAB

Animals and plants may be taken back to the laboratory for microscopic examination while they are alive, or they may be preserved for later study. The most humane way of dealing with animals that need to be killed for later study is to transfer them first to ice (or dry ice) in a portable freezer box, where they will rapidly become torpid and gently 'fall asleep'. This method will greatly reduce the stress of removal from their natural environment, transport to the laboratory, and direct preservation. Back in the laboratory they can either be stored frozen or (better) they can be thawed, fixed and preserved. **Fixation**, as the word implies, fixes the tissues in a close-to-lifelike state, while **preservation** maintains them in that condition. The best method of fixation is as follows. Prepare a 4% solution of formalin by adding 100 ml of full-strength formaldehyde to 900 ml of water. (Concentrated 'formalin' is a solution of 40% formaldehyde in water, so the solution you make will be 4% formaldehyde) Add a couple of broken sticks of ordinary white blackboard chalk to the container to neutralise the formalin. Fix the specimens in the 4% formalin for 24 – 48 hours, and then keep them preserved by storage in 70% ethyl alcohol (=ethanol). Formalin and alcohol are both obtainable at pharmacies, but ethanol is extremely expensive because of excise tax. A safer and cheaper substitute for storing (but not for fixing) specimens is a l% solution of phenoxytol (ethylene glycol monophenyl ether). PLEASE NOTE that formalin is a very dangerous substance and a proven carcinogen: handle it with extreme caution. For instance, while preparing the solution wear rubber gloves and a face mask, and use a fume cupboard if possible. The fumes are extremely unpleasant, while accidental ingestion of formalin must be treated immediately under medical supervision. (NEVER use an open glass-bulb pipette to transfer formalin, or alcohol for that matter.) While formalin is the most effective way of fixing a specimen, permanent storage in formalin is not ideal. If formalin is not available, preserve the specimens directly in 70% ethyl alcohol. If you wish to send your material away for identification, then it is essential to preserve it according to requirements of the specialist concerned. For genetic studies a variety of different preservation techniques may be required and need to be investigated before the specimens are collected.

It is worthwhile bringing living animals back to the lab, and even setting up a small aquarium. Ice (but not dry ice) can be added to the water to chill the animals, thereby reducing stress and preventing them from moving around too rapidly. Before transport, the larger beetles, dragonfly nymphs and other ferocious predators should be separated from other organisms, or you will arrive at the lab with fewer specimens than you started off with. Hard-shelled animals, such as snails, should be separated from soft-bodied ones in order to reduce damage and to ensure that everything gets back in one piece. Wide-mouthed vacuum flasks or plastic ball-jars with watertight lids are useful for transport. Animals should be transferred to cool, aerated water in the laboratory as soon as possible. To keep a few invertebrates alive for a couple of days, put them in a small clean ice-cream container or something similar with water just a couple of centimeters deep, and a teaspoon or so of the detritus from the sampling locality. (If there is too much organic material then the bacteria will get busy, your subjects will die, and you will land up with a nasty smelly mess.) You could also set up a larger aquarium, but you will probably have to use a pump and filter, as in a fish tank, to keep the water clean. In either case, provide the inhabitants with a stick or two protruding from the water so that emerging insects like dragonflies have a dry perch on which to moult.

If a picture is worth a thousand words, then seeing the beauty of a living aquatic organism under a microscope is worth a hundred thousand. The sheer delight and enthusiasm that can be generated in a group of students



A glass slide and coverslip in place under the lens of a microscope.

Both Jenny Day)

Light microscopes come in two kinds: dissecting microscopes (left) for low magnification (to about 50x) and compound microscopes (right) for magnification up to about 2 000x.

when they see a living ***Hydra*** for the first time is one of the greatest rewards of teaching biology. Invertebrates can be examined with a hand-lens or – if possible – a dissecting microscope at a magnification of about 10x. A simple dissecting microscope has a large working distance between the specimen and the lens so that the material under investigation can be manipulated using a fine needle or a pair of forceps (tweezers). Dissecting microscopes usually offer magnifications between 5X or 10X to 50X. Compound microscopes, used for higher magnifications, have a very small working distance between objective lens and the specimen. Specimens to be viewed under a compound microscope need to be laced on a microscope slide and covered with a coverslip (see figure above). Do not be fooled into buying a cheap toy compound microscope, which will probably produce an almost invisible image and cannot be used with specimens larger than a millimeter or so. A hand lens is much better than this.

Some microscopes come with a built-in camera, which is a very useful accessory but does increase the purchase price. You can often take a reasonable photograph down one of the tubes of a dissecting (or even a compound) mike using a cellphone camera.

IDENTIFICATION AND CURATION OF BIOLOGICAL COLLECTIONS

If you intend to take material back home or to the laboratory, here are some ***very important*** hints. Student projects have become useless, and expensively collected material has been fit only for the dustbin, because these simple but crucial rules have not been followed.

- Always label the samples immediately upon collection in the field. No matter how good you think your memory is, you will probably forget important details within a day or two, and if the specimens are to become part of a reference collection, over the years there will definitely be things that you forget, even about the most memorable sampling trips.

- Always write the relevant information ***in pencil*** on labels that are placed ***inside*** the specimen containers. Ink runs and almost all ink runs and even dissolves in alcohol. DO NOT write the label only on the outside of the sample jar, and even more important, do not label the samples only on the lid. Samples may be moved from one jar to another; lids may be misplaced and labels of the outsides of jars are very likely to rub off. Ergo, always have a complete label ***inside*** the jar with the specimens. When the collection has been sorted to species, each vial must have its own label that contains the same information as that on the original label of the whole sample.

- Make notes about your collections and collecting trips. We cannot overemphasise the importance of recording information as a collection is being made. If you make notes on a laptop, ***make a copy*** as soon as possible. If you use a notebook and pencil, keep the notebook safe, preferably protected from potential fires.

- For all purposes related to biodiversity assessment, taxonomy and ecology, it is imperative to know the 'provenance' of specimens: where they were collected, by whom, when, and under what circumstances. This means that ALL specimens need to be properly labelled with all of that information.

- The label should consist of suitable paper (normal A4 'bond' paper falls to pieces after some time in alcohol) and be of suitable size (about 25 x 20mm is commonly used). Working labels are usually written in pencil (preferably 3B or softer), and labels ready for curation in black ink. The ink used by most laserjet printers is stable in 70% ethanol but if hand-written, artists' Indian ink should be used. (If you want to use any other ink, ***experiment first***). Whatever else you do, write labels on one side of the paper only. Suitable paper and other 'entomological' supplies can be purchased through Mad Hornet at https://madhornet.co.za/about-us/.

- The label should contain at least the following information:
  date of collection
  name of collector
  site of collection (including sample number if appropriate)
  identification (as far as possible)
  name of identifier
  collecting gear (if appropriate)

> 22.02.2022
> coll. C. Kent
> wetland 3XQ
> 'Daily Planet' parking lot
> ***Kryptus krypton*** (Kryptonidae)
> I.D. Lex Luthor
> hand net

Jenny Day

Examples of labels, written in ink or pencil, and a microscope slide.

Notebooks with Belinda Day's sketches of specimens.

STORAGE

For initial storage before the specimens have been identified, keep the whole sample in one fairly roomy vial (so that the amount of alcohol is sufficient to keep the material preserved and submerged). When they have been identified and separated into the different species, store a few specimens of each species separately in small glass or plastic vials. Choice of vial depends on how long you plan to keep the material. If it is just for the duration of the project, plastic vials are adequate. You do need to check that they will not leak before you purchase them, though. Plastic vials are no good for long-term storage because the plastic starts to crack or to perish and the lids don't last long. Glass vials, on the other hand, will not perish but they are – of course – easily broken. We have found that glass vials with tightly-fitting plastic lids are the most satisfactory, and for permanent storage, the smaller the better. Fill the vial about ¾ full with 70% ethanol and add the label before placing the lid firmly on the vial. (Do not overfill or the top is likely to pop off.) If you plan to keep a reference collection of specimens, it is best to fill the vials about ¾ full and then stuff a small wad of cotton wool tightly into the mouth. Discard the lids. Keep these vials together in a larger jar filled with 70% ethanol. This is the safest way to avoid specimens drying out but even using this method it is necessary to check on them every couple of years and to top up the ethanol if the level of alcohol has dropped. ***Label them all properly*** before putting them away in a cupboard or sending them to a museum! Each jar needs to contain a list of the contents and you should provide a detailed list of site data containing the same information as on the labels.

For reference collections, or if you intend to ask an expert to identify specimens, each vial should contain at least several specimens (up to 100 if very tiny) of just one species/morph. Where possible, include males and females and both juveniles and adults. Use the smallest vial that the material will comfortably fit into (e.g., don't use a gigantic jar for minute copepods and daphniids). Make sure that the label contains all the necessary information (see above). If there aren't enough specimens in any one sample, you can merge samples from the same site but NOT from different sites (in case they turn out to be new species, in which case they will form the type specimens; and each sample of type specimens must be from a single site).

For sending by mail or courier – Today the South African Post Office is unreliable and few courier companies accept any goods containing ethanol (even perfume!). As long as specimens have been preserved in ethanol for some time, they will probably survive out of ethanol for a few days as long as they are kept moist. It's probably best to pack the contents of each vial as a little sandwich of specimens between sheets of labelling paper inside cotton wool that has been soaked in ethanol but then squeezed out. It would be simpler to omit the paper, but the limbs of many arthropods get tangled in cotton wool and the paper can prevent this from happening. Place each sandwich in a plastic bag together with a detailed label and pack several of them in a larger sealed bag and these in turn in a rigid container such as a small plastic box.

Ensure that you comply with national regulations about export and import of biological specimens. (See Hamer ***et al*** 2021 in the reading list.)

Biological supply houses stock most of the items mentioned above.

IDENTIFICATION

The major challenge will be in identifying your specimens once you have collected them. Fortunately, over the last 20 years or so a number of identification guides has become available. A series of volumes published by the South African Water Research Commission (WRC) between 2000 and 2007 provided the most up-to-date information available on each invertebrate taxon. They are still very useful but challenging to use for non-biologists. More recently, Charles Griffiths, Mike Picker and I produced a photographic guide called ***Freshwater Life*** (Struik 2015) and Elsevier is soon to produce a volume of keys to aquatic Afrotropical invertebrates. Within a year or two from now, we will be well served with literature on the identification of our aquatic invertebrates.

Christopher Cook (2004) and Karin van Ginkel and colleagues (2011) have written books on the identification of southern African freshwater plants, while Martin Hill and colleagues (2020) deal with alien invasive plants. Paul Skelton's classic book on South African fishes is in its second edition (2017) and the latest book on South African frogs is by Vincent Carruthers and Louis du Preez (2017). It is interesting to note that in the last 20 years or so, identification guides to almost South African aquatic taxa have been produced, making it relatively easy to do projects on aquatic invertebrates.

A NOTE ON TAXONOMY

Identification of plants and animals is based on the science of taxonomy (Greek ***taxis*** = arrangement + ***nomia*** = 'method'). The word ***taxon*** means a group of any rank from species to phylum and taxonomists are people who identify, describe and catalogue plants and animals, usually confining themselves to expertise in just one taxon. Although they are sometimes thought of as stuffy museum types fiddling around with pickled animals in dusty corners, taxonomists do the important job of keeping track of, and describing, new species and also assisting the rest of us in identifying our material. Not only do they describe animals and plants new to science but they also distinguish between species that, while closely related, live in very different environments. Such species tell us important things by their very differences. Without the efforts of taxonomists there could be little progress in almost any field of biology: until scientists know precisely which species of organism they are working on, they cannot reliably relay their results to, or compare their results with, those of other scientists.

The science of ***taxonomy*** Is complex, so here we will briefly outline just the major principles. Each organism known to science has been described by someone somewhere, and has been given a special double Latin name, the ***Latin binomial,*** a system devised nearly three hundred years ago by the Swedish botanist Carolus Linnaeus. The system, although technical is, in fact quite simple and is necessary to avoid the very real confusion that can arise from the use of common names. For example, there is a fish called the elf in the Cape and the shad in KwaZulu-Natal; in Australia the same fish is called the tailor and in the United States it is known as the bluefish. But scientists the world over know that the animal they are talking about is called ***Pomatomus saltatrix.*** And there are certainly many very different species of animal called 'mud prawn' all over the world. Without formal Latin names, it would be impossible to tell which was which. The formal system includes both a generic name, which always has its initial letter capitalised (for example, the elephant genus ***Loxodonta),*** and a second, the specific epithet, which is not capitalised ***(africana*** for the African elephant).The formal scientific name for the African elephant is thus ***Loxodanta africana;*** that for the human species is ***Homo sapiens,*** derived from ***Homo*** (human) and ***sapiens*** (wise or shrewd). Conventionally, in order to show that the Latin binomial is being used, the generic and specific names of all organisms are always italicised in print, or underlined in handwriting to indicate italics. You will note that these conventions are used throughout this book. You will also notice that once the Latin binomial has been written in full, the generic name may later be abbreviated to the first letter. So now we could refer to the African elephant as ***L. africana*** and to humans as ***H. sapiens***. (Note that the specific epithet is never abbreviated.) In summary, all species names consist of two words – the generic name (think of it as the 'surname') and the specific epithet (equivalent to the forename). There may be a number of species in the genus. Genera are grouped together to form Families, which are grouped to form Orders, which are grouped to form Classes, which are grouped to form Phyla. Humans and elephants belong to the phylum Chordata and the class Mammalia; at this point they separate, elephants belonging to the Order Proboscidea and the family Elephantidae, while humans belong to the Order Primata and the family Hominidae.

Reference collections are stored in museums worldwide and are invaluable. Not only do they save time and money when used to train students to identify the various taxa but they also provide a wealth of historical data. For instance, reference to the actual collection that resulted in published lists of species found in the scientific literature allows direct checking and

Charles Darwin's beetles, collected when he was a student; the large ones near the top left are British water beetles.

comparison with one's own collections made ten, twenty or even a hundred years later. This, in turn, provides enormous insights into tong-term environmental change, whether natural or human-induced. Schools and tertiary institutions can play an important part in the collection and curation of this type of information. Good well-curated collections may be accepted by museums and form part of their own holdings. (The Albany Museum of Natural History in Makhanda is the repository of most South African freshwater collections.)

SOME SIMPLE MEASUREMENTS

QUANTIFYING THE BIOTA

Here we get down to the nitty-gritty of studying the organisms we have collected. Sorting animals and plants from large quantities of sediment and dead plant material can be very tedious, but if we count the numbers of individuals in a sample we can add quantitative information to our assessment. By knowing the area covered by the box sampler or the 'bite' of the grab, and counting the number of individuals of each species caught, we can calculate the number of animals per standard surface area (usually per square meter: m^{-2}) and we can then compare samples from different places or collected at different times of year. Plankton samples can also be quantified by calculating the volume of water filtered (volume in m^3 = area of the mouth of the net x number of metres travelled).

Usually, numbers and weights of animals in samples are expressed in terms of unit area (e.g., number of individuals per square meter – individuals m^{-2} – or dry mass per square metre – mg m^{-2}). Dry mass (often called 'dry biomass') is a commonly used measure of the amount of living material at a site or in an area. It can be obtained by weighing specimens that have been dried in an oven at about 60°C for 24 hours. Although it is useful to have a quantitative measure of biomass, this is not easy to achieve without access to a very accurate balance because invertebrates may have a dry mass of only one or two milligrams each. For this reason, many very useful studies deal only with numbers of individuals and not with biomass. Note that because of the different ratio of water to tissue in the bodies of different invertebrate species, wet mass is not a suitable measure. Just think of jellyfish, in which about 95% of the body is water, as opposed to a crab at about 70% water.

Because it is almost impossible to sample quantitatively in rocky-bed streams because of the uneven nature of the bottom, ecologists sometimes sample just the under surfaces of specific stones, after which they measure the surface area sampled and convert invertebrate numbers to numbers m^{-2}. While this technique is somewhat more quantitative, the disadvantages is that only certain taxa (those that cling to the stone as it is taken from the water) will be collected. Once again, you will need to decide which technique is best suited to answering the questions you are asking.

PHYSICAL AND CHEMICAL MEASUREMENTS

Without specialised analytical equipment it is difficult to obtain useful information on the chemical constituents in the water itself, although it is possible to make some useful but fairly simple measurements. These are necessary because differences in the species composition of different communities can nearly always be traced to differences in the physical or chemical environment.

Physical measurements

The temperature of water and sediments can be measured with an ordinary lab. or pool thermometer. Remember that temperature changes through the day, so if you want to make any comparisons, you will have to take temperature readings at the same time of day at each site. For those interested in longer-term studies of seasonal temperature fluctuations, old-fashioned maximum-and-minimum thermometers can be used. (There may be one or two gathering dust in an old store cupboard at the back of the science lab.) Today, small temperature 'buttons' can be deployed. They take (usually) hourly readings and can be left in the field for some months. Depending on the type (and cost), some can even be remotely downloaded. They are relatively inexpensive and are valuable for getting real temperature data, which is becoming more and more important as climate change kicks in. (You may need to camouflage them carefully to reduce human interference or theft – always a problem when recording devices are left in the field.) One solution is to hollow out a small cavity in a brick and insert the button.

The flow rate of running water can be measured by throwing a floating object (an orange is best) into the stream and measuring the time it takes to cover a measured distance. Repeating the measurement several times at different points at the same site will allow you to obtain an average speed. The results are usually expressed as current speed or flow rate in metres per second (m/s). Of course, sophisticated flow meters are more accurate, but they can cost tens of thousands of rands. If you do use a proper flow meter, however, remember that due to friction, surface flows towards the middle of any stream are always faster than those close to the banks or the bed, and that the average current speed actually occurs approximately two-thirds down from the surface. The discharge, or volume of water passing a given point of a river per unit time, can be calculated by multiplying the flow rate by the cross-sectional area of the stream. This, in turn, can be obtained by multiplying stream width by average depth (calculated from depths at various points across the stream). Discharge is normally expressed as cubic metres per second (m^3/s), often abbreviated to 'cumecs'.

As for the biotopes inhabited by benthic organisms, it is often useful to measure the particle size of the substratum upon which, or within which, they are found. (Note that the terms ***substrate*** (singular) and ***substrates*** (plural) normally refer to the food sources of microbes, such as bacteria and fungi, while in ecology the terms ***substratum*** (sing.) and ***substrata*** (pl.) are used to denote the surfaces that organisms such as invertebrates and attached plants use as their 'homes'.) For comparative purposes, the easiest way to do this is to estimate visually the proportion of bedrock, large boulders, smaller cobbles, gravel, and mud in a given area of stream bed. This can be done on a small scale by estimating the proportion of each type in a quadrat of particular size. A quadrat can be simply a square frame of known area.

Simple chemical measurements

The degree of acidity or alkalinity of waler, using the pH scale, can be estimated with universal indicator paper, obtainable from suppliers of swimming-pool products. The scale runs from 0 (most acid) through 7 (neutral) to 14 (most basic or alkaline: see Chapter 7). Natural waters vary from about 4 (acid, black waters in the south-western Cape) to 9 or even 10 in waters with high levels of photosynthesis. Although some wetlands are naturally rather alkaline, values of 9 and above usually indicate eutrophic conditions. (See page XX for details on pH in natural waters.)

In chapter 7 we wrote mostly about EC or electrical conductivity, which is a surrogate for the amount of salt in water, or Total Dissolved Solids (TDS). These days EC is used more commonly than TDS because very good, accurate and not very expensive EC meters are available, and it is much easier to measure EC than to perform the necessary lab work to measure TDS. In your case, however, unless you are fortunate enough to have an EC meter easily available, you will need to do some simple lab work. A sample of water should be filtered using the finest pore size of filter paper available (0.45 µm is best), then a known volume (usually a litre) of the filtered water is placed in a clean, dry, weighed beaker. The water is allowed to evaporate to dryness in an oven at 60°C and then the dry, cooled beaker is weighed again. The difference in weight of the beaker before and after evaporating the water will be the amount of salt left in the beaker after evaporation. If the water is very pure, you should use a small beaker (250 to 300 ml capacity) and keep topping up the volume as the water evaporates, until the entire quantity has evaporated. In this way, the weight of the beaker is fairly small relative to that of the residue, and experimental error is reduced. Seawater has a TDS value of about 35 mg/L (often expressed as a salinity of 35 or 35‰, where ‰ means 'parts per thousand') while some fresh waters may contain no more than 20 mg/L TDS and the TDS of tap water is usually of the order of 100-200 mg/L. See further details on TDS on page 153.

The amount of oxygen dissolved in water depends on physical factors such as temperature (less oxygen stays in solution as temperature increases), salinity, turbulence and pressure. Altitude will have an effect on the amount of oxygen dissolved in the water since atmospheric pressure falls with increasing height above sea level. Chemical factors like salt content (TDS) and biological factors like the ratio between the production of oxygen by plants and its consumption by microorganisms, plants and animals, all affect the amount of oxygen that can dissolve in water. The amount may also differ with time of day: at night there may be a net loss of oxygen, for there can be no photosynthesis without light. Given these facts, it should be clear that taking a single measurement of oxygen may mean very little. So, the question is whether the level of dissolved oxygen is high or low in relation to the total amount that ***could*** be dissolved in water of this salinity at this temperature, at this pressure and at this time of day. It is necessary, therefore, to find out the amount of oxygen that saturates water of a particular salinity and at a particular temperature and pressure. This is considered to be 100% saturation and figures obtained are usually calculated as a proportion of this. For example, a sample of fresh water and another of sea water, both at 20 °C, may each contain 5mg/L of oxygen But, this is about 98% saturated for sea water and only 76% saturated for fresh water. In the example, then, it looks as if there is far more decomposition and respiration going on in the fresh water than in the sea water. Most textbooks on water chemistry give tables that show the amount of oxygen needed to saturate fresh water at a particular temperature, and some include nomograms for different salinities and pressures too. Having said all that, it has to be pointed out that although oxygen meters are very easy to use, reliable ones are very expensive. It is possible to titrate for oxygen, however, and thus avoid the expense of an oxygen meter. Details of the methods (usually the Winkler Method) are available in Golterman ***et al*** (1978). Winkler titration is in fact, the most accurate means of measuring oxygen levels if it is done carefully. Details of the Winkler method are available on many websites, one of which is given at the end of this chapter.

Chemical analyses are usually difficult and expensive to undertake, and not many are useful for your purposes. The kits used by aquarists can be used to measure some of the more important abiotic features of water, including hardness (a measure of the amount of calcium and/or magnesium present) and pH. Nutrients such as nitrates, ammonium and phosphates can also be measured using commercially available kits, but these are relatively expensive, and seldom measure low concentrations accurately, so you should purchase them only if you are sure that they will give you useful results. Note that the analytical techniques used in these kits are usually not sensitive enough to measure the very tiny concentrations of nutrients found in most natural waters. They are, however, useful for analysing polluted water, particularly for monitoring changes resulting from alterations in management practices. Finally, there are various commercial labs that will analyse water samples, but usually at considerable expense.

BIOASSESSMENT

Bioassessment refers to the use of living organisms for assessing various aspects of the biological integrity (some call it the 'health') of ecosystems. Bioassessment techniques are based on the premise that living organisms, especially the more sedentary ones, reflect the conditions in which they have lived throughout their lives. In aquatic systems these are usually the physical and chemical conditions in the water that together determine 'water quality' (see Chapter 7). If it were possible to measure continuously the changes in the concentration of every single chemical substance, and in the magnitude of every single physical attribute of the water, then bioassessment would not be necessary if we could also interpret the significance of all these changes. But it is not possible to do either. In real life, even where chemical monitoring is routinely carried out on a river weekly or monthly, the chances are very small that a sample will have been taken during the brief period of a transitory pollution event. Furthermore, some of the most toxic substances (pesticides, for instance) are difficult and expensive to detect and quantify. This means that they are seldom, if ever, included in routine monitoring programmes. We need to rely on the organisms to tell us what has been happening in their world.

Numerous methods have been developed for bioassessing the integrity of aquatic systems. Some of these are based on some aspect or other of a single species (the bioaccumulation of heavy metals in a particular species of fish, for instance), but most are based on attributes of whole assemblages of organisms such as fish, algae or invertebrates. Interestingly, although some methods have been available for many years, biomonitoring has only recently become a routine tool in the management of inland waters. SASS, the South African Scoring System, a technique that uses invertebrates as tools in the rapid bioassessment or water quality in rivers, has become part of the routine assessment in South Africa, and it now has offshoots in various other African countries from Botswana to Tanzania. Because SASS is a relatively simple tool that provides useful information about water quality, we describe it here in some detail.

SASS: THE SOUTH AFRICAN SCORING SYSTEM

The late Dr Mark Chutter developed SASS in the 1990s. The technique is loosely based on a British biomonitoring system that was modified and improved to fit local conditions. Although the basics of the system are now well established it continues to be refined, for instance, by incorporating new information on invertebrates from different parts of the country. The current version is known as 'SASS 5'. Two premises underpin SASS. The first is that that some invertebrate taxa are much more sensitive to chemical pollutants than others are. Some families of fly larvae, for instance the blephariceridś, are found only in the purest waters in mountain streams, whereas others such as syrphids may naturally occur even in foul water polluted by the decaying carcass of a large mammal. The assemblage of families of invertebrates present at a site in a natural river may at one time include some that are fairly sensitive to, and others that are relatively tolerant of, pollution. But the more polluted the water, the fewer sensitive species will be able to survive in it. The second premise is that the invertebrate faunal assemblage at any site at any time is dependent not only on the water quality at the time of sampling, but also on the conditions that have pertained at that site over the entire lifespan of the individuals that make up that assemblage. This is particularly true for the more sedentary forms, since mobile ones are able to move away and later to recolonise as soon as conditions are suitable again. If the water quality of the system has been reduced by low-grade pollution over a long time, or if a transient 'pollution event' has passed over the site, the more sensitive families will have been unable to survive there. Aerial spraying of an insecticide onto crops may result in pollution of a nearby river, for example. The species that are sensitive to the insecticide will be killed. Their absence days or weeks later indicates to us that such an event has occurred even though we may have no chemical analyses showing that the insecticide was briefly present in the water. In summary, SASS uses the presence or absence of riverine invertebrates as a means of estimating water quality in the river over time.

Two issues need to be mentioned at the stage. The first is that SASS does not work for wetlands. This is extremely annoying because it would be great to have either SASS or a similar system available for wetlands. The reason for its failure in wetlands is probably that the aquatic invertebrates in wetlands are generally much less sensitive to water quality than those that live in wetlands, so there is less distinction between sensitive and tolerant taxa. It may also have something to do with the fact that there are generally far fewer different taxa in wetlands than in rivers, at least in the upper reaches. The second is that SASS is now used very much as a general indicator of environmental conditions in rivers, although it is based specifically on an understanding of the effects of physical conditions and chemical constituents on the different taxa. It probably works because water quality is itself a reflection of general environmental condition. The distinction needs to be remembered in interpreting SASS results, however.

It may interest readers from other southern African countries that modified versions of SASS are available for rivers in all or part of Botswana, Tanzania, Zambia and Zimbabwe. See reading list.

Collection of a SASS sample in the field

Invertebrates are collected with a 'kick-net', a rectangular scoop-net on a stick (a broom handle works well). The sides of the frame should be about 300 x 400 mm. The mesh should be no larger than 1 mm and the bag should be deep enough (at least 400 mm) that the sampled material is not easily washed out by the force of the current. The material on the bed of the river is literally kick-sampled. Holding the net immediately downstream, vigorously turn over the rocks or pebbles of the substratum with a gumboot- or wader-shod foot so that the disturbed material, including leaves, twigs, sediment and animals, is washed into the net by the flow of the water. Sample all the biotopes available, as follows. Note that SASS is not a quantitative technique, but the sampling procedure should be followed exactly so that samples collected over time or at different sites can be compared.

- If **stones-in-current** biotopes are all kickable (i.e. can be turned over with the foot so that animals from the undersides will be washed into the net), they should be sampled for two minutes. If they cannot all be kicked they should be sampled for a maximum of five minutes.
- Wetted **gravel** is kicked for half a minute
- Marginal and aquatic **vegetation** is swept backwards and forwards over a distance of 2 m
- **Sand and/or mud** is stirred with the foot and the net swept over the disturbed area for half a minute
- **All other biotopes** are sampled for half a minute each

Dana Grobler

A SASS net in use.

The general Information on the SASS form is then filled in. Temperature, pH, conductivity and oxygen concentration are useful as supplementary information but are not essential for the SASS process. The contents of the net are tipped into a white tray because animals are easiest seen against a white or pale background (a photographic printing tray or pot-plant drip-tray about 400 x 330 mm is ideal). The leaves, sticks and other debris are removed, and the invertebrate families seen in the sample are ticked off on the SASS form. In routine sampling the sample in the tray is searched for 15 minutes or for 5 minutes after the last 'new' taxon has been spotted. The entire sample is then returned to the stream. If you are unfamiliar with the taxa in the sample you will probably have to take them back to the lab for identification using keys and a microscope. If the specimens will not be dealt with within an hour or two, they will need to be preserved first (see page 482 above).

Generating the SASS scores

For an example of the scoresheet, see the article by Chris Dickens and Mark Graham (https://communities.unep.org/download/attachments/38306043/SASS5%20Method.pdf?api=v2. Each taxon (usually each family) of invertebrates from South African rivers has been allocated a score, ranging from 1 for those taxa most tolerant of pollutants to 15 for those most sensitive to pollutants. The combined scores for all of the taxa at a particular site will be high if the taxa are mostly pollution-sensitive and low if they are generally pollution-tolerant. Thus the highest total scores are to be expected in the clean waters of upper rivers and the lowest scores in heavily polluted rivers. To complete the SASS exercise, add up all the scores (the Total SASS Score). Also count the number of taxa. Divide the Total Score by the number of taxa to obtain the ASPT: the average score per taxon.

Interpretation of the results

It is perhaps easiest to interpret SASS results by referring to an actual example. Table 12.1 compares SASS results obtained for three sites down the length of a hypothetical urban stream. The first site is a small mountain tributary; the second is a cobble-bed stream; and the third is a concrete canal a few hundred meters further downstream.

***Table 12.1.* An example of SASS-generated data from three sites along a hypothetical urban river.**

Sites			
Component of SASS	**Mountain (boulder bed)**	**Middle (cobble bed)**	**Urban (canal)**
Total score	198	133	21
Number of taxa	25	25	5
ASPT	7.9	5.3	4.3

The number of taxa is a measure of the biodiversity at a site. In our table, 25 taxa were recorded at both Mountain and Middle, while only 5 occurred in the canal. (This is because there is virtually no place for animals to live in canals unless they can cling to the bare concrete in the face of the rushing water.) The total scores are 198 for the site in the Mountain Stream, 133 for the Middle site and 21 for the Canal site. Since the first two have the same number of taxa, but the total scores are different, we can conclude that the taxa at the upper-most site are more sensitive to pollution than those at the Middle site: in other words, the upper of the two sites is less polluted than the lower. But what of the canal site? It has a single, rather inhospitable biotope, so how can we compare sites with different kinds and numbers of biotopes? Rivers in some stretches merely have sandy bottoms, perhaps with a little marginal vegetation, while others have patches of gravel, boulders underlying runs and riffles, instream and marginal vegetation, and dead logs and other 'snags' under or on which the invertebrates can live. Surely the number of taxa (and therefore the total SASS score) will be influenced by these differences, even if water quality is high at both sites? Yes, they will be, and that is why the calculation of the ASPT is essential in the interpretation of SASS scores. Generally, even if the number of taxa and the SASS score are low because of a limited number or biotopes, the ASPT will still reflect the overall sensitivity or otherwise of the organisms that are able to live at a particular site. In this way, it is possible to compare sites at a particular time, as well as being able to monitor changes at a particular site over time. In the case of the three sites compared above, Mountain has the highest ASPT, and therefore the fauna is telling us that the water at this site is least polluted. The other two sites have considerably lower ASPT values than the Mountain site but the difference between the two suggests that, although the number of taxa is restricted by the canal, the water quality is not ***severely*** impaired, if at all.

What SASS can be used for

As mentioned above, SASS was specifically designed for estimating impairment of water quality. It can be used for many purposes, among them:

- assessing the 'state of the river' at different sites;
- following changes in water quality over time at particular sites;
- routine monitoring to detect 'unseen' and transient pollutants;
- following the success (or otherwise) of rehabilitation measures.

Cautions

Despite its remarkable value in many respects, words of caution need to be issued. These mainly concern what SASS Is ***not*** designed to do:

- It cannot distinguish between different types of pollutants, because we do not know enough about the effects of particular types of pollutants on particular taxa;
- It cannot predict changes in the water quality of a river; it can provide useful information only about the present and the recent past;
- It cannot provide information about degradation of habitat (although careful examination of the relationship between total score and ASPT may give a clue that there is something wrong);
- Comparisons cannot be made over wide geographical areas, or different zones of a river, because even under 'pristine' conditions the faunal assemblages may differ in their responses to water quality, and water quality itself will differ;
- SASS values will differ from season to season even at a single site, so valid comparisons cannot be made unless normal seasonal variations are known;
- It cannot be used reliably in wetlands.

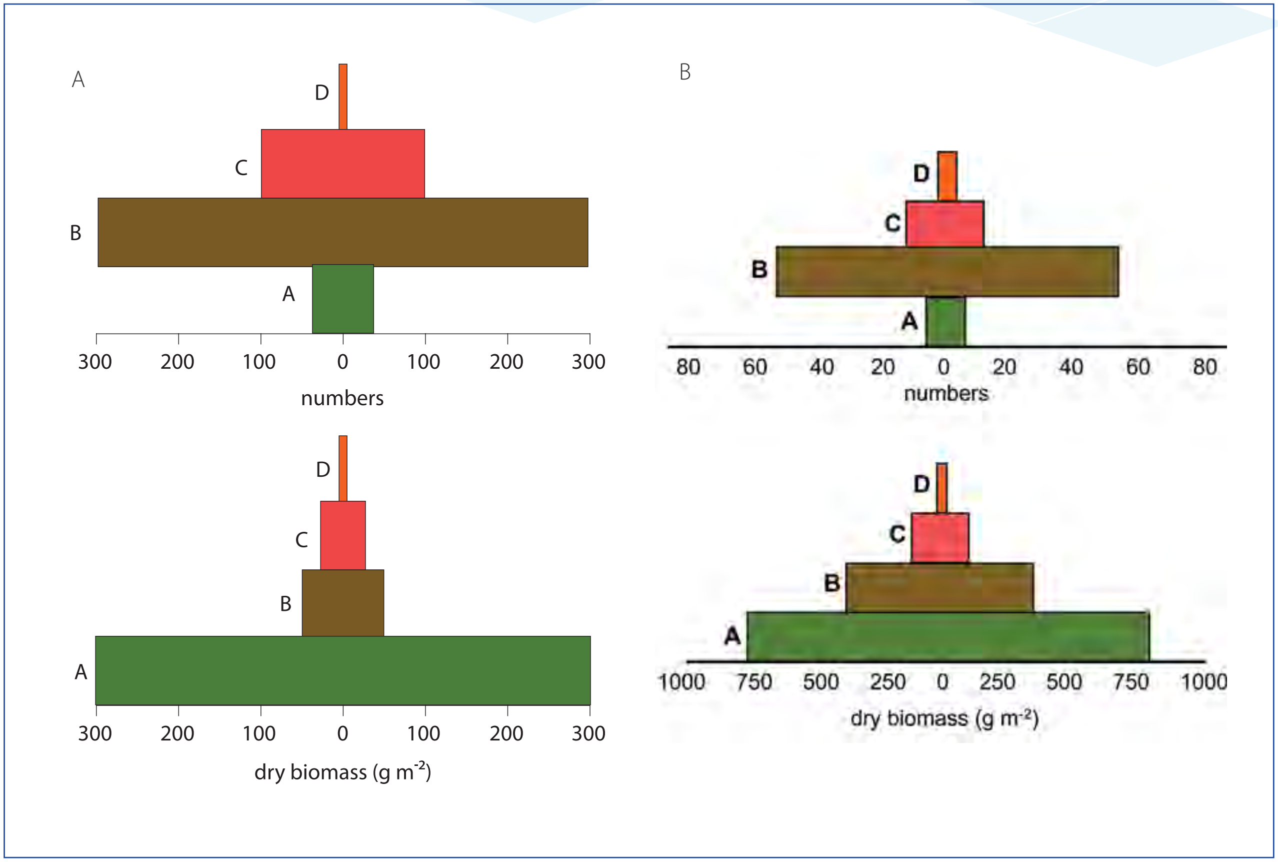
These words of warning are intended to prevent you from trying to make sense of inappropriate SASS data. We do believe, though, that if you take these into account, you will be able to get a lot of valuable results – and have fun – using SASS.

The description above of SASS is no more than an introduction. Helen Dallas has written a number of papers on the topic. See the reading list for one of her earliest papers on the subject (Dallas 1997) and one of the latest (Dallas 2021). Helen's 2021 paper discusses variants of SASS that have been developed and are employed elsewhere in Africa. Mini-SASS, a junior version of SASS, is described in the text box on page 497.

HOW TO PRESENT YOUR RESULTS

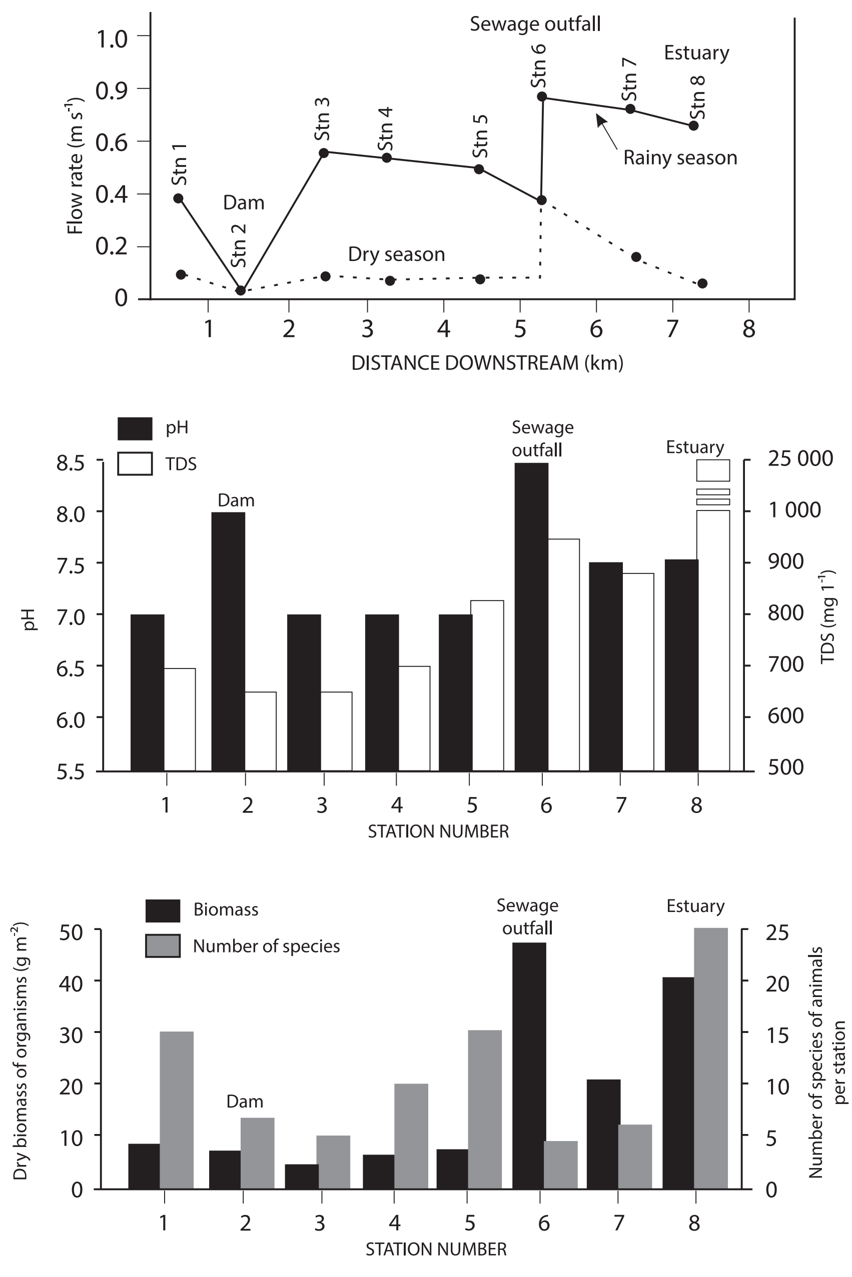
When you have finished collecting, sorting and identifying your samples you will be in possession of lots of data on water chemistry, flow rates, and substrate size, many little labelled vials containing animals, lists of species' names, biomass figures, and so on, but the endpoint of all research must be an organised report of one sort or another. You can gather valuable data from year to year but, unless you write down your results and put your conclusions on paper, you will lose insight into the way in which your system and its components operate. It also helps, before you start your project, to ask yourself just what you are trying to achieve so that you will collect useful information and not just a random collection of numbers and bugs. Some questions often asked by ecologists include:

- What does the trophic pyramid of this system look like?
- Are pyramids similar if based on biomass and numbers? What does this mean?
- If the pyramid is 'top heavy', what is replacing the primary producers In the system?
- Are there differences in the biomass or the structure of the trophic pyramid down the length of the river, or in different parts of a wetland, or at different times of year? If so, how different are they, and why?
- Are there more species in one region than in another? Why might this be?
- Does a particular part of the system appear to be more greatly influenced by human activities than another?
- Over what distance does it take for a river to recover from the effects of a dam or a human settlement?



Trophic pyramids for a hypothetical wetland constructed a) for numbers of individuals and b) for dry biomass values. A = primary producers; B = primary consumers (herbivores); C = secondary consumers (carnivores); D = tertiary consumers (top carnivores).

It is very useful to produce simple line graphs or histograms and they are effective ways of displaying your data. There are a few points to remember when you are producing them, though. Firstly, it is important to give enough information in the caption to explain what you are attempting to convey in the illustratlon. Secondly, in graphs and histograms, the axes must be clearly labelled and it is absolutely essential that units of measurement are given: time in years or days or seconds; mass in micrograms, milligrams, kilograms; concentration in mass per unit mass or volume (e.g mg/L, g/kg), etc. In the figure on page 492 for instance, the flow rate is clearly given as msec-1 or m/s on the vertical, or 'y', axis and distance in km on the 'x' axis. Thirdly, if you compare the diagrams in this figure, you will see that that histograms are used in two, while a line graph is used in the other. The reason for choosing one or the other lies in the type or data that you have. If there are continuous numerical values for both variables, for example flow rate vs measured distance downstream, then a line graph must be used. If, on the other hand, you have chosen stations and arbitrarily numbered them or given them names, ignoring the real distances between them, then they are ***discontinuous*** and their uniform separation on the 'x' axis is purely fortuitous. You may, for example, have chosen more or fewer sites, or a group of sites close together in the upper parts of a river and a couple far apart further down. There is no numerical relationship between them, and under these circumstances you must produce a histogram and not a graph.



Examples of how quantitative results may be presented A) as line graphs and B) and C) as histograms. Note that in all cases both axes are labelled, units are provided and information is given about the various sites.

SOME SUGGESTIONS FOR PROJECTS

Using the information in the first part of this chapter, you will be able to undertake projects designed to find out many different things about your local river, wetland or estuary. We leave it to your imagination to expand, contract or modify these suggestions as appropriate to your needs. Although the projects are not listed in any particular order, they vary from simple to highly technical.

- Map the distribution of the alien and invasive aquatic plants in your area. Find out who is selling alien aquatic plants locally, which authority is responsible for prosecuting offenders and if this is not being done, why not. Give the maps to SANBI or your local nature conservation agency for further action.

- Investigate the extent of industrial, domestic and/or agricultural pollution in your area. What types of wastes are being discharged when, where, in what quantities, and by whom? As an additional challenge, find out the legality or otherwise of these activities. Are permits granted locally to allow legal avoidance of pollution-control standards?

- What garbage is there in your local river or wetland? Who dumps it? What legislation exists to prevent littering? Is the legislation effective? Who cleans up the mess, and how much does this cost the local council? Who ultimately pays?

WRC archives

The annual 'frog night' at Chrissiesmeer (Lake Chrissie) provides visitors with the unique opportunity to catch and identify some of the amphibians in the Mpumalanga Lake District.

- By consulting your local council office, find out the routes of the stormwater drains and what they carry. How old are they? How much stormwater is discharged in times of flood? Perhaps take some photographs or videos during a rain event. What sorts of wastes do stormwater drains convey during storms? Or the water mains in your town may be old and decaying. How many water mains leak in your area? What losses are entailed and what does it cost the ratepayers? What damage do the leaks create and where does the missing water end up?

- The sewers in your town may be old and decaying. How often do they leak? Where does the sewage go? What effect does it have on the health of the local community? What environmental damage do the leaks create and what plans does the council have to reduce this?

- Design a means of detecting water leaks.

- If you have a local water body that Is heavily used for recreation, find out what recreational activities are most common. Are these in conflict with each other? If so, which of these conflicting interests (e.g. power boating, bird-watching) 'wins'? How much money has been invested in recreational equipment by the local community? Estimate the purchase price of the holiday residences, water craft, angling equipment, and so on. How many jobs are created by all of these pursuits, and what does this mean for the local economy? How large a proportion of the income of the local community does this figure represent? What proportion is provided by out-of-town tourists? Once these figures have been worked out, you can compare the amount of money spent by the community in the upkeep and management of the water body against the income derived from it. Its worth will soon become apparent!

- Map the types and distribution of land-use in a small nearby catchment. Who Is responsible for the overall management of the land? Present your findings to the local residents. Map the exotic plants that are primarily responsible for bank erosion (for example, the black wattle, ***Acacia meamsii)***. How fast are they spreading? Is anyone keeping a check on them? Is Working for Water involved? If it isn't, how can it be contacted and asked for assistance?

- Investigate estimates of population growth in relation to water consumption in your area. Make projections for increased demand and find out how much water is actually available to meet that projected demand. Consider what should be done if the area is actually in water deficit.

- Visit a local dam. Find out what problems it causes. When and why was it built? Who uses the water? Is it a local recreational asset? What are the 'operating rules' (i.e. when is water released, and why) and are these followed? Are they appropriate?

- Investigate the farm dams in your area. Where are they? How much water is stored in them, and for what purpose(s)? What water rights do the farmers who own them think they have? What rights do they actually have? How many more dams do they intend to build and why?

WRC archives

Students studying the identification of wetland plants.

Farm dams situated close together make fascinating biological and ecological studies too.

- Investigate the wetlands in your area. Where are they? Find out the local attitudes to these important systems. Find out what ecosystem services they provide and to what sustained use they can be put. Convince yourself that they are not wastelands and then set out to convince others.

- Keep a record of when your local estuary opens and closes. Correlate this with climatic data like rainfall. Are humans involved in the final act of closure or opening of the mouth, or does this occur naturally? What reasons are given by the responsible authority for opening (or not opening) the rnouth artificially? Are bridges or culverts causing detrimental changes to your local river or estuary? Has there been an increase in siltation or changes in flow pattern or flooding since construction? Should the remains of old bridges and pilings be removed? (If so, by whom?)

- Design a water-saving device. Estimate the amount of water it will save. Does your local council offer incentives for the installation of such devices? If not, why not? Investigate the cost to your local council of the treatment of water before it arrives in your tap and after it leaves your home. Where exactly does your water come from? Where does the sewage effluent go after it leaves the wastewater treatment plant?

- Ask each pupil to monitor how much water is used in the home and to log the water meter. Get similar information for your school or college. Find out the cost in terms of water of their everyday activities. (Even the simple act of switching on a light bulb requires the use of some water, somewhere.) Calculate the amount of water used directly by the people who live in your street or your college and from there, the amount used by the local community. If carefully recorded, these data can form a useful long-term record.

- Compare the amount of water used by a garden microjet irrigation system with the amount of water used by spray irrigatlon system for areas of equal size. (To get some realistic answers would require some quite careful experiments.) How many gardens in your area use mulch and how many have water-thirsty plants? Calculate the surface area of grass lawns and then find out the quantity of water, fertiliser and pesticides they need for maintenance. What kinds of plants does your local council use for road verges and parks, and why?

- Set up an aquarium or a small garden pond for your family using local aquatic animals. You could even use a glass or plastic bowl with a few tadpoles. Feed tadpoles a ***small*** amount of boiled green vegetable every day and replace the water every couple of days to keep it clean. Remember to return the tadpoles to their original home when they begin to grow legs.

- Compare the amount or water used by a family that habitually showers against one that baths. If you have one, how much water does your swimming pool use? What chemicals do you put into it, and how much? What happens to the water when the pool is cleaned? Find out how many households have swimming pools and what volumes of water they hold, then calculate the amount of water they contain in total.

- Set up a study of a local stream or wetland with your biology students. Monitor the changes in water quality and animal and plant communities from week to week and from year to year. Try to correlate them with climatic, seasonal and human-induced events. Find out if everyone in your area has piped water and if not, find out where they obtain their water. How long does it take them to collect the water and how much energy do they have to expend collecting it? How clean Is the water?

- How salty is the water in your local river? Monitor the salt levels and investigate the causes. HINT: measure TDS (see page 486). How much soil erosion takes place locally? How does this affect the cost of water treatment and thus the local ratepayer? Who or what is causing the erosion? Can it be slowed or stopped?

- Investigate the ecology of a local farm dam. How much water does it contain? What invertebrates are present? What terrestrial animals use it for drinking water or as a source of food? What does the farmer use it for?

- Are any waterborne diseases rife in your area? Are they vector-transmitted? What methods are employed to control the vectors? What are the Impacts of these control methods on local aquatic organisms? Are the diseases on the increase? If so, why?

- Do you have trout in your local river? Who put them there? What is the impact of trout on the local fauna? Are the trout still being stocked? Which other fish once occurred there? What other alien fish and/or invertebrates occur in your area? What do they live on? Are the fish commercially useful? What indigenous fish have been harmed by them?

- What rare and endangered aquatic species do you have locally? List them, and find out where they occur, where they used to occur and whether or not they could be reintroduced into the areas they once frequented. ***Why*** are they endangered? Can you recommend ways of improving their chances of survival? Discuss this with your provincial nature conservation agency.

- Where does your local river come from and where does it go? Map it. What human activities go on in its catchment and what effects do these have on the river? Can any be ameliorated? How many people live in its catchment? Is its water used more than once before it reaches the sea?

- Conduct a survey designed to gauge public attitudes towards recycled water. Why are some people opposed to the idea? How much water evaporates from your local impoundment in summer? And in winter? How are evaporation losses affected by alien vegetation, particularly by floating plants?

- Set up simple home aquaria to grow and hatch out the adults of some common insect larvae. The information you gather might be of considerable value to entomologists, at the Albany Museum, for instance. Investigate the activities of SANBI in regard to the conservation of your local aquatic ecosystems.

- Find out about recent incidents of pollution in your local streams. Could they have been avoided? Was anyone prosecuted? If not, why not? Find out how much water your municipality uses for watering road verges and parks and for street cleaning. Where does this water come from?

- What is the state of your rivers? What animals live in them? How does this vary from reach to reach? Using SASS or mini-SASS, assess the status of water quality in your river at different sites. Inform your local authority of the results. Your school might sample a number of sites each year, and see if water quality becomes better or poorer over the years.

- Using SASS, follow the success (or otherwise) of rehabilitation measures implemented by Working for Water or your local council on your local stream. Start a 'Friends' group for your stream or wetland. (Contact WESSA for assistance.)

- Investigate SoDis (solar disinfection), particularly if you live in a remote area where safe drinking water is not available. All you need is a few empty 2-litre cooldrink bottles and a bit of sunshine.

These are just a few suggestions. But what of the woman- and man-in-the-street? You, too, can be involved and you can make a real difference. Why not start by asking your town councillors and members of parliament or political parties about their environmental policies, and then find out what they are actually doing in this regard. Environmental issues still take a back seat in our political life and politicians need to be reminded that, in fact, these are the most crucial issues for the future of the country. Try to stir them into some meaningful action before it is too late.

Resist to the best of your ability any environmentally insensitive alterations to natural systems. Keep an eye out for the illegal sale of alien aquatic plants from local nurseries. Speak to the owner and if that has no effect, inform nature conservation authorities. You are not 'letting the side down', you are helping to save our aquatic ecosystems (and the money in your own pocket – think of the later costs or eradicating the weeds).

Above all, instil into your family, your friends, your pupils or students, a respect for the natural environment and an appreciation of the value of water to us all. After all, we are all part of the environment and we and future generations will simply not be able to survive if we continue to abuse it through ignorance, pollution and overconsumption.

Have fun and enjoy your fresh waters while you still have some fresh waters left to enjoy!

‘WATER KITS’

Once upon a time one could obtain ‘water kits’, which consisted of some very basic equipment for measuring simple physical and chemical conditions in inland waters. Although the kits are no longer available, the following list will help you to re-create some of the components in the kit. Most items will be available from swimming-pool or aquarium (fish-tank) suppliers.

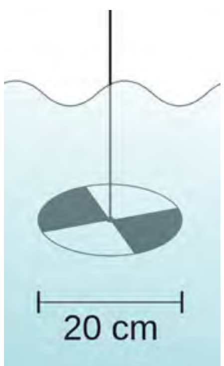
Physical conditions

current speed	an orange or other floating object
temperature	a pool thermometer
turbidity ***in situ***	Secchi disc: see illustration
turbidity of water	turbidity tube

Chemical conditions

pH	pH sticks for swimming pool
TDS	evaporation (see p. 486)
[nitrate]	nitrate sticks for swimming pool

Teacher’s kits, educational material about water, and a few simple instruments are available at
https://bit.ly/3lKNUhH
http://www.groundtruth.co.za



A Secchi disc is made from a disc of metal or plastic and painted. It is lowered vertically into the water on a graduated cord marked off at 10 cm intervals. The depth at which it disappears from view is recorded, as is the depth at which it can be seen again as it is pulled up. The ‘Secchi reading’ is an average of the two.

Mini-SASS

Ros Koch

School children using a SASS net (left) and (right) identifying their ‘catch’.

Mini-SASS (Stream Assessment Scoring System) is, as its name implies, a ‘junior’ version of SASS. It was developed by Mark Graham and colleagues (Graham et al 2004) for South African schools and has become a commonly used tool for citizen scientists wanting to assess the condition of local rivers. It is sponsored by the national Department of Water and Sanitation, the Water Research Commission, Ground Truth and WESSA (the Wildlife and Environment Society of South Africa). It is now also being used in various other countries in southern Africa, as well as in Canada and Australia: a Good News story indeed. Essentially, the same process is used as in regular SASS but the number of taxa scored is much smaller, and results are presented as categories ‘very good’ to ‘very poor’. Results can be uploaded on the mini-SASS website (https://minisass.org/en/), where they are integrated with others taken from different sites at different times. Millennials will appreciate being able to download their data and compare them with results obtained from other schools and in other areas.

Details are provided in the websites listed under Further Reading and the implications of this technique for citizen science are discussed in papers by Jim Taylor (Centre for Water Resources Research, University of KwaZulu-Natal, Taylor et al 2021) and colleagues. The website is very helpful in explaining how mini-SASS can be done, and how to interpret results.

READING LIST

Branch GM and M Branch (2018) ***Living Shores: interacting with southern Africa's marine ecosystems***. Struik Nature, Cape Town. 320 pp.

Chutter, FM 1998. ***Research on the rapid biological assessment of water quality impacts in streams and rivers.*** South African Water Research Commission Report no. 422/1/98 [the beginning of the SASS system].

Cook C (2004) ***Aquatic and wetland plants of southern Africa.*** Backhuys Publishers, 282 pp.

Dallas, HF and JA Day, 2004. ***The effects of water quality variables on aquatic ecosystems.*** Water Research Commission Report no. TT 224/04.

Dallas HF 1997. A preliminary evaluation of aspects of SASS (South African Scoring System) for the rapid bioassessment of water quality in rivers, with particular reference to the incorporation of SASS in a national biomonitoring programme. ***Southern African Journal of Aquatic Sciences*** **23**: 79-94.

Dallas HF (2021) Rapid bioassessment protocols using aquatic macroinvertebrates in Africa – considerations for regional adaptation of existing biotic indices. ***Frontiers in Water***. Doi: 10.3389/frwa.2021.628227

Day JA, BA Stewart, IJ de Moor and AE Louw AE (eds) (1999) ***Guides to the freshwater invertebrates of southern Africa, Vol 2. Crustacea I: Notostraca, Anostraca, Conchostraca and Cladocera.*** South Arican Water Research Commission Report no. TT121/00.

Day JA, BA Stewart, IJ de Moor and AE Louw (eds) (2001a) ***Guides to the freshwater invertebrates of southern Africa, Vol 3. Crustacea II: Ostracoda, Copepoda and Branchiura.*** South African Water Research Commission Report no. TT148/01.

Day JA, BA Stewart, IJ de Moor and AE Louw (eds) (2001b) ***Guides to the freshwater invertebrates of southern Africa, Vol 4.Crustacea III. Bathynellacea, Amphipoda, Isopoda, Speleogriphacea, Tanaidacea and Decapoda.*** South African Water Research Commission Report no. TT141/01.

Day JA and IJ de Moor (eds) (2002a) ***Guides to the freshwater invertebrates of southern Africa. Vol 5: Non-Arthropods***. South African Water Research Commission Report no. TT 167/02.

Day JA and IJ de Moor (eds) (2002b) ***Guides to the freshwater invertebrates of southern Africa. Vol 6: Molluscs and arachnids***. South African Water Research Commission Report no. TT182/02.

De Moor IJ, JA Day and FC de Moor(eds) (2003a) ***Guides to the freshwater invertebrates of southern Africa. Vol 7: Ephemeroptera, Odonata and Plecoptera***. South African Water Research Commission Report no. TT207/03.

De Moor IJ (ed.), JA Day (Series Editor) and FC de Moor (ed.) (2003b) ***Guides to the freshwater invertebrates of southern Africa. Vol 8: Insecta 2. Hemiptera, Megaloptera, Neuroptera, Trichoptera and Lepidoptera.*** South African Water Research Commission Report no**.** TT214/03.

Day JA, AD Harrison and IJ de Moor (eds) (2003) ***Guides to the freshwater invertebrates of southern Africa. Vol 9: Diptera.*** South African Water Research Commission Report no. TT201/02.

Golterman R, S Clymo and MAM Ohnstad, 1978, ***Methods for the physical and chemical analysis of fresh waters.*** Blackwell Scientific, Oxford. 214 pp.

Graham, M, CWS Dickens & RJ Taylor (2004) miniSASS – a novel technique for community participation in river health monitoring and management. ***African Journal of Aquatic Science*** **29:** 25–36.

Griffiths CL, JA Day & MD Picker (2015) ***Freshwater Life: a field guide to the plants and animals of southern Africa.*** Struik Nature. 368pp.

Hamer M, K Behr, I Engelbrecht & L Richards. Permit requirements, associated challenges and recommendations for biodiversity collections and research in South Africa. ***South African Journal of Science***. 2021;117(9/10), Art. #11765. https:// doi. org/10.17159/sajs.2021/11765

Skelton PH (2013) ***A complete guide to the freshwater fishes of Southern Africa*** 2nd ed. Struik Publishers, Cape Town. 395 pp

Stals R and IJ de Moor (eds) (2003) ***Guides to the freshwater invertebrates of southern Africa. Vol 10: Coleoptera***. South African Water Research Commission Report no. TT214/03.

Taylor J, M Graham, A Louw, A Lepheana, B Madikizela, C Dickens, D Chapman & T Warner (2021) Social change innovations, citizen science, miniSASS and the SDGs. ***Water Policy*** wp2021264. https://doi.org/10.2166/wp.2021.264

WEBSITES

Bioblitz
https://www.homeriverbioblitz.org/

Citizen Science
http://biodiversityadvisor.sanbi.org/participation/citizen-science/

iNaturalist
https://www.inaturalist.org/places/south-africa

mini-SASS
http://www.minisass.org

Winkler titration
https://serc.carleton.edu/microbelife/research_methods/environ_sampling/oxygen.html

ACRONYMS

0157:H7	a particularly virulent strain of *E.coli*
AE&CI	African Explosives and Chemical Industries
Al; Al^{3+}	aluminium; the aquo-Al species of Al
AMD	acid mine drainage
ASPT	Average Score per Taxon
ATTZ	aquatic-terrestrial transition zone
BC	before Christ
BBC	British Broadcasting Company
BIG	basic income grant
BOD	biological oxygen demand
C	carbon
Ca; Ca^{2+}	calcium; the calcium ion
CABI	Centre for Agricultural and Biosciences International
CAPE	Cape Action for People and the Environment
CARA	Conservation of Agricultural Resources Act (South Africa)
CBD	Convention on Biological Diversity
CECs	chemicals / compounds of emerging concern
CEO	chief executive officer
CFR	Cape Floristic Realm / Region
Cl; Cl^-	chlorine; the chloride ion
CMA	Catchment Management Agency
Co	cobalt
CO	carbon monoxide
CO_2	carbon dioxide
CO_3^{2-}	bicarbonate ion
COP	Conference of the Parties
CPOM	coarse particulate organic matter
CSIR	Council for Scientific and Industrial Research (South Africa)
Cu	copper
CV	coefficient of variation
DDT	dichloro-diphenyl-trichloroethane
DFFE	Department of Forestry, Fisheries and the Environment (South Africa)
DME	Department of Minerals and Energy (South Africa)
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DOC	dissolved organic carbon
DOM	dissolved organic matter
DRC	Democratic Republic of the Congo
DRIFT	Downstream Response to Imposed Flow Transformations
DWA	Department of Water Affairs (South Africa – previously)
DWAF	Department of Water Affairs and Forestry (South Africa – previously)
DWS	Department of Water and Sanitation (South Africa – current)
EC	electrical conductivity
EDCs	endocrine disrupting chemicals / compounds
E-FLOWS	environmental flows
EIA	environmental impact assessment
ENWC	Eastern National Water Carrier (Namibia)
EPA	Environmental Protection Agency (USA)
ESKOM	Electricity Supply Commission (South Africa)
ESs	ecosystem services
EV	electric vehicle
EWA	environmental water allocations
EU	European Union
FDA	Food and Drug Administration (USA)
FeS_2	pyrite
FFG	functional feeding group
FPC	flood-pulse concept
FPOM	fine particulate organic matter
FS	Free State (South African province)
Gr	Greek
GCTWF	Greater Cape Town Water Fund
GDP	Gross Domestic Product
GM(O)	genetically modified (organism)
GNH	Gross National Happiness
H; H+	hydrogen; the hydrogen ion
HCO_3^-	the bicarbonate ion
HIV/AIDS	human immunodeficiency virus / acquired immunodeficiency syndrome
IBT	inter-basin transfer
ICOLD	International Commission on Large Dams
IDH	intermediate disturbance hypothesis
IFR	instream flow requirements
IPCC	International Panel on Climate Change
IUCN	International Union for the Conservation of Nature

K; K^+	potassium; the potassium ion
KZN	KwaZulu-Natal
L	Latin
LED	light-emitting diode
Li	lithium
LHWP	Lesotho Highlands Water Project
MAR	mean annual rainfall/runoff
MAP	mean annual precipitation
MDG	millennium development goals
MDR TB	multiple-drug-resistant tuberculosis
MEA	Millennium Ecosystem Assessment
Mg; Mg^{2+}	magnesium; magnesium ion
miniSASS	mini-South Africa Scoring System
MPA	marine protected area
N_2	molecular nitrogen
Na; Na^+	sodium; the sodium ion
NO_2	nitrite
NO_3	nitrate
NO_xes	nitrogen oxides
NH_3; NH_4^+	ammonia; the ammonium ion
NEMA	National Environmental Management Act (South Africa)
NEM:BA	National Environmental Management: Biodiversity Act (South Africa)
NEM: PAA	National Environmental Management: Protected Areas Act (South Africa)
NFEPA	National Freshwater Ecosystem Priority Area
NW	North-West (Province of South Africa)
NWA	National Water Act (South Africa)
OFDA	Office of Foreign Disaster Assistance (USA)
P; PO_4^{3-}	phosphorus; the phosphate ion
PCBs	polychlorinated biphenyls
(P)PCPs	(pharmaceuticals and) personal care products
PET	polyethylene terephthalate
PFAS	per- and polyfluoroalkyl substances
POM	particulate organic matter
POPS	persistent organic pollutants
P: R	production: repsiration
PUFAs	poly-unsaturated fatty acids
RBM	Richards Bay Minerals
RCC	river continuum concept
REE	rare-earth elements
REMP	River Eco-status Monitoring Programme
RHP	River Health Programme
RNA	ribonucleic acid
RWQOs	receiving water quality objectives
S; SO_4^{2-}	sulphur; sulphate ion
SA	South Africa
SANBI	South African National Biodiversity Institute
SASS	South African Scoring System
SDC	serial discontinuity concept
SDGs	sustainable development goals
SO_2	sulphur dioxide
SRP	soluble reactive phosphorus
TDS	total dissolved solids
TMG	Table Mountain Group
TNC	The Nature Conservancy
TOCE	temporarily-open-closed estuary
TSS	total suspended solids
UAE	United Arab Emirates
UCT	University of Cape Town
UN	United Nations
UNEP	United Nations Environmental Programme
USA	United States of America
USSR	Union of Soviet Socialist Republics
UV	ultraviolet
UWC	University of the Western Cape
WC	Western Cape (province)
WCD	World Commission on Dams
WDM	water-demand management
WESSA	Wildlife and Environment Society of South Africa
WfW	Working for Water / Working for Wetlands
WHO	World Health Organization
WRC	Water Research Commission
WWTW/P	wastewater treatment works / plant

NOTATIONS USED IN THIS BOOK

An ***exponent*** refers to the number of times a number is multiplied by itself. For example, 2 to the 3rd (written like this: 2^3) means: 2 x 2 x 2, which equals 8.

……………………..

Surface area is expressed as ***square*** units – e.g. m^2 (square meters), km^2 (square kilometres).

…………………..

Units used to refer to **volume** can be very confusing. The simplest are one litre, one cubic metre (m^3) and one million cubic metres ($10^6 m^3$). Here are the various units and their equivalents.

$1\ m^3$ = a thousand litres = 1 kilolitre = 1 ton
a half-full bathtub contains about 100 litres of water

$10^3\ m^3$ = a thousand cubic meters = 1 megalitre (Mℓ) = a million litres
an Olympic swimming pool contains about 2 $500m^3$ of water

$10^6\ m^3$ = a million m^3 = $1Mm^3$ = 1 gigalitre (1 Gℓ or 10^9 litres) = 1 hm^3 (one cubic hectometre)
before the 2015/17 drought, Cape Town used about $10^6 m^3$ of water per day

$10^9\ m^3$ = a billion m^3 = 1 teralitre = 1 km^3
South Africa uses about 16 km^3 of water per year

The International System of Units (SI) only recognises multiples of a thousand (or thousandths), so with regard to volumes, the ***litre*** is not an officially accepted unit. The officially accepted unit is cubic decimeter (dm^3) and the word 'litre' can be considered to be a special name for the dm^3. It is usually printed as an italicised lower case L: ℓ. Millilitre (mℓ) is a special name for the cubic centimeter (cm^3). There are a thousand mℓ or cc's in one litre. There are a thousand litres in one cubic meter (m^3).

Units used in measuring volumes of water

Americans use the antiquated and clumsy unit of volume called the ***acre-foot***. It obviously refers to an acre of land (just over 4 000 m^2) covered with water to a depth of one foot (about 0.3 m). It is equivalent to 1 233.5 cubic metres. Australian water managers use the unit ***gigalitre***. Some water authorities prefer the unit ***megalitre***, which is a thousand cubic meters, or ***gigalitre***, which is a million cubic meters. In South Africa we tend to use ***litres*** and ***millions of cubic meters*** (Mm^3), depending on circumstances. The ***hectolitre*** (one hundred litres) is often used for beer and wine.

AND …

			symbol
10^0 = 1	one		
10^1 = 10	ten	deca	da
10^2 = 100	hundred	hecto	h
10^3 = 1000	thousand	kilo	k

			symbol
10^{6} = 1 000 000	million	Mega	M
10^{9} = 1 000 000 000	billion	Giga	G
10^{12} = 1 000 000 000 000	trillion	Tera	T
10^{15} = 000 000 000 000 000	quadrillion	Peta	P
10^{18} = 1 000 000 000 000 000 000	quintillion	Exa	E
10^{21} = 1 000 000 000 000 000 000 000	sextillion	Zetta	Z
10^{24} = 1 000 000 000 000 000 000 000 000	septillion	Yotta	Y

10^{-1} = 1/10	one tenth	deci	d
10^{-2} = 1/100	one hundredth	centi	c
10^{-3} = 1/1000	one thousandth	milli	m
10^{-6} = 1/1 000 000	one millionth	micro	μ*
10^{-9} = 1/1 000 000 000	one billionth	nano	n
10^{-12} = 1/1 000 000 000 000	one trillionth	pico	p
10^{-15} = 1/1 000 000 000 000 000	one quadrillionth	femto	f
10^{-18} = 1/1 000 000 000 000 000 000	one quintillionth	atto	a
10^{-21} = 1/1 000 000 000 000 000 000 000	one sextillionth	zepto	z
10^{-24} = 1/1 000 000 000 000 000 000 000 000	one septillionth	yocto	y

*μ is the Greek letter ***mu***

Units greater than 1 start with a capital letter (e.g. M for mega) and units less than one start with a lower-case letter (e.g. m for milli). Examples are Pg for petagrams (10^{15} grams) or pg for picograms (10^{-12} grams) or hm for hectometers (10^{2} meters) or μm for micrometers (10^{-6} meters)

Here are some more units and notations used in the book

cc	cubic centimetre
/g	per gram
ha	hectare (an area of ten thousand square metres or 100 x 100m)
/ha	per hectare
/km	per kilometre
km^3	cubic kilometre
Kw	one thousand watts
/L	per litre
m^3	cubic metre
/m	per meter
$/m^2$	per square metre
$/m^3$	per cubic metre
m/sec	metres per second
m^3/sec	cubic metres per second
MW	one million watts
My	millions of years
μm	micrometer
/sec	per second
ton/tonne	a metric ton (one thousand kg)
/year	per year

More details can be found at
https://en.wikipedia.org/wiki/Metric_prefix

INDEX

A

B

C

E

F

G

H

N

O

P

Q

R

S

X

Y

Z

WATER
RESEARCH
COMMISSION