
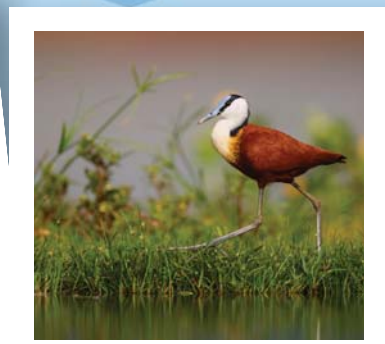


VANISHING WATERS

Third Revised Edition

Jenny Day and Bryan Davies

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PREFACE

The first edition of ***Vanishing Waters*** was a slim volume that arose from a series of lectures that Bryan Davies and I gave for the University of Cape Town's (UCT's) Centre for Extramural Affairs in 1986. The book was an amateur affair, produced with a dot-matrix printer and laid out by hand, then printed by UCT's Printing Department. It soon sold out and we took on the more ambitious task of producing a 'proper' book, which was published by the short-lived UCT Press in 1998.

We wrote the book in order to provide a perspective on water and inland water ecosystems, and their uses and abuses. It was designed primarily as a resource for our students and their students in years to come (there being no internet at the time we wrote it). We tried to write it in a style that would be accessible to high school students and teachers and interested members of the public as well. It seems to have hit the target and it, too, soon sold out. We often spoke about a third edition, but the time was never right.

Bryan died a couple of years ago, and I retired from undergraduate teaching. In 2021, with a small grant from the South African Water Research Commission (WRC), I undertook a complete revision of the text. The world is more complex now than it was 25 years ago, as are the issues facing water as a resource, and the aquatic ecosystems that provide it. So revising the book has proved to be more time-consuming and more challenging than I had thought it would be. I have updated the text, which now reflects the situation as of late 2022, but events will soon overtake it, so I encourage you to consult that ever-amazing internet if you want to keep up to date with events in the world of water.

The book largely follows the format of the second edition, but I have included an additional chapter on conservation (of both water and aquatic ecosystems) and what I call 'Planet Management'. So many current environmental issues are not confined to water but extend to every aspect of our lives and the ways in which we manage our home planet. Despite Elon Musk's efforts to reach Mars, Earth is likely to stay our only viable home for as long as we exist as a species. We therefore need to manage it much more sensitively and effectively in the future than we do now.

Jenny Day

EXCERPT FROM THE FOREWORD TO THE SECOND EDITION

Professor Kader Asmal
Minister of Water Affairs and Forestry
28 October 1997

Vanishing Waters is an important work. It combines scholarly insights on the functioning of aquatic ecosystems with direct challenges to water management policies. I welcome that. Part of the metamorphosis of South Africa, part of its renewal following the democratic elections of 1994, has been to invite criticism in all its guises.

Davies and Day do not hold back, and there is a great value in their honesty. I may not always agree with them – particularly when having to trade off (as one occasionally must) conservation imperatives with developmental initiatives to combat the desperate levels of poverty, inequality and injustice in our country and the sub-region. But the authors do strike a chord when attacking the way in which we, like so many others, engineer water to subsidise inefficiency.

I want water managers to read this book. We may choose to disagree with some of the perspectives, we may question some of the arithmetic, but in ***Vanishing Waters*** we find a great deal of wisdom that will be central to the way in which we manage our scarce resources in the future.

…

I am an optimist and must thus end on a positive note. We have the capacity to take control of our future, Let our management of water be an example of our move to a more sustainable living practice. This book can point the way to understanding not only why it is important to take these steps, but also how relatively easy it is to do so. The choice is ours.

ACKNOWLEDGEMENTS

A book of this kind is the result of interactions over many years with friends, colleagues, and students; of field trips to out-of-the-way places; of reading hundreds of scientific papers and opinion pieces; of browsing the internet; and of observing how the world works. I owe a debt of gratitude to every one of the people, many anonymous, whose work I have read, and whose opinions I have encountered.

My greatest debt of gratitude, however, is to the late Bryan Davies, colleague and friend, and co-author of both previous editions of this book. Writing the previous versions with him was challenging, but it was fun. We didn't always agree on what should be included, or how it should be written. Bryan was passionate by nature (hence he was a superb lecturer) and sometimes I would sneakily tone down some of his more dramatic statements. But overall, we agreed on the important things, especially the future integrity of our rivers and wetlands, and ways of maintaining them in the best condition possible.

I am deeply grateful to the Water Research Commission for publishing this volume. Mrs Lani van Vuuren has steered the book through all the phases of production with efficiency, assisting whenever I needed help. Mrs Anja van der Merwe has done a wonderful layout job, making the book a pleasure to read. I thank them both.

Mr Bonani Madikizela (Diks to his friends) has long been a stalwart manager of environmental research at the WRC. I would like to take the opportunity to thank him for his commitment to his job and 'his' researchers over many years. In the current context, Bonani managed the production of this volume and the participation of a number of reviewers, ably assisted by Mrs Gerda Kruger.

I am most grateful to the following people for critically reviewing one or more of the chapters in the book: Matt Bird, Belinda Day, John Day, Liz Day, John Dini, Justine Ewart-Smith, Dalton Gibbs, Mo Kagee, Tony Leiman, Steve Lowe, James Machingura, Heather Malan, Steve Mitchell, Tally Palmer, Karl Reinecke, Jody Reizenberg, Mike Silberbauer, Kate Snaddon, Francois Theron, Lara van Niekerk and Alan Whitfield. Thank you all – you were generous of your time and perceptive in your comments.

Belinda Day produced many of the diagrams and a couple of beautiful watercolour illustrations – thank you, Lin. Others kindly contributed photographs, all at no cost. Their names are printed alongside the relevant images, as are the attributions of images from Wikimedia Commons. Jody Reisenberg and Belinda Day managed a WRC project that produced both ***Vanishing Waters*** and a volume entitled ***WRC@50 Celebrating a half-century of excellence***, published in September 2021(https://bit.ly/3Cu87LW).

Various iterations of this book were researched or written during sabbatical leave at the University of Florida, where I was hosted by Dr Tom Crisman; the Albany campus of the University of Western Australia in Albany, where I was hosted by Dr Barbara Cook; and Glasgow University's Scottish Centre for Ecology and the Environment at Rowardennan on Loch Lomond, where I was hosted by Prof Colin Adams. I am grateful to the University of Cape Town for providing the opportunity to take sabbatical leave, which allowed me to visit remarkable wetlands and to work with respected colleagues who soon became friends.

ABOUT THE AUTHORS

BRYAN DAVIES

The late Bryan Davies, born in Birmingham, England, was a Professor of Zoology at the University of Cape Town (UCT). He obtained a PhD degree from the University of Newcastle-upon-Tyne, England, with a doctoral thesis on Loch Leven in Scotland. He worked in Mozambique on the effects of the Cahora Bassa Dam on the Zambezi River system, before joining the Department of Zoology and Entomology at Rhodes University where, apart from teaching, he worked on Swartvlei and the Wilderness lakes with the late Prof Brian Allanson. In about 1980 he joined UCT's Zoology Department. He was a Past President of the Southern African Society of Aquatic Scientists and was awarded the Society's Gold Medal in 2003.

Bryan was passionate about everything he did. He was a marvellous lecturer and postgraduate mentor, receiving the UCT Distinguished Teacher award, and an enthusiastic researcher. He was also a passionate 'greenie' in the days before this was fashionable, and made it very clear to river managers what he thought of their attitudes towards water provision at all costs. The Freshwater Research Unit (FRU) was instituted at UCT in 1984, mostly as a result of Bryan's efforts, and continued until Jenny's retirement at the end of 2011. It was the premier freshwater ecological institute in the country for all of this time, graduating dozens of Honours, MSc and PhD students.

Bryan suffered poor health for several years before he retired. He had been in a helicopter crash in Mozambique during his post-doc days (the pilot ran out of fuel!) and although he didn't see any ill effects at the time, he later suffered from severe back and joint pain. He also developed a mysterious disease, probably Lyme Disease, which left him chronically weak and somewhat disabled. He retired to Pringle Bay in about 2003 and died of an aortic embolism on 2 July 2015.

JENNY DAY

Jenny Day was born in Johannesburg and grew up in Zambia. She graduated from UCT with a First Class Honours Degree in Zoology and undertook her doctoral research on the systematics of a group of marine shrimps through the same university. She was at various times Head of the Department of Zoology, Deputy Dean in the Faculty of Science, and Director of the Freshwater Research Unit at UCT. She is particularly interested in arid areas, most especially the Namib Desert, where she has studied the ecology of hyper-saline streams and temporary water bodies. Further north she has been a member of the Board of the Water Research Fund for Southern Africa (WARFSA) and the East African Universities' Lake Victoria Research Initiative, as well as teaching on the WaterNet inter-universities MSc programmes. After her retirement from UCT at the end of 2011, she was appointed Extraordinary Professor in the Institute for Water Studies at the University of the Western Cape (UWC), where she has been involved in various research projects and where she still co-supervises a number of PhD students.

Her research has focused on the conservation and management of freshwater ecosystems, particularly with regard to water quality and invertebrate biology.

She is a Past President of the Southern African Society of Aquatic Scientists and was awarded the Society's Gold Medal in 2013.

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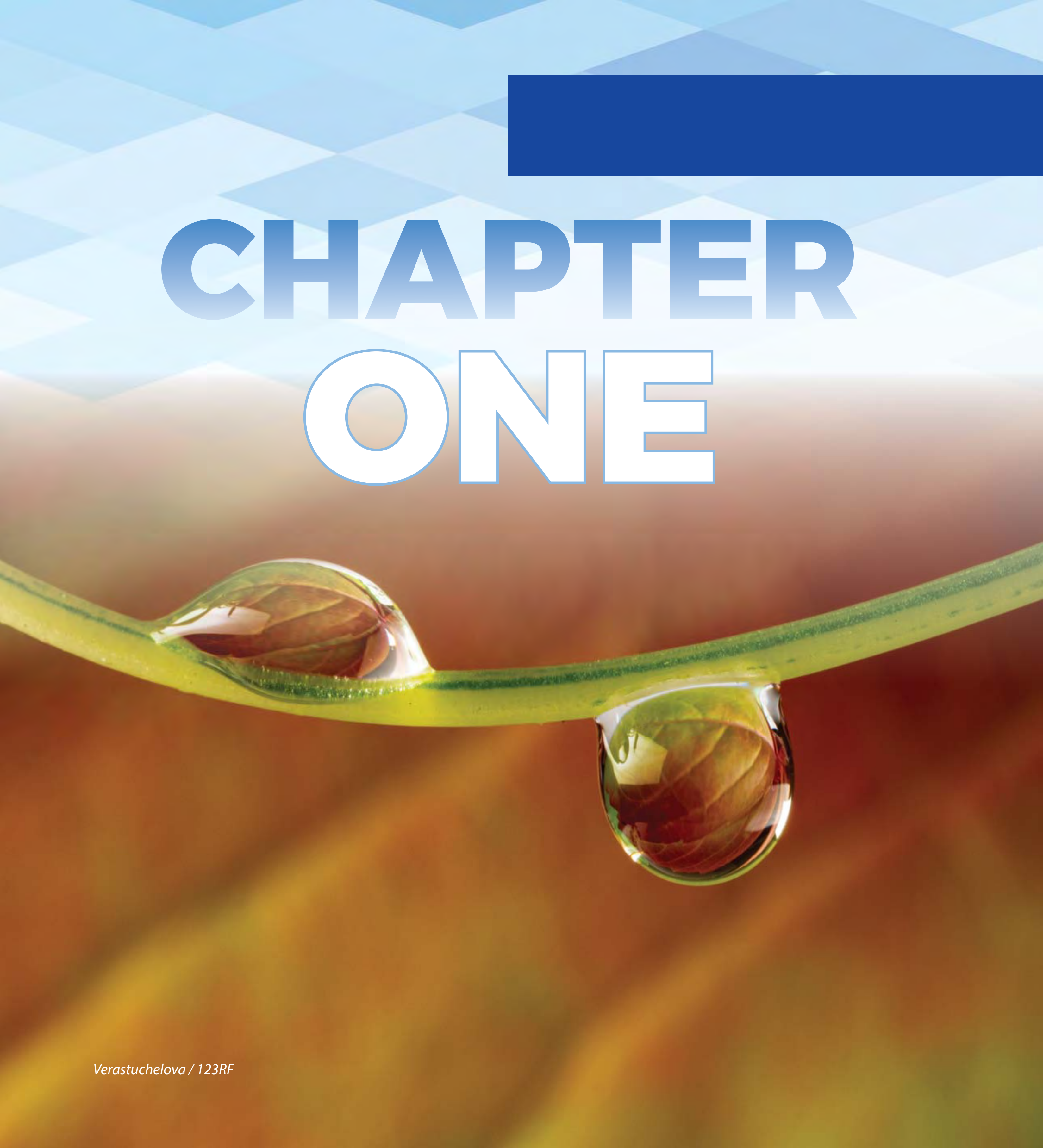
CHAPTER ONE



Verastuchelova / 123RF

Introduction: Ribbons of Life

We never know the worth of water until the well runs dry.

Thomas Fuller: Gnomologia

In 1852, in response to a request by the United States government to purchase land from indigenous people for colonists who were arriving thick and fast from the east, Chief Seattle gave a long and moving speech[1]. Henry A. Smith, a pioneer, made notes of the speech and later translated it into English. While the words are Smith's, the meaning is Seattle's. As Joseph Campbell[2] says, Chief Seattle was '…***one of the last spokesmen of the Paleolithic moral order***.' His reply to the President of the United States is still relevant today.

ABOUT WATER, HE SAID,

The shining water that moves in the streams and rivers is not just water, but the blood of our ancestors. Each ghostly reflection in the clear waters of the lakes tells of events and memories in the life of my people. The water's murmur is the voice of my father's father. The rivers are our brothers. They quench our thirst. They carry our canoes and feed our children. So you must give to the rivers the kindness you would give any brother …

[1]It is hard to find a reference to Smith's original text but the text on the following website seems to be authentic: http://www.synaptic.bc.ca/ejournal/smith.htm
[2]Campbell, J., B. Moyers & B.S. Flowers (ed.) 1988. The power of myth. Doubleday.

Jenny Day

Shining waters: Malkopsvlei, Betty's Bay, Western Cape.

FINALLY, AND PROPHETICALLY, CHIEF SEATTLE WROTE,

What will happen when the buffalo are all slaughtered? The wild horses tamed? What will happen when the secret corners of the forest are heavy with the scent of many men and the view of the ripe hills is blotted by talking wires? … Where will the eagle be? Gone! And what is it to say goodbye to the swift pony and the hunt? The end of living and the beginning of survival.

Our original intention when Bryan and I wrote previous editions of this book was to produce a book on limnology – the scientific study of lakes, rivers and wetlands. Our experiences as teachers of limnology soon made us realise, however, that there are no longer many good examples of the kinds of systems we were lecturing about: rivers running free to the sea, untouched wetlands, or unpolluted seasonal pans. We found ourselves spending more and more of our teaching time on aquatic ecosystems that have been affected by human activities. Eventually our courses could have been named "Rivers and how to manage them", or "Effects of humans on wetlands", for instance. This approach has spilled over to our writing, particularly of this book. In the following pages you will certainly read about rivers and wetlands in their natural state, but there is also a lot of discussion on the effects of anthropogenic (human-generated) activities on these systems. To make the point, in this chapter we describe several of the mega-engineering water projects around the world.

Significant human impacts on this planet probably started with the use of fire, the first settled agriculture and the seasonal movement of stock animals and their herders. The natural environment seems to have coped fairly well with these changes because the number of people was small and their impacts were localised. Improved technology allowed the building of houses and the sewing of warm clothes: humans could live in more and more unfavourable climates as they developed an increased ability to 'control' nature. Since water is one of the primary requirements for life, meddling with ('developing') water supplies was one of humankind's earliest technical triumphs. Groundwater was first extracted by means of a series of qanats (excavated tunnels) in the Middle East four or five thousand years ago; the Romans stored surface water in reservoirs and distributed it to cities ***via*** aqueducts; Eastern peoples have grown rice in flooded paddies for millennia.

SH Rashedi, UNESCO site_1506_00024) whc.unesco.org/en/documents/141554.

A series of qanats in Iran. The holes surrounded by mounds are vertical chimneys leading to underground water sources. The image shows evidence of at least four separate underground 'rivers'.

This well is the only source of water for a Himba family in the extreme desert of Namibia. Note the toy trucks made by the children from clay and wire.

With the increase in human populations, it has become necessary to store more and more water for industrial and domestic supply, as well as for irrigation. More recently, water has been transported over long distances to compensate for the uneven distribution of human populations. Natural stores of underground water have been tapped, and in some cases virtually drained dry, while vast inland seas such as the Aral Sea (page 19) in Uzbekistan-Kazakhstan and Lake Chad (page 24) in the Sahara Desert are but small puddles relative to their former selves. Humankind's quest for water, particularly in dry lands, has affected rivers in many ways, some of which are discussed in Chapters 8 and 9.

A less obvious, but equally serious effect of human activities is pollution, which may be in the form of litter and rubble but is far more often invisible and toxic. When human populations were small, and technologies were simple, pollutants were confined to human and animal wastes, and perhaps also to effluent from the occasional iron smelter. The more people there are, and the more sophisticated their technology, though, the more they consume and the more toxic are the wastes they produce. Water chemistry, and human-induced perturbations in water chemistry, are the subjects of Chapter 7. Humans have had all sorts of other impacts on natural aquatic ecosystems too, of course. Some are obvious and some insidious; some threaten the very existence of natural biotas and some are probably more of a nuisance to humans than a threat to survival. The effects of physical alteration of aquatic environments, as well as some of the effects of these alterations on the biotas, are addressed in several chapters.

When we began to write our first book together in the 1980s, a great drought had just broken but we nonetheless made what seemed to be an emotive statement: '*... it may very well be that this is the last time that we will be so lucky – the next drought to come along will probably never break*'. We went on to say that this was '*… because, since there will not be enough water to supply our burgeoning population, there will not be enough to break the next drought that afflicts us. There will not necessarily be less rain overall but the demand for water will simply be too great to be met by available resources*'. (This was before we were aware of the all-encompassing effects of climate change.) That we were right – in part – is no cause for celebration. Since we wrote those words, the reality of climate change, together with pressure from the human population, explains why most parts of the subcontinent have recently had the most serious water shortages in living memory. The Gauteng and Cape Town regions have had months of severe water restrictions, while northern KwaZulu-Natal, parts of the Eastern Cape, and sections of the Free State, the Northern Cape, Limpopo and the North-West province, as well as our neighbours to the north, have all been critically short of water at one time or another. A while ago, towns on the Garden Route had to ask tourists to stay away during the lucrative summer season because they did not have enough water to support their own citizens, let alone an influx of tourists. Water has had to be trucked in by tanker to some communities whose wells no longer ran, and where water pumps clanked hollowly in the dry wind.

Still other parts of the region have emerged from, and returned to, drought several times in the last twenty years, interspersed with some of the most severe floods in living memory. The lesson is clear: we live on a sub-continent notorious for its unpredictable rainfall. There is nothing we can do about that; and worse will follow as the effects of global warming continue to magnify.

Petro Kotzé

Parched farmlands outside Kenhardt in 2020, eight years into a severe drought in the area.

James Brent Styan

The Gamka Dam, which supplies Beaufort West in the Western Cape, dried up completely during the 2015 – 2018 drought. Restrictions were lifted in 2019 but were reinstated in January 2022 when water levels dropped to less than 25%.

Sylvia Ferguson

Unpredictable weather events may result in flooding, such as seen here at Swartvlei in the Southern Cape in 2007.

Water and aquatic ecosystems represent, in microcosm, the issues regarding the management of this planet; in South Africa we find examples of almost every one. On the face of it, virtually everything in South Africa seemed to change in the new century. Not only did we see essential political change but we also saw the human population increase by several million, from 40.6 million in 1994 to 60.1 million in 2021. While these things have changed, others have not. Our water resources, and the aquatic ecosystems and living things that depend on them, are under greater pressure than even we would have predicted twenty years ago. Since the turn of the century we have witnessed numerous disheartening developments, some intentional and some resulting from ignorance or political failure. For instance, two


Jenny Day

The Palmiet River in the Kogelberg World Heritage site, the heart of plant diversity in the fynbos biome.

of South Africa's Ramsar wetlands, at the Orange River Mouth and Blesbokspruit, have been placed on the Montreaux Record (Ramsar wetlands downgraded because they have deteriorated significantly since they were initially listed – see page 47). Many people have died from contamination of the environment by mercury and pesticides (page 238). The Sabie River in the Kruger National Park dried up for the first time in recorded history, and other once-perennial rivers such as the Luvuvhu, Letaba and Limpopo now dry up virtually every winter. Hundreds of fishes and crocodiles in the Kruger National Park died as a result of an inexplicable disease called pansteatitis (page 442). At present, most municipalities in South Africa are not capable of managing their water supplies and sewage effluents within the water quality standards set by the Department of Water and Sanitation (DWS), resulting in potentially unpotable water in the taps of some towns, and the gross pollution of many rivers (page 259).

We must have seen some positive things too, surely? Yes, we certainly have. The Greater St Lucia (now the iSimangaliso) Wetland Park, which was earmarked for rutile mining, has been declared a World Heritage Site instead. The Kogelberg State Forest, heart of the Cape Floristic Kingdom, was declared a World Heritage Site in 2004, precluding (in theory at least) the possibility of building a massive dam near the mouth of the Palmiet River.

In addition, South Africa is said to be on target for meeting the country's Sustainable Development Goals (SDGs) with regard to the provision of water; the Department of Water and Sanitation (DWS) has brought piped water and even sanitation to many rural and informal settlements. Innovative projects such as Working for Water and Working for Wetlands combine job creation and catchment management (see chapter 5); our trend-setting National Water Act (see chapter 10) was a world first. We have seen the first prosecutions of environmental transgressors. And we are always looking out for more good-news stories. On the other hand, I have just seen an update on the story of rutile mining in the iSimangaliso Wetland Park (***Daily Maverick*** 08.11.2018). It seems that a new application has been made for prospecting rights on the southern border of the Park. The application has been made by Eyamakhosi Resources (Pty) Ltd, a previously unknown company owned by a former Richards Bay Minerals (RBM) employee; there are concerns that this person may be acting as a proxy for the Rio-Tinto-controlled RBM, whose application for mining this site was turned down when the Park became a World Heritage site. You win some, you lose more.

In a developing country like South Africa, the challenge is to strike a balance between the immediate need to uplift a largely poverty-stricken populace, and the long-term need to conserve and protect the natural environment and the goods and services that it provides. Poverty is not only a social ill: in almost every way it is an environmental ill as well. Very poor people are, naturally, concerned more about their own day-to-day struggles to survive than about their surroundings, which are often grim. On the other hand, conserving 'nature', including water resources, is a long-term process, often in direct conflict with the immediate needs of the poor. This paradox is very difficult to resolve. Further, because the urban poor in particular live lives so far divorced from a sustaining environment, they may have no conception of, and feel no responsibility for, the world's wild places, or resources derived from them. As a result they often do not realise that their actions are detrimental to the very systems that they depend on - and that their children, too, will depend on in the future. And who can blame them for this attitude when, for instance, rivers running through poverty-stricken communities are frequently nothing more than foully polluted drains?

Emma Green / Groundup / CC A-NoDerivatives 4.0

A 'river' in an informal settlement in Cape Town. No wonder people who live in these circumstances are seldom committed 'greenies.'

Polluted rivers tighten the poverty cycle by contributing to general ill-health and to the spread of diseases such as cholera and diarrhoea. Every day some 30 or so South African children die of diarrhoeal infections caused by exposure to insanitary conditions. Similarly, living resources such as trees and reeds are seen by poor people as direct solutions to immediate problems of fuel and shelter. To worry about the long-term existence of such resources is to court immediate personal disaster. Until poverty is alleviated, and people are appropriately educated, we will not remove such perceptions or remedy such problems. (This subject is discussed further in chapter 11.)

If we look at poverty strictly from an environmental point of view, ignoring the plight of the poor themselves, the world might be better off if everyone enjoyed a modicum of wealth – but not too much. Ironically, wealth itself also creates severe environmental ills, in that the wealthier one is, the more one consumes and the more waste one produces. It does not take much thought to realise that if the aspirations of the poor to higher standards of living, and to houses, running water, swimming pools, and so on, are ever met, then even greater stresses will be placed on our water resources. It is a frightening thought that if the world were a better place, and every squatter family in the country lived in a decent house with running water, a garden, a flush toilet, a kitchen sink and a pool, the domestic demand for water would far outstrip supply. Careful management of our water resources will be required for this reason if for no other.

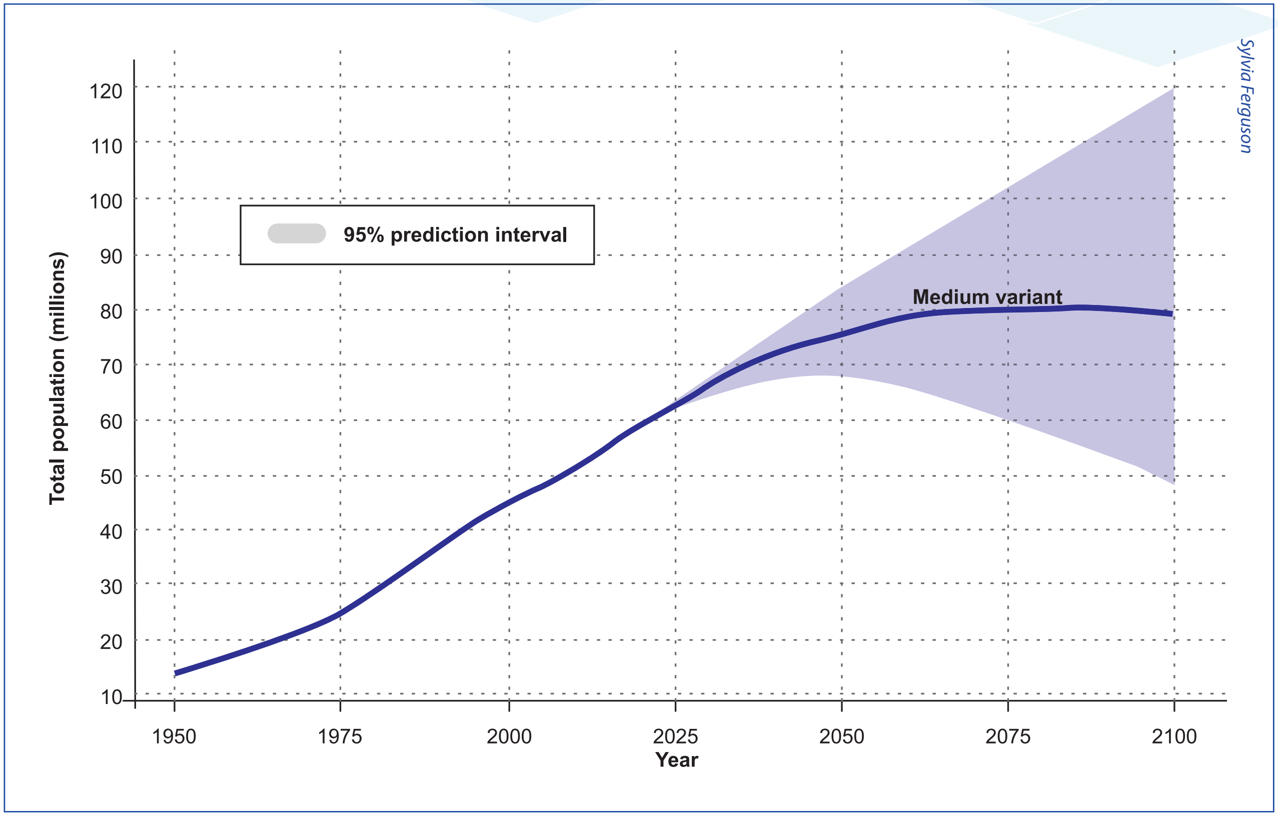
On the positive side, we have seen the passage of some excellent legislation: the National Water Act 38 of 1998 (NWA), and also the National Environmental Management Act 107 of 1998 (NEMA) and other associated legislation. (We discuss these in some detail in Chapter 11). Other encouraging signs include the growth in awareness of 'green' issues, particularly amongst the more affluent sectors of the population, which are, of course, those who consume the lion's share of South Africa's resources. 'Friends' groups are formed by local communities who 'adopt' a wetland, a vlei, an estuary, a river, or any other area of special environmental interest, and are encouraged by the Wildlife and Environment Society of South Africa (WESSA) to become involved in its rehabilitation and management. Wetlands forums, which consist of wetlands professionals and interested members of the public, are well attended. World Wetlands Day and Water Week are now well entrenched and widely celebrated. Even then-President Zuma started a short-lived discussion about the 'green economy' at one stage. These are encouraging signs.

In the previous edition of this book we said the following: *'Presently, it is almost certain that we will have between 60 and 75 million people living in South Africa by the year 2025. … Even if this prediction was inaccurate, and our population growth rate were to drop right now to replacement levels only (the famous 'ZPG', or 'zero population growth'), the population would still at least double because of the young people currently growing up and yet to reproduce. This is a truly daunting picture*'. The statisticians have been right so far: the population in mid-2022 is 60.6 million and is expected to grow to about 62.8 million in 2025, on the low end of the predicted range, mostly an effect of the HIV epidemic of the 2010s. The spectre of global warming hovers, however. Rainfall is predicted to decrease over most of South Africa as temperatures increase. So, we have the prospect of a large and growing population, with less water to go around even than we had expected a decade ago. Yet the prime commodity for all of these people will be safe, clean, water for cooking, drinking, washing, mining, cleansing wastes, manufacturing, growing forests, producing electricity, cooling industrial processes, watering stock and crops, growing fish and fishing. They will no doubt also want some pleasant expanses of clean, attractive water for recreation. But where is this water to come from? Discussion on this knotty problem continues in Chapter 10.

A GLOBAL PERSPECTIVE

Lest you think that water problems are the particular burden of the southern tip of Africa, we must stress that water is fast becoming critically short in many parts of the world. The book ***Towards the blue-green city: building urban water resilience*** http://bit.ly/3UUyt2R deals with several of these issues.

Around the world we can see enormous projects, requiring great engineering expertise and costing vast sums of money, that have been – or are being – constructed to ameliorate water shortages. Others in more mesic parts of the world are being constructed mainly for provision of hydropower. Generation of hydropower requires a very different flow regime from that in the unregulated river, causing different challenges to the organisms living in the river (see chapter 9

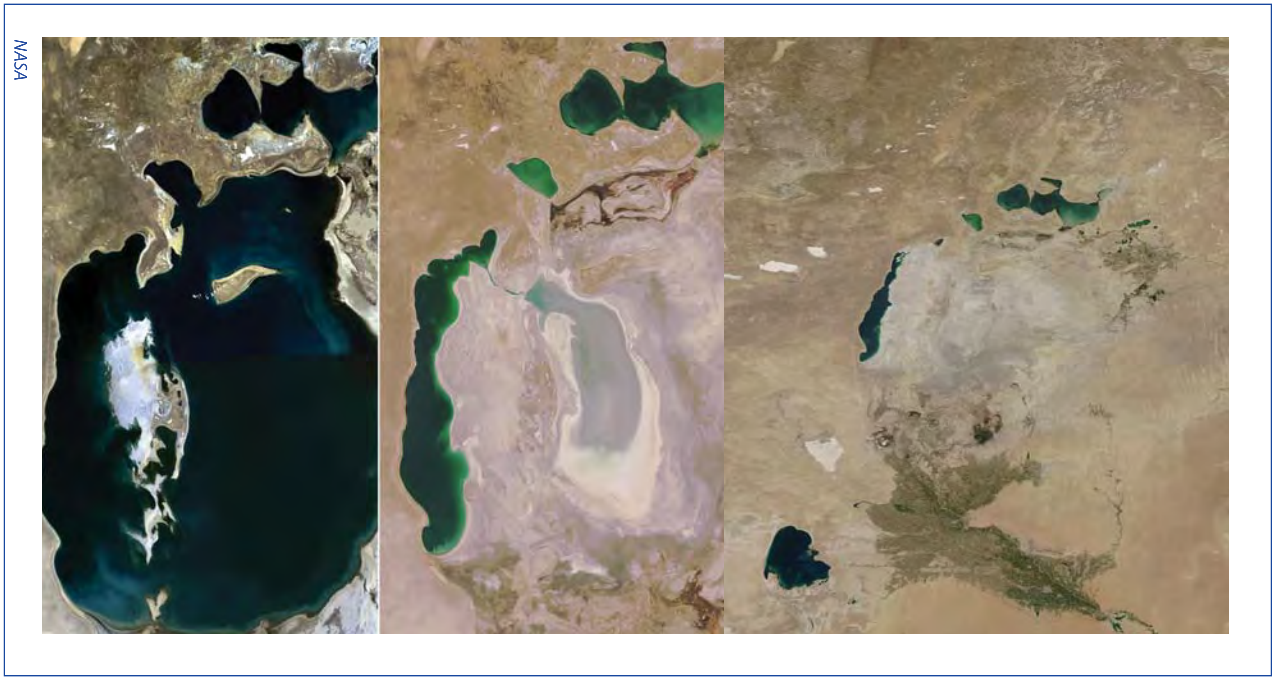


South African population growth from 1950, showing future projections. The 'upper variant' is unlikely to be reached – see Chapter 11. (UN DESA CC -BY 3.0 IGO http://population.un.org/wpp/).

for details). Almost every large water-supply scheme creates new problems as fast as it solves old ones. Let us have a look at a few case studies.

Until the 1960s the Aral Sea, straddling Kazakhstan and Uzbekistan, was the fourth-largest inland body of water in the world. As a result of grandiose irrigation schemes conceived and built in Soviet times, huge amounts of water were abstracted from the lake and from the rivers flowing into it. By 2005 the surface area of the lake had been reduced to about 10% of its original area. Instead of being a vast fresh-water sea, it became a series of three small, pesticide-polluted salt lakes. Large ships are aground on a sea of sand a hundred kilometres from the current shoreline and the remaining water in most parts is saltier than the sea. Most of the aquatic animals of the Aral Sea have died out.

Furthermore, the soil of many of the fields onto which its waters were poured are now so salty that they can no longer bear useful crops. Desert winds carry the salt- and pesticide-laden dust from the dry lake bed as far as Pakistan, while polluted water in rivers leaving the lake are claimed to be the cause of a local rise in infant mortalities and childhood anaemia. At various stages suggestions have been made to revive the sea by diverting northward-flowing rivers southwards, or by diverting water from the adjacent Caspian Sea. The Kazakhs had a better idea, at least from their own point of view. The 'Small Lake', the northernmost of the three remaining lakes, lies in Kazakhstan. The Kazakhs built a dyke across the southern edge of the lake, effectively damming the waters of the Syr Darya River, which flows southwards into Small Lake. Of course this means that the two remaining lakes now receive even less water than before. Small Lake is



Satellite views taken in a) 1989, b) 2008 and c) 2021 showing the dramatic drying out of the Aral Sea.

apparently recovering well – even to the extent that a fishery is being re-established. To the south is the much poorer country of Uzbekistan, whose economy relied heavily on cotton grown on land irrigated by water from the Aral Sea. Wars have been fought over less.

Further east in Asia, water flowing down the Yangtse River in China is now interrupted by the Three Gorges Dam, which has devoured billions of Yuan (about US$30 billion) and has been the source of endless controversy. It is the world's largest hydroelectric power producer (22 500 MW when fully operational). A major reason for building the dam, though, was to control floods in the river. In 1931 a massive flood drowned about 200 000 people, and another 2 million died as a result of the devastating effects of the floods on farmlands and villages in the catchment. The reservoir behind the new dam wall displaced about 1.3 million people from their land as well as inundating over 630 km^2 of land and creating a lake over 600 km long. Although a babe-in-arms in terms of inundated area (Lake Kariba, for instance, inundated over 5 000 km^2), the cost of the Three Gorges dam is staggering in terms of disruption to human life and of damage to the river itself. The principal is disturbing: apparently vast numbers of people can be shifted merely at the will of those in power. Furthermore, the Yangtze River carries an annual silt load of over 530 million tonnes. Unless the reservoir is carefully managed so that the silt is flushed through it every year, the reservoir will probably only last for about 20 years before it fills with silt. The huge weight of water in the reservoir has caused an increase in earthquakes and landslides in the area, while even local officials are concerned about the ecological degradation of the river and the presence of massive algal blooms downstream. There is little doubt, too, that the Yangtse River dolphin has become extinct, although this is probably mostly as a result of the massive pollution of the river's waters.

Undoubtedly China has problems of water supply, particularly in that Beijing and other northern cities suffer from periodic droughts. As a result of an idea first mooted by Mao Zedung (Mao Tse Tung), the Chinese have already initiated another huge water project: the South-North Water Transfer Project. (Does this sound ominous, having just read about the Aral Sea?) Water is already being transferred along two separate

Zhanat Kulenov / Wikimedia/ CC BY-SA 3.0

A ship graveyard on what used to be the shoreline of the Bay of Zhalanash, Aral Sea, Kazakhstan – now more than 100 km from the shore.

routes over distances of 1 000 km or more, northwards to the arid regions drained by the Yellow River, which often dries up completely. A third route, which starts in Tibet, has not yet been constructed and is a source of considerable controversy, even in China itself. This is not the place to go into details but readers interested in water politics can find an entry to internet sources in the url given at the end of this chapter.

Nsbdgc / Wikimedia / CC BY-SA 4.0

The South-North Water Transfer Project in China: the starting point of the Central Route in Xichuan County, Henan.

In the United States, rivers such as the Colorado – one of the largest in the western United States – are so regulated by dams and water abstraction schemes that they no longer reach the sea, and the bulk of the water supplying most of California comes from areas well beyond its borders, while enormous canals carry Colorado River water to keep gardens in desert cities like Las Vegas and Phoenix in the manner to which their owners have grown accustomed. Indeed, there has even been talk of a truly gigantic project to divert water southwards to California from rivers as far north as western Canada, in order to alleviate the water-supply problems of the arid south-western United States. At this stage the project is only a gleam in the eyes of a handful of planners; most are hoping that desalination, water-demand management and other less gigantic schemes will be able to supply the needs of the area. The devastating droughts over the last few years in southern California are doubtless brightening those gleaming eyes, though. California clearly has existential problems with water, given the effects of climate change, which are already being felt in the form of uncontrollable wildfires, and a large and affluent population.

Westwards, across the Pacific, the once-mighty Murray-Darling River in south-eastern Australia, the fourth-longest river in the world, is reduced to a swimmable stream at its mouth owing to the enormous amounts of water that are extracted upstream for irrigation, domestic and industrial purposes. Virtually all of the water in the system is already used. This is reflected in the fact that some years ago Brian, hardly an Olympic athlete on his own admission, swam across the mouth in under a minute. The water in its lower reaches is so salty as to be almost unpalatable, probably contributing to human ill health (e.g. hypertension and kidney diseases), as well as to industrial losses as a result of corrosion, and agricultural losses as a result of salt-encrusted soils. With the recent record-breaking drought in Australia, Adelaide (the city near the mouth of the Murray) virtually ran out of water and what water they did have was almost too salty to drink. Plans were put in place to truck water into the city, which has a population of about 1.3 million people. The drought has broken – for the present – but Australian climatologists are beginning to think that the droughts of the last few years are the face of things to come, and that Australia is the first part of the world to experience a new, lower rainfall datum: the new normal.

Sometimes it seems that engineering megalomania for water projects knows no bounds. For instance, much against the will of many of her people, including her indigenous populations, Brazil has already built several massive hydropower dams and plans to build as many as 70 more on tributaries of the lower Amazon and Tucuruí rivers within the next few decades. One such structure, the Itaipú Dam, was the world's largest single hydroelectric power producer until the advent of the Three Gorges dam in China. A high Government official recently refused to open one of the dams in the Amazon Basin because of embarrassment at the environmental and economic ills caused by the structure. Not only had thousands of indigenous people been forcibly removed from the flooding basin but the water had become so acid due to decomposition of drowned vegetation that the turbines generating hydro-electricity became corroded to the extent that they could not function. The current populist government clearly has no interest in environmental or human equity and has indicated that if 'uncertainty' around current regulations protecting Indigenous peoples and biodiversity is resolved (read as "regulations are altered to allow untrammeled environmental devastation"), then more dams will be constructed, some on indigenous lands.

Santo Antônio Energia

The Santo Antônio dam (seen here) and the neighbouring Jirau dam have been documented as having significantly contributed to disastrous upstream flooding on the Madeira River in 2014, extending from Brazil into Bolivia. Today, both dams block aquatic migrations and have negatively affected river fisheries.

In north Africa, until the 1960s Lake Chad was ranked at the world's sixth-largest inland water body, some 25 000 km^2 in extent. Since then it has shrunk dramatically, to less than 10% of its original area. This reduction was initially attributed to a severe drought in the region in the 1960s-80s, together with abstraction of water for human needs. Currently, though, it is considered that climate change also made a significant contribution to the shrinking of the lake. Today water levels seem to be more or less constant – although still at only 10% of 1960s levels – thanks to increased supply of ground water from two major tributaries that arise far south in the tropics. As long ago as 1982 an Italian water engineer suggested that the Lake could be re-filled by topping it up with water from the Congo River, diverted northwards and including a series of hydropower-generating dams on the way. The engineer in question considered that less than 8% of the Congo's water would be required and would not be a threat to the DRC's Grand Inga Dam. Well now!

The Grand Inga Dam project is another megalomaniacal project, and here South Africa is also a player. Two relatively small hydropower dams already exist on the Congo River and the Congolese government wants to build a third, much bigger, dam. A treaty beween South Africa and the DRC was signed in 2013, South Africa acting as guarantor for the project, expected to cost in excess of R200 billion. The DRC is currently attempting to find construction companies to build the dam but is not having much success – something for which we in South Africa should be grateful since, if it goes ahead, the cost to South African consumers has been estimated at R4.3 billion annually for a relatively small amount of power. At the same time, the cost of renewable generation of electricity is expected to decrease significantly over time. If you are not sufficiently depressed by what you have read so far, have a look at the South African ***Mail and Guardian's*** article at ***bit.ly/3Adwxus***

NASA

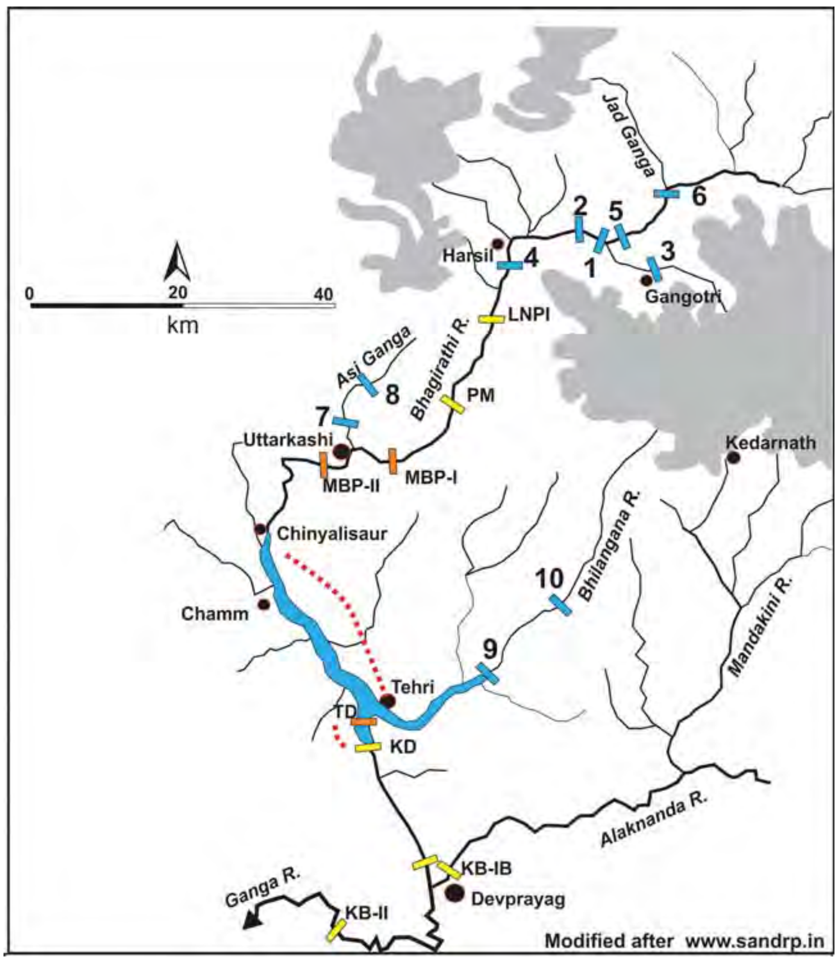
Sani Ahmad Usman / Wikimedia / CC BY-SA 4.0

Lake Chad from Apollo 7, 1968 (left) and the shores of Lake Chad today (right).

To the north, in Libya, Colonel Gaddafi had a grand vision of making the desert into a grain basket by using the huge supplies of fossil groundwater in the Nubian Sandstone Aquifer, which underlies much of Libya, Egypt, Sudan and Chad. Libyan engineers designed and built a series of canals and pipelines – the Great Man-Made River – to carry 5 million m^3 of water a day (100 km^3 per year) across 1 600 km of Sahara Desert. The desert is indeed blooming but the water being used accumulated over hundreds or thousands of years when the Sahara was much wetter than it is now. Another oil-rich country, Saudi Arabia, has done a similar thing and for a short time this desert country was the eight-largest producer of wheat in the world. Virtually none of this fossil water is being replaced by rainfall and so it will eventually run out – from desert to desert ***via*** a few billion dollars.

On the Indian subcontinent, engineers have planned and are constructing a cascade of 18 massive dams on the River Bhagirathi in the headwaters of the mighty Ganges, India's holiest river. The 260 m-high Theri Dam (twice the height of Kariba Dam and more than two-thirds the height of the Empire State Building) has already been built, as has the smaller Loharinag Dam. Theri Dam, which created a lake with two arms, one 35 and the other 45 km long, will contain 3.5 km^3 of water at full supply level and will be used for irrigation and the generation of hydro-electric power, as well as providing desperately needed water to the city of New Delhi.

The most worrying feature of the planned series of reservoirs is that the Himalayas, where they are being built, is one of the most geologically unstable and earthquake-prone regions on Earth. Massive artificial water bodies created by dams have a tendency to increase the frequency, and perhaps the intensity, of earthquakes. These particular dams have also significantly reduced the amount of water flowing in the River Ganges, much to the displeasure of local people for environmental and religious reasons. Interestingly, several of the planned dams have recently been cancelled by the Indian government for religious reasons, since the river is holy in the Hindu faith – the faith of the populist Indian Prime Minister, Narendra Modi. Also in India is the highly controversial Narmada Valley Project.



A map showing the distribution of dams on the Bhagarathi River, India; blue rectangles represent proposed dams; yellow rectangles represent dams under construction; orange rectangles represent completed dams (from Sati et al 2020).

Started in 1962, this scheme involves some thirty large and over 3 000 smaller dams in a gigantic irrigation and hydro-electric scheme. Construction of the largest dam, the 80 m Sardar Sarovar, began in 1987. The wall has been raised at least five times, so that it is now 122 m high and has drowned some 300 000 ha of natural forest, as well as destroying the homes of millions of indigenous people. The World Bank stopped funding the project some years ago and the Indian government called a halt to further development for a number of years. The dam was completed under the auspices of Prime Minister Modi in 2017.

Back in Africa, even the Nile, the longest river in the world, has not been left untouched. The Nile Valley, which has been described as the cradle of civilisation, once carried about 130 million tons of life-giving silt to its floodplain and delta, and into the eastern Mediterranean, every year. These annual deposits supported a rich agriculture while the finer silts carried into the sea provided nutrients for the food web that includes the fish stocks of the coastal region. The river no longer carries enough silt to mention because various dams, particularly the Aswan High Dam (over 100 m high) now prevent annual inundation and also act as sediment traps: life-giving silts now clog the reservoirs instead of fertilizing the floodplain. Lake Nasser, the reservoir created by the Aswan High Dam in 1964, is 500 km long and 60 km wide, and is one of the largest artificial lakes in the world.

Since closure of the dam the Nile Delta, which has supported

NASA

The 500 km-long Lake Nasser, formed by the Aswan High Dam on the Nile River, Egypt.

human agriculture for at least 8 000 years, has eroded landward by up to 2 km. Further, the bars protecting the freshwater lakes Manzalla and Barullus in the delta are in danger of collapse, and an estimated 1 000 km^2 of river bank have been lost to the farmers of the lower valley. Furthermore, the delta at the mouth of the river is slowly decreasing in size as a result of sea-level rise combined with the fact that very little sediment comes downstream because of the Aswan Dam.

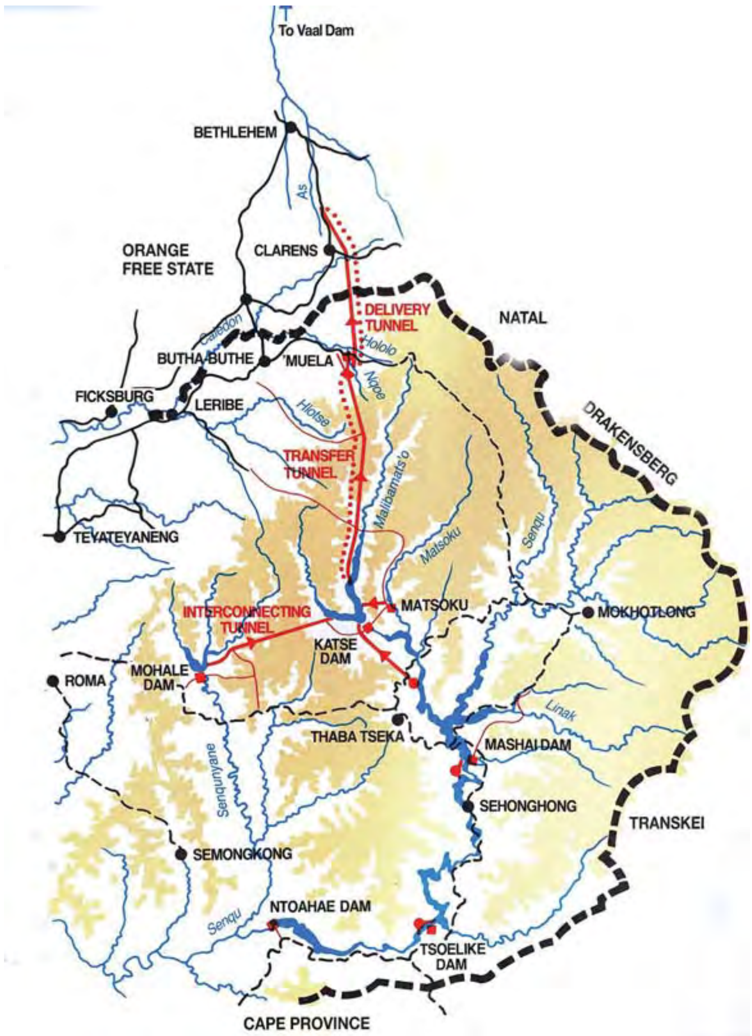
Mucking around with Mother Nature is often a dangerous thing to do. Is the end of mega-engineering not yet in sight?

NASA

The Nile Delta at night, the Mediterranean Sea to the north. This image beautifully illustrates how much the Egyptian people depend on the river.

THE SITUATION IN SOUTHERN AFRICA

These examples, and many others besides, are depressing and have frightening implications: if such things can happen to the world's mightiest rivers, what can we expect for the puny rivers of our own dry land? Well, to drive the point home, the Orange-Vaal River system, which is South Africa's largest in terms of length and catchment area, and the most important in terms of the population centres it serves, is already grossly overexploited. Its flow now relies in part on water pumped from several other river basins, so complex that a map of the roads, transfers and pipelines resembles a wiring diagram for a computer motherboard.



A map of the Lesotho Highlands Water Project. The thick dotted black line shows the boundary between South Africa and Lesotho; red represents dams, power stations and tunnels; the Katse Reservoir is shown in blue.

Inter-basin water transfers (IBTs: Chapter 9) include those from the Tugela-Vaal Water Transfer Scheme, which pumps water more than 500 m up and over the Drakensberg Mountains from the Tugela (also spelled Thukela) River in KwaZulu-Natal into the Vaal via Sterkfontein Dam. Indeed, during the worst of the drought in the early 1980s, the flow in the Vaal River was reversed, flowing upstream over several hundred kilometres in order to re-use used water leaving the Gauteng area. Could this be a global first?

The enormously expensive Lesotho Highlands Water Project (LHWP) consists of a series of dams, tunnels and pipelines designed for hydroelectric power but more importantly to provide water for the water-stressed Witwatersrand (the cities of Pretoria and Johannesburg, and the surrounding gold-mining areas). The idea had been discussed for decades before construction began in 1994. In 1998 the first phase of the project included the Katse Dam, which came on stream in 2002, followed by the Mohale Dam in 2004. These dams spill water down the Ash/Liebenbergsvlei River, into the Vaal from the headwaters of the Orange River in Lesotho. This is a sort of gigantic 'robbing Peter to pay Paul', as the Vaal and the Orange rivers form part of the same system (see Chapter 9).

Jenny Day

The Senqu River prior to the construction of the Katse Dam.

Wootan51 / 123RF

Katse Dam, the first of a series of dams constructed as part of the Lesotho Highlands Water Project.

Imdesert / 123RF

The reservoir formed by Katse Dam.

The scheme has been somewhat downscaled relative to the original plans and the entire system was expected to be completed by 2020. In fact, tenders for construction of the Phase 2 dam, the Polihali, were called for only in August 2021, so the project is considerably behind schedule. When the dam is completed, volumes of water reaching Gauteng will incrementally increase from the current 780 x 10^6 m^3/y to 1 270 x 10^6 m^3/y while the power supply for Lesotho will almost double.

As well as distribution of water on a large scale, there is the equally difficult problem of distributing it on a small scale to individual villages and households. At present, fully four-fifths of the people in developing countries who are ill at any one time are suffering from diseases such as cholera that are directly attributable to inadequate or contaminated water supplies. In 1980 it was estimated that about 50 000 people died every day from these diseases and other consequences of inadequate water supplies. Water the life-giver becomes water the killer, as has been potently illustrated in refugee camps worldwide. (For details on waterborne diseases refer to Chapter 8.)

Recognising these water-related problems, the United Nations declared the 1980s to be the International Drinking Water Supply and Sanitation Decade. The purpose of this ambitious programme was to bring clean water and adequate sanitation to every person in the world by the end of the 1980s. Since more than one-third of the world's population did not have access to safe drinking water, and almost three-quarters had no sanitation, not even a bucket or pit latrine, this was no mean undertaking. Unfortunately, the project failed in many respects. For success, from mid-1985 to 1991, every day an additional half a million people would need to have been provided with running water and safe sanitation. Furthermore, the difficulties in finding the appropriate technology, and teaching people how to install, to use, and to maintain equipment, were formidable, while the costs were mind-boggling. In 1977, the scheme was projected to cost US$133 billion. By 1981, this had already escalated to US$300 billion. On the positive side, although the programme failed in its primary objective of providing potable water to every human being, many valuable lessons were learned, and a great deal of appropriate technology was developed for water provision, treatment, and storage in remote areas. Worldwide, though, diarrhoea alone kills nearly half a million people a year and the United Nations Environmental Programme estimates that currently at least 1.8 million children under the age of five die every year from unsafe water, and that 'more people die as a result of polluted water than are killed by all forms of violence, including wars'. Many countries, including South Africa, are, however, attempting to reach the Strategic Development Goals (SDGs), which were established at the World Summit in Johannesburg in 2002. South Africa claims to be well on her way to achieving the goal that deals with water supply and sanitation.

WHAT THIS BOOK COVERS

So far, we have outlined the issue of water as a scarce resource from a human point of view. The scarcer water is for human use, the greater the impact on natural aquatic ecosystems, particularly rivers. So, in thinking about the conservation and wise use of water, we always have at the backs of our minds the fact that rivers are diminished by every extra demand for water, and that rivers and wetlands are polluted by waste or degraded by human interference. So two themes recur throughout this book: water as a resource required by humans, and water as a resource required by aquatic ecosystems themselves, both as providers of that resource and as dependants on it. (The conflict between rivers as both providers of, and dependents on, water exercises the minds of ecologists and water-managers alike whenever the development of a new water resource is planned.) As mentioned above, we originally became interested in aquatic systems from simple academic curiosity. But it soon became evident to us that all natural systems, even the smallest and least impressive, are becoming less and less natural. They are being altered by the construction of dams, or through the accumulation of wastes, salt and silt; they are being destroyed entirely by building operations or the dumping of fill, by diversion and canalisation, and by floodplain and marina developments; their nature is being altered by salinised irrigation return-flows or by a variety of pollutants. Naturally, we wondered why such changes seemed to be a universal feature of our local waters. It became clear that there are five underlying reasons:

- the lack of sufficient water for the growing population, agriculture, and industries of southern Africa;
- ignorance on the part of by politicians, farmers, planners,

engineers, and people-in-the-street of the consequences for aquatic ecosystems of over-use of water, and consequences for those same people of deteriorating aquatic ecosystems;

- misconceptions that water is in unlimited supply, that it just comes from a tap and that water that is left to run to the sea is water wasted;

- the fact that, while South African water law (the National Water Act 36 of 1998) is an admirable piece of legislation, its implementation is fraught with difficulties (see Chapter 10); and

- the fact that where a choice has to be made between economic gain and environmental protection, financial considerations nearly always take precedence over environmental considerations, regardless of long-term consequences.

Some years ago there was an infamous sign near Richards Bay in KwaZulu-Natal, at a gypsum-producing plant, proudly announcing to the world that the company owning the plant was 'reclaiming' the wetland adjacent to the factory by dumping wastes into it. We can report with satisfaction that attitudes to ecosystems like wetlands are changing rapidly amongst many sectors of the population of South Africa, although there is a long way to go before attitude rather than legislation will protect them from harm. On the other hand, when humans need more water than is available at the time, there is the indignant cry of 'all that unused water running uselessly to the sea'. It seems to escape notice that rivers had been doing that very thing long, long before humans arrived on the scene, and that the planet seems to need to 'waste' water. In flowing to the sea, rivers are carrying out vital planetary roles (see also chapter 11):

- erosion of mountains, resulting in deposition of silt that makes fertile floodplains on land, and sediments in the deep ocean basins, which aeons later become mountains;

- provision of food and habitat for a myriad estuarine organisms such as prawns;

- provision of nutrients to the coastal zone, without which coastal fisheries would cease to exist.

Furthermore, rivers are self-cleansing and self-regulating providers of potable water for terrestrial animals, including humans - who are, after all, simply one component of the amazing diversity of life on this planet.

All of this makes depressing reading. We could have avoided describing some of the more extreme examples of 'people against Nature' but it's important that our readers are aware of the dire nature of the threats we face on this planet. And it really ***is*** the threats that ***we*** face. Although "Saving the Planet" is an easy catchphrase, the Earth itself doesn't need saving from us. The planet will still be here long after the human species becomes extinct, and will recover from our puny scratchings on her surface. We need to look after that thin skin that is the biosphere, because it is the only home we have, and to keep it in a comfortably habitable state. We hope that this book will provide you with the information needed to make you knowledgeable about our inland waters, and the enthusiasm to be involved in addressing – and solving – the problems we face. And, of course, there are competent and dedicated professional ecologists and managers who work tirelessly to improve the state of our rivers and wetlands, and the water we use and re-use. If you are interested in helping to resolve this dilemma, you can have a look at the websites of local and international non-profit organisations (NPOs) listed at the end of this chapter.

We believe that the attitudes that have led to the crass exploitation of natural areas are, by and large, a matter of ignorance and not of malicious intent. We also believe that people are becoming far more environmentally aware: witness the rebirth of the ethic of recycling in our consumer society (yes, 'rebirth' – our grandparents knew all about recycling), and the growing environmental activism of a number of organisations and individuals. An open-minded and caring approach to environmental issues must become part of everyone's attitude from an early age, although, of course, it is never too late to learn. If this book does no more than provide an awareness of our reliance on water, and instil a respect for aquatic environments, their diversity and their life forms, then we shall not have written it in vain. Many readers will already be dedicated conservationists, while some still at school are only now awakening to the wonders of the world and the challenges we all face in preventing harm, or even reversing it. We hope that the book will also provide ammunition in the form of hard facts for the first group, and an introduction to a fascinating and problem-ridden topic for the rest.

The issues surrounding water supply are complex, involving politics, engineering, sociology, law, planning, and economics, and we are no more than amateurs in all of these fields. But, of course, they also involve ecology, that most complex of sciences that covers all of the interactions between plants and animals, with all of the additional complexities of physics, chemistry, geology, geomorphology, climatology, and so on. As ecologists we have attempted to pull together some of these disparate strands into a coherent account of the ecology of rivers and wetlands, and the problems of managing them and the services they provide to us as humans.

STRUCTURE OF THE BOOK

This chapter outlines the problems facing freshwater ecosystems as a result of human demand for water. Chapter 2 introduces water as a remarkable substance, then describes hydrological and other geochemical cycles and finally describes the different kinds of inland waters – rivers, reservoirs, wetlands, estuaries, pans and so on – and their distribution across the country. Chapter 3 examines standing waters like lakes, vleis and ponds, the plants and animals that live in them, and the ways in which environment and organism interact with each other.

In Chapter 4 we examine rivers, describing natural, unaltered rivers, their plants and animals, and the natural processes that drive them. Chapter 5 deals in a similar way with wetlands, and Chapter 6 with coastal lakes and estuaries. With this background, in Chapter 7 we describe some of the contributors to water quality and pollution, after which we switch the emphasis of the book from the natural to the not-so-natural, and begin to consider the effects of human intervention on inland waters, detailing the myriad types and effects of pollution.

In Chapter 8 we examine the effects of alien species, plant, animal and microbial. The problems encountered by regulated rivers, and the potential problems resulting from moving water from one river to another, are detailed in Chapter 9. Chapter 10 discusses water management, dipping briefly into the complexities of current South African environmental legislation before examining aspects of water management at municipal level, and then indicating how readers can save water through their individual actions. Chapter 10 also offers a few solutions to some of the human-induced problems of South African aquatic ecosystems by examining how some altered systems may be rehabilitated.

Chapter 11 is new to this edition and deals with the conservation of aquatic ecosystems, the ecosystem services they provide, and some issues of planetary importance. Finally, Chapter 12 describes a variety of methods for studying the physical and chemical properties of fresh waters and the organisms, of freshwater systems. This chapter also includes a list of potential projects that we hope will be useful for school teachers.

The book ends with a glossary of terms. The reading list at the end of each chapter is no more than an introduction to the literature on the subject. It includes a few seminal works and some useful modern ones as well as a number of web addresses: the internet is a marvellous resource, as long as it is used with some scepticism.

FURTHER READING

Adler RA, M Claassen, L Godfrey & AR Turton (2007). Water, mining, and waste: an historical and economic perspective on conflict management in South Africa. ***The Economics of Peace and Security Journal*** **2**: 33-41.

Sati SP, S Sharma, YP Sundriyal, D Rawat & M Riyal (2020). Geo-environmental consequences of obstructing the Bhagirathi River, Uttarakhand Himalaya, India, ***Geomatics, Natural Hazards and Risk***, **11**: 887-905 https://doi.org/10.1080/19475705.2020.1756464

SOME USEFUL WEBSITES (LAST ACCESSED IN SEPTEMBER 2022)

Africa
https://mg.co.za/article/2019-04-12-00-inga-dam-deal-is-a-grand-delusion/
https://www.bbc.com/news/world-africa-43500314
https://www.nature.com/articles/s41598-020-62417-w

Amazon dams
https://news.mongabay.com/2020/10/brazils-amazon-dam-plans-ominous-warnings-of-future-destruction-commentary/

China water projects
https://storymaps.arcgis.com/stories/4521fb4a742741fb811f4f7cb354113a
https://www.newsecuritybeat.org/2021/08/build-build-western-route-chinas-south-north-water-diversion-project/

Demographics
https://www.worldometers.info/world-population/south-africa-population/
https://www.macrotrends.net/countries/ZAF/south-africa/population-growth-rate
http://www.statssa.gov.za/?cat=15

Department of Water and Sanitation (DWS) SA
https://www.dws.gov.za

Drylands
https://news.globallandscapesforum.org/50717/everything-you-need-to-know-about-drylands/

Orange River and the Lesotho Highlands Water Project
http://www.dwa.gov.za/orange/
https://www.esi-africa.com/industry-sectors/water/the-lhwp-ii-is-delayed-expensive-and-wastes-water/

Sustainable Development Goals (SA)
https://pmg.org.za/search/?q=SDGs+2021
https://pmg.org.za/committee-subscriptions/#freepremium

Water crises 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.

World Heritage sites (SA)
http://whc.unesco.org/en/statesparties/za

ENVIRONMENTAL NGOs

Global Water Partnership (GWP)
https://www.gwp.org/en

International Union for the Conservation of Nature (IUCN)
https://www.iucn.org/about

The Nature Conservancy (TNC)
https://afr100.org/content/nature-conservancy

Wildlife and Environment Society of South Africa (WESSA)
https://wessa.org.za/

World Wildlife Fund (WWF)
https://www.wwf.org.za/

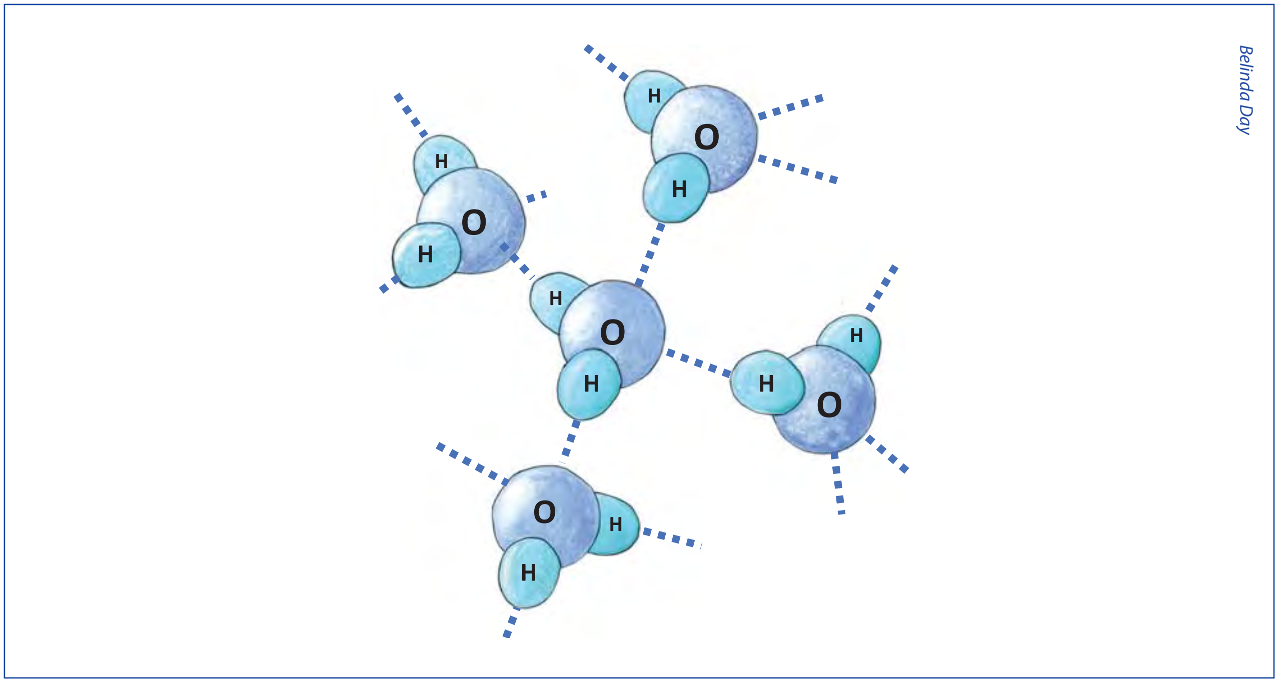
CHAPTER TWO

The building blocks of inland water ecosystems

> If there is magic on this planet, it is contained in water.
>
> *Loren Eiseley, American author, 1907-1977*

In this chapter we look at building blocks: the structure of water as a substance; the materials that make up the bodies of living things, and the major elements and biogeochemical cycles that rule life on Earth. Having looked at these abiotic (Gr: a = not, biōtikós = pertaining to life) building blocks, we look at aquatic ecosystems and how they are structured. We end the chapter by looking at the diversity of ecosystem types, from rivers to ponds and salt flats, using South African examples to describe the characteristic features of each.

WATER: WHAT IS SO SPECIAL ABOUT IT?



Water molecules consist of two smaller hydrogen atoms linked to one larger oxygem atom; many of the remarkable properties of water are conferred by the hydrogen bonds (dotted blue lines) that attract water molecules to each other.

Water is truly a magical molecule. We all know that it is essential for life, but why is this so? Let's set the scene by looking at some of its properties. It is one of the most versatile materials known and yet each water molecule consists simply of one atom of oxygen bound to two atoms of hydrogen. So, what makes water truly magical? The hydrogen bond! Hydrogen bonds are caused by the electromagnetic interaction between the hydrogen and oxygen atoms of a water molecule. The bond is weaker than the kinds that hold molecules themselves together and so it is relatively easily broken and yet it is strong enough to cause water molecules to stick to each other. Almost all of water's properties can be seen to depend on those hydrogen bonds.

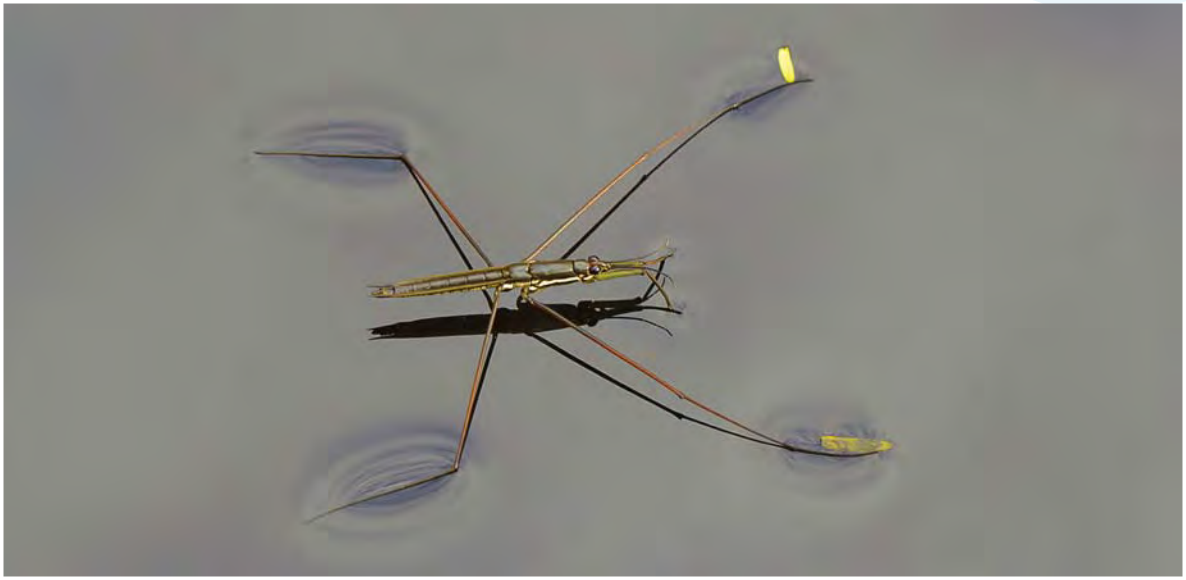
- **Solid, liquid, gas:** While molecules of CO_2 and O_2 are gaseous at ambient temperatures, water is liquid. Why? Because H-bonds make the molecules cling tightly to one another, water has unexpectedly high melting and boiling points; indeed, water is the only substance that occurs naturally on Earth as a gas (water vapour), a liquid and a solid (ice). For the same reason, water has a very high heat capacity: a lot of energy is needed to break H-bonds when water is heated so that, for instance, swimming pools take a long time to heat up or cool down. On a global scale, the heat carried in ocean currents affects the climates of entire regions. Water also has an exceptionally high latent heat of vaporisation (converting water into steam) and latent heat of fusion (the energy needed to melt ice). The oceans thus have a strong moderating effect on global temperatures. In fact, the moderate ambient temperatures of our planet as a whole result largely from these remarkable properties of water.

- **The cohesive nature of water:** Water is 'sticky' because of H-bonds. This means that molecules on the water surface cling together, small volumes pulling together into drops and larger volumes forming a surface tension 'skin', which can support small objects like insects. Some kinds of insects such as pond skaters and whirligig beetles take advantage of this phenomenon, living specifically on the water's surface. Males of some species even use the water as a means of communication with mates by vibrating their legs at a specific frequency and causing minute ripples in the water that are picked up by the females of the same species.

- Water is the only compound that is **lighter as a solid than as a liquid**: molecules in liquid water pack more densely than they do when arranged regularly in the crystal matrix of ice, which means that ice forms on the surface of the water, insulating the deeper layers, which do not freeze. If it were not for this phenomenon, living organisms would not be able to live under the surface of the water during cold winters.

- Some water molecules dissociate to produce H_3O^+, the positively charged hydronium cation, and OH^-, the negatively-charged hydroxyl anion. These properties confer remarkable **dissolving powers** on water, for the charged ions may combine with a huge variety of other chemicals. Water is thus a supreme solvent, its charged ions 'pulling apart' and dissolving substances such as salts and sugars, and soluble dirt. Moreover, water can maintain many substances in solution at once, which means that organisms can absorb them, distribute them around the body in sap or blood, and carry out the biochemical reactions necessary for life.

- Water is **transparent at visible wavelengths**, which is why plants can grow under water.



RealityImages / 123RF

A water strider. Insects like this can walk on water because surface tension makes the water molecules at the surface stick to each other. The points of light are caused by the feet of the bug deforming the water surface.

andrey7346rf / 123RF

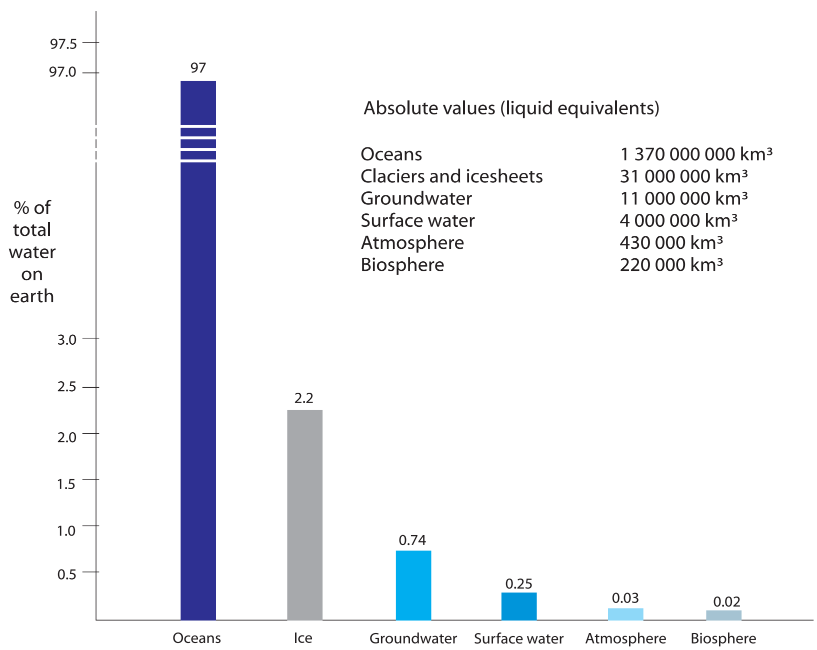
The fact that ice floats makes it possible for organisms to live under the surface when water reaches freezing point.

WHERE DOES OUR WATER COME FROM?

The water on Earth originated as hydrogen from the Big Bang at the beginning of time, and oxygen from nuclear reactions in stars. Water forms in space, and in fact most oxygen in space is bound to hydrogen, forming water, or to carbon, forming carbon monoxide (CO). Is water being formed on Earth, though? Apparently not. Astrophysicists disagree about details, but they do agree that either Earth's water was retained when the planet consolidated from a proto-solar nebula (which presupposes that the Earth contains a lot of water, which emerges with tectonic movements & volcanoes), and/or from asteroids/comets hitting the Earth. Is water not generated naturally on Earth, then? The answer is that the amount generated on Earth is trivial and due only to purple sulphur bacteria fixing carbon and synthesizing water as a by-product of their photosynthetic pathway, which uses H_2S and CO_2. In short, no significant quantities of water are generated on Earth: what we have is what we've got.

WATER ON EARTH

Water forms our oceans and lakes, rivers and estuaries, polar icecaps and clouds, and in liquid form covers approximately 70% of the total surface of the planet. Our oceans have an average depth of 3 800 m, or 3.8 km. As rivers, waves, and floods, water sculpts landscapes; it dissolves soft soluble rocks (such as limestone) and erodes hard insoluble rocks (such as granite); it obscures the sun as clouds and in storms; it carries chemicals dissolved in it; it transports suspended materials that will be deposited on floodplains, along coastal margins, and on deep ocean floors. Its capacity for heat exchange drives our weather systems. Within our own bodies it is the most abundant molecule. Indeed, if dried out, the human body would not amount to much! Each living cell of our bodies is more than two-thirds water which, as a solvent, allows the transport of vital materials such as foodstuffs and oxygen into the cell, supports all our life processes, and exports waste products such as ammonia and carbon dioxide from it. Water makes up about 60% of the human body (most of the rest is bone), 60-80% of fish bodies, 90% of worm bodies and 95% of jellyfish bodies.



Distribution of fresh water on Earth. The proportion of water that is fresh and potable (drinkable) is tiny. (Modified from Metlink.org and based on http://dx.doi.org/10.1175/2011JCLI4171.1)

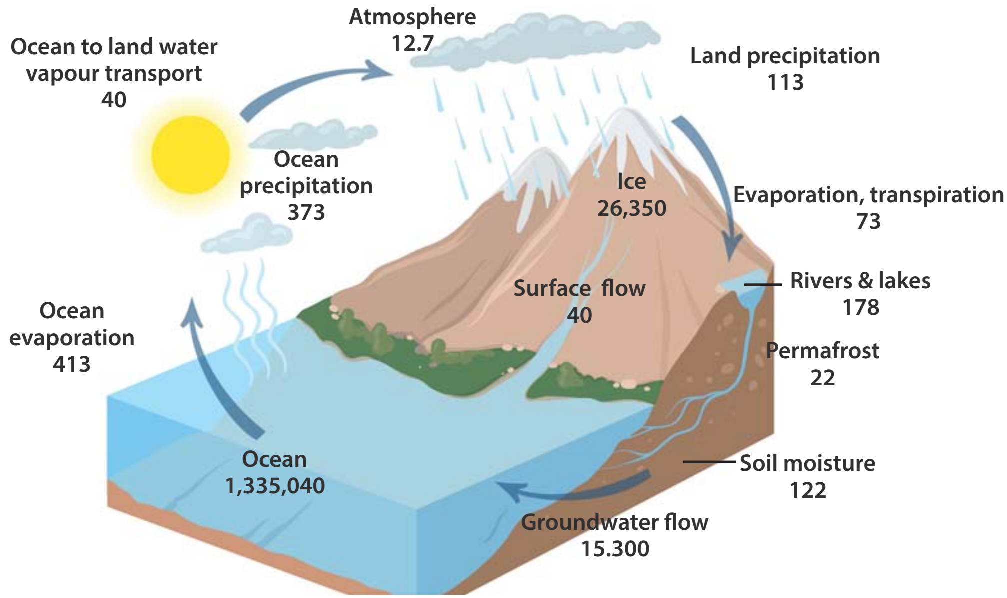
The figure on page 40 shows the proportional distribution of water on Earth. The total amount is enormous – some 1.42 billion cubic kilometres (1.42 x 10^9 km^3). Despite the existence of this mind-boggling amount of water, very little of it is directly available as fresh water. For instance, more than 97% (1.4 x 10^9 km^3) resides in the oceans as salt water, unfit for human use. While at first sight the ice sheets of the planet appear to be considerable, they contain only 2.2% of the Earth's water, or about 31 million cubic kilometres (3.1 x 10^7 km^3). This is enough, though, that if all the ice were to melt, sea level would rise by some 60 m to 70 m, inundating many major centres of human population, including most of Cape Town and all, or nearly all, of London, New York, Adelaide, Chittagong, Havana, Karachi, Saigon, Lagos, Bangkok, New Orleans and Liverpool, most of Maputo, Marseilles, and Mombasa, and a lot of Sydney, Casablanca, Rio de Janeiro and East London. Additionally, several small island states like the Marshall Islands would cease to exist. The proportion of water that is both fresh and liquid is small: just under 1% of the total. Of this, about a third (4 x 10^6 km^3) is surface water and the remainder (1.1 x 10^7 km^3) is groundwater. In the atmosphere only about 0.03% of all water on the planet, some 430 000 cubic kilometres (4.3 x 10^5 km^3), is in circulation as water vapour. Although it seems to be a very small proportion of the overall amount, this vapour is of vital importance to the planet for it is the source of rain, mist and snow. Overall, very little of the water on Earth is both available and suitable for human use.

THE HYDROLOGICAL (WATER CYCLE)

Water is moving all the time, as well as changing from liquid to gas or solid and back again. Evaporation from the sea and other open water surfaces, as well as transpiration of land plants, produces water vapour. Condensation of that vapour results in clouds that eventually precipitate as rain. Rainwater infiltrates soils and forms groundwater as it fills up crevices and spaces between sand grains; it runs off into rivers and is stored in lakes and wetlands, or in ice fields, from which it again undergoes evaporation and/or transpiration. This continual process of transformation and redistribution is known as the hydrological, or water, cycle.

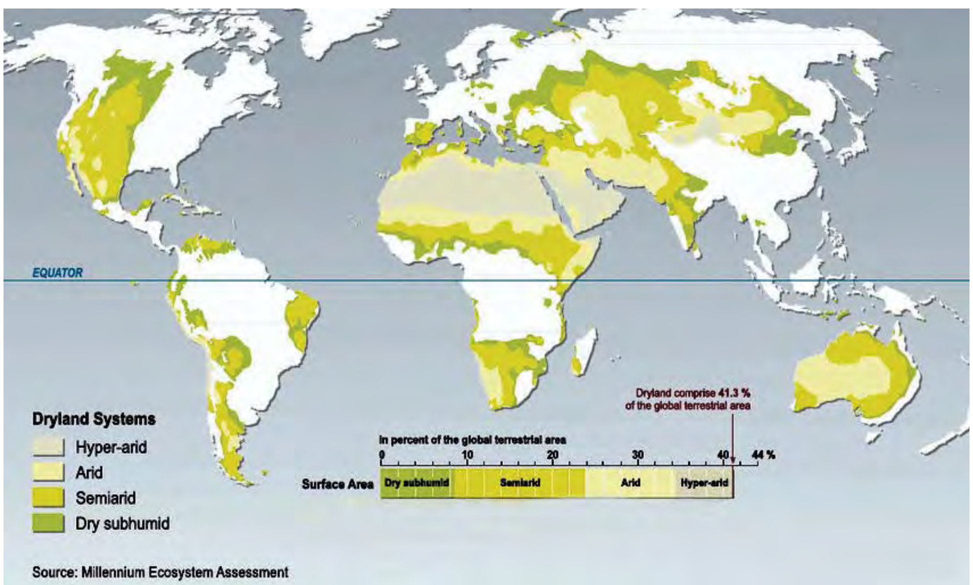
The juxtaposition of land masses and mountain ranges, and cold and warm currents in the oceans, prevents equal distribution of rain around the world so that fresh water is not only scarce in global terms, but it is also unevenly distributed. The figure on page 42 illustrates this fact, showing the distribution of drylands around the world. Drylands are areas receiving less than 500mm of rain a year. They can be divided into semi-arid areas that receive 200–500 mm of rain a year; arid areas that receive 25–200 mm/y; and hyper-arid areas, which receive less than 25 mm/y. Note that continental Africa has more than its fair share of drylands and also that almost all of southern Africa, with a major water deficit, is classed as dryland by world standards.

stockshoppe / 123RF



The hydrological cycle: storage of water in thousands of km^3 and fluxes (exchanges) in thousands of km^3 per year.

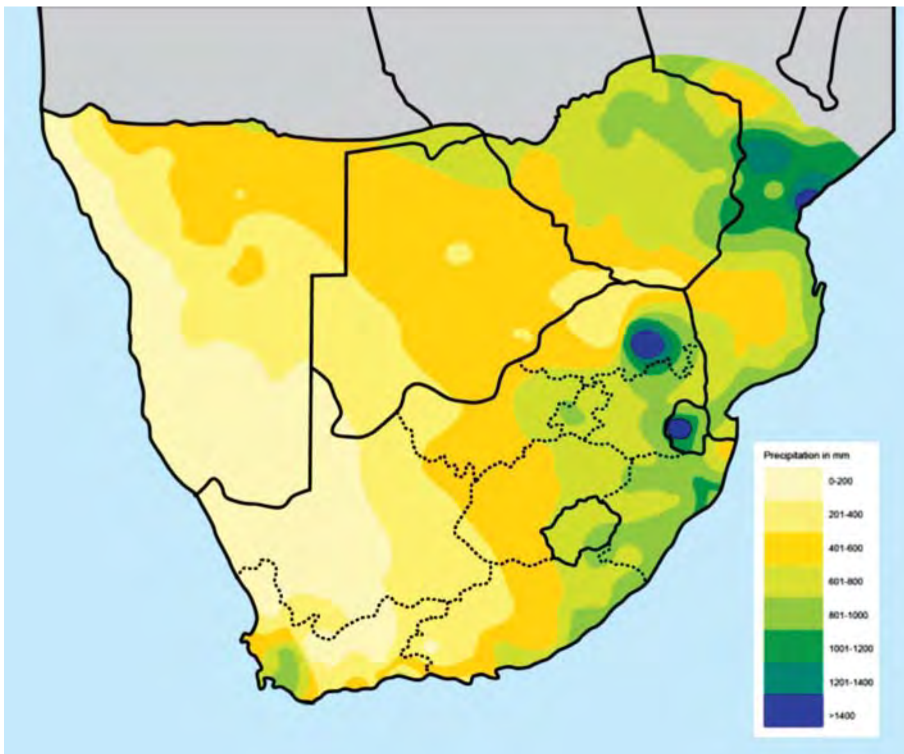
Millennium Ecosystem Assessment and Graciela Metternicht



Map showing the world's drylands; precipitation in hyper-arid areas <100 mm/y; in arid areas 100-250 mm/y; in sub-arid areas 250-500 mm/y; in dry sub-humid areas <700 mm/y.

SOUTH AFRICA AS A DRY LAND – TOPOGRAPHY AND CLIMATE

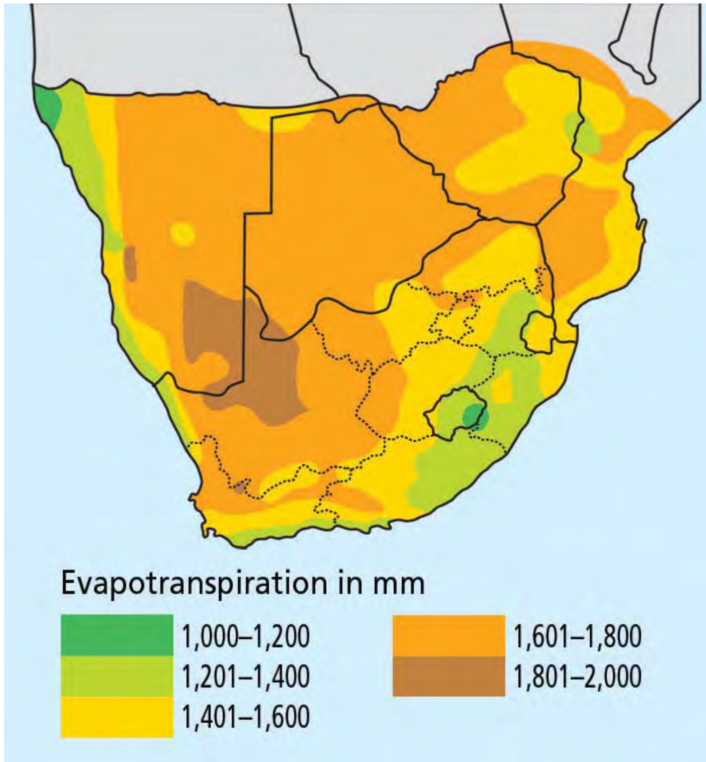
With this background, we can now turn our attention to our own land. Drylands dominate much of the globe, and of Africa in particular. Southern Africa ranges in climate from semi-arid to hyper-arid, only a few relatively humid parts having rainfall greatly exceeding 500 mm/y. Mean Annual Rainfall (MAR) or Mean Annual Precipitation (MAP) (see figure below) decreases while evaporation (see figure on page 44) increases westwards and northwards across the southern part of Africa. South Africa's overall average rainfall is 452 mm/y, but vast areas receive much less than this. Furthermore, in the southern part of the region, mean annual rainfall exceeds mean annual evaporation only on a few mountain tops in the Drakensberg and the south-western Cape, while evaporation far outstrips precipitation in many parts of the region. In the industrial heartland, Gauteng, evaporation is about twice as great as rainfall and in the lower Orange River valley it is ten times as great. In simple terms, there is no such thing as a water surplus in South Africa. In fact, for much of southern Africa, any rain that does reach the ground soon evaporates and re-enters the atmospheric phase of the water cycle.



Griffiths et al (2015)

South Africa's mean annual precipitation (MAP). Note the strong gradient in rainfall from relatively high values in the east to very low values in the west. The 600 mm isohyet (contour) marks the limit of dryland agriculture.

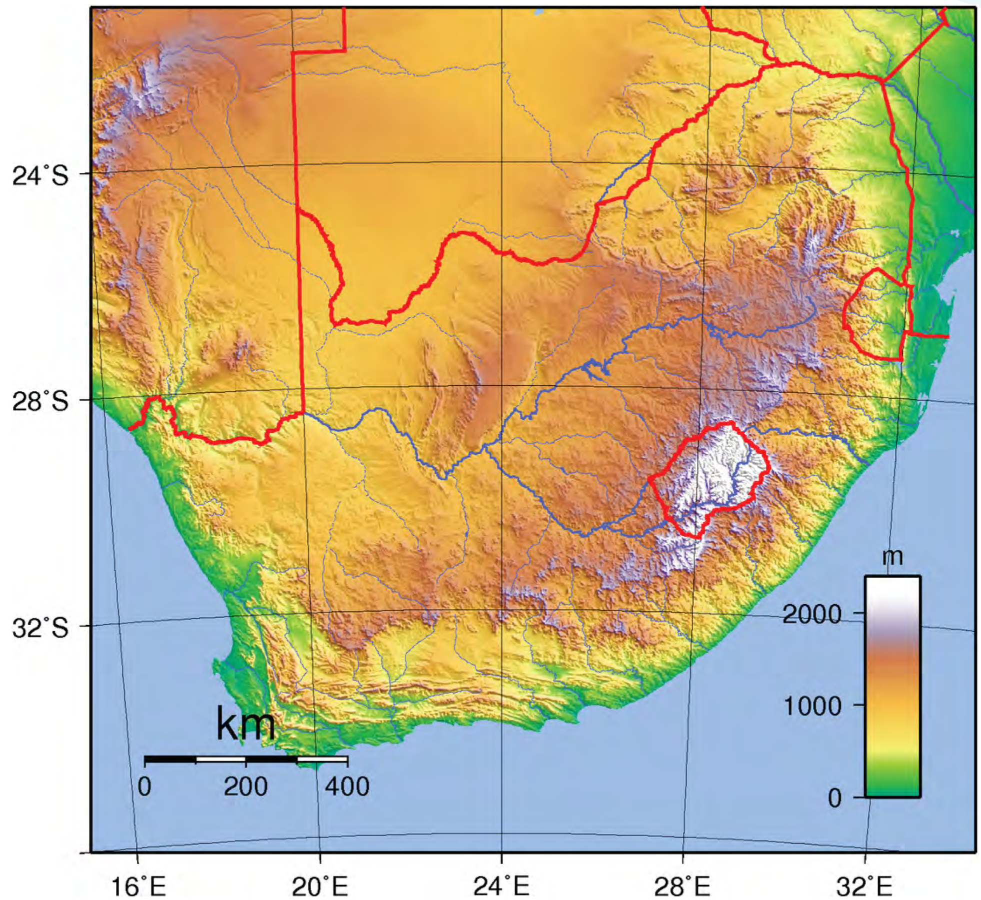
Griffiths et al (2015)



Mean annual evaporation (MAE) for South Africa. Unlike MAP, MAE is greatest in the west and least in the south and east.

Not only is South Africa a dry land, but it is also very ancient. Except for the mountain ranges associated with the escarpments that separate the coastal plains from the interior, the land is high but flat. Indeed, some of the oldest rocks in the world (about 3 800 million years old) are exposed in the Barberton Mountain Lands of Mpumalanga. The fact that these rocks are exposed at the surface implies that the entire subcontinent has been subjected to intense erosion and removal of younger, overlying rocks. This has led to the flattening of surface features and the infilling of broken country within which lakes might have developed. In fact, the entire central part of the country comprises the huge Karoo Basin, once an inland sea but now filled with sediments that have hardened into rock. (It is these rocks that bear the fossilised remains of ancient reptiles such as dinosaurs.) In addition, the Southern Hemisphere has largely escaped the major Pleistocene glaciations that have been a feature of the northern continents over the past couple of million years. Thus, deeply dissected glacial valleys, which in warmer times might serve as beds of deep lakes or rivers, simply do not occur here.

The distribution of rain in time and space is also markedly skewed. Firstly, rainfall is highly seasonal, being produced by different weather systems in different regions at different times of the year. In winter the prevailing north-westerly winds hit the western part of the country first and drop much of their rain there, leaving the southern interior, including the Karoo, in a 'rain-shadow'. In summer, rain normally falls in the north and east while dry, high-pressure air masses may persist for long periods in the south and west and do not produce rain. Thus, South Africa experiences a wide range

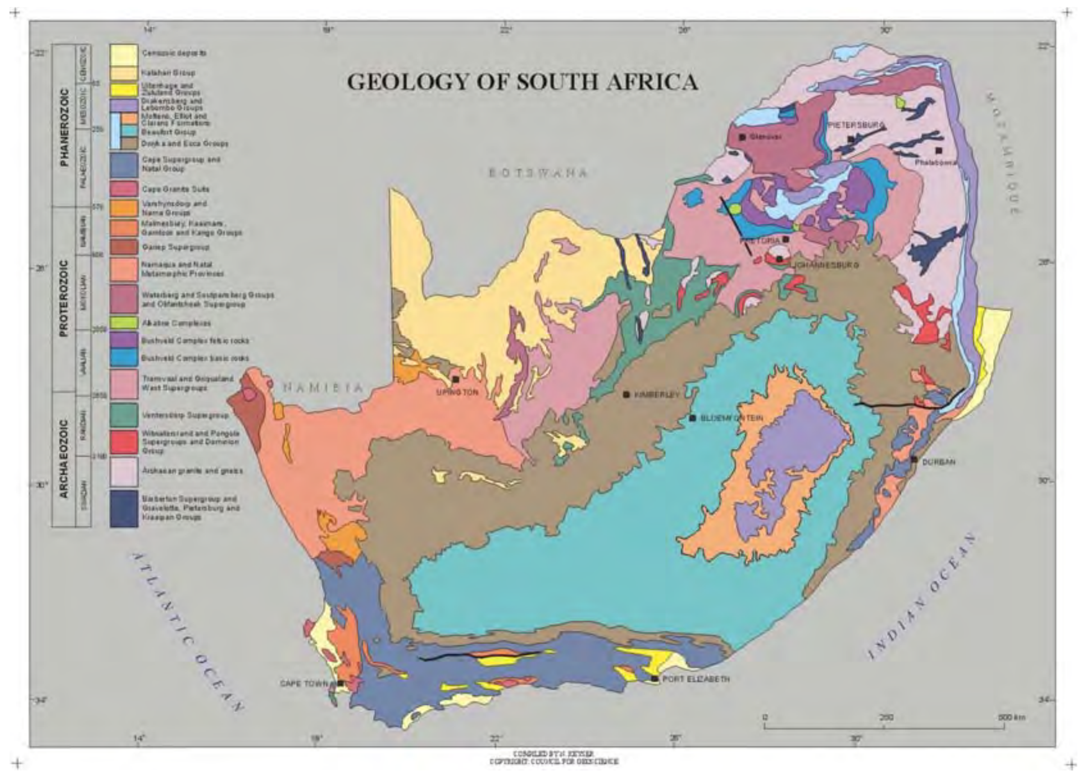


Saddalmelik / Wikimedia / CC BY-2.0

The topography of South Africa, showing the relatively steep rise from the coastal forelands in the south and east, and the high-lying central basin. Rivers are indicated in blue and international borders in red.

of climates, from winter rains and warm windy summers in the south-western Cape; to erratic, non-seasonal rainfall and extremes of temperatures in the Karoo; to hot summers with thunderstorms and bitterly cold winters on the Highveld; and subtropical, usually mesic, conditions on the KwaZulu-Natal coast. Secondly, rainfall varies erratically from year to year, resulting in unpredictable periods of drought and flood. Thirdly, the major industrial centre of the country, Gauteng, grew where it did because of the discovery of gold, despite the fact that the semi-arid Highveld is not an ideal population centre. Putting this in perspective, the task of South African water managers is frightening. Not only must they supply water to huge populations in semi-arid regions but they also need to store enough water to contend with droughts of unpredictable magnitude occurring at unpredictable times (see Chapter 9). They know that even if they do their jobs efficiently and competently, they will probably always lose the race against increased demand for water generated by more and more people.

Council for Geoscience



A simplified map of South African geology.

THE INLAND WATERS OF SOUTHERN AFRICA

Water bodies generally can be divided into standing (lentic) and running (lotic) systems (from the Latin: ***lentus*** = slow; ***lotus*** = washing, therefore flowing). This classification is useful because, by and large, different suites of organisms inhabit lentic and lotic ecosystems – although, as is so often the case, some do not fit neatly into either category. Furthermore, because of the running water in rivers and estuaries, these systems tend to flush out material. To put it crudely, they are drains rather than sumps. In contrast, wetlands are sinks, or sumps, accumulating material as a result of the low gradient and slow or non-existent flow of water.

Essentially, lotic systems consist of rivers and their estuaries. In this country, though, many estuaries are seasonally 'blind': they are periodically lentic and then lotic. Similarly, floodplains, although parts of rivers, may support almost permanent standing waters, or seasonal wetlands, or both. Furthermore, many South African rivers are intermittent or seasonal systems with no water flowing, or indeed with no water at all, for long periods. In the same vein, truly lentic systems traditionally comprise lakes and ponds, although in South Africa either type may dry up on occasion and therefore appear not to be water bodies at all.

In this section we deal briefly with the kinds of lotic and lentic water bodies found in this country and explain some of the basic ecological terms that will be used later on. True inland lakes are poorly represented in southern Africa, and yet are the simplest aquatic ecosystems to understand. Thus, having introduced readers to the wide variety of water bodies that occur in South Africa, we will discuss standing waters, especially lakes, in Chapter 3 before turning our attention to rivers in Chapter 4, wetlands in Chapter 5, and coastal lakes and estuaries in Chapter 6.

STANDING WATERS

Lakes and ponds

It is an astonishing fact that we have only one water body – Lake Fundudzi in Limpopo – that truly fits the definition of a lake (a permanent body of water with areas deep enough that rooted plants do not occur). Obviously, a lake or a pond can exist only if there is a suitable depression that can retain water. Other characteristics of any water body depend upon factors such as size and depth; the balance between rainfall and evaporation; topography and geology; and the type of vegetation in the catchment. Lake Fundudzi happens to be situated where a natural rock fall dammed a river, but it is also in the only part of the country where mean annual rainfall exceeds mean annual evaporation. In contrast, Barbers Pan and Lake Chrissie, which are often viewed as lakes, have been known to dry out on several occasions because they are situated in areas where evaporation exceeds rainfall. See chapter 5 for a map of South Africa's wetlands.

An almost bewildering array of terms has been used to describe standing waters: vleis, pans, floodplains, lakes, ponds, coastal lakes, sponges, bogs, mires, marshes and swamps. Many of these systems are grouped under the collective term 'wetland' and, in fact, the Ramsar Convention uses the term 'wetland' to refer to all inland water bodies, including rivers, and even coastal waters to a depth of 6 m.

The Ramsar definition of wetlands is:

Areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.

The particular nature of each system also depends on the often unique mix of species of animals and plants, bacteria and fungi that they support, as well as the interactions between species and their physical and chemical environments, and each other. Although there is no universally accepted definition, water bodies large and deep enough to have regions where rooted plants cannot grow are called lakes. Except for coastal lakes, and one or two in the interior, there are no permanent natural water bodies in South Africa that can justifiably be defined as lakes, although several artificial reservoirs or impoundments (dams) can be. Fortunately in South Africa we have the very useful Dutch word ***vlei*** (pronounced ***flay***), which can be used for almost any kind of wetland. A detailed description of the development, physics, chemistry and ecology of lakes is to be found in Chapter 3.

Ben van der Waal

Lake Fundudzi, Limpopo, a sacred site for the Venda people.

Jenny Day
Mike Silberbauer
Jenny Day

A variety of wetlands, all of which include the word 'vlei' in their names. A) Potberg Vlei, a large perennial pond near de Hoop Vlei on the south coast; B) Soetendalsvlei, one of the largest bodies of fresh water in South Africa; C) Rietvlei, an artificial estuarine lagoon near Cape Town.

Coastal lakes and estuaries

The coastal strip of the better-watered parts of South Africa is dotted with shallow lakes or vleis. Some of these contain fresh or almost-fresh water, while others are brackish. It is likely that most or all of them originated as estuarine lagoons and indeed some, such as the interlinked Wilderness Lakes along the southern Cape coast, or the Kosi system in northern KwaZulu-Natal, are normally open to the sea. Well, they were, until humans started to abstract water from their rivers, or to dam them. Interestingly, in systems such as Rondevlei in the Wilderness Lakes, and the upper reaches of Lake St Lucia in KwaZulu-Natal, the sections furthest from the sea are the most saline. Reversed salinity gradients occur particularly during drought and are caused by the combined effect of a reduced inflow of fresh water from tributary rivers and groundwater seepages, and a high rate of evaporation. Together, these result in a concentration of the salts already present in the water. Sometimes the water in St Lucia becomes so salty that crocodiles are too buoyant to be able to submerge in them. Other coastal lakes, such as Lake Sibaya in northern KwaZulu-Natal, are now quite fresh, although their estuarine histories can be inferred from the 'relict' faunas that include crabs, fish and mussels whose closest relatives are marine. Many of these coastal systems are particularly sensitive to disturbance. They, and estuaries, and their conservation are discussed in detail in Chapter 6.

The Wilderness lake system near Knysna on the south coast.

An aerial view of the rivers that make up the greater St Lucia system on the coast of KwaZulu-Natal.

Wetlands

It is difficult to define precisely what we mean by wetlands. Intuitively, we tend to think of wetlands as shallow swampy or marshy areas with little or no water flow. They are commonly defined as 'areas with waterlogged soils dominated by emergent vegetation'. Technically, though, wetlands include any ecosystems whose soils show evidence of at least periodic waterlogging. Thus, wetlands include a variety of types of soggy areas, many of which are breeding grounds for mosquitoes and midges and may appear to be useless 'wastelands' taking up valuable space. They are favourite haunts of birdwatchers but otherwise received scant regard until late in the twentieth century, when the term was first used. Because of the stigma attached to them ('noxious mires' and 'foul fens' are two old English views of wetlands), even today they are often considered to be 'wasted' land fit only to be drained in order to put them into 'productive' use (for farming, perhaps, or as solid-waste landfill-sites). As a result, wetlands are some of the most threatened and the fastest disappearing group of inland waters in South Africa and worldwide. But are they really 'wasted' lands? Are they useless and unproductive? Nothing could be further from the truth.

Globally, wetlands of all types – including rice paddies – cover more than 230 million hectares of land – slightly less than twice the total surface area of South Africa. The characteristics of each wetland are dominated by factors such as geology, soil-type, topography and climate. Wetlands perform vital functions, most of which depend on the presence of dense stands of reeds or other large emergent plants. In chapter 11 we discuss the 'ecosystem services' provided by wetlands.

Jenny Day

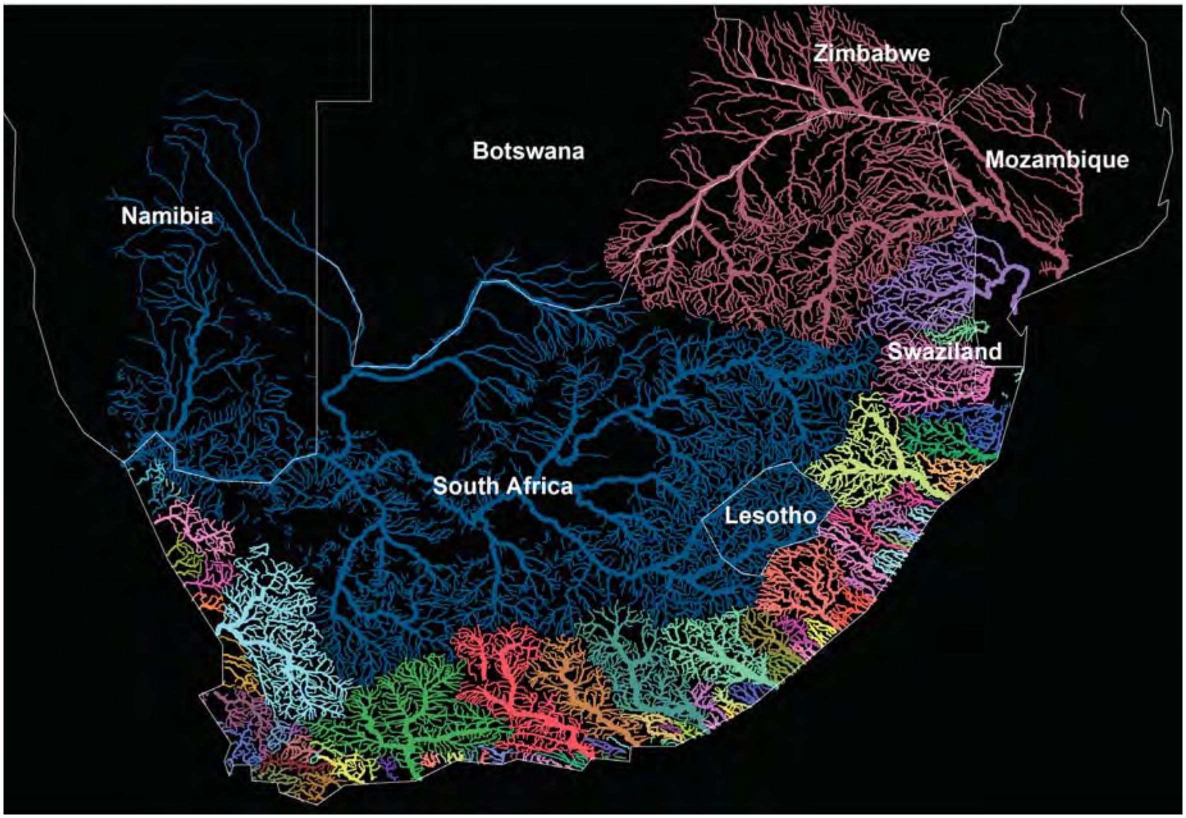
Jenny Day

SanA secretariat / Wikimedia / CC BY-2.0; C) Ant West

Wetlands come in all shapes and sizes, and many are created or modified for human use. A) a rice paddy in Rwanda: B) an artificial wetland in China, used for sewage purification; C) Geelvlei, a temporary wetland in the Karoo.

RIVERS

It might be reasonable to assume that, although there is a paucity of lakes in southern Africa, the subcontinent is well endowed with rivers. Although this is true for the eastern part of the region, which receives a large proportion of the rainfall, it is not true for the rest of the country. Many rivers in the west are shown as dotted lines on most maps because they are intermittent or ephemeral systems, flowing for only part of every year in wetter areas, or flowing only in occasional wet years in the driest areas. Indeed, in these regions, riverbeds provide a convenient network of roads that only occasionally become impassable due to water flow.



Sukhmani Mantel

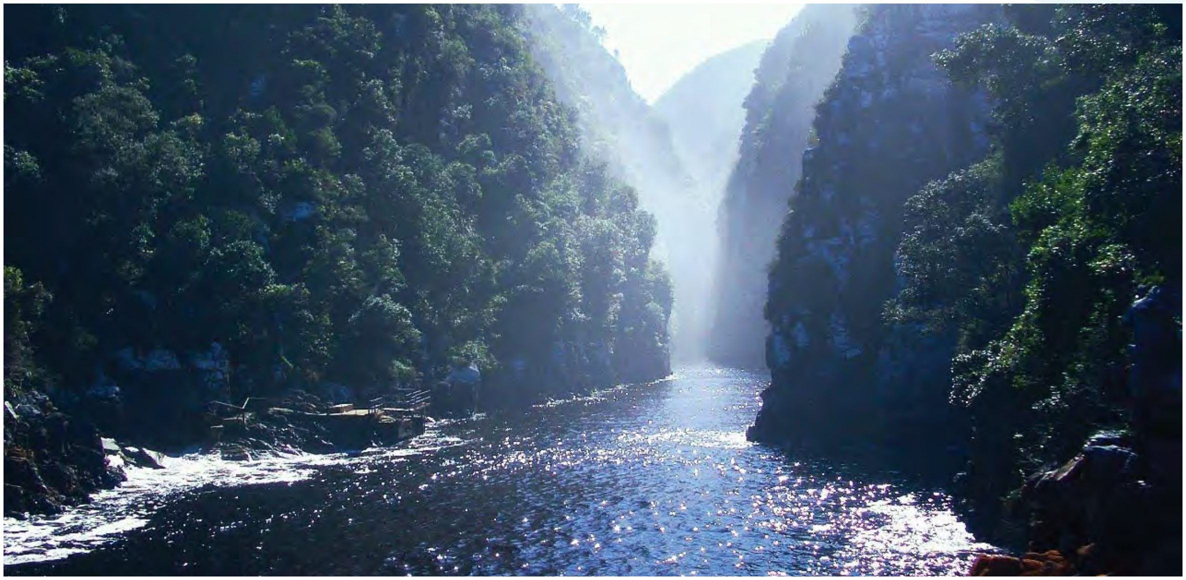
The rivers in each of South Africa's river basins are given a separate colour in this remarkable map, which illustrates perfectly the contrast between the many short coastal rivers and the two huge inland basins – the Orange River basin in blue and the Limpopo River basin in dark red.

Jenny Day

The dry Mudorib River in the Namib Desert.

More than 56% of the South African 'virgin' or unregulated MAR (mean annual runoff: the average amount of water running annually from the surface of the land) is channelled into the Indian Ocean through the many rather short rivers along the southern and eastern seaboards, while the southern and western coastal regions deliver another 13%, through a few small rivers such as the Olifants, Berg, Palmiet, and Breede. Although it represents more than half of the surface area of the country (and supports a majority of the human population), the central plateau contributes no more than 22% of the total runoff. Most of this region lies within the huge (650 000 km^2) catchment of the Orange-Vaal system. So, although the Orange River itself is by far the largest river system south of the Zambezi River, it contributes only 13.5% to the total MAR from South Africa; the Vaal River, its primary tributary, contributes just 8.6%. This means that although the bulk of the South African population, and the industry that drives our economy, is located near these 'major' rivers, the country still suffers a massive water deficit. Additionally, vast areas of the country are virtually uninhabited because of their extreme aridity. The land has 'blossomed' in a way, though, where irrigation schemes have been developed, suggesting that if water were available in sufficient quantities and of suitable quality, the agricultural potential of the country might be greatly increased. Unfortunately, this is not necessarily the case; we will return to the issue of aridity again and again throughout this book.

Because of the dryness of our land, we can hardly be considered a land of mighty rivers in the sense of Africa's giants – the Nile, Niger, Volta, Senegal, and Congo rivers – although we do have the much smaller Orange-Vaal, Tugela, Limpopo, and Phongolo rivers. And to the north is the greatest river in southern Africa – the Zambezi. From its source at 1 400 m above mean sea level (AMSL) on the southern slopes of the Southern Equatorial Divide, the Zambezi flows south-eastwards for 2 500 km to the Indian Ocean, draining an enormous catchment of some 1 193 500 km^2. The Zambezi is an ancient system that has alternately broken away from and rejoined a variety of other rivers, including the Limpopo.



John Day

The Storms River arises on the south flank of the Outeniqua Mountains, about 15 km from the sea; being very sinuous, its total length is probably close to 100 km. It enters the sea in the Tsitsikamma National Park.

Udokies / 123RF

The Orange River as it flows through the Richtersveld.

We know this not only from geological and geomorphological evidence but also from the wide variety of fish (156 species) that it harbours, many of which have close relatives in other nearby, but now separate, drainages. The Zambezi also has links with the giant Okavango system in Botswana via the Chobe River, but only at times of high rainfall.

Further to the south, the Phongolo: (also spelt Pongola) River rises in the Lebombo Mountains and flows north-eastwards, being joined by the Usutu before entering Delagoa Bay in Mozambique. Like the Zambezi, this river forms extensive and very fertile floodplains in its lower reaches. Such floodplains are of great significance for the local human populations because of the fisheries associated with the floodplain pans and the agricultural potential of the rich alluvial silts that are deposited on the banks with each flood. (See further discussion on the Phongolo River in chapter 9). Further to the south, the Highveld is dissected by the ancient and centrally situated Orange-Vaal system which, despite its small contribution to the total runoff from South Africa, plays a vital role in supplying the industrial heartland with its water. The lower reaches of the Orange River are allogenic (literally, 'generated elsewhere'), the headwaters rising in the relatively wet mountains of Lesotho but flowing through ever more arid country until, where it reaches the sea, the rainfall is less than 100 mm/y. See a brief discussion on the Lesotho Highlands Water Project in Chapter 1.

Martin Mwaura / 123RF

The truly mighty Zambezi River, seen here at the Victoria Falls.

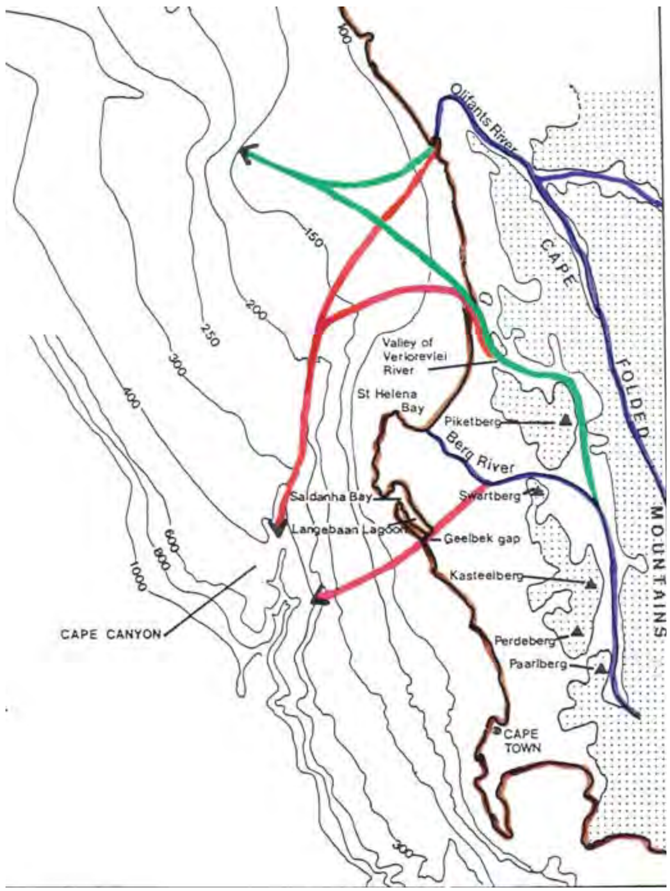
Dickiyon / Wikimedia / CC BY-SA 4.0

The gradient of the Chobe River is so low that the river can flow either way, depending on where rain has fallen in the wider catchment.

Jenny Day

The Makatini Flats, the floodplain of the Phongolo River below Pongolapoort Dam.

The remaining perennial rivers of southern Africa are much shorter than the Orange, although some of them are probably much older. Those of the eastern and southern coasts have cut down deeply into the earth as the coastal margins of the subcontinent have tilted and sea levels have fallen during relatively recent geological time. Now they often flow through deep gorges and are frequently subjected to enormous hydrological fluctuations. The eastern rivers tend to be warm and turbid, with neutral to slightly alkaline waters. With few exceptions, the rivers of the south-central and south-western coastal regions are clear and often carry cool, acid, 'black' waters. The south-western rivers like the Berg and the Olifants are very ancient, their courses being traceable back for 80 million years or more. As sea level has risen and fallen, they have become connected to each other near the sea, and then have separated again. The distribution patterns of the aquatic animals living in them can often be explained by these ancient drainage patterns.



The likely courses of the Olifants and Berg rivers (blue) about 80 million years ago in the late Cretaceous (green), and 30 million years ago in the early Tertiary (red). The green lines show the two rivers meeting when sea level was about 150 m lower than it is currently. The two northern courses shown in red are the Olifants and Verlorenvlei rivers joining offshore and forming the submarine Cape Canyon, while the southern red line shows an independent Berg River flowing through the southern end of what is now Langebaan Lagoon (after Hendey 1983).

FLOODPLAINS

Rivers continually erode their catchments, at times transporting vast quantities of silt, clay, sand and even large boulders, and depositing them wherever the power of the water is diminished. Many rivers, such as those along the south-eastern, southern and south-western seaboards of South Africa, have dug their way into the surrounding land. As a result, they seldom overspill their banks and most of the material that they transport reaches the estuary and the sea. The topography of the land through which other rivers flow is relatively flat, and these rivers may, during times of flood, overtop their banks, fan out, and slow sufficiently to drop eroded material as alluvium, forming a floodplain. Few rivers in South Africa presently have large floodplains, but where they do occur they are of great local significance. The major floodplains of southern Africa are those of the Okavango, Chobe, Zambezi and Kafue rivers to the north; the Limpopo, Luvuvhu, Phongolo and Mkuzi rivers to the north-east; the relatively small Sundays, Swartkops and Gouritz rivers to the south-east; and the Berg River in the south-west.

The wide, flat areas that constitute floodplains are usually inundated annually during the rainy season. The flood waters carry nutrient-rich silts and organic matter so that floodplains can be very rich environments (see information about the Nile delta in Chapter 1). It is through these alluvial plains that the river meanders, sometimes cutting here, sometimes depositing there, to form a richly diverse mix of biotopes, from permanently wet to partially wet, from infrequently wet to nearly always dry, and from the river itself (truly lotic), to lentic wetlands and ponds and, occasionally, to fairly substantial lakes. The meanders migrate through the system with time, progressively increasing in curvature as sediment is eroded from the outer bends and re-deposited as point bars on the inner bends: floodplains are as dynamic as the rivers that create them.

Floodplain at the confluence of the Cuito and Cabango (Kavango) rivers on the Angolan / Namibian border. The Cabango runs through Namibia's Caprivi Strip before entering the Okavango Swamp.

Joachim Huber /Wikimedia/ CC BY-SA 2.0

An aerial view of the spectacular Okavango delta wetlands in Botswana.

Rivers always borrow a great part of their character from the terrestrial landscapes – the catchments – through which they flow. Indeed, in metaphorical terms they can be regarded as mirrors of the landscape: if it is in good condition, then the river is too. If it is badly treated, then the river flowing through it will mirror that abuse. Thus, in the case of a river and its floodplain, it can safely be argued that where linkages between river and floodplain are broken, perhaps through river regulation by impoundments, or by transfers of water from one river to another, or by pollution and other forms of human abuse such as floodplain 'development', then both the river and the associated floodplain environments will be changed, almost always for a poorer, less diverse and more degraded state. In this respect, floodplain rivers like the Pongolo and the Zambezi mimic situations found in many, many other dryland regions of the world (see Chapter 9).

INTERMITTENT RIVERS

Some dryland rivers flow perennially, while many cease to flow seasonally or even for indefinitely long periods. Of the 65 000 km or so of river channels in South Africa, perhaps half are subject to natural interruptions of flow. 'Intermittent' systems range from rivers with seasonal flow (seasonally intermittent streams) to ephemeral or episodic rivers, which flow only after occasional, unpredictable rainfall. Standing pools in a dry riverbed act as refuges, sometimes only briefly, sometimes for longer periods, for riverine animals and plants. In other systems, environmental extremes have dictated a range of biological adaptations of species that can survive in these systems.

When flow ceases and the water is reduced to standing

Jenny Day

The dry Tankwa River, which drains an extremely arid part of the Karoo. The relatively lush riparian vegetation taps into groundwater, which extends beyond the limit of the riverbed.

pools, species that are dependent on currents to supply food or oxygen, or to maintain a suitable chemical or physical environment, will be eliminated. If they last long enough, however, the pools may be colonised by animals normally found in nearby standing waters. When all surface water disappears, the survivors will be fewer still. Those mobile species (e.g. flying insects) that are able to disperse elsewhere may soon abandon a river that stops flowing. Often, the survival of less mobile ones depends upon the rate at which drying occurs and how intense the desiccation is. For instance, opportunistic species with wide feeding preferences are more likely to survive the altered conditions than are those with very specific dietary requirements. When all the water has evaporated, it is a matter of waiting out the drought. Plants normally survive as seeds, while animals have a variety of adaptations. If the bed of the river is soft, some animals will burrow into the bottom mud, where they wait out the dry period encased in a cocoon (fish such as the killifish, for example), or protected by their hard shells (some molluscs). Where the bed is stony, those species that are able to live in the hyporheos (the interstices or spaces within the bed of the river) will be favoured. When the river starts flowing once again, those species that can reproduce quickly and abundantly will be the first to succeed, but others will soon join them.

Although intermittent rivers are probably some of the most common worldwide, they are the least understood ecologically, and very few studies are available which allow an accurate assessment of their importance or of the

Nothobranchius rachovii, *a killifish from the lower Shire River in Mozambique.*

extent to which they have been modified, by abstraction of groundwater, for instance. This lack of knowledge has two roots: the dominance of research in more humid zones of the planet, and the difficulty in predicting the occurrence of hydrological events, and therefore in planning suitable research programmes, in arid areas. Nonetheless, from research that is just beginning in South Africa, intermittent rivers appear to have a comparatively rich invertebrate fauna and also appear to serve as reservoirs of colonists for other aquatic environments.

GROUNDWATER

Soils are seldom completely dry. They are normally not saturated but contain pore water, which is what plants use. What is groundwater, then? It is water that accumulates below the surface, sometimes in sufficient quantities to be extracted from boreholes for human use. The water table is the boundary between unsaturated soils and the saturated zone below. Although it may occur as underground 'rivers' or 'lakes', groundwater more commonly occurs in small spaces in fractured rocks, gravel and sand. These accumulations of groundwater are called aquifers.

Except for water lost by evaporation, sooner or later all the water falling as rain, mist or snow into a single drainage area or catchment will either be stored underground or will reach the sea via an estuary, or by seeping seawards under the surface. Although much of this water is not evident, the invisible portion forms a vital connecting link between the various parts of the catchment. Somewhere between two-thirds and three-quarters of all rain filters into the soil, from there being stored in aquifers, or running beneath the ground to emerge in rivers or lakes, or sometimes seeping directly into the sea. The reason that rivers flow when no rain is falling is that they are being fed by groundwater. The distribution and quality of groundwater has been investigated in South Africa for many years. After all, people over more than half the country rely on groundwater for their domestic supplies as well as for irrigation. Only recently, however, has the connection between ground and surface water has become a popular subject of study in South Africa and elsewhere. A major investigation is presently underway on the Table Mountain Group (TMG) aquifers, an enormous, very deep accumulation of groundwater that underlies much of land between Cape Town and Port Elizabeth. It is still not clear just how much water this series of aquifers contains, the rate at which they are re-filled by rainfall, or the extent to which any surface ecosystems depend directly on their water. Geohydrological (groundwater) investigations are underway on the rate of recharge at the same time that ecologists are examining potentially groundwater-dependent ecosystems such as small streams and seeps. In the previous edition of ***Vanishing Waters***, we said: "It is only after these investigations have been completed that decisions will be made on the extent to which the water from the aquifers will be exploited. Water managers in the Cape Town Metro are to be congratulated on the responsible manner in which they are approaching the exploitation of this potentially valuable resource, which might also be very sensitive to manipulation." See pages 386 and 387 for what has actually happened.

In 2005, Alan Woodford and Peter Rosewarne estimated the total store of groundwater in South Africa to be about 235 500 Mm^3 (millions of cubic metres), of which about 30 000 Mm^3 is recharged and 19 000 Mm^3 can be extracted and used, annually. (In comparison the mean annual surface runoff (MAR) is estimated by DWS to be in the region of 43-48 000 Mm^3, of which some 12 500 Mm^3 is used.) In 2013 groundwater constituted between 12,5% and 20% of South Africa's total water use and this percentage has increased by an average of 0,6% per annum over the last three years. It may seem that these large quantities of groundwater will cushion us from the effects of climate change as the amount of surface water becomes reduced. Unfortunately, since most aquifers are also fed by rainfall, this resource, too, is expected to diminish in the future. On the other hand, groundwater is a good 'bridging' resource that can be used intermittently during periods of drought, if the aquifer is then left to recover. Good examples in the south-western Cape are the TMG, Atlantis and Cape Flats aquifers.

Groundwater, then, is often a major underground link between surface waters. Pollution of a lake may result in polluted sub-surface water percolating downwards to enter an apparently unconnected stream. Removal of groundwater from boreholes for agricultural or domestic purposes, particularly if the water has been accumulating over a very long time, may drop the water table to the extent that surface vleis dry up, or trees die, or the ground subsides. Of course, the most apparent effects of tampering with water supplies in a catchment are on rivers themselves. Because they are

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Groundwater-dependent ecosystems may result from a) 'overflow' of water during very wet conditions or b) from groundwater slowly percolating to the surface, as seen in this small desert spring in the Tankwa-Karoo National Park.

one-way systems, the removal of water will have immediate and sometimes drastic effects further downstream: witness, for example, the number of estuaries in this country that are becoming shallow and silt-laden and whose mouths are more commonly closed than open as a result of water abstraction (see Chapter 6).

RESERVOIRS ('DAMS') AND OTHER ARTIFICIAL WATER BODIES

So far, we have sketched a simple outline of the types and the limited distribution of natural water bodies in southern Africa. It should be clear by now that the burgeoning population of the region cannot possibly rely solely on natural lakes and rivers for its water because of the unreliable rainfall and limited natural storage of water. The bulk of our surface water supply is therefore held in storage reservoirs behind barrages, weirs and dams.

Large reservoirs

The two most gigantic dams of southern Africa – Kariba and Cahora Bassa – both impound the Zambezi River. Lake Kariba, which lies on the border between Zambia and Zimbabwe, covers an enormous surface area (5 364 km^2), the lake being held back by a concrete wall 128 m high, while Lake Cahora Bassa, covering 2 769 km^2 of land in Mozambique, is held back by a spectacular double-curved concrete wall some 176 m high. Humankind's 'harnessing' of the Zambezi River, the most significant water resource of the whole region and southern Africa's largest river, has been partially successful in the case of Kariba and disastrous in the case of Cahora Bassa. Cahora Bassa was designed to be the largest single power producer on the continent, and to export almost all of that power to South Africa. These two dams are discussed in more detail in Chapter 9.

Peter Seyffert

Kariba Dam during construction, about 1957.

NASA

Aerial image of Lake Cahora Bassa in Mozambique.

Pegleg01 / 123RF

Gariep Dam and reservoir.

Lani van Vuuren

The Vaal Dam spilling in 2006.

Further to the south, in South Africa, the largest impoundments are tiny when compared to their northern siblings. The five biggest reservoirs in South Africa each cover an area of a little more than 100 km^2. They are Pongolapoort on the Phongolo River, the Vaal Barrage, and lakes Gariep, Vanderkloof and Bloemhof on the Orange-Vaal system. Although hydroelectric power production was incorporated into the design of some of them (Gariep, for instance), their primary role is the storage of water for irrigation, stock-watering and urban water supply. Another 500 or so moderate to large reservoirs are scattered throughout South Africa, most of them designed to provide water for farming communities or potable water for towns and cities. It is safe to say that there are few substantial rivers that do not have some sort of reservoir on them and virtually none is free-running all the way from headwaters to the sea.

Farm dams

Anyone who looks out of an aeroplane window near dusk or dawn on a sunny day, almost anywhere in southern Africa, cannot fail to be impressed by the myriad reflections from small water storages scattered across the landscape. They form a vast network with two denser clusters, one in the KwaZulu-Natal midlands (erratic summer rainfall), and the other in the south-western part of the Western Cape (winter rainfall, summer irrigation demand). In 1993 James Adams, then an Honours student, estimated that in the Western Cape alone, over 4 000 farm dams stored more than 100 million m^3 when full. Being a winter-rainfall area, virtually no small natural wetlands hold water during the hot, dry summer months. Farm dams therefore provide a previously unknown kind of ecosystem in the region. Helen Davies, then an MSc student at UCT, and more recently, Suhkmani Mantell and her colleagues from Rhodes University, have investigated the significance of these relatively small structures as new aquatic environments, and as modifiers of rivers and of the water cycle. We shall explore this subject further in Chapter 9.

Jenny Day

Dozens of small farm dams dominate the winter landscape near Ceres in the Western Cape.

CATCHMENTS – THE INTERDEPENDENCE OF WATER BODIES

It would seem, from the scattered distribution of rivers, lakes and pans in South Africa, that each aquatic system is quite isolated from the rest and that events in one cannot have any effect on another. It is true that bodies of fresh water are isolated in many ways: for example, many aquatic organisms cannot easily move from one to another, so that there are cases of similar but distinct species having evolved in adjacent streams or lakes. The small fishes and amphipods of streams in the south-western Cape provide good illustrations of this: see chapter 11 for more detail. In some sense, then, the biotas of rivers and vleis really are isolated from each other, and have been for millions of years (see Brett Hendey's 1983 article in the reading list). When water is shunted from one river to another by interbasin transfer schemes, however, their biotas are no longer isolated. This may well lead to reduction in further speciation and to the extinction of rare species – a source for grave concern (see Chapter 9).

Inland waters are also isolated in the sense that the transfer of material from one to another is not common, except for the movement of adult flying insects emerging from aquatic nymphal or larval phases, occasional wind-blown dust containing resting phases of organisms, and the incidental transport of some invertebrates on the feet and feathers of birds. Furthermore, rivers are one-way, open-ended systems, continually exporting materials downstream, so that although events in the upper reaches influence the lower river (see Chapter 4), the reverse is improbable. By contrast, most lakes appear superficially to be closed systems, since they receive inputs of various kinds from adjacent areas but, unless they have rivers draining from them, have no outlet and therefore accumulate rather than transport material (see Chapter 3).

But to think of water bodies as being independent of each other is not only simplistic but downright wrong. In order to substantiate this statement, we need to look at a broader picture than that of a river or lake alone: we have to look at a whole catchment. A catchment is essentially the entire area, from mountains to seashore, that is drained by a single river system. The whole of South Africa, for example, can be divided into a few dozen areas drained by individual river systems. The catchments in the south and east are generally small and drained by rivers arising in highlands near the coast. Where the coastal plain is narrow and the mountains steep, as they are on the south coast, rivers such as the Palmiet and Storms plunge into the sea almost as mountain streams with no classical 'lower' river at all (see Chapter 4). But a vast area of South Africa consists of a single catchment, that of the Orange-Vaal system.

INTERBASIN WATER TRANSFER SCHEMES (IBTS)

We appreciate that the removal of water from one part of a catchment to another, or from one entirely separate catchment to another, does not necessarily involve the creation of separate aquatic ecosystems in the way that large reservoirs or farm dams do. IBTs mix and match entirely different waters and biotas, however, and, in an insidious way, they create ecosystem chimaeras that are very different from the originals. We outline their features here, adding details in Chapter 9.

South Africa is one of the world leaders in IBT technology. Of the schemes already in existence, the Orange-Sundays-Great Fish River Water Transfer Scheme (the Orange River Project, or ORP), is probably the largest: it was certainly one of the earliest. This transfer scheme draws water from the Orange River at Lake Gariep and pipes it through over 100 km of tunnels and canals to the Sundays River and from there to the Great Fish River in the Eastern Province, thus improving the quality and increasing the supply of irrigation water for a dryland farming area. In another, probably more spectacular, scheme, water is transferred from the upper reaches of the Tugela River in KwaZulu-Natal through a series of dams, then upwards (more than 550 m) and westwards over the Drakensberg Mountains into the upper catchment of the Vaal River, and thence into the large reservoirs on the Vaal that supply water to the urban and industrial complex of Gauteng. Various smaller schemes have been developed in the Western Cape, while the feasibility of others is currently under investigation.

The recurring droughts of several decades forced South Africa to consider the purchase of water from neighbouring states; the Lesotho Highlands Water Project (LHWP) is described in Chapter 1. Another large scheme, the Eastern National Water Carrier of Namibia, links a series of dams, the intention being to extract water from the Okavango River for use in Namibia, particularly Windhoek. (Needless to say, Botswana is not happy about the proposal, since it will reduce flow in the Okavango River and ultimately provide less water for the Okavango Delta.)

Schemes of this nature will certainly increase in number, but they need to be designed so as to minimise their impacts both on the rivers receiving the transferred water and on the donor rivers. Those that transfer water across international boundaries also have far-reaching political and socioeconomic implications, particularly when we consider that South Africa is a signatory of the 'Helsinki Accord', an internationally binding agreement that deals with the fair apportionment of water in rivers that cross international boundaries. In southern Africa there are many shared rivers, including the Zambezi, Orange, Pongolo, Limpopo, Crocodile, Sabie, Okavango, Kunene and Letaba. River Basin Commissions or similar organizations have been set up to deal with all of the major shared water courses in the region. Some of the main basin agreements are

- INCOMATI Accord (sometimes NKOMATI): South Africa, Swaziland and Mozambique; originally a non-aggression pact
- OKACOM (Okavango River Basin Water Commission): Cubango-Okavango River Basin;
- LIMCOM (Limpopo Commission): Botswana, Zimbabwe, South Africa and Mozambique;
- ORASECOM (Orange Senqu River Commission): Botswana, Lesotho, Namibia and South Africa
- ZAMCOM (Zambezi Water Course Commission): Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe (the DRC seems not to have signed the agreement).

It is difficult to obtain agreement between just three or four countries. Imagine the complexities of managing the Zambezi, which has nine riparian states, or the Nile, which has twelve!

Having now briefly reviewed the types and distribution of South African inland waters, we turn our attention in Chapters 3 to 6 to 'the way things were': natural standing and running waters, and how they 'work'.

Jenny Day

The controversial open canal is part of Namibia's Eastern National Water Carrier.

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Carbon cycle
https://en.wikipedia.org/wiki/Carbon_cycle

Department of Water Affairs, now Department of Water and Sanitation
http://www.dws.gov.za

Drylands
https://news.globallandscapesforum.org/50717/everything-you-need-to-know-about-drylands/

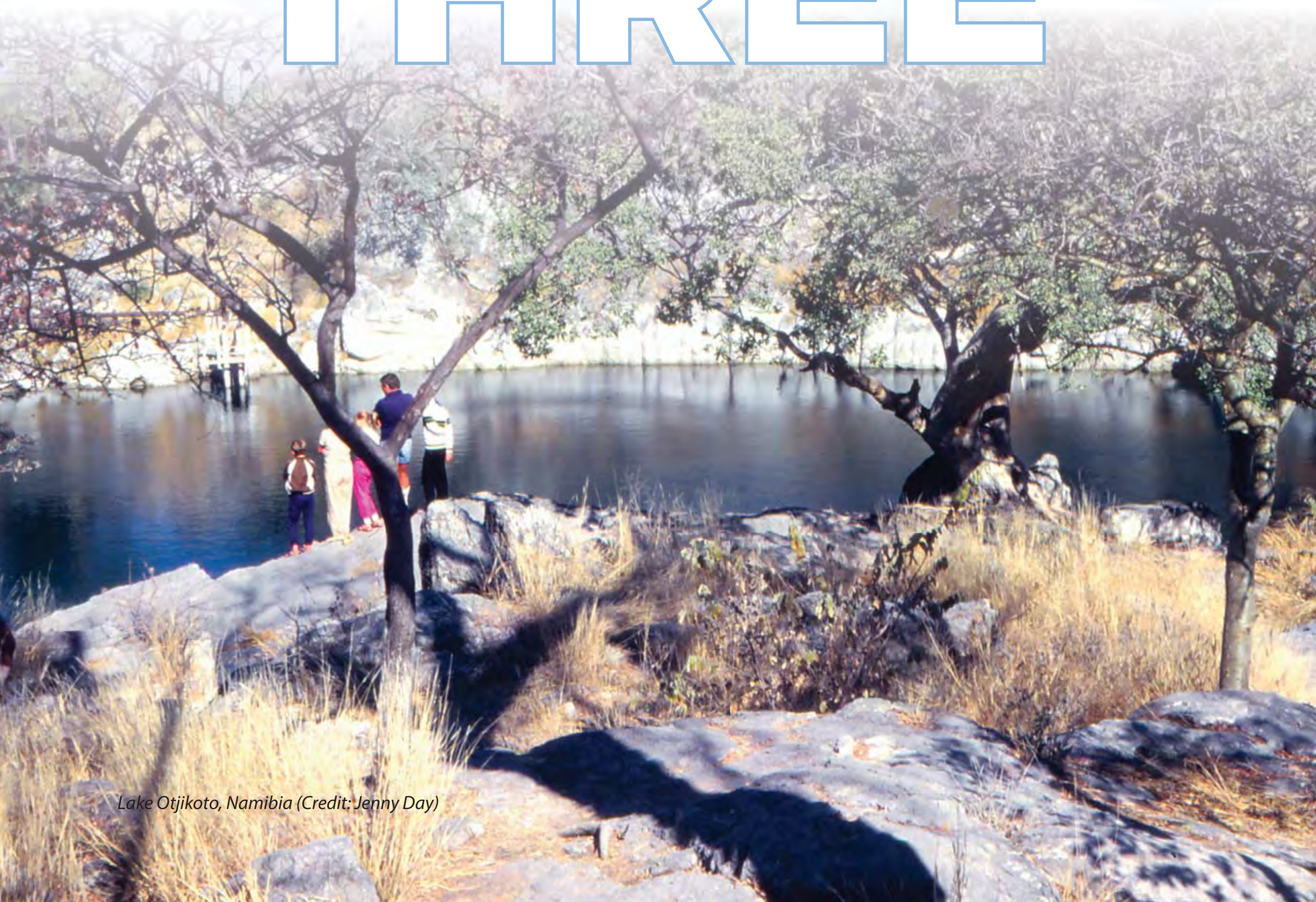
Millennium Assessment
https://www.millenniumassessment.org/documents/document.291.aspx.pdf
http://www.millenniumassessment.org/documents/document.776.aspx.pdf

Ramsar Convention
www.ramsar.org

SADC water
https://www.sadc.int/pillars/water-0

South Africa's contribution to the Inter-Governmental Panel on Climate Change (IPCC)
www.csag.uct.ac.za/

CHAPTER THREE



Lake Otjikoto, Namibia (Credit: Jenny Day)

Natural standing waters and their inhabitants

Like living organisms, lakes and ponds come into being, mature, grow old and eventually fade away. By whatever mechanism they are created – perhaps a hollow left by a glacier, a landslide across a river or a geological fault – young lakes differ from old ones. Because they accumulate material (dust, soil and organic matter) that builds up over long periods, lakes and ponds naturally become shallower and shallower over time until they turn into marshland or swamps and finally disappear completely. This is a natural ageing process. Indeed, man-made lakes and reservoirs may also have very limited lifespans, maybe only a couple of hundred years, because their basins become filled by sediments carried down to them by floodwaters. The very long, deep, ancient lakes like those of the African Rift Valley (see box on page 102), and Lake Baikal in Siberia, are exceptions.

FrankBothe / Wikimedia /CC BY-SA 4.0.

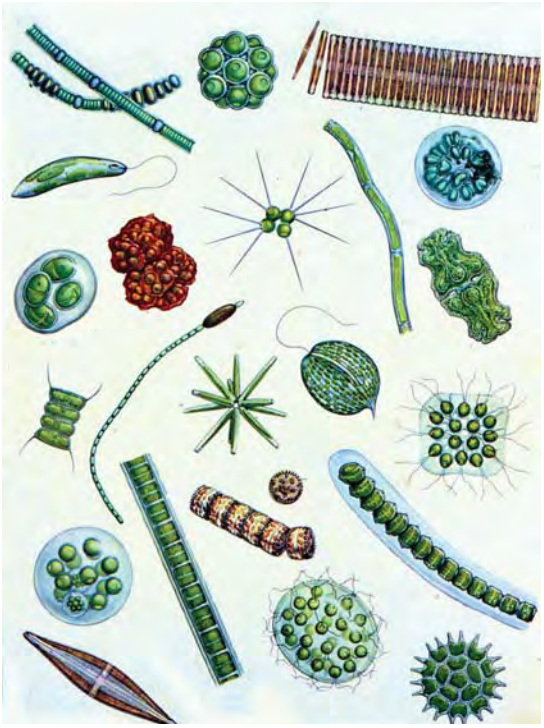
Lake Baikal in summer.

Lake Baikal in in winter.

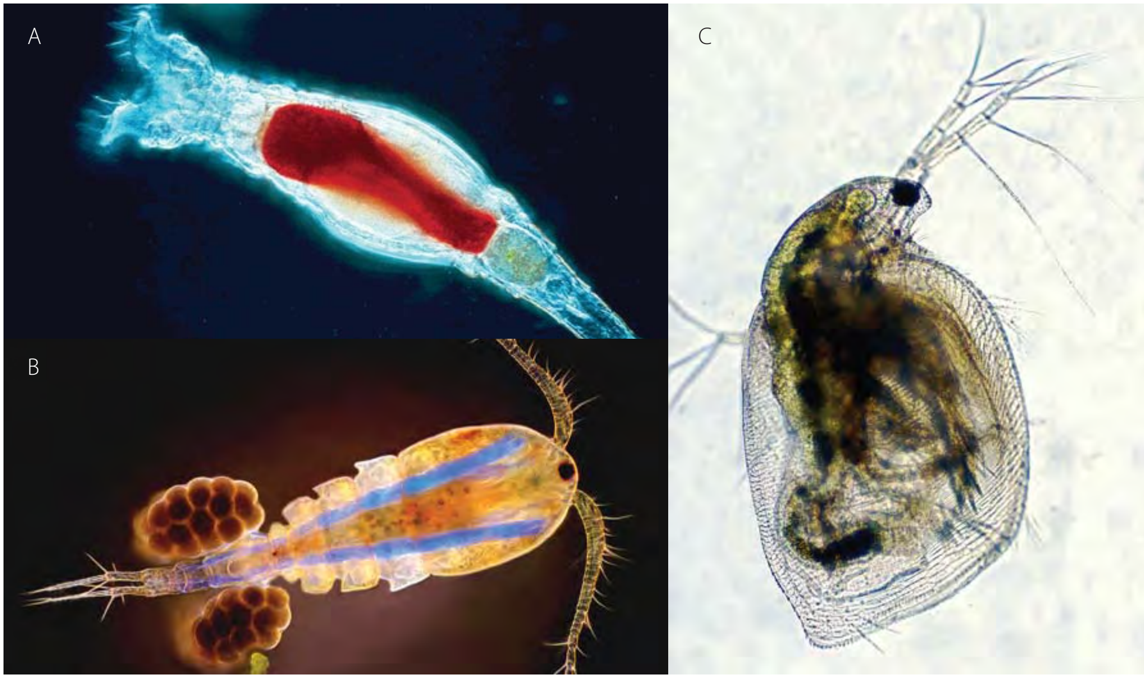
LAKE SUCCESSION

In a young lake, some tens or hundreds of years old, there has been little time for sediments or organic material to accumulate. Thus, the bed is usually rocky and the water is clear. The commonest organisms frequenting the system at this early stage (the pioneer stage) are minute and free-floating – the plankton. The plankton consists of two major components: microscopic plants (the phytoplankton) and tiny free-swimming animals (the zooplankton). Over time, nutrients build up as water draining into the lake leaches materials from the surrounding rocks and soils. Plants and animals colonise the lake and succeeding generations live and die, their bodies decaying and contributing to the universal cycling of material (see page 97). The lake also accumulates wind-blown dust from the air, and silt from inflowing rivers and from overland runoff during rain. Gradually organically-rich sediments build up on the bottom and so the lake becomes shallower. Along with planktonic organisms and fish in the water column, the rich muds may support a variety of bacteria, fungi, worms and midge larvae (see page 93 below on food webs). At the same time, submerged rooted plants become established around the shallow margins. Examination of the plants of our evolving lake shows a community of small animals and plants growing on them. High-power magnification, using instruments such as scanning electron microscopes, reveals the most extraordinary and sometimes bizarre forms of underwater life. As soon as sediments accumulate at the edge of the lake, the margins may begin to support rooted fringing or emergent vegetation growing above the water surface. Large visible plants of this kind are known as macrophytes and include bulrushes, sedges and reeds. In a mature lake, then, we can expect to find plankton and fish in the water, a rich organic ooze on the bottom, and submerged and emergent macrophytes in the shallow littoral (near-shore) zone.

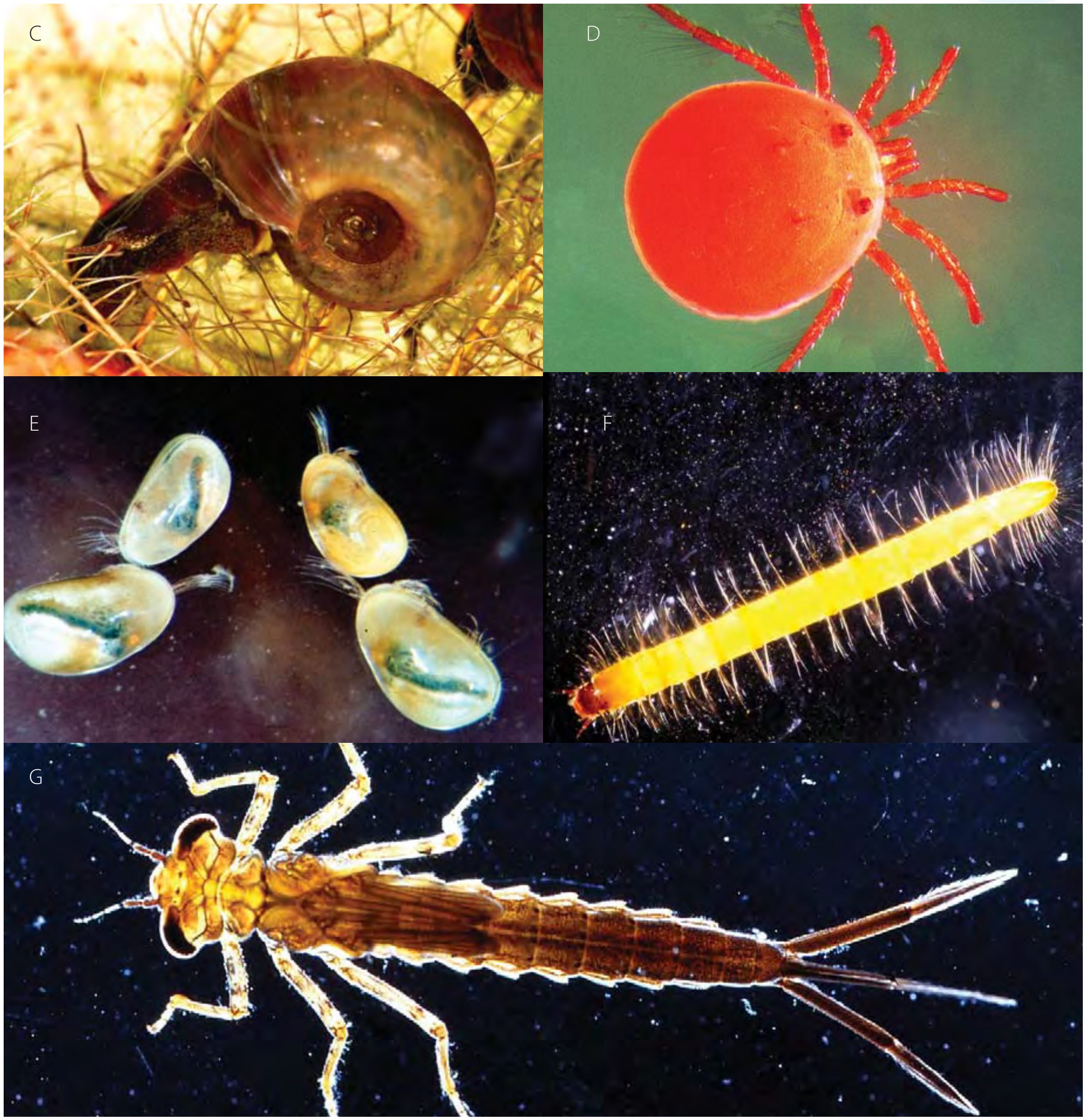
All lakes, other than deep tectonic ones, ultimately become filled with sediments, becoming shallower and shallower, passing through stages of wetlands of one sort or another, and finally becoming dry land. As we mentioned in Chapter 2, with the exception of Lake Funduzi in the far north, South Africa has no true inland lakes in which this process can be examined (Lake Chrissie dries out on occasion), and our coastal lakes are all associated with estuaries and marine processes. We do, though, have a number of man-made lakes ('dams') in which sediments accumulate, sometimes at impressive rates. Welbedacht Dam, on the Caledon River in the Free State, for example, has lost more than 90% of its storage capacity due to siltation. This accumulation of sediments is a consequence mostly of soil erosion resulting from inappropriate agricultural practices, although in the interior of the country, rivers are naturally silt-laden and dams would fill up, albeit more slowly, even without human interference. It has been estimated by Gerrit Basson from the University of Stellenbosch that by 2050, more than half of the world's current reservoir storage capacity may be filled with sediment.


HJ Walter

Painting of a variety of phytoplanktonic organisms – minute photosynthesisers that live in the water column.



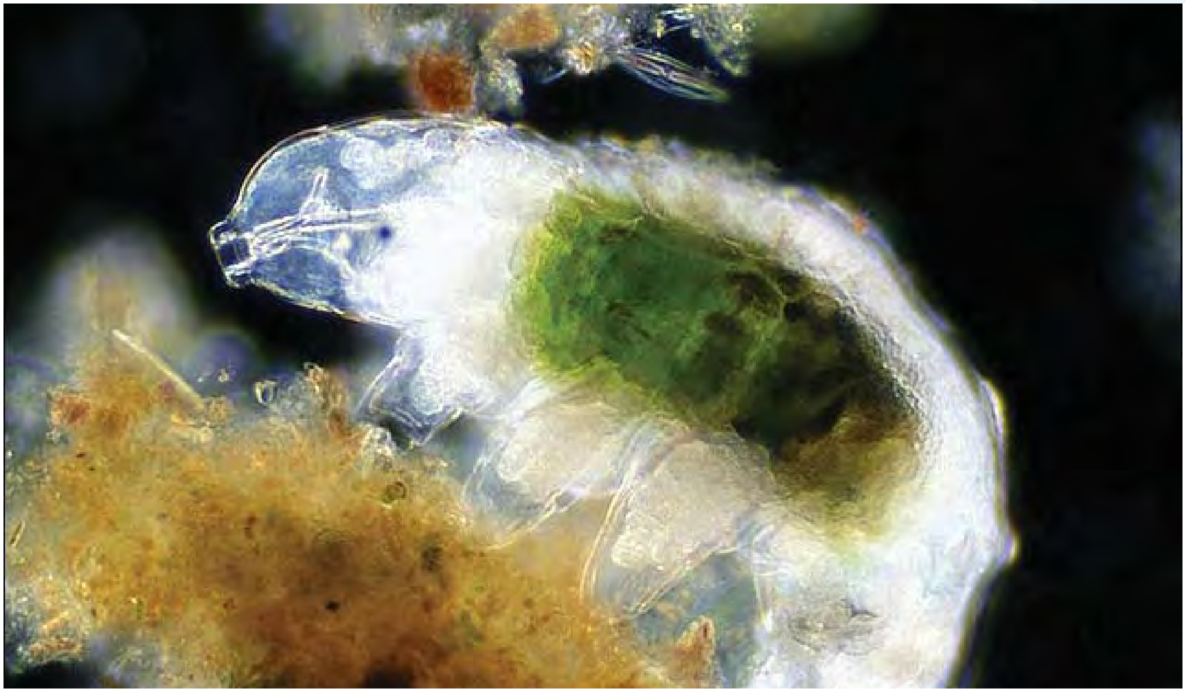
The commonest members of most zooplankton communities are (A) rotifers (2 mm); (B) copepods (1.2 mm) and (C) cladocerans like Daphnia *(2 mm).*



There are many kinds of intvertebrates found in the littoral (shoreline) vegetation of ponds and lakes. These include: (A) A hydra (green because of symbiotic algae living in its tissues, 5 mm); (B) flatworms (7 mm); (C) snails (10 mm); (D) water mites (0,7 mm), (E) ostracods (2 mm); (F) beetle larvae (6 mm); and (G) damselfly nymphs (10 mm).

Jenny Day

Minute green diatoms and a larger brown-shelled amoeba attached to a single algal filament; diameter of filament 0.5 mm.



Charles Krebs

Tardigrades are remarkable little freshwater creatures, less than a millimetre long, that feed on the contents of plant cells. When the water that they live in dries out, they become entirely desiccated, forming a waterproof outer skin called a tun.

Jenny Day

Large plants like these commonly grow as a fringe in the shallow waters of lakes and wetlands. (A) Phragmites australis*, often called* fluitjiesriet*, grows widely throughout the world; (B)* Schoenoplectus scirpoides *seems to be native to eastern and southern Africa; (C)* Cyperus papyrus*, the famous papyrus reed from which Egyptians made paper, is native to all of Africa except the southern Cape; (D) the submerged* Isolepis fluitans.

WHAT DRIVES LAKE SUCCESSION?

Lakes mature and grow old because of the interplay of a number of features, the most important of which are the availability of nutrients, the accumulation of sediments, and light. Let us examine each of these.

NUTRIENTS

Nutrients are those chemicals required for plants to grow, and they are, in fact, no different from the fertilisers that we use to make our gardens lush or to enhance the yield of crops. Every element that is needed for plant growth is a nutrient in some sense, but technically the term refers to those that may sometimes be scarce enough to limit plant growth. In freshwater ecosystems, plant growth is usually most encouraged by the addition of phosphorus, in the form of the phosphate ion PO_4^{3-}, and nitrogen, mostly in the form of the nitrate (NO_3^-) and ammonium (NH_4^+) ions.

In a new lake, or a mountain stream, nutrient levels are usually very low. These systems are said to be oligotrophic (from the Greek: ***oligos*** = poor, ***trophein*** = to feed) and support rather small numbers of organisms. Slow leaching of nutrients from the rocks and soils, and from decaying vegetation in the catchment, eventually results in an increase in nutrient levels in the waters of the young lake, at which stage its waters are said to be mesotrophic (from the Greek: ***mesos*** = middle). Lakes of this kind support both larger numbers of organisms and a greater number of species than young lakes do.

Over time, the increased availability of nutrients encourages the growth of more and more plants. When the levels of nutrients build up to a point where the growth of algae and rooted plants becomes noticeably enhanced, the water is becoming eutrophic (from the Greek: ***eu*** = well, good): that is, the process of eutrophication is occurring. This important term is often linked with human-induced pollution (see also Chapter 7), but we must stress that eutrophication is also a natural process in the life of lakes and ponds. Although these days we tend to use the word 'pollution' to refer to the presence of foreign substances that are generated by humans and that impair the quality of water, natural systems can also become 'polluted' in a variety of ways. For instance, eutrophication may be extreme in small, natural ephemeral ponds as they dry up (from the faeces of a single antelope, for instance). It is only when the rate and degree of enrichment becomes excessively high as a result of human intervention that 'cultural' eutrophication can be said to occur, as in the lake created by Hartbeespoort Dam near Pretoria, or Lake Chivero near Harare in Zimbabwe.

Plants, particularly phytoplankton, can grow very rapidly under eutrophic conditions and, since plants represent food for animals, the entire community of plants and animals will increase in abundance: not only will there be more individuals, but more species may also become established. Eventually, though, physical and chemical conditions in extremely eutrophic or hypertrophic (from the Greek: ***hyper*** = above, over) systems may degenerate to the extent that only a few very tough species can survive, although each species may be represented by astronomical numbers of individuals.

To our cost, many of the species that are particularly well adapted to hypertrophic conditions in lakes and wetlands can be problematic in one way or another. One of the most troublesome groups is the blue-greens, or Cyanobacteria. The blue-greens have had a chequered taxonomic history. Until fairly recently, they were called 'blue-green algae' and placed in the Cyanophyta. They are now recognised as being photosynthetic bacteria, however, and are classed as Cyanobacteria, so the more correct common name is simply 'blue-greens'. Some blue-greens can form massive surface scums (see Chapters 7 and 8), while others impart a nasty taste and odour to the water. Under certain circumstances, Cyanobacteria such as ***Microcystis aeruginosa*** produce toxins that can kill animals living in and drinking the water containing them (see Chapter 7). On other occasions, decaying blooms of blue-greens can deplete the water of oxygen and result in the deaths of large numbers of fish.

Heidi Snyman / WRC archives

Hartbeespoort Dam, in North West Province, has the unfortunate distinction of being one of the most hypertrophic dams in South Africa.

CSIR

A thick, paint-like scum of Microcystis *from Hartbeespoort Dam in the 1980s, before water hyacinth displaced the blue-greens.*

ACCUMULATION OF SEDIMENTS

A second feature that determines the lifespan of a lake is the accumulation of sediments, both organic and inorganic. Inorganic particles enter the lake as dust on the wind, as fine muds and clays from weathering of rocks in the catchment and in the lake itself, and sometimes in water from influent rivers. Organic particles may enter in the same ways, but most of them are the dead bodies and other bits and pieces of organisms that grew in the lake itself. Much of the organic material is likely to decay, but the rest, together with most of the heavier inorganic particles, will sink downwards. Eventually a layer of sediment builds up on the bottom of the lake. It is these sediments that ultimately fill the entire lake, turning it first into a shallow wetland and finally into dry land. Sediments on the bottoms of deep lakes are not colonised by plants, because too little light penetrates, but the margins of these lakes soon become vegetated. In fact, as the lake gets shallower, the rooted plants contribute to further shallowing by trapping sediments near the shoreline; the offspring of these plants in turn colonise the newly stabilised sediments. The rampant growth of reed beds as a result of eutrophication is sometimes a major consequence of human activities in lakes and wetlands (see Chapters 7 and 8).

LIGHT

The third of the three major factors contributing to the character of lakes as they age is light penetration. Rooted plants cannot live in the deeper waters where insufficient light penetrates (remember from Chapter 2 that this is what distinguishes lakes from ponds). Later, as the lake shallows, submerged plants will take root over most of the bottom. The zone in which sufficient light is present to allow photosynthesis is known as the ***euphotic zone***. The deeper limit of this zone is usually considered to be the depth that receives 1% of the amount of light received just below the surface. This depth would be several hundred metres in pure water but in lakes the euphotic zone is usually much shallower because suspended particles such as silt and plankton, or dissolved organic compounds, stain the water, interfering with the penetration of light by scattering, reflecting or absorbing it.

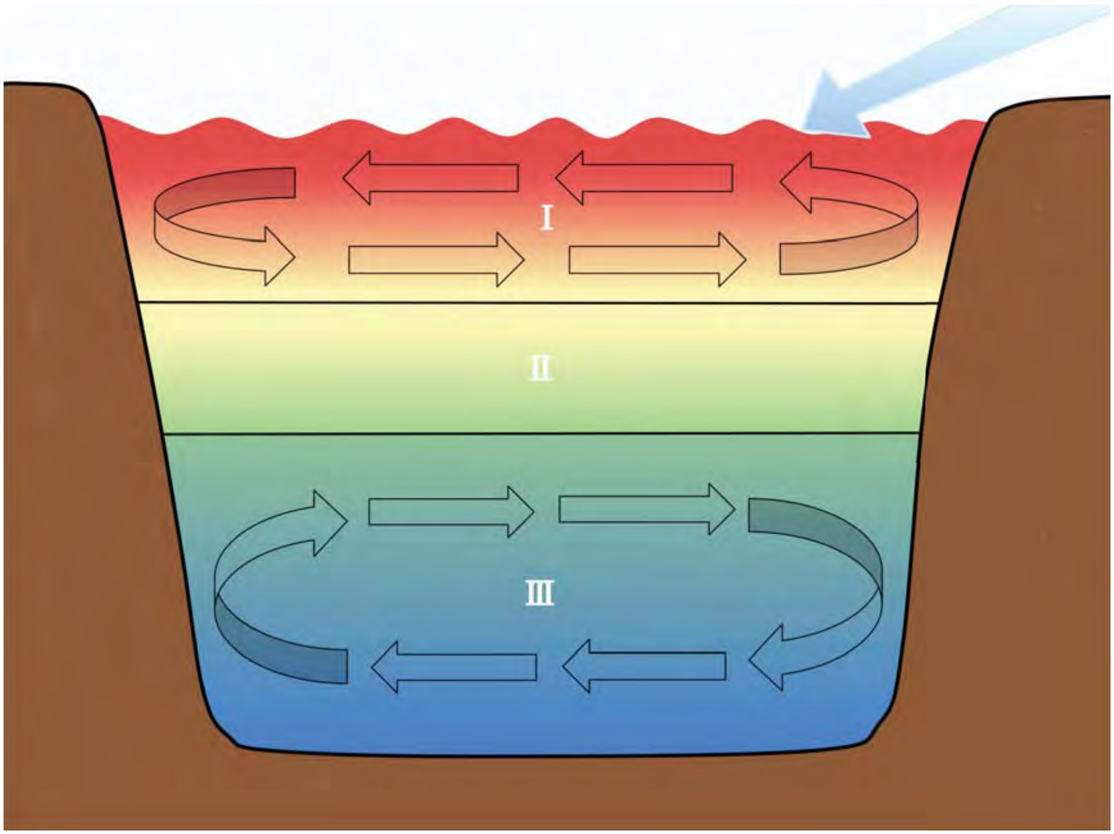
The euphotic zone in South African lakes is highly variable, depending as it does on the soils, geology and vegetation of each catchment, and also on the climate. The degree of anthropogenic disturbance, such as eutrophication, or soil erosion through overgrazing, also affects the depth of the euphotic zone.

In summary, the interplay of nutrients, sediments and light determines the overall character of a lake by altering the depth and controlling the growth of plants, and therefore also of animals and microorganisms. Regardless of the age or successional stage of a lake, though, other physical and chemical processes, many of them seasonal, are also at play. We will discuss these next.

THE ANNUAL CYCLE OF LAKES

SUMMER AND THE THERMOCLINE

One of the unique properties of water is its remarkable change in density with change in temperature (see the next page). In its liquid form, water is most dense at 4°C, while cooler water is less dense and therefore rises to the surface (that is why ice always floats – which is fortunate, otherwise we would have solid lakes and rivers in winter), while water warmer than 4°C is also less dense and rises to the surface. This is primary-school physics. Many people fail to appreciate this fact, however, when it is applied to standing water bodies: as lakes heat up through the absorption of energy from the sun, the warmer upper waters will stay near the surface and therefore heat up even more, becoming less and less dense as heating continues. The deeper water, on the other hand, remains cool so that eventually a shear plane develops between the upper (warmer) and lower (cooler) water masses of a lake. The region of this shear plane, technically known as the metalimnion, is evidenced by the thermocline (a very rapid change in temperature over a very short vertical distance), which effectively separates the two water masses from each other, rather like two carefully poured layers in a cocktail. Separation of lake water into a warmer upper layer (the epilimnion), and a cooler, lower layer (the hypolimnion), is known as thermal stratification. Stratification is sufficient to prevent the mixing of the two water masses until their temperatures equilibrate once more, usually in autumn or winter. You may well have experienced the thermocline while swimming in a vlei or farm dam – suddenly your lower limbs encounter the surprisingly cold water of the hypolimnion, while your trunk and upper limbs experience the warmer and much more comfortable temperatures of the epilimnion. This can be a dangerous situation for the inexperienced swimmer, since it may lead to cramps due to differential heating of the body, and hence to drowning. This is an all-too-common event in rural South Africa during the summer, particularly in combination with an excessive intake of alcohol.



MBrookings19 / Wikimedia / CC BY-SA 4.0

Lake stratification: the warmer epilimnion (red) becomes separated from the cool hypolimnion (blue) by the metalimnion, which is charaterised by a steep temperature gradient known as the thermocline.

Stratification usually develops rapidly in warm weather, with profound consequences for the flora and fauna. Interestingly, the more that surface waters are warmed by the sun, the less dense they become; and the less dense they become, the more they are warmed, and so on. The thermocline usually develops relatively near to the surface, at a depth of somewhere between 5 and 30 m, so that in deep lakes the epilimnion is frequently much smaller than the hypolimnion. The two major zones of the lake cannot mix vertically with each other during the spring and summer growing periods unless very strong winds are present, causing vertical mixing that breaks down the density gradient. Lake organisms normally inhabit the warmer, upper waters of the euphotic zone, where light penetration is good and so photosynthesis can take place. Growth of these organisms removes nutrients from the epilimnion, which thus becomes nutrient-depleted because it cannot mix with, and receive nutrients from, the lower, cooler hypolimnion.

The material lying on the bottom of the lake (benthic matter) is rapidly decomposed by microorganisms, a process that uses up oxygen. In extreme conditions (in fact, fairly frequently in warm climates), the decomposition of dead material leads to complete exhaustion of the oxygen supply (anoxia) of the hypolimnion, and the chemically reducing conditions consequently lead to the production of large quantities of toxic hydrogen sulphide (H_2S, or bad-egg gas). This is because the decomposer organisms that are reliant on oxygen die and are replaced by others, particularly bacteria, that continue the process of decomposition, though more slowly, by extracting oxygen from sulphates (SO_4^{2-}) and turning them into hydrogen sulphide (SH^-) ions, which in water form H_2S. After Lake Kariba filled, for instance, hydrogen sulphide formed in the waters of the hypolimnion for at least nine years, until much of the organic matter from drowned vegetation had been decomposed. Anoxia and the production of hydrogen sulphide completely prevent the utilisation of the hypolimnion by any of the aerobic (oxygen-requiring) organisms normally living in the upper waters. Near the bottom they would die, either from asphyxiation or from hydrogen sulphide poisoning, thus adding to nutrient supplies in the hypolimnion. This explains why the bottom sediments of lakes are usually devoid of all but a few anaerobic organisms (organisms that do not require oxygen for respiration), mostly bacteria, which may occur in vast numbers, and a few invertebrates with haemoglobin in their blood, allowing them to function in almost anoxic conditions.

Stephen Marshall

Red midge larvae such as this Chironomus *(10 mm) have haemoglobin in their blood and so they are able to live in almost completely anoxic conditions. This individual has curled up but midge larvae are usually wormlike when alive.*

WINTER AND OVERTURN

If the process of stratification were utterly irreversible in all lakes and wetlands, then the productivity, the cycles of life, the biological diversity and the community structure of such systems would be very different from what they are. Fortunately for the continuation of the cycle of life, in most lakes and wetlands water densities slowly equilibrate in autumn, due to the cooling action of wind and decreasing air temperatures. As the chillier winds of autumn gather strength, the epilimnion loses heat to the atmosphere and its temperature and density fall closer and closer to that of the deeper hypolimnetic waters. Eventually the temperatures (and thus densities) of the epilimnion and hypolimnion become almost identical and the water of the lake mixes as a result of stirring by the wind. This event, known as overturn, is a vitally important phenomenon of renewal since the nutrients within the hypolimnion are vertically redistributed throughout the lake, which is now said to be holomictic. So, although the plankton will tend to grow more slowly and to decline in numbers well before the end of the summer growth season due to nutrient depletion in the epilimnion, overturn in autumn or winter will allow for a new outburst of growth in the following spring: a cycle of birth, death and rebirth continues.

Some lakes never mix through wind action. They are very saline or they are permanently ice-covered, usually occurring well within the Arctic and Antarctic circles (one – Tyndall Tarn – has, however, been noted by Professor Heinz Löffler near the summit of Mount Kenya; at 4 800 m it is the highest lake in Africa). These amictic (non-mixing) systems of both types are fascinating. The layers of water beneath the ice of cold amictic systems are not necessarily freezing and barren – far from it. The surface of Lake Vanda in Antarctica (latitude 77°S) is permanently frozen, and the lake water is extremely saline, but some 65 m below the surface of the ice cover, the temperature of the water can reach a staggering 25°C, presumably as a result of geothermal influences. Even further south (at 79°S), amictic lakes have been shown to support living organisms ranging from single-celled protozoans through far more complex multi-cellular tardigrades (water bears), nematodes (ubiquitous roundworms) and rotifers (wheel animals), for instance. Small, very saline ponds (so-called solar ponds) on the coasts of Israel and Namibia are also amictic. The intense heat warms up the saline waters, producing such strong and stable gradients of both salinity and temperature that mixing never occurs. Oddly, they are usually warmest near, or on, the bottom; I have recorded a temperature of 50°C on the bottom of a highly saline 'solar pond' in the Namib Desert. These reversed temperature gradients result from the trapping of the sun's heat in the denser, lower layers. These systems, too, may support complex communities of microbes, algae and small invertebrates. Perhaps the most famous of all amictic lakes, though, is the hypersaline Dead Sea in Israel. To be precise, it ***was*** amictic. The incoming waters of the Jordan River evaporated from the surface and the sea became saltier and saltier with an apparently indestructible chemocline. But humans can do almost anything, even if they don't intend to. In the 1960s and 1970s, fresh water was diverted from its normal path into the lake and used for domestic purposes. This resulted in the upper layers of the Dead Sea becoming saltier and saltier until no chemocline was left. Then all it took was lowered temperatures in the winter of 1978 to cause the entire lake to overturn. A salinity and density gradient that, according to some sources, had been in place for anything up to 12 000 years, had been destroyed, unwittingly, in less than two decades.

NASA

Wright Valley, Antarctica, with Lake Vanda.

Prostooleh / 123RF

Not only is the Dead Sea extremely salty, but it is also the lowest place on Earth: its beaches are 430 m below mean sea level.

THE CURIOUS CASE OF LAKE NYOS

Michel Halbwachs

Lake Nyos in Cameroon with a CO_2-laden water spout.

Some lakes are meromictic, the deepest waters remaining unmixed while the bulk undergoes the classical pattern of thermal stratification and overturn. In two extraordinary incidents, two meromictic lakes in Cameroon, West Africa, released thousands of tons of carbon dioxide during what seemed to be overturn events. The dense cloud of gas that swept out of Lake Monoun early one morning in August 1984 asphyxiated cattle, sheep and goats and killed 37 local people. A similar but more devastating event took place in 1986 when Lake Nyos overturned, resulting in the deaths of at least 1 700 people and 3 000 cattle. It seems that the CO_2 in the deepest parts of the lakes has its origin in the slowly cooling rocks deep below the surface of this geologically active area. Here an understanding of lake stratification becomes handy. The lakes are very deep (>200 m) and are situated close to the equator. If they were farther north or south, they would overturn annually, thus preventing buildup of CO_2. But equatorial lakes like Nyos and Monoun may become permanently stratified, while the accumulating CO_2 is kept under pressure by the lake water above. It is not clear what caused overturn or outgassing to begin in the lakes, but it may have been a small volcanic eruption deep below the bottom of each lake. In any event, destabilisation of the stratification initiated the release of the gas, which reached the surface as great silent invisible bubbles, causing a surge of water up to 25 m above the normal lake level. The Earth belched. The first person to understand the circumstances was Haraldur Sigurdsson, a volcanologist from the University of Rhode Island. He had investigated conditions in Lake Monoun even before the second eruption, and submitted a paper to the eminent journal ***Science.*** His paper was rejected because the reviewers considered his explanation to be too far-fetched. He has since been proven to be correct, of course. But what if the lakes were to outgas again? Nearly 20 years after the events occurred, French scientists under the leadership of Michel Halbwachs came up with an idea for alleviating the problem, and the US Office of Foreign Disaster Assistance (OFDA) provided the funds to do the work. Permanent pipes were lowered vertically to the bottom of the lakes and water from the bottom was pumped up to the surface. Gas and water immediately shot up to the surface and formed a fountain up to 30m high. The fountains have continued ever since and it is thought that, more than 20 years after the pipes were placed in the lakes, the levels of CO_2 are no longer dangerous. The paper by Michel Halbwachs and colleagues (2003) and an accompanying website are listed at the end of the chapter.

Interestingly, Lake Kivu, a much larger and deeper lake in East Africa, also stores massive quantities of two gases, methane and CO_2. The potential for outgassing is considerable, particularly since the lake is very close to the active volcano Nyiragongo. In collaboration with international contractors, Rwanda has developed a plant that separates the two gases and uses the methane to generate electricity. It is the first plant in the world to do so, and now produces about 30% of Rwanda's electricity. Isn't it good to have a 'win-win' situation for a change: 'free' electricity ***and*** reduced threat of outgassing?

Less dramatic examples of the effects of overturn are fairly frequently seen in lakes where the hypolimnion regularly deoxygenates. Mixing during overturn may cause the sudden release of oxygen-depleted or hydrogen-sulphide-laden waters into the upper parts of the lake, which in turn may cause localised fish kills in one or more parts of the lake.

Finally, we must observe that humans may disturb the cycle of stratification, nutrient depletion, overturn and nutrient replenishment. They do this by polluting lakes with domestic effluent or agricultural fertilisers, thus adding essential

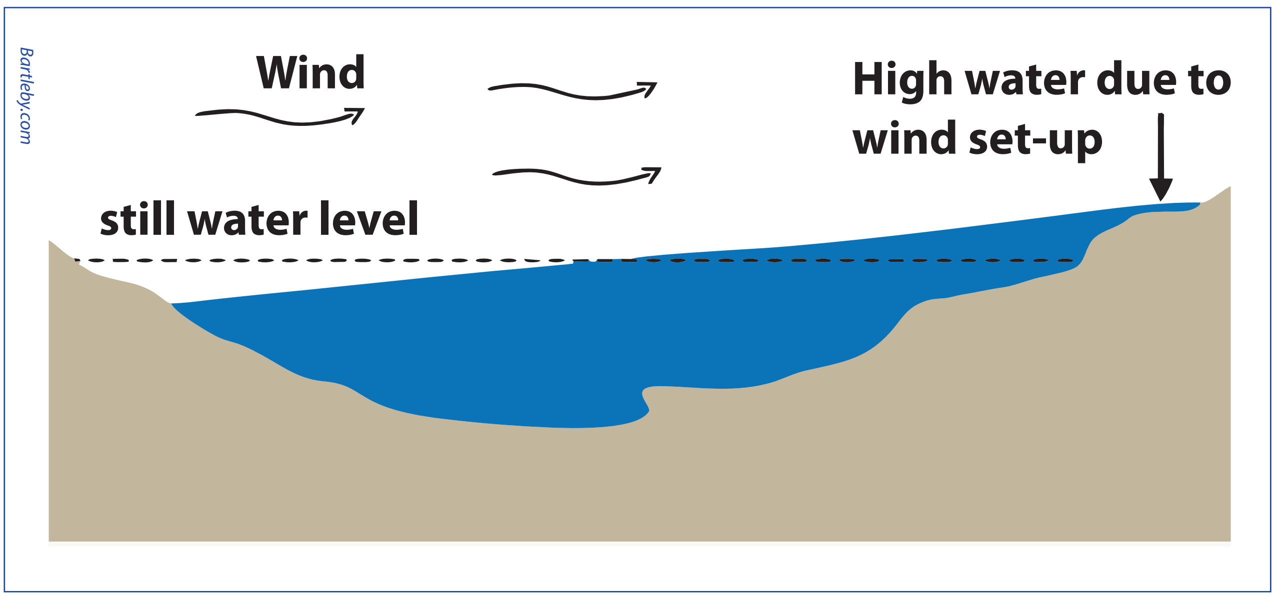
WRC archives

Although fish kills can be the result of natural phenomena, human-related influences such as pollution are increasing the scale and magnitude of such events.

nutrients to the epilimnion. 'Topping up' the nutrients, encourages the continuous growth of organisms within the epilimnion right through the warmer periods of the year, and sometimes even during winter, because there is no longer a lack of nutrients within the epilimnion to limit growth. 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 – as if stratification were not present. An example of this phenomenon is found in Hartbeespoort Dam near Pretoria, which will be discussed in Chapters 7 and 8 as a prime example of a hyper-eutrophic system.

SEICHES

In his *Textbook of Limnology,* Gerald Cole noted that the Latin word ***siccus*** accounts for the modern word 'desiccation' (the process of drying out), and also for the many difficulties experienced by students in spelling that word. The same Latin root has also given limnologists another difficult word – seiche, pronounced ***saysh***. People who are fortunate enough to own waterfront properties on lake shores frequently note (but more frequently fail to appreciate) that shallow areas may inexplicably dry out for a few hours (or days) and then miraculously reflood. This is due to seiche action. A seiche is the free oscillation of water in a basin as it 'seeks' to re-establish equilibrium after it has been displaced. Lakes are dynamic systems, water moving in complex ways, including 'sloshing' backwards and forwards like the contents of a giant bathtub. Energy in almost any form can create a seiche, but wind is the most common. It is not difficult to see how a strong wind blowing from one direction for several hours could force water into a 'heap' against the far shore. Once the wind stops, a counter-current of water will flow back towards the side from which the wind was blowing, as the hydrostatic head on the downwind side re-equilibrates. Repeated wind events from different directions can lead to even more complex equilibrating flows. These can be monitored by complex equipment, but a very simple approach is to place a graduated pole at a fixed point on the margin of a lake and to record changes in water level, as measured on the pole, over time.



A seiche is essentially a wind-generated internal wave that causes the water surface to slope.

These surface events can have great impact upon the subsurface waters of thermally stratified lakes. Even small standing waves generated by wind action upon the surface may influence the differential density layers of the system, and the thermocline. For example, when water piles up on one side of a lake, its weight depresses the thermocline; this rebounds as surface flow that commences once the wind stops and the thermocline begins to rock, as an internal wave below the lake surface, usually out of phase with the wave(s) above. Thus, a very complex pattern of surface and internal standing waves is generated. This may be of profound importance when energy released in the rocking motion creates eddies and turbulence along the thermocline between the epi- and hypolimnion, allowing for some mixing between the two. (For the serious student, a definitive description of these and related processes may be found in the work of Professor Jorge Imberger, listed in the reading list for this chapter.)

The importance of seiches becomes particularly apparent when we contemplate large, very deep meromictic lakes. In these systems, permanent stratification separates the warm epilimnion from the cool hypolimnion and no mixing through temperature equilibration or by wind action can take place because the energies required would be too enormous. The following question can be posed: if materials are being continuously lost from the epilimnion to the hypolimnion of such systems through the rain of dead organisms sinking to the bottom, how do such lakes carry on producing living material, year after year? Well, of course, nutrients may blow in as dust from the surrounding land, but internal waves do the job too, in two ways. Firstly, as we outlined above, internal seiches produce eddies and currents at the metalimnetic boundary, allowing some mixing at localised points along the boundary. In addition, the morphometry (bottom topography) of all lakes, irrespective of size, is complex: they are not simply giant, steep-sided bathtubs but comprise a variety of shorelines and embayments, and sub-basins of various depths. With this in mind, it is easy to see that the development of internal seiches within the main basin may, from time to time, cause the hypolimnion to be rocked so much that it literally spills into some of the shallower submerged bays at the edges of the lake. This colder, nutrient-laden water can then turbulently mix with the warm epilimnetic water in the bay or basin. This phenomenon explains why very deep lakes like Lake Malawi are very rich fishing grounds. (A parallel situation exists in shallow marine systems, where offshore winds cause vertical currents that bring nutrient-rich bottom waters up to the surface. One of the best studied of these areas is the rich Benguela fishing ground off the south-western Cape coast.) In other words, seiche movements may bring the cooler, nutrient-laden hypolimnetic waters welling up into bays, releasing nutrients for the continued growth and production of the organisms living in shallower, warmer, but nutrient-poor waters. Of course, there are occasional dangers in this type of mixing for, as we pointed out earlier, the hypolimnion may be oxygen-depleted or laden with toxic hydrogen sulphide. Thus, large mixing events may force such waters near the surface, causing localised fish kills. In the long-term, though, more is gained by the release of vital nutrients from the hypolimnetic store than is lost by the very occasional toxic spills from the hypolimnion. In 1994 the marine equivalent, a freak 'black tide' caused by deep hydrogen-sulphide laden seawater reaching the surface, killed hundreds of thousands of fish, rock lobsters and other organisms along a section of the west coast of South Africa.

THE LIVING WORLD OF LAKES AND PONDS

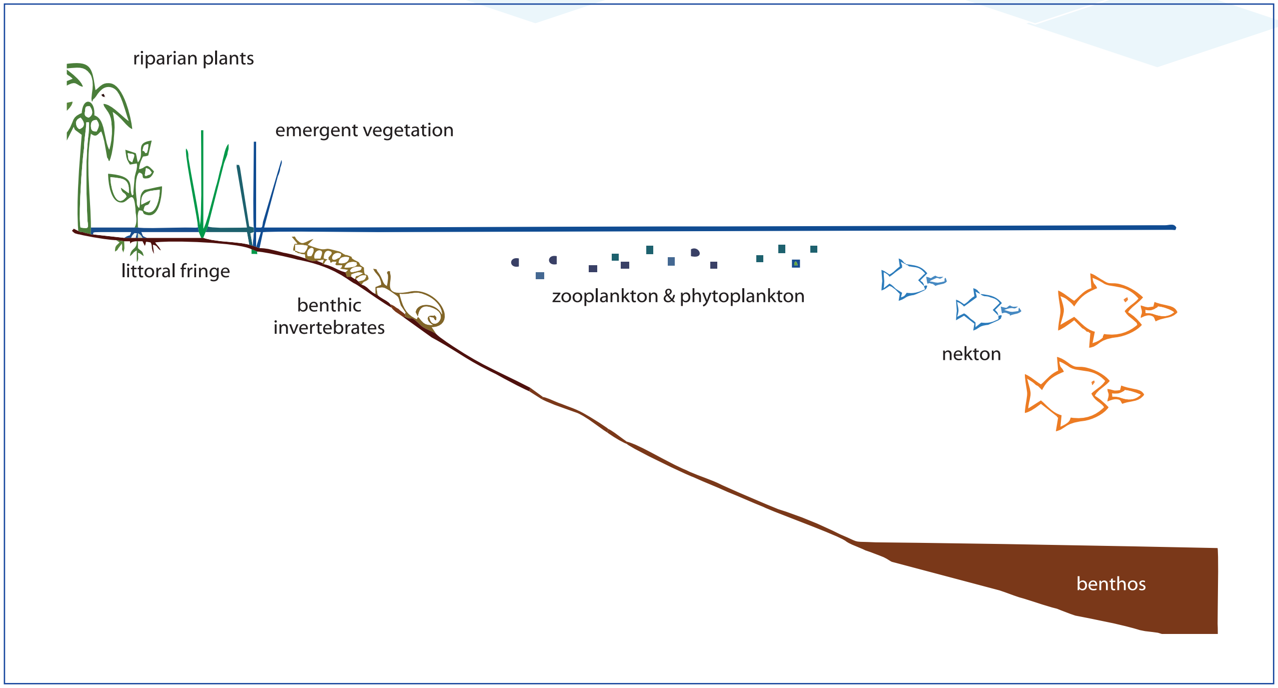
Having looked at some of the physical processes that take place in lakes, let us now turn our attention to their biotas, the microbes, plants, algae and animals that live in them. Because lakes are relatively simple systems, biologically speaking, this seems to be an appropriate place to introduce some very basic ecological principles. The following section therefore introduces some important terms, then describes the sorts of organisms found in lakes and ponds, and how they interact with each other and with their environments. Because rivers have flowing water, they pose rather specific challenges to the organisms that live in them, and we discuss them separately in Chapter 4.

It is useful to start by thinking about the different kinds of habitat available, and the kinds of organism that occupy each. In lakes and ponds we can distinguish two broad kinds of habitat: the water column, and the bottom or benthos. On the bottom we find rooted macrophytes; the word means 'large plants' but we generally use the word to refer to large emergent plants like reeds and sedges. Some aquatic plants are submerged, meaning that they don't usually appear above the water surface; others float on the surface. The marginal vegetation is, as the name suggests, the assemblage of plants at the edges and close to the banks. Plants in contact with the water, whether floating or rooted, are usually coated with a slimy layer that consists of countless single-celled algae, protozoans and fungi. This assemblage is usually called the periphyton (see box). The bottom of a river or pond is known as the benthos, although this term is usually used for the animals that live there – benthic invertebrates, for instance. Organisms that burrow into the sediment are said to be components of the infauna. Suspended in the water column are minute algae – the ***phytoplankton*** – and animals – the ***zooplankton***. Finally, animals like fish that swim in the water column are part of the limnetic zone, while the area close to the shore is known as the littoral (zone).

SOME TRICKY TERMS: EPIPHYTON, PERIPHYTON AND EPILITHON

In German, the slimy stuff that covers rocks and plant surfaces is known as ***Aufwuchs***: 'over-growth'. It consists of algae, fungi, minute animals and mucous, with embedded inorganic particles. In English it is sometimes referred to as a biofilm. Three other English terms are used to mean roughly the same thing: epilithon (Gr: ***epi***- upon + ***lithos*** – a rock) on rocks, and epiphyton (Gr: ***phytos***: plant) on plants. The third term, periphyton is the most commonly used even though it doesn't really make sense. The term derives from the Greek ***peri***, meaning around, or surrounding, + ***phyton***, so it should refer to minute plants attached to hard substrata such as rocks. Or – wait a minute – maybe it means slimy stuff on plants? In fact, it has come to mean slimy stuff of all kinds, on all kinds of surfaces. And if you want a real mouthful you can talk about the microphytobenthos (literally, tiny plants on the bottom).

Jenny Day



Different parts of a waterbody provide conditions suitable for different kinds of organisms: the bottom (benthos) provides soft mud to burrow into, or rock to hide under; vegetation provides both food and shelter; open water is suitable for many fishes; although others prefer sheltered hidey-holes.

Lakes, as well as ponds and other wetlands, are characterised by particular communities of organisms. Plants form the basis of the food chain in virtually all ecosystems, but they are especially important in standing waters since, generally speaking, little food material arrives from outside the system. Thus, the food available in a standing water body is largely produced within its own boundaries and is therefore said to be ***autochthonous*** (from the Greek: ***autos*** = self; ***chthon*** = the ground). In contrast, material is said to be ***allochthonous*** (from the Greek: ***allos*** = other) if it is imported into the system from outside. As an example, the food of animals living in the upper reaches of rivers is allochthonous (see Chapter 4).

TROPHIC RELATIONS: WHO EATS WHO(M)

Plants and algae, by photosynthesising, provide the base of the food chain in nearly all ecosystems. Plants are fed upon by ***herbivores:*** small grazing animals such as insects and snails, and some fish, which in turn are fed upon by ***carnivores***. Decaying material, including faeces produced by both herbivores and carnivores, is decomposed by microorganisms, particularly bacteria and fungi. The rotting particles, with the bacteria, fungi and algae adhering to them, are eaten by animals called ***detritivores***, which either sieve food particles out of the water (***filter feeders***) or feed on whole carcases or on the particles of the oozy mud itself (***deposit feeders***). Small predatory invertebrates feed upon the grazers, collectors and detritivores and are in turn fed upon by other larger invertebrates, fish, frogs and birds. The whole complex of 'who eats whom' is termed a food web. The plankton and fish form a second food web consisting of freely-drifting and swimming organisms. Minute plants forming the phytoplankton are fed upon by planktonic animals (the zooplankton), which in turn form the food of filter-feeding invertebrates and other larger organisms such as fish. The two food webs are interlinked because part of the food supply of the benthos (the animals living on the bottom) comes from a rain of particles from the open water above, the domain of the plankton and fish, while some fish feed on the benthic organisms living on the bottom.

Animals, by definition, are unable to photosynthesise and must therefore obtain their carbon, energy and nutrients directly from plants or from other animals. Herbivores take in and process plant food, breaking down some of it to release energy for their own activities and using some for building new tissue as they grow. Some parts of the food are generally difficult to process and these are voided as faeces, while excess nitrogen from protein metabolism is excreted in the urine as ammonia or urea. Faeces, then, represent waste products containing nutrient- and sometimes energy-rich organic molecules that can in turn be fed upon by other organisms, while the soluble organic compounds in urine may be used by bacteria and fungi.

FOOD WEBS

We are familiar with the idea of food chains from school biology lessons, knowing that plants form the bases of food chains, and you have no doubt seen flow diagrams such as:

grass → cow → human
(people eat cows, and cows eat grass)

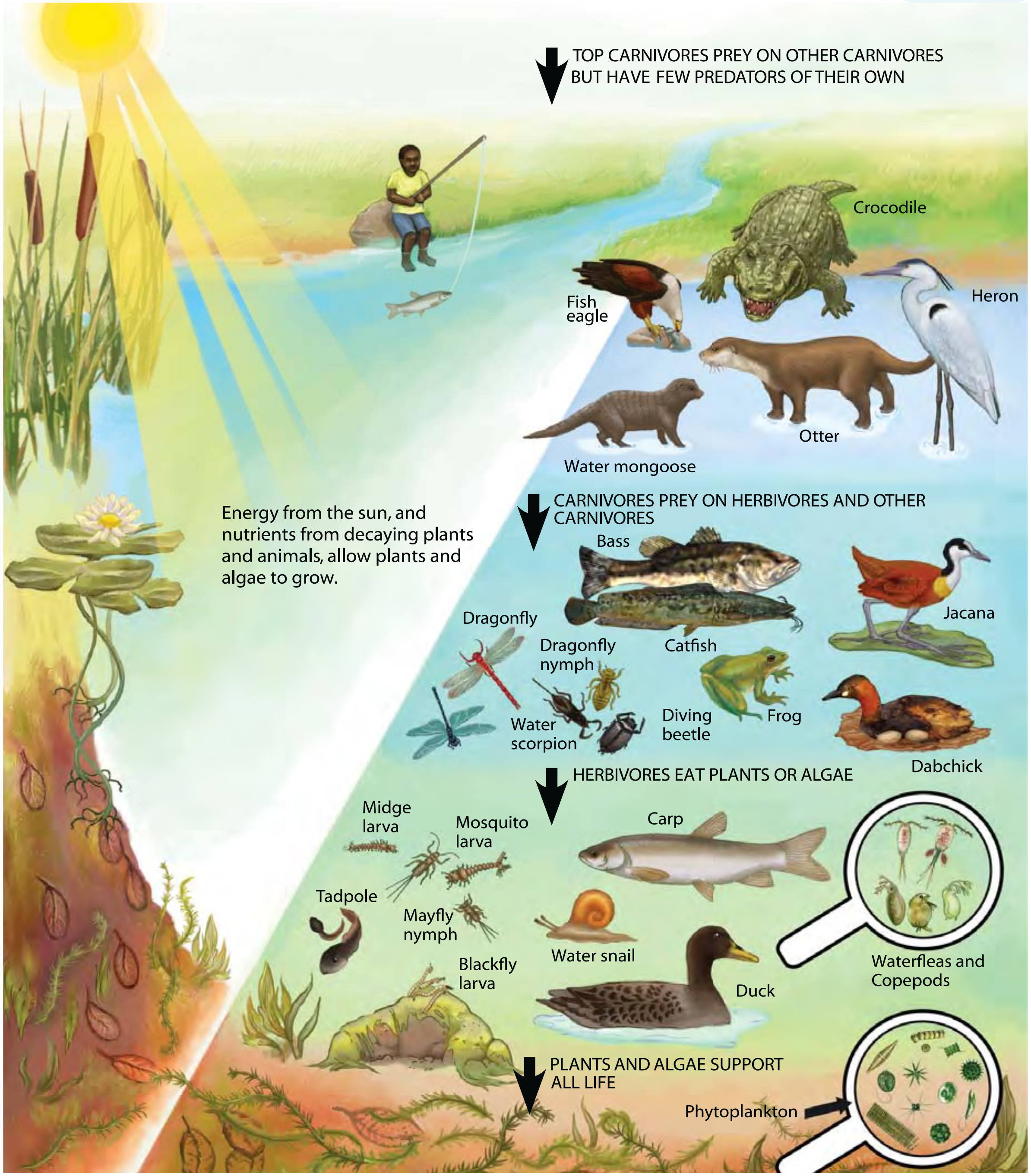
or the more complex

energy from the sun → phytoplankton → zooplankton → pilchard → snoek → human

which is a slightly longer chain and reminds us, too, that plants depend for their growth on energy from the sun. But these food chains are a gross oversimplification of the story. Very few organisms are dependent on only one source of food or are fed upon by a single species of animal. Thus, it is more accurate to talk about ***food webs***, a term that indicates the inter-relationships between organisms in an ecosystem. A food web for a shallow African lake may look something like that illustrated below.

nightowlza / 123RF

The Nile crocodile – an example of a predator at the top of the food web.

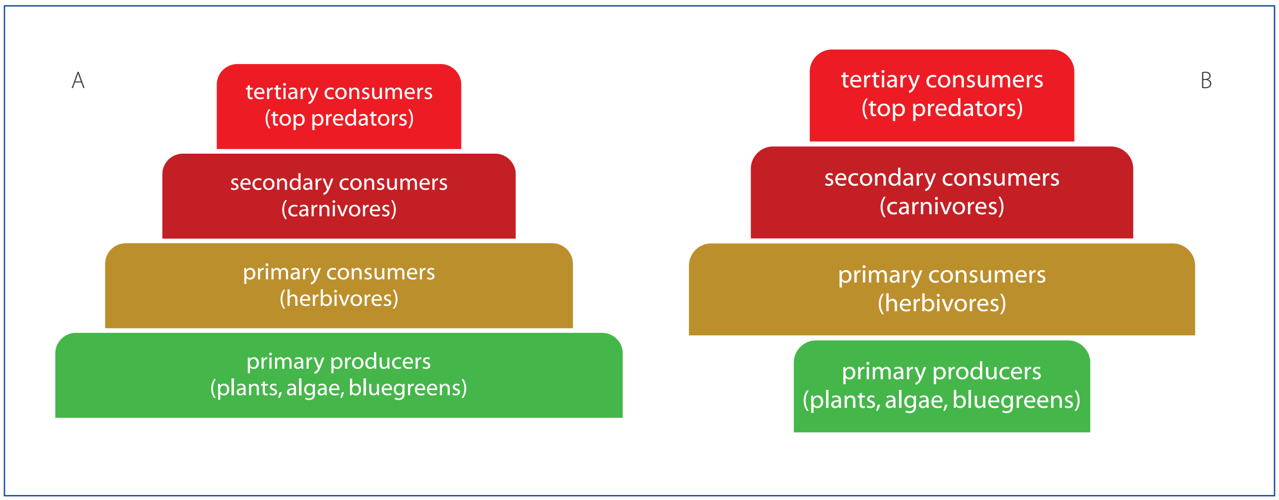


A generalised aquatic food web illustrated with common African animals.

It is not easy to make sense of such diagrams immediately, and it would have been even more complicated had we tried to include the individual species, each of which might feed on, and be fed on by, several others, or the fact that predator and prey are sometimes determined by the age or size of individual organisms. A large dragonfly nymph may feed on a small fish, while the tables may be turned if the fish is large and the nymph small, for instance. The understanding of trophic relationships (who eats whom) can be greatly simplified by dividing organisms into major feeding types or trophic levels. These are:

1. primary producers (plants of all kinds, including phytoplankton)
2. primary consumers (herbivores: feeders on primary producers)
3. secondary consumers (carnivores feeding on herbivores)
4. tertiary consumers ('super-carnivores' feeding on other carnivores)

Now it becomes relatively easy to count the number of individuals in each trophic level. But numbers alone give no indication of sizes (a single bacterium is not trophically equivalent to a single fish, for example), or of how much inert matter such as bone or shell is incorporated into each. It is far more informative to find out how much bulk there is of each kind by drying and weighing them to find the dry biomass (in other words, the weight of living tissue, minus water) in each trophic category. A simple pyramid can then be drawn, demonstrating the trophic relationships between the organisms in a system. Such a pyramid is shown below. The length of each block (representing each trophic level) is proportional to the biomass of organisms in that group. In addition, it is even more informative for comparative purposes to calculate these values for equivalent areas of an ecosystem (for instance, as g dry mass m^{-2} of marshland). In this way, data for different ecosystems may be compared in terms of the amount of living tissue they can support within each trophic level.



These 'trophic pyramids' represent numbers of individuals at a particular site. The classic pyramid (A) shows the greatest number of individuals in the bottom box, and the fewest in the uppermost box. In many case there are fewer primary producers and so the pyramid is 'top heavy'. See text for details.

In rivers, for example, pyramids sometimes seem to be 'top heavy'. This happens when the base of the food web is allochthonous (imported): the food base does not consist only of the visible plants that live in the system. Nevertheless, trophic pyramids are usually pyramid shaped. Why should this be? It has been found that, when looking at ecosystems as diverse as estuarine lagoons and tropical rain forests, coral reefs, savannahs and kelp beds, energy in food is transported with an efficiency of about 10% from one trophic level to another. This means that for every 100 kJ consumed by one trophic level, only 10 kJ is available for consumption by organisms of the next trophic level. Thus, a human being (or any other animal) must eat about 10 kJ of an animal such as a fish to gain 1 kJ worth of nourishment, most of which will be used for the production of energy. Obviously, we obtain both mass and energy from the food we eat, and it turns out that the '10% rule' follows pretty much for biomass as well as for energy. Thus, for instance, 10 kg of fish will have been produced by feeding on 100 kg of insect larvae or small fish, which had to eat 1 000 kg (a ton) of zooplankton which, in turn, consumed 10 tons of phytoplankton. Of course, if one could be persuaded to skip out a level or two and eat zooplankton instead of fish, then the total amount required to drive the system would be much less. This explains why there are so many more plants than insects, why there are few big fish and why, weight for weight, beef is so much more expensive than mealie-meal or bread.

Plants and animals are not immortal. When they die their bodies, too, will become food for others. Carrion feeders are the most obvious of the organisms feeding on dead material, but they are relatively unimportant. Decay is largely due to the microscopic decomposers – bacteria and fungi – that increase their own numbers by breaking down organic matter of almost any kind and turning it back into its constituent parts – carbon dioxide and water, and nutrients such as nitrogen and phosphorus compounds. During the breakdown process, some minute particles of organic matter (particulate organic matter, or POM) and some dissolved organic compounds (DOC, or dissolved organic matter – DOM) are released and can in turn be taken up by minute animals such as protozoans (including *Amoeba*, that favourite of school textbooks), bacteria and fungi. Even detritus – the litter from broken bits of plants, dropped leaves, bits of animals and so on – is rapidly colonised by decomposers. Since detritus is the organic remains of living things, it forms part of the POM in a system.

BIOGEOCHEMICAL CYCLES

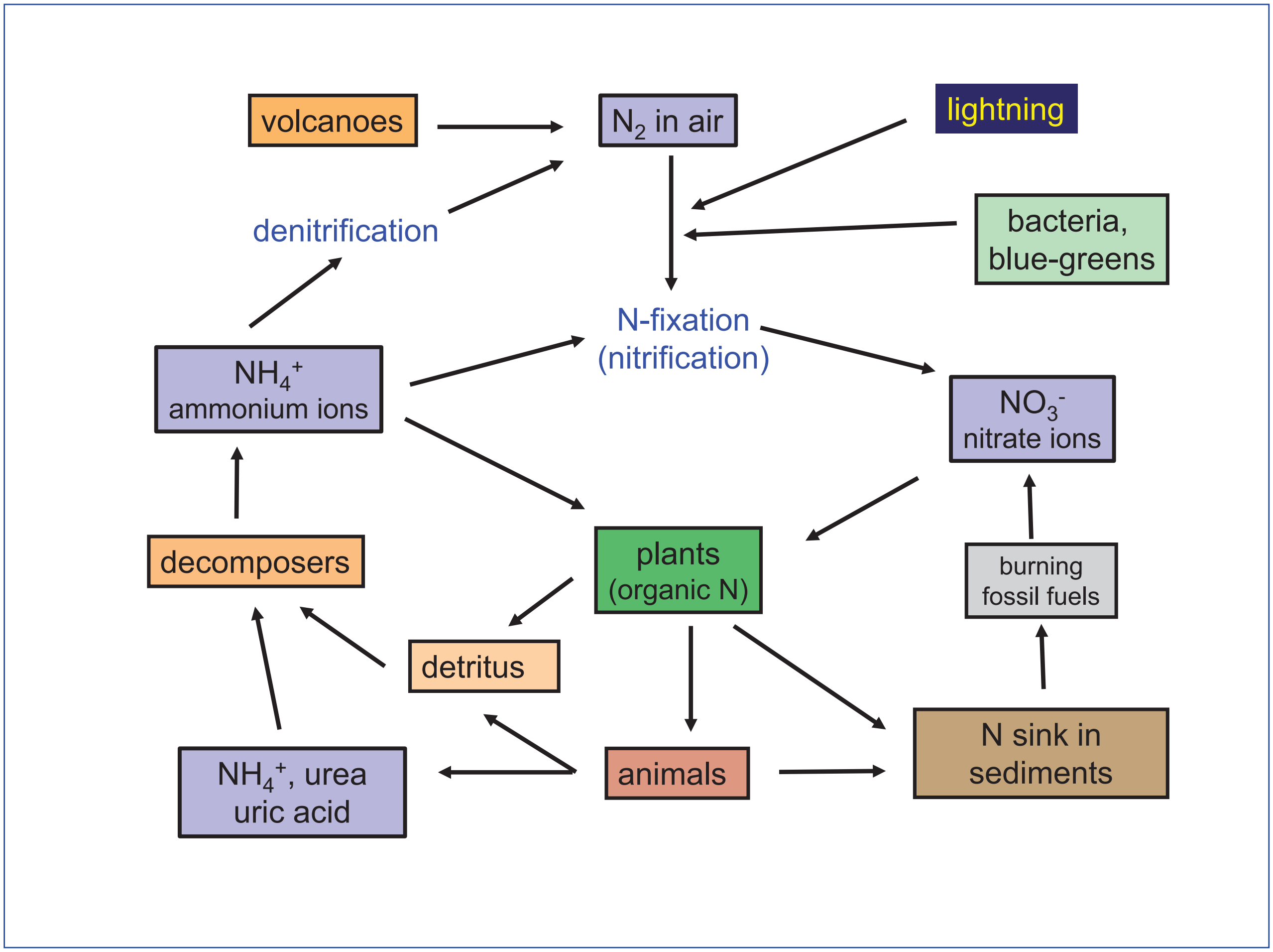
That big word in the title of this section is actually pretty simple to understand: it deals with the ways in which both biotic and abiotic processes are involved in the cycling of individual elements.

The continuous functioning of any ecosystem, and indeed of the biological world as a whole, depends on the recycling of water and other resources. Although living things are composed mainly of water, they obviously also contain a number of other elements that combine to form living tissues. The most important of these elements are carbon, oxygen, hydrogen, nitrogen, phosphorus, calcium, magnesium, sulphur, sodium, potassium and chlorine. Each of these elements is involved in what is known as biogeochemical cycling, since each is taken up and used in living organisms but is ultimately released from dead tissues and subjected to other physical and chemical processes before once again being incorporated into living tissues. Below we describe the biogeochemical cycling of carbon and then of nitrogen and phosphorus, but it is important to remember that all the biologically important elements are subject to parallel processes.

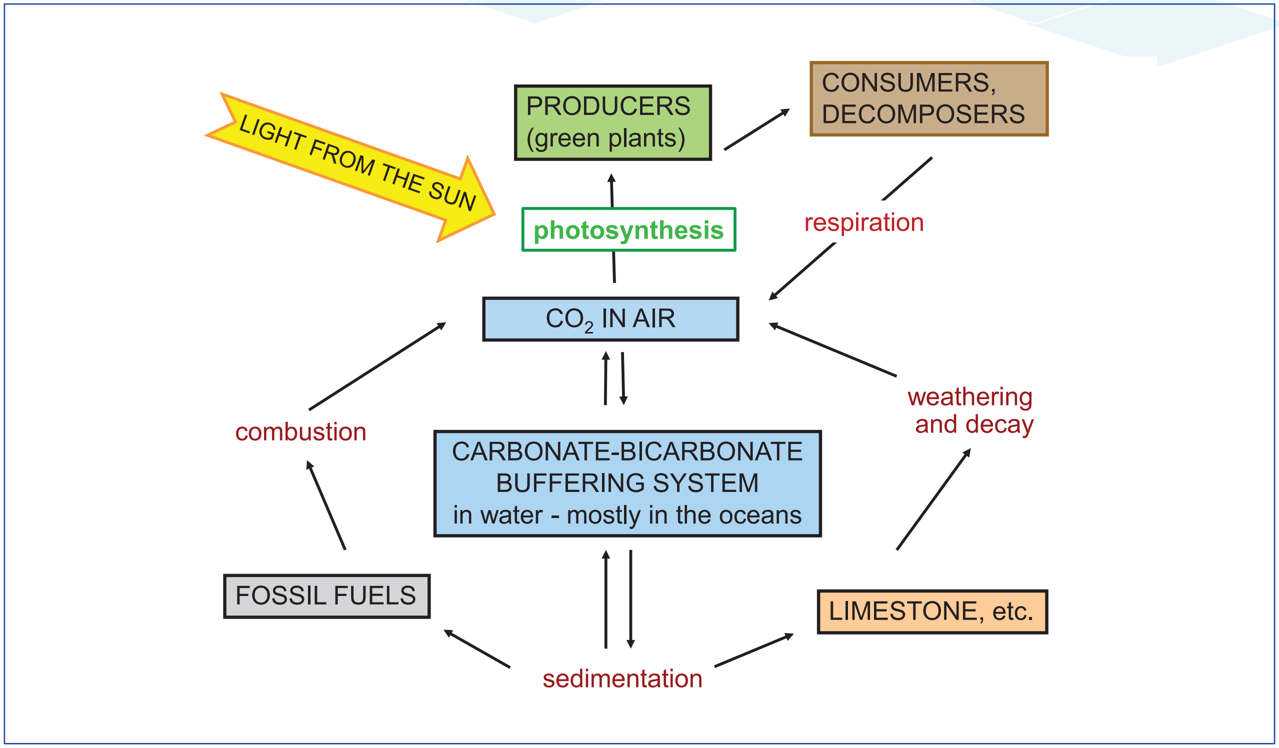
The end-products of food webs, when the energy contained in the organic molecules is finally used up, are carbon dioxide, water and nutrients. The carbon dioxide and water are released back into the atmosphere to start the cycle again, while nutrients, particularly nitrogen and phosphorus, are taken up by other living organisms such as plants. Some nitrogenous compounds are broken down by denitrifying bacteria, which liberate gaseous nitrogen (N_2) to the atmosphere. The amount of nitrogenous material available as nutrients remains more or less constant due to the action of nitrifying bacteria, which convert atmospheric nitrogen and oxygen into nitrates. An example is the nitrifying bacteria housed in the root nodules of leguminous plants of the pea family. In contrast to the highly variable fate of nitrogen compounds, phosphorus compounds cannot be made gaseous by living organisms. Thus phosphorus either remains in solution or is absorbed onto particles in the soil or sediment until it is taken up again by plant roots or microorganisms. The biogeochemical cycling of nitrogen is illustrated below. The phosphorus cycle is discussed in Chapter 7.

While the hydrological cycle (page 41) and its importance to all organisms on this planet is easy to understand, ***carbon cycling*** is much more complex. On earth, the bulk of carbon is stored in the form of carbonates in rocks such as limestone or marble, in sediments in lakes and the sea, in living and dead organisms, and in oil, coal and shale gas. The other major pool of carbon is the gaseous carbon, especially carbon dioxide (CO_2), in the atmosphere and dissolved in water. Cycling of carbon on a planetary scale largely involves four processes:

1. the uptake, or fixing, of carbon in the form of CO_2 by plants through the process of photosynthesis, and its release back into the atmosphere or into water through the processes of respiration and decomposition
2. the equilibrium between dissolution of carbon dioxide in the sea and its release to the atmosphere
3. the weathering and dissolution of carbon-rich rocks
4. the balance between accumulation and loss of dead plant material

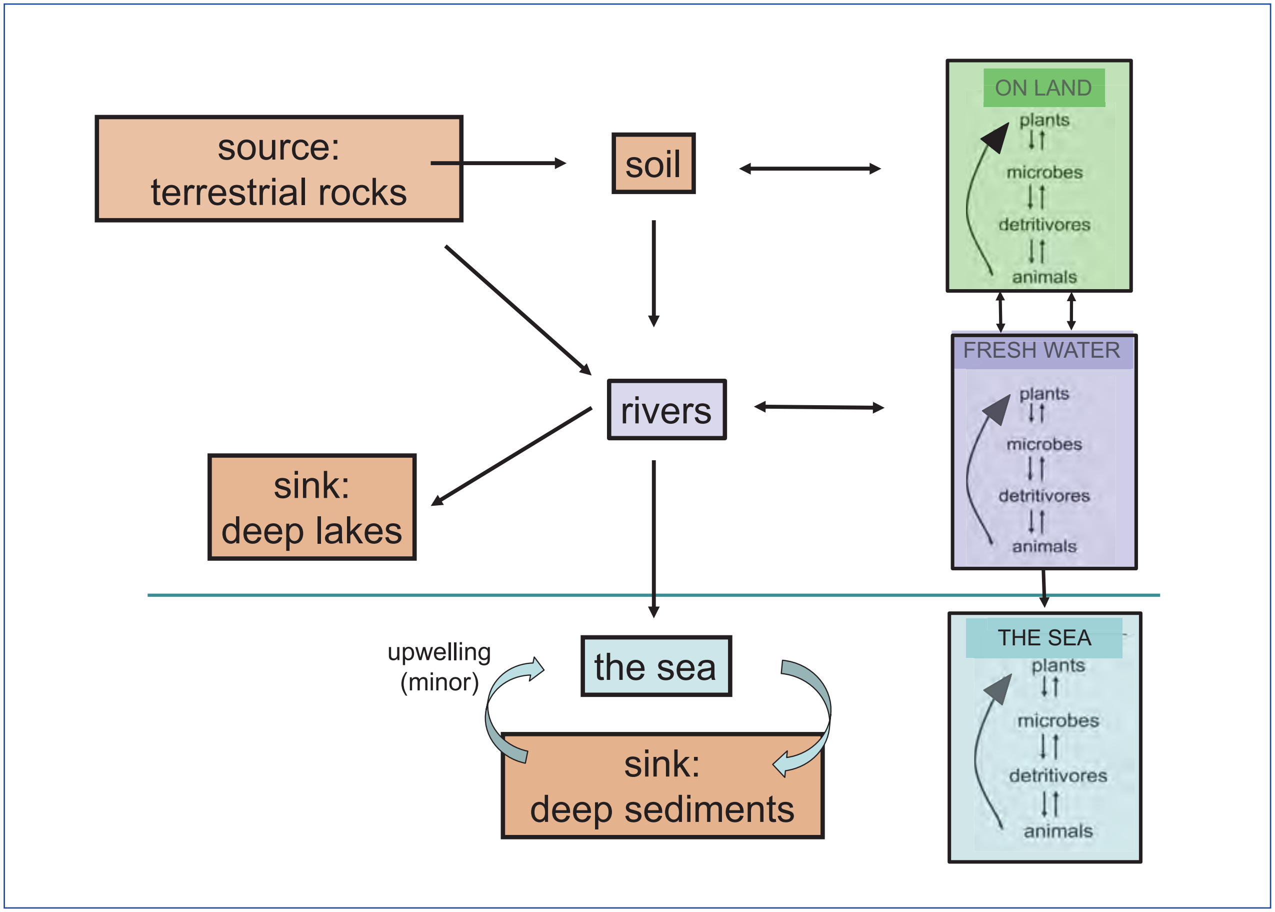


A much simplified nitrogen cycle. See text for details.



A much simplified carbon cycle. See text for details.

"All living things (and their dead counterparts in the form of coal, gas, and oil) dominate the carbon cycle by determining the amount of carbon dioxide in the air and in water."



A much simplified phosphorus cycle. See text and box on phosphorus (Chapter 7) for details.

At some stages in the Earth's history, the rate of decomposition of living things has been much slower than the rate at which they have formed, resulting in the accumulation of huge quantities of dead and only partly decomposed plant material. This material exists today in the form of oil and coal, which are the fossilised remains of the massive forests and the accumulated remains of plants and animals in the deep sea during past aeons. As usual, human beings have unwittingly interfered with the carbon cycle by burning coal and oil (the fossil fuels), thus liberating millions of tonnes of carbon dioxide into the atmosphere, where it and other gases such as methane (CH_4) are altering the heat balance of the Earth and causing global warming. The accelerating increase in the quantity of CO_2 in the atmosphere over the past century is easily quantified by examining the amount of CO_2 in both Arctic and Antarctic ice sheets. Datum points around the world show a steady rise in sea level (a few millimetres a year at the moment) as the oceanic waters of the planet expand and the polar ice sheets retreat in response to rising temperatures. In future we will live in a warmer world; and while most of the planet will be wetter, climate modelling suggests that south-western southern Africa will be significantly drier. This topic is addressed again in Chapter 11.

All living things (and their dead counterparts in the form of coal, gas, and oil) dominate the carbon cycle by determining the amount of carbon dioxide in the air and in water. Why should this be so? In essence, it is because carbon is the most important component of all living organisms. Carbon compounds act both as major structural components of living organisms (all cells of all living organisms contain dozens of organic molecules) and as the immediate source of energy: all foods (such as sugars, fats, starches, proteins) are carbon compounds. It is the chemical bonds within some of them that store the energy used in life processes. By definition then, organic matter, made up of individual organic (i.e., carbon-containing) molecules, contains carbon manufactured by living things. In contrast, inorganic carbon consists of carbon itself and simple carbon-containing compounds, such as carbon dioxide and carbonates, that are not necessarily produced by living things. (The term 'organic', as in organic produce, is a misnomer that has become entrenched in the language.)

Using the energy of sunlight, plants are able, by the process of photosynthesis, to join up molecules of carbon dioxide and water to produce simple organic molecules such as sugars (an example is glucose), which 'trap' some of the sun's energy within their structures. Plants can then use the energy in these substances to do work, in the first instance for taking up and using other elements such as nitrogen, phosphorus and sulphur to build up their tissues, and later in the production of flowers and fruits, for instance. In other words, organic compounds form part of the structure of plants, and can also be broken down to release the energy needed for living. The process of breaking down organic molecules into their constituent parts, with the concomitant release of energy, is known as respiration, which is really no more than highly-controlled combustion at a low temperature. (It should be remembered that all organisms respire, even plants, when breaking large molecules into smaller ones with the release of energy.) Carbon tied up in excretory products, or in the tissues of dead organisms, or in bits of organisms such as moulted hair, skin, feathers or exoskeletons, is also recycled in the process of decomposition. Decomposition, which is carried out by decomposer microbes and by detritivores (animals that feed on dead material), is an essential process in any ecosystem. (Just think what would happen if there were no decay: the world would be kilometres deep in dead but undecomposing bodies of everything from elephants to microbes, and there would be no more material from which to make new bodies!)

It is important to remember that the process of recycling does not involve carbon alone. Decomposition also results in the release (mineralisation) of all the other elements that were originally tied up in living tissue. This is particularly significant in the case of the elements like nitrogen and phosphorus, because they are usually present in very small quantities, and might otherwise not become available for reuse. Incidentally, this means that, unexpectedly, biologically rich ecosystems like tropical forests, estuaries, coral reefs and wetlands are often nutrient-stressed because the vast bulk of the nutrients is stored within living tissues.

Recycling, then, is the operative word for the resources of the planet. As we will see again and again in the chapters to follow, though, human activities often have unintended consequences. A case in point is the biogeochemical cycling of phosphorus, one of the elements crucial to plant growth. The phosphorus story is best illustrated with reference to nitrogen, another of the major fertilisers. Nitrogen in its free form is an inert gas (N_2) that is present in large amounts in the atmosphere. When it is liberated from decaying material it is therefore able to circulate freely through the air and in water and can be picked up by microbes that convert it into biologically useful materials (ammonium and nitrates), thereby starting the cycle again. Phosphorus, on the other hand, is chemically very active, forming compounds with numerous other substances and virtually never found in elemental form in nature. It has no significant gaseous phase, instead tending to adsorb onto soil and sediment particles. As a result, phosphorus tends to accumulate in soil and ultimately on the sea bed, where it is essentially unavailable to terrestrial organisms. The phosphorus on the sea bed eventually becomes incorporated into sedimentary rocks. It is only recycled at geological time scales, when the rocks are lifted to the surface and face a new round of erosion, releasing the phosphorus and allowing plants to take it up. You may already have thought about why this is problematic. We are using phosphorus fertilisers – taken from surface rocks - at a greater rate than it can be recycled. In essence, we are running out of phosphorus. This is one of the explanations for fertilisers (and food crops) becoming so much more expensive recently, and even why there is less phosphorus added to washing powders (chapter 7).

With this background to standing waters, food chains and food webs, we turn our attention in the next chapter to rivers.

ANCIENT LAKES

As we have indicated, the lifespans of lakes tend to be short – of the order of a few hundreds or thousands of years – because they become filled with material such as silt, sand and organic debris. Lakes also tend to be relatively shallow – usually no more than a couple of hundred meters in depth. Around the world we do have a few remarkable exceptions, though – and many of these are in Africa. These are the very deep Ancient Lakes such as Baikal in Siberia, Biwa in Japan, Titicaca in South America, and Malawi (Nyasa), Tanganyika and Albert in East Africa. As well as being very deep and very old, they support very diverse faunas. Lake Baikal in Russia is the deepest, at 1 642 m (average 744 m) and oldest (about 30 million years), and so large that it holds nearly 20% of the Earth's fresh water. Of the 2 600 species of animal in the lake, 80% are endemic. Lake Tanganyika in East Africa is 1 470 m deep and 650 km long with a surface area of 75 000 km^2 and more than 400 species of fish, of which about 60% are endemic, and a flock of endemic gastropod molluscs. Lake Nyasa (Malawi) has about 500 species of cichlid fishes. Lake Biwa had more than 2 000 species before a mass-extinction episode in the 1960s caused by human manipulation of water level, eutrophication and the introduction of numerous alien species.

Why are these lakes so different from all the others? The answer is that they lie on boundaries between tectonic plates, where the Earth is being torn apart as the plates move away from each other. The rate at which they are filled up by sediments is slightly less than the rate at which they are widening, so they are deep. Because they are so old, there had been ample opportunity for speciation. Each of these lakes may, in some remote future, widen and form part of an ocean as geological processes tear the continents apart.

Great Rift Valley map-fr.svg: Sémhur / Wikimedia / CC BY-SA 4.0

African Rift Valley, showing lakes Albert, Tanganyika and Malawi, and the almost circular Lake Victoria.

Jenny Day

Lake Titicaca.

READING LIST

NOTE: we have tried where possible to include easily accessible and up-to-date references for each chapter, but we have not been particularly successful for this chapter, which by and large deals with well known ecological and limnological topics. The best limnological texts seem to be Dodds & Whiles (2019), and the classic Cole & Weihe (2015), which is freely available online.. The reader is also referred to any good undergraduate texts on ecology for information on most of the topics covered in this chapter.

Beadle LC (1981, 2nd ed.) ***The inland waters of tropical africa. an introduction to tropical limnology***. Longman, London and New York. 475 pp.

Carmouze JP, JR Durand & C Lévêque (eds) (1983) Lake Chad: Ecology and productivity of a shallow tropical ecosystem. ***Monographiae Biologicae* 53**. W. Junk, The Hague. 575 pp.

Cole GA & P Weihe (2015, 5th ed). ***Textbook of Limnology***. Waveland Press, https://www.researchgate.net/publication/286448265_Textbook_of_Limnology

Dodds WK & MR Whiles (2019, 3rd ed.) ***Freshwater Ecology: Concepts and Environmental Applications of Limnology (Aquatic Ecology)*** Academic Press.

Halbwachs M, JC Sabrouet & 10 others (2004) Degassing the "Killer Lakes" Nyos and Monoun, Cameroon. ***Eos* 85**: 281-285

Imberger J (1998) ***Physical limnology***. Kluwer Academic Publishers. 600 pp.

Martens K, G Boudewijn & G Coulter (eds) (1994) Speciation in Ancient Lakes. ***Advances in Limnology* 44**. Schweizerbart'sche Verlags-buchhandlung (Nägele und Obermiller). Stuttgart. 508 pp.

Msiska OV (2001) A review of limnology in Malawi; pp 121-189 in RG Wetzel & B Gopal (eds), ***Limnology in developing countries* 3**. International Association of theoretical and applied limnology (SIL)

Palmer CM, MC Tarzwell & HJ Walter (1955) Algae of importance in water supplies, ***Public Works Magazine***, New York

Parsons R (2003) Surface water: groundwater interaction in a South African context – a geohydrological perspective. Water Research Commission Report no. TT 218/03, Pretoria. (An excellent introduction to groundwater)

Polunin NVC (2008) ***Aquatic ecosystems: trends and global prospects***. Cambridge University Press, 512 pp.

Wetzel RG (2001, 3rd ed.) ***Limnology: lake and river ecosystems***. Saunders College Publishing, New York.

SOME USEFUL WEBSITES, ACCESSED OCTOBER 2022

Siltation of reservoirs
https://infrastructurenews.co.za/2021/08/03/increasing-dam-storage-capacity-through-the-natsilt-programme/

Lake Nyos
https://globalchange.umich.edu/globalchange1/current/lectures/kling/killer_lakes/killer_lakes.html

Seiches
https://www.ijc.org/en/they-come-waves-seiches-and-type-tsunami-affect-great-lakes

CHAPTER FOUR

Jenny Day

The brown gods

I do not know much about gods; but I think that the river
Is a strong brown god – sullen, untamed and intractable,
Patient to some degree, at first recognised as a frontier;
Useful, untrustworthy as a conveyor of commerce;
Then only a problem confronting the builder of bridges.
The problem once solved, the brown god is almost forgotten
By the dwellers in cities – ever, however, implacable,
Keeping his seasons and rages, destroyer, reminder
Of what men choose to forget. Unhonoured, unpropitiated
By worshippers of the machine, but waiting, watching and
waiting.

T.S. Eliot, 'The Dry Salvages', from Four Quartets

Eliot reminds us that humans seem to have forgotten the vital and contradictory roles that our rivers play as cleansers and renewers, destroyers and creators, sculptors of landscapes, givers of life, and takers of life. A quick search of the internet shows that in 2021 alone, there was severe flooding in Germany, Peru, Argentina, Canada and the north-western USA, eastern Australia and China, where the flow of water at the Three Gorges reservoir reached an unimaginable peak of 54 000 m^3/s. At home, virtually every province has been affected, and as I write this (April 2022), there have been devastating floods in KwaZulu-Natal, resulting in the loss of hundreds of lives. And let us not forget the floods in the Limpopo River in Mozambique in 2001, with nearly 900 deaths and a baby born in a tree. These floods can almost always be attributed to massive downpours that cause otherwise benign rivers to overtop their banks. Such floods are not a new thing, but they are becoming increasingly common as global warming results in increasingly unpredictable weather events coupled with inappropriate river engineering and loss of wetlands in the catchment (see Chapter 5).

In this chapter, we show how these tireless 'brown gods' function, and what kinds of plants and animals live in them. In Chapter 9 we will look at the ways in which we humans have taken advantage of rivers and have sometimes caused their demise.

The Limpopo River from Crook's Corner in the Kruger National Park. Straight ahead is Mozambique. Across the river is Zimbabwe. Contrast the bleak aridity of this image with the next one.

People waiting to be rescued from a damaged bridge over the Limpopo River, Mozambique, after the floods in 2000.

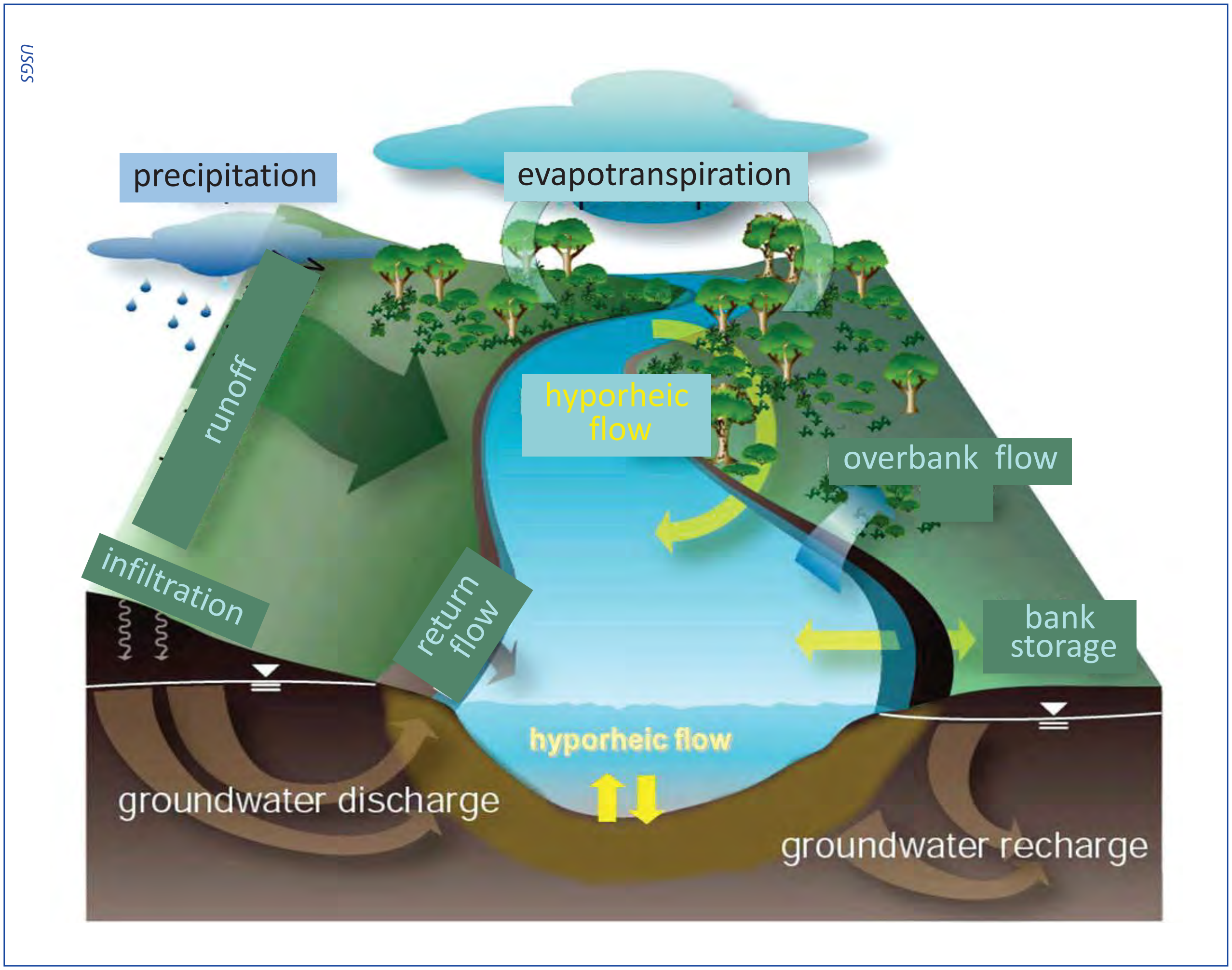
GCIS

The April 2022 floods and mudslides in KwaZulu-Natal killed 461 people and caused an estimated R7 billion in damage.

THE RIVER AS A CONTINUUM

When Bryan and I were students, the given wisdom was that river ecosystems could safely be likened to a string of pearls, rather like a necklace of separate ecosystems. We were informed that no two sections of a river were the same and, to prove it, we were taken out sampling. Clutching hand nets, buckets, simple equipment for chemical analyses, stopwatches and oranges (still a useful technique for estimating flow rates: see Chapter 12), hand-lenses, enamel trays and tweezers, we were taken first to a mountain stream, then to the river in the foothills, followed by the lower reaches, and finally to the estuary. All of this would be on the same river and usually on the same day. (A lot of rivers in this part of the world are really short!) Back in the lab, with microscopes, burettes, pencils, notebooks and graph paper, and a little basic arithmetic, 'e voila!' – there it was plain to see: different animals, different chemistries, different amounts and flows of water, and different plants. Each site we had sampled was a separate 'bead' in a 'string' of ecosystems. Our tutors were right: we were quite clearly looking at very different parts of a river. But they were wrong in that rivers are far from being the equivalent of separate pearls on a stringed necklace: they are more like the string itself. In fact, forget the pearls and the beads – the metaphor is completely misleading.

River ecologists of those days failed to grasp the simple truth that, although we were looking at different parts of a river, with different communities and exhibiting different properties, the unifying feature – water flowing in time and space – had been completely ignored: a classic example of failing to see the wood for the proverbial trees. Although complex, rivers simply do not comprise a loose group of isolated ecosystems: each river is a single four-dimensional entity with vertical, cross-sectional, longitudinal and temporal (time) components (see figure on page 110 - 111). Most certainly, different rivers are isolated from one another; they occupy separate basins, forming biogeographical 'islands', and that is part of what makes them so fascinating. But within their own boundaries, each operates as a coherent whole, with the processes and features of the upper reaches successively influencing lower and lower reaches down the system, from the source to the sea. Rivers are, indeed, longitudinal functional units.



Rivers change along their lengths, across their widths, through their depths and with time. As well as discharging longitudinally, water moves laterally betwee the air, the banks and the subsurface (hyporheos) of a river.

THE RIVER CONTINUUM CONCEPT (THE RCC)

The RCC, which attempts to unify a number of views of rivers, and which has led to a myriad consequences for the understanding of river functioning, management and conservation, was almost revolutionary when it was first published by Robin Vannote and colleagues in 1980. The concept is actually rather obvious: all rivers are continuous longitudinal ecosystems and activities at each point have consequences downstream. Note that the RCC is firmly based on an understanding of invertebrates and rivers in temperate North America, and the authors seem almost to be unaware of variations across the planet. Nonetheless, the RCC provides a useful conceptual understanding of the river as a longitudinal flowing system. The essence of the RCC can be found in the text box on page 112.

juergenb22 / 123RF

The Lisbon Falls are located in a tributary of the Blyde River that flows through Mpumalanga. Interestingly, the river separates into three streams at the bottom of the falls.

Upper reaches: stream bed narrow, rocky; shallow, fast-flowing with trees meeting overhead; water cool and pure; food chain based on leaves, etc. coming from upstream. Invertebrate community dominated by shredders of leaves, with some predators.

Middle reaches wider, deeper, slower-flowing; bed sandy; trees no longer meet over the stream; water warmer with more salts and nutrients; much of the food made by algae on the stream bed. Invertebrate community dominated by grazers on the algae, collectors of particles coming from upstream, and predators.

Lower reaches: wide, deep, slow-flowing; bed sandy or muddy; water warmer still with even more salts and nutrients; food mostly small particles drifting from upstream. Invertebrates mostly collectors of particles, and predators.

Artist's impression of the original River Continuum Concept (Vannotte et al 1980) as it would apply in a pristine catchment.

RIVER CONTINUUM CONCEPT (RCC)

In simple terms, the RCC views all rivers as possessing continuous gradients in physical and chemical conditions from the headwaters to the sea. The concept deals with the river as a continuum not only in space, but also in time. It details the role of 'driving variables' in rivers (flow, nutrient loads, temperature, altitude and so on), and the responses ('response variables') they elicit in the biota. For instance, the patterns of community structure (the species present) reflect changes in the driving variables down the length of a river. In other words, simply because of gradient and substratum, each environmental attribute varies down the length of the river, forming physical and chemical gradients. This can easily be demonstrated. Each species of riverine organism will be confined to those parts of the river where physical and chemical conditions are suitable for its members. Those with similar requirements will thus form species assemblages characteristic of particular reaches of the river (which is where the idea of 'beads on a necklace' came from). In turn, the organisms themselves alter the conditions that prevail further downstream. So, whatever happens in upstream reaches – leaves being eaten, chemicals being leached from soils, animals and plants dying – will influence processes such as decomposition and nutrient cycling, and therefore the species present, further downstream. In this way, continuous gradients of physical and chemical conditions elicit a series of biological responses down the length of any perennial river.

The primary thesis of the RCC, then, is that all components of a river at any point along its length are dictated by abiotic and chemical conditions and modified by gradients of biological variables and processes that occur upstream of the point under consideration. The second very important feature of the RCC is that it makes predictions about the kinds of (invertebrate) riverine communities that should occur at any point in the continuum, based on the physical, chemical and biotic conditions at that point. In particular, it deals with the supply of food for the invertebrates of the system and the ways in which those organisms both produce and use that food. In other words, it describes the form of, and changes in, the balance between allochthonous (externally-generated) and autochthonous (internally-generated) food resources as they vary down the length of the river. An allochthonous system is heterotrophic, consuming more organic material than it produces, while an autochthonous system is autotrophic, usually producing more organic material than it consumes. The balance between the two states is reflected in the P:R ratio. The P:R ratio is the ratio of production (P – plant material produced by photosynthesis) to respiration (R - respiration: the combustion of plant and animal material to release energy needed for daily living). The P:R ratio can be measured in rivers as the ratio of oxygen evolved in photosynthesis to the amount of oxygen taken up during respiration, or as the amount of carbon dioxide taken up relative to the amount of carbon dioxide evolved. The RCC postulates that in general the P:R ratio will be less than 1 (more respiration than production) in headwaters, greater than 1 (more production than respiration) in the middle reaches and, again, less than 1 in the mature, lower river (see later in this chapter).

Based on the idea that the upper and lower reaches obtain most of their food resources from outside the system, while phytoplankton, algae and macrophytes are produced in the middle and lower reaches, the RCC also deals with the ways in which food resources are utilised by animals in different stream reaches. Vannote and his colleagues posited that different groups of organisms, which they named Functional Feeding Groups – FFGs) are adapted to feeding on different kinds of food (such as large or small particles, living or dead plant material, and so on) and so, by definition, also use different food-gathering techniques. In rivers, the basic invertebrate functional feeding groups are said to be the shredders, grazers (sometimes called scrapers), collectors, and predators. In the view presented in the RCC, if different parts of a river are dominated by different kinds of food, then invertebrates will occur in varying ratios of FFGs down the length of the stream. We deal with FFGs in more detail in the text box on page 120, where we will also raise some of the controversial issues that surround this aspect of the RCC. But before we turn our attention to the finer details of river ecosystems, the organisms they contain and the processes that take place in them, we should note that other theoretical concepts also help us to understand certain aspects of rivers and the ways in which they operate. We will alert the reader to these concepts as we reach appropriate points on our journey downriver.

Jenny Day

Geordie Ratcliffe

Jenny Day

Martin Mwaura / 123RF

(A) A canopied mountain stream where little sunlight reaches the bottom. (B) An uncanopied mountain stream in full sun. (C) Middle reaches of the Molenaars River, a tributary of the Breede River. (D) A very mature river – the Zambezi.

The classical view of any river is of a mountain stream, cool and sparkling, cascading down a mountainside, gradually slowing and widening as it enters the foothills to be joined by other tributaries, and ultimately becoming a majestic, meandering river depositing life-giving muds laden with nutrients on a floodplain before reaching its estuary and finally entering the sea. Along its length, there are complex networks of plants and animals of different kinds that are adapted either to the cool, fast-flowing and eroding waters of the upper reaches or to the warmer, silt-laden waters of the depositing zones of the lower reaches. Through their activities, these organisms keep the water clean right down to the sea (see Chapters 5 and 6). At least that was the way things were.

It is difficult, if not impossible, to find a whole river system like this in South Africa today. Uses and abuses of rivers and their waters by humans often result in natural communities of organisms being unable to survive (see Chapters 7–9). When this happens, the river may become no more than a dirty, sluggish drain, sometimes flowing over a concrete bed through a landscape covered by brick, concrete, roof tile, or tarmac. A widespread feature of South African rivers is that the greater part of their waters is now to be found in artificial lakes (reservoirs) formed by the impoundment of rivers by dam walls. This is such an important topic that it is the sole subject of Chapter 9.

Let us look now, though, at an imaginary river, free from interference. It probably rises in a mountain range, either as a spring or as a seep in a sponge or bog, and begins its journey to the sea by tumbling down a steep, narrow channel.

THE MOUNTAIN STREAM

Mountain headwater streams are characteristically cool, clean, clear, fast-flowing, systems and, except when in spate (flood), they are free of silt, for the land they drain is frequently rocky, with very little loose soil. It is the very flow of water that sculpts the channel, dictating what remains on, or in, the bed of the stream and what will be washed downstream. Mountain-stream inhabitants must overcome the forces of friction, drag and lift, as well as abrasion and crushing, and occasionally smothering.

Mountains comprise hard rocks that weather slowly, so that often the river water leaches only small quantities of minerals (including nutrient elements such as nitrogen and phosphorus) from the rocks in its bed and along its banks. Thus, the water is usually oligotrophic (low in nutrients) and said to be of 'good quality'. Physical harshness, together with low levels of nutrients, conspire to produce an environment that is difficult to endure. Normally the water is rich in oxygen because it incorporates bubbles of air from the atmosphere as it tumbles over boulders and stones. Trees may cover the slopes and line the banks, forming a canopy over the stream so that it is in perpetual semi-shade, further inhibiting the growth of plants along the sides and the bed of the stream. If this is so, then what do mountain-stream animals live on?

FOOD SUPPLY IN MOUNTAIN STREAMS

The main food supply and energy base in headwaters comprises allochthonous plant material, such as leaves, twigs, bark, flowers and fruits, that falls in from the riparian canopy, or which is washed or blown in from surrounding terrestrial vegetation. Leaves usually form the bulk of this material, but they are frequently augmented by twigs, bark and branches and, seasonally, by fruits and flowers, as well as a small but continuous supply of animal material falling in from the terrestrial environment.

Sometimes a tree will collapse and fall across the stream forming a 'debris dam', behind and within which other organic material accumulates. (Beavers make debris dams in temperate streams in the northern hemisphere.) It is fundamental to the eroding nature of mountain headwaters that small-rooted plants have the greatest difficulty in gaining and maintaining a foothold in the water, because they are crushed or scoured during spates. This is why, although some hardy mosses and algae may occur on the bed, the bulk of the food is produced outside the stream (as described in the FFG text box on page 120). This is why the RCC predicts that the P:R ratio in headwaters will normally be skewed towards respiration (i.e. P:R <1), with the vast majority of stream animals relying directly or indirectly upon material imported from the riparian and terrestrial environment.


Jenny Day

Food for mountain stream invertebrates: woody debris and leaf-packs.


Jonathan Taylor

Diatoms – minute, single-celled algae protected within siliceous shells known as frustules.

Such material, often falling seasonally, is a vital resource for the myriad animals of the stream. It accumulates in large or small amounts on the stream bed, frequently as 'leaf packs' caught between boulders or tree roots or in crevices, while loose accumulations of plant material may also form in pools and backwaters. This material, known as ***detritus***, is colonised by bacteria and fungi, which are frequently joined by algal cells, particularly diatoms, whose exquisitely sculpted cells have walls made of silica. This thin film of bacteria, fungi and algae, known as periphyton (see page 92), is found on the rocks of the riverbed too. (It is this layer that causes underwater rocks to feel slippery.) Where sunlight reaches the bed of the river, algal cells may dominate the periphyton; in dim light, bacteria and fungi are more common. As leaves decompose, the resulting particles fill crevices and slowly enter the interstices within the stream bed, so much so that during periods of low flow, water extracted from beneath the stream bed is often laden with dissolved and particulate organic material.

The quality and quantity of food falling into the stream determines not only the number of animals – from small invertebrates through carnivorous birds and fish to mammals – that can be supported by the stream, but also the type and complexity of the whole food web. The kind and amount of food available has profound implications for land management, for decisions about deforestation and afforestation, for the introduction of plants from other parts of the world, and for riverbank clearance. Any alteration in the amount, timing and availability of plant material entering the stream may influence the responses of the flora and fauna of the stream by altering the timing of food availability, as well as the quality and digestibility of food; and this in turn influences growth rates, the timing of reproductive maturity and, ultimately, the species composition of the entire community.

MOUNTAIN STREAM ORGANISMS

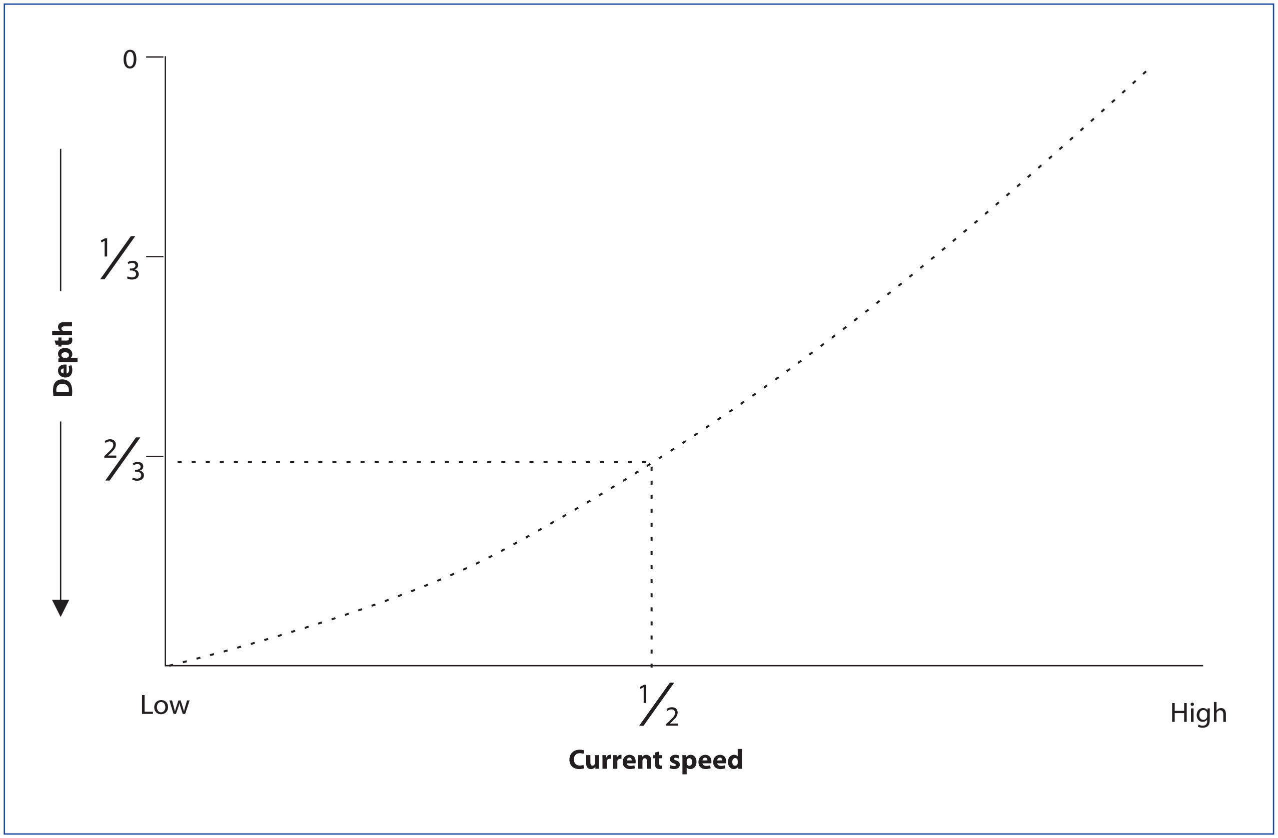
What lives in these cool, shaded, and frequently inclement waters? As we mentioned earlier, large plants are rare because, among other things, the abrasive movements of the riverbed boulders and stones during spates would destroy any newly established seedlings. Algae and small aquatic plants are also rare because little light reaches them, so that photosynthesis is slow and limited. Even where small shrubs or grasses line the river, and allow some sunlight to reach the water, the biomass of green plants is low since the stream is oligotrophic (low in nutrients). There is always danger, however, in making general statements, particularly about systems as varied as rivers. There are always exceptions. For instance, the catchments of the headwaters of many Highveld streams, such as the Vaal, are grass-covered with no large riparian plants. These streams have been shown to support considerable growths of algae at certain times of the year. In the south-western Cape, too, the fringes and exposed lower surfaces of boulders of the uncanopied headwaters of the Palmiet River are coated with green filamentous algae during spring and summer, after the winter spates have subsided. Surprisingly, algae in the Palmiet favour the lower exposed surfaces of boulders rather than upper surfaces, possibly because tadpoles and invertebrates actively graze the algae on more accessible upper surfaces. It may also be that algae on the upper surfaces are bleached and killed by the sun's intense radiation in summer. Generally, though, fish and small planktonic organisms are also rare, but this is because they cannot maintain their positions in the stream and would be swept away by the current.

In a mountain stream, most life forms that can be seen with the naked eye are insects (often over 90% of all visible organisms), ranging in size from the just-visible to those as long as matchsticks. The most common are the immature stages of mayflies (Ephemeroptera), stoneflies (Plecoptera), caddisflies (Trichoptera), alderflies (Megaloptera), dragonflies and damselflies (Odonata), and a variety of true flies (Diptera), including craneflies (Tipulidae), biting midges or blackflies (Simuliidae) and non-biting midges (Chironomidae), as well as adult and immature beetles (Coleoptera: the most speciose group of organisms on the planet). Other groups of organisms in these upper reaches of a river include small flatworms (Turbellaria), ubiquitous roundworms (Nematoda), segmented worms related to the familiar earthworms (Oligochaeta) and leeches (Hirudinea), crabs and small, laterally-flattened amphipods (both Crustacea), as well as snails (gastropod Mollusca), a few 'pea mussels' (bivalve Mollusca) and encrusting organisms such as sponges (Porifera) and moss animalcules (Bryozoa). Collectively, the numbers of headwater-stream insects and their fellows may reach hundreds or thousands of individuals per square metre of riverbed (m^{-2}) and some groups such as caddisfly larvae may be represented by ten or more different species at any one site.

Belinda Day

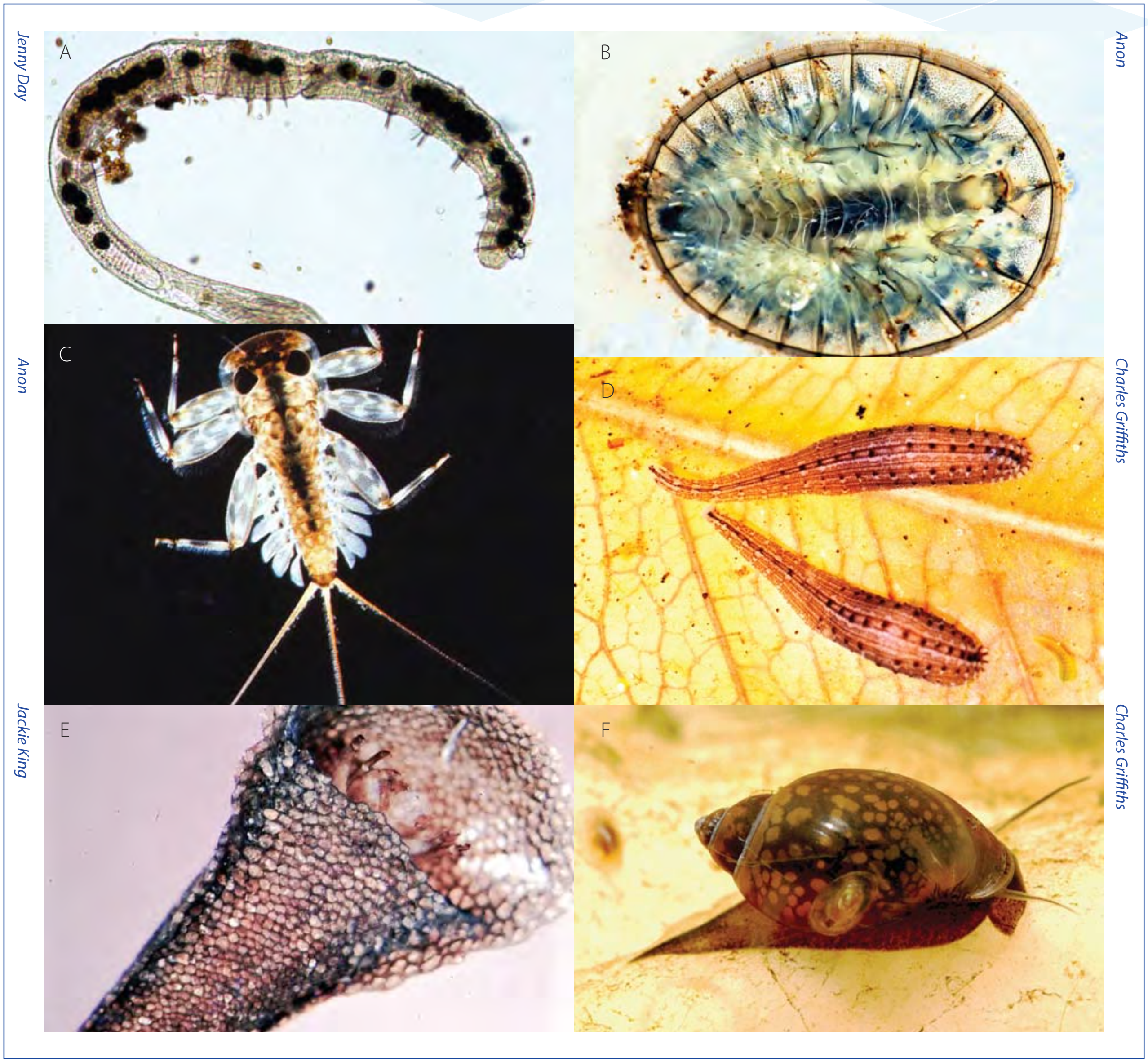
The banks of Highveld streams are often vegetated by grass rather than trees.

As noted earlier, the mountain stream is a physically harsh environment for its inhabitants. The flow of water within the stream is the driving force, sculpting channel shape and structure (geomorphology), and dictating the form of animal and plant life. (Imagine living in a house with walls, floor and roof in continual motion.) So how do living organisms manage to survive here? The answer lies in the physics of flowing water, and the remarkable adaptations that allow many stream organisms to stay in place. Far from being uniform, flow within the stream is governed not just by the gradient of fall, but also by friction. The surface current in the middle of a river is faster than at the edges because friction is greatest against the bank and, in turn, modifies the horizontal velocity profile. Similarly, friction plays a part in structuring the vertical velocity profile. The figure on page 118 shows a vertical view of a point in the same stream, upon which is superimposed a theoretical 'velocity profile'. Here the flow rate of the water is plotted against the depth of the stream. It is clear that friction between the water and the stream bed retards flow so that the surface waters move much faster than bottom waters. Interestingly (and most usefully in field studies of streams), the average speed at which the whole water mass is moving occurs about two-thirds of the depth down from the surface. In other words, the current speed drops off very quickly towards the stream bed due to friction and, at the bed, the flow of water shears into two almost separate components. Why should this matter? An examination of the illustration shows that right at the interface between stream and bed the water flow falls to zero, belying the effect of the fast flow at the surface that we observe from the bank of the stream. Furthermore, a detailed examination of the flow on the bed shows that it is neither uniform across the channel nor linear downstream: the myriad crevices, fast-flowing portions and deeper pools, and the roughened surface of the bed, dictate that the current is constantly accelerating or slowing as it flows over and around obstacles, and through deeper, more uniform reaches. In fact, the very heterogeneous nature of the stream bed is vital, for it creates a variety of micro-environments, or biotopes, such as riffles (short stretches of broken, turbulent flow), backwater pools, waterfalls and chutes, swift-flowing deeper sections and slower-flowing reaches, together with nooks, crannies and crevices near exposed rocky surfaces and the downstream surfaces of rocks that are subjected to tumbling flows. Each of these biotopes may be the home of highly specialised species, whereas less fussy ones may carve out a living in several of them.



Relationship between current velocity and depth, average velocity occurring at two-thirds of the distance from the surface.

The variety of shapes of animals in a stream can be explained by the physics of flowing water (refer to the images on page 119). For instance, those organisms that are streamlined can escape the force of the flowing water by pressing themselves against the substratum, into what is known as the boundary layer, where the current drops to zero. Indeed, the very shapes of their bodies assist the process of staying in one place, even in sections that appear to be flowing most rapidly. Not only is the body flattened and streamlined (see next page: A & B), reducing drag, but the head may be shaped like the 'spoiler' on the front of a racing car that prevents lift and so prevents it from becoming 'unstuck' from the surface (C). Many stream-dwelling organisms are also rather small, so that they remain within the millimetre or so of the boundary layer, where the current is negligible, or they burrow into the bottom sediments. Others, frequently also small, may employ an exquisite and fascinating array of adaptations to life in the fast lane: as a result of natural selection, they have the ability to stay in one place when the roof and the walls are moving! Hooks, grapples, claws, suckers (D & E) and friction-pads allow them to maintain position on the stones and boulders of the river bed; silky or sticky secretions are employed as life-lines attaching the animals to underwater boulders; ballast, often in the form of sand grains (F), increases effective body mass; spines and nets lock organisms into place; the eggs of stream-dwellers may bear coil-like devices on their surfaces for hooking into the substratum, and so on.



A) Minute (0.1 mm) oligochaete worms live within the substratum in slowly flowing rivers. B) Undersurface of the flattened larva of a water penny beetle (3 mm): if you look carefully you will see the head to the right, three pairs of segmented legs and a mass of thin white gills posteriorly (i.e. to the left). C) The very flattened shape of a heptageniid mayfly nymph (3 mm): note the spoiler-shaped head and the paired flattened gills on the abdomen. D) Small (10 mm) free-living, non-parasitic leeches of the genus Helobdella*; like blephariceric larvae, they maintain station in the current by means of suckers. E) The larva (3 mm) of* Petrothrincus*, a caddis fly endemic to the southwestern Cape of South Africa, lives in a case, made of hundreds of minute sand grains, which provide ballast as well as protection. F)* Physa acuta *(10 mm), alien to Africa, lives out of the current, thus avoiding being swept downstream. Look very carefully and you will see another gastropod, this time a tiny limpet,* Burnupia *(2 mm) on its shell.*

FEEDING AND FUNCTIONAL FEEDING GROUPS (FFGS)

Feeding adaptations of all kinds have evolved among the small invertebrates, allowing them to exploit the food sources in almost every conceivable way. As far as the RCC is concerned, widely disparate types of animals, which are only distantly related to each other in an evolutionary sense, are regarded as belonging to the same Functional Feeding Group (FFG) simply if they exploit a particular type or size of food in a particular way. For instance, some animals categorised as ***shredders*** break up the large particles, such as leaves, petals and twigs (coarse particulate organic matter, or CPOM) by shredding them, leaving behind just the tougher veins and stalks. The ***grazer*** organisms feed on whole living plants, or else they efficiently 'browse' on periphyton. Yet another group, the ***collectors***, collect and consume fine particulate organic matter (FPOM). Some collectors, known as ***filter feeders***, erect barriers of nets, brushes, fringes, fans, tunnels or strings of saliva with which they fish, sieve, or otherwise trap fine particles of food sweeping downstream in the current. To catch this material, such organisms must have a very fine collecting apparatus (sometimes, distances between catching hairs are closer together than the length of the average bacterium), and must also live in a part of the riverbed most likely to have suitable food material passing by. Other collectors may feed by re-suspending the sediments of the riverbed, collecting this material as it flows over them, while yet others, like small vacuum cleaners, consume FPOM directly from the riverbed. These collectors are also known as ***deposit feeders***. Another category is sometimes identified. This consists of the so-called ***scrapers***, which sweep the layer of bacteria and fungi off the surfaces of decaying leaves with brush-like mouthparts (like taking the "peanut butter off the cracker" as one American author put it). At the top of the food-web lie members of the last FFG, the ***predators***, mainly insects such as dragonfly nymphs and beetle larvae, which may feed on any of the shredders, scrapers, grazers or collectors, or even on smaller predators than themselves. Examples of these tiny feeders can be found on page 121.

In mountain streams, the shredders frequently form the greatest proportion of the fauna because of the large quantity of whole leaves, fruits and twigs falling on to the riverbed, while scrapers, grazers, predators and collectors are usually less common as their food is less abundant. Either way, the eternal cycle of feeding and then defaecating waste products provides food for other organisms, and at the same time, organic debris is used over and over again until almost all of the energy, which was originally trapped by photosynthesis in the living plants overhanging the riverbank, is exhausted. Any organic material not consumed by the organisms living in the headwaters will be swept downstream to be collected and used as food or to be mineralised and recycled into new generations of living organisms (see Chapter 2).

We must point out that details of the RCC with regard to feeding have generated considerable debate between northern- and southern-hemisphere biologists. The debate centres on the global applicability and usefulness of the idea of FFGs, focusing on some basic differences to be found between streams of North America (where the RCC was first generated) and Europe, and southern hemisphere streams such as those in South Africa, New Zealand and Australia. For instance, we have already noted that many Highveld headwaters have no tree canopy and are dominated by in-stream plant communities; the open-canopied fynbos streams of the Western Cape are other examples. Why, then, are there shredders and collectors in such headwaters? Additionally, in the Western Cape and in much of Australia, leaf fall – the supposed primary energy source for headwaters in general – is not a sudden autumnal affair (as in the 'fall' of North America and Europe), but a protracted event that, in the Western Cape at any rate, commences in spring and continues throughout summer, ceasing in autumn – the very reverse of north American streams. Furthermore, many river ecologists (ourselves included) have argued that different life-history stages of stream organisms will, because of differences in size, be equipped to handle only certain sizes and types of food. Thus, although a large shredder may well be able to utilise large particles in the form of leaf material, when it is younger and smaller, it is unlikely to be able to adopt the same mode of feeding, or perhaps even to use the same food source. It may be a collector at this stage, for instance. Further, a real difficulty lies in assigning species to FFGs. If one looks at it from the point of view of processing food, then a tiny shredder that eats minute particles should be classified as a collector, because it is 'collecting' FPOM. If one looks at it from the point of view of what the animal is doing, it is clearly shredding its food. It is the lack of clarity on these issues in Vannote ***et al***. (1980), and later papers, that makes a potentially useful idea impractical to apply. For further details on FFGs, the reader is directed to King ***et al***. (1988) in the reading list.

A last word on this topic: although many stream invertebrates may well act as shredders or scrapers or grazers, and therefore fit into a particular FFG, others living in marginal habitats probably "take what they can get when they can get it", depending upon their size and the availability of food. They are opportunists and we should perhaps refer to them, tongue in cheek, as 'opportunivores'. Ken Cummins (2019) provides a good review of the subject of FFGs; for a South African view of FFGs, see the paper by Tinotenda Mangadze and colleagues (2019) on the highly disturbed Bloukrans River in the Eastern Cape.

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Examples of invertebrates placed in different FFGs: ***Shredders:*** *(A) a stonefly nymph (4 mm); (B) an amphipod (5 mm) on the leaf it has just shredded, leaving the hard veins;* ***Grazers:*** *(C) a mayfly nymph (3 mm) that uses its mouthparts to 'take the peanut butter off the crakcer'; (D)* Ferrissia*, a tiny (<1 mm) grazing limpet that uses its radula to scrape thin layers of algae off hard surfaces.*

Filter-feeding collectors: *(E) a caddisfly larva (5 mm) that spins a fine silken net in which it catches small particles of food;* ***Deposit-feeding collectors:*** *(F) A rat-tailed hoverfly larva (9 mm) and (G) oligochaete worms (5 mm), both of which consume rotting organic matter;* ***Predators:*** *(H) an alderfly larva (12 mm); (I) the head and mouth parts of a damselfly nymph (10 mm);* ***Omnivore:*** *(J) a river crab (30 mm) – the ultimate omnivore, consuming everything and anything it can get its claws and jaws on.*

ADAPTATIONS TO LIFE IN THE FAST LANE

Apart from the morphological (structural) adaptations listed above, animals may also be behaviourally adapted to life in rapidly flowing water. Given the heterogeneous nature of the bed, some organisms actively seek out nooks and crannies and crevices to live in. Some prefer the undersides of stones, where current speeds are slowest, or leaf packs, which can be utilised for food as well as for shelter. Even within the bed of the stream, in the hyporheos ((Greek: ***hypo*** = below, under; ***rheein*** = to flow), some organisms are able to find their way down between the rocks and pebbles to a depth of a metre or more, where the current is minimal. This deep and more stable region may also be a refuge for surface-dwelling animals during spates or droughts, and for eggs and newly hatched individuals before they make their way upwards towards the flowing water.

As well as providing surfaces to which to cling, and shelter from predators, the stones and boulders of the riverbed serve as miniature dams where fallen leaves may become trapped as leaf packs. Without the unevenness of the stony bottom, leaves would simply be swept away and the base of the food chain for this region of the river would not exist. (This is why canalised, concrete-bottomed streams are frequently devoid of living animals, totally altering the nature of urban rivers: see Chapter 9.) Despite the retention of some organic debris, however, food is usually scarce in mountain streams. As a result, the animals, from the herbivores and detritivores through to the small carnivores, such as dragonfly nymphs, to the top carnivores such as fish, tend to grow slowly and to be relatively small even at maturity. In all, such systems are said to have a low productivity, since the rate at which they produce living tissue is slow. Further, because of their slow growth and the relatively constant conditions in which they live, there is little change in species composition from season to season and many species produce just one generation in a year. For many of the insects, for example, a new generation annually replaces that which emerges as aerial adults, so that a single species is represented at different times of the year by eggs, larvae, pupae (or nymphs), and adults. Such life histories are said to be univoltine (one generation per year), in contrast to the multivoltine (many generations per year) life histories of many insects in lakes and wetlands, and in the warmer, lower reaches of some rivers. Most of the animals living in mountain streams are able to survive only within a very narrow range of environmental conditions, so that even minor disturbances may have profound effects on the composition of the community and, therefore, on the ecosystem as a whole (see, for instance, Chapters 7 and 12). Recovery from disturbance, if it occurs, may be slow for species with limited abilities to disperse upstream.

Jenny Day

Not a river but a concrete drain – a small stream on the Cape Flats, Cape Town.

THE HYPORHEOS

A frequently overlooked but important component of many rivers is the hyporheos, the region of sediment and porous spaces within the bed where river and ground water meet (refer to the illustration on page 108). The hyporheic zone is an ecotone – in this case an interface between river and groundwater – that links the two ecosystems and has been recognised as a unique biotope since first studied by Dr P Chappuis in 1942. Research on the zone is relatively scarce, due to the obvious difficulties of sampling below the bed of the river, particularly in rivers with cobble or boulder beds or where the sediments are compacted. In addition, below-surface waters (including groundwater and the hyporheic zone) were traditionally seen as the territory of geohydrologists, whereas biologists and ecologists tended to study the benthos (the 'bottom' of the river) and its inhabitants. The hyporheos is now recognised as an important hydrological and ecological component of river ecosystems because of the exchange of water, nutrients and organisms between river and groundwater, as well as the biological and geochemical processes that occur within it.

Although little serious research has been undertaken in southern Africa on the inter-relationships between streams and their hyporheic systems, some preliminary exploration, both here and elsewhere, suggests that nutrient processing in rivers is complex. In many rivers the flowing water that we see is just the upper surface of extensive subsurface waters, where other processes may be going on. Some years ago Justine Ewart-Smith investigated nutrients and periphyton in streams. Her results indicated the presence of strong vertical nutrient gradients between the river and the hyporheos, suggesting that there really are three-dimensional differences in nutrient concentrations in different parts of a river. During periods of low flow, nutrient cycling of the type commonly seen in lakes may take place in 'nodes' in the river – in leaf packs trapped in crevices, or in riffles, or in interstices deep within the hyporheos, for instance.

There is no doubt that both POM and DOM, as well as nutrients, accumulate in the hyporheos and that during spates groundwater wells up through the stream bed, releasing its contents into the river itself. In our part of the world, for instance, as temperatures rise in spring, current speeds drop

Jenny Day

Dark, peat-stained water and foam in the fast-flowing Dawidskraal River in Bettys Bay after heavy rain.

markedly, so that fallen leaves and other particulate material become entrained in the hyporheos. Export from the system slows dramatically although nutrients must still be cycling below the bed of the river. When discharge increases as a result of the winter rains, groundwater is flushed to the surface. This groundwater contains POM and also large quantities of peaty DOM leached from the leaves that fell into the river in the previous spring and summer. The DOM is sometimes present in sufficient concentrations to form thick, brown spate-generated foams that coat the rocks and banks. This foam contains high concentrations of plant-derived carbohydrates and amino acids (which contain nitrogen) and that may provide alternative sources of food for the invertebrate and decomposer communities in winter. Further details can be found in Koch ***et al***. (1994), cited in the reading list.

The hyporheos is not only a repository of food and nutrient resources; it is also a refuge during floods and possibly a nursery area where eggs of invertebrates wait out unfavourable conditions before the larvae hatch and move into the benthos. A review of the hyporheos by Belinda Day can be found in a WRC report by Dominic Mazvimavi and colleagues from the University of the Western Cape (Mazvimavi 2021).

THE MIDDLE REACHES

As a stream leaves the mountains and flows through the foothills, more water arrives from tributaries, so the bed widens, while current speeds decrease owing to the gentler slope of the bed. Even though trees may still line these middle reaches, the stream is wider so that some sunlight reaches the water. Patches of vegetation, such as palmiet, ***Prionium serratum***, occur where sufficient sediment has accumulated between rocks. Because of the increased amount of sunlight, water temperatures also increase, further encouraging the growth of small aquatic plants and even of some plankton in sheltered backwaters. The water is a little less pure than it was in the mountain stream both because of abiotic processes, such as leaching of minerals, and the activities of the living communities upstream. The water is often more turbid, too, for there is more soil on the river banks that can be washed into the river. Because the current speeds are generally lower, the stream bed tends to be somewhat smoother, and the water is warmer and less turbulent, so less oxygen dissolves in the water. Rocks on the river bed support a more extensive growth of microscopic algae than do those in the shady mountain stream; in summer they may acquire a greenish coating of threads of filamentous algae.

The middle reaches of the Berg River, now inundated by the Berg River Dam.

Jenny Day

Dense stands of the endemic palmiet, Prionum serratum*, on the banks of the Breede River near Worcester. Palmiet may form an almost impenetrable barrier to riverbanks.*

Thick clumps of dark green algae cover many of the rocks in the Krom-Antonies River, Western Cape.

PROCESSES AND ORGANISMS IN THE MIDDLE REACHES

Just as the physical and chemical conditions of our generalised middle river are different from those of the mountain stream, so the flora and fauna differ from those of the headwater reaches. The invertebrate fauna largely comprises grazers and collectors (see info on FFGs on page 120). Shredders are far less important than they were upstream, because proportionately less of the width of the river receives terrestrial plant debris, and so less shreddable food is available. In other words, the food web has shifted away from allochthonous detritus, and is now based on the autochthonous production of food in the form of rooted emergent plants and periphyton. The periphyton becomes richer in blue-greens and algae, contributing to production wherever light penetrates sufficiently. The P:R ratio is different from that upstream. Here in the middle reaches primary production outstrips respiration, so P:R >1. Although detritus still remains a significant source of food in this part of the river, the bulk of the food material comprises fragments of leaves and other material lost during feeding activities upstream, as well as larger particles coming in from the riverbanks. While collectors still form an important proportion of invertebrates, they frequently comprise different species from those in mountain streams, while shredders are, in the main, replaced by grazers. Predators are present, of course, but again the species may be different from those upstream, being adapted to the different conditions of the middle reaches. Adaptations of the invertebrates are similar, however, because current speeds are still relatively fast and the substratum still comprises mainly rocks and stones; many species are streamlined and flattened, although hooks, suckers and grapples frequently tend to be less well-developed.

Conditions such as temperature vary seasonally here, as they do in the headwaters. As a result, most species of invertebrates cannot survive year-round but tend to occur either in summer and autumn, or in winter and spring. Thus, seasonal communities replace each other in an endless cycle, with the missing set of animals 'waiting in the wings', as eggs, larvae or nymphs, for the change in season that will trigger their next appearance. Especially during the summer months, the combined effect of high temperatures and the larger biomass of animals and bacteria than in the headwaters, oxygen concentrations may be relatively low. Thus, species appear that possess larger, often branched, gills, because branching increases surface area for the absorption of oxygen. The fauna, as a whole, is more varied, more abundant and more productive than it is upstream. Not only are there more species, but individual animals grow faster and often reach a greater size. As a result, there is a greater biomass of potential food for fish and birds, both of which abound in these reaches.

THE LOWER RIVER

As our generalised river continues its journey, the gradient decreases until it flows onto a plateau, usually the coastal plain, widening further as it is joined by more and more tributaries. Although discharge increases, current speeds drop as the gradient decreases and, instead of eroding the sediments on its bed, the slow-flowing water begins to deposit the suspended material that it has carried from upstream. As the current slows the heaviest particles of sediment are the first to settle out of the water column, smothering stones and bedrock, and forming a relatively uniform sandy, or silty, blanket. The slower the current, the finer the particles that settle out, so that the substratum gradually becomes finer and muddier towards the sea. The smoother substratum and the slower current result in less turbulent flow, so that less oxygen from the air becomes dissolved in the water. This reduction in oxygen uptake by the water column is exacerbated by the fact that dense communities of microorganisms use up oxygen as they colonise and decompose the organic material deposited on the bed. In this way, the water may become noticeably less oxygenated than it was further upstream. Leaching and weathering of rocks and soils continue all the way down the river, so more and more salts become dissolved in the water. These include nutrients that have been leached from the soils and washed in from the banks, and those that have infiltrated through groundwater, washed down from upstream, and been released from dead plants and animals.

Jenny Day

A typical lower river: the relatively wide and slow-flowing Breede River with trees (invasive alien plants, unfortunately) and reeds along the banks.

PROCESSES AND ORGANISMS IN THE LOWER REACHES

This slow, wide, depositing system is now an ideal environment for the development of dense stands of emergent plants, such as reeds (*Phragmites australis*) and bulrushes (*Typha capensis*), which proliferate along the banks. Even if trees still line the banks, they shade only a minor portion of the river's surface; the sunny open stretches encourage the growth of planktonic algae that can survive in the sluggish flow for some considerable time before being washed out to sea. These plants form the basis of a rich food web, with zooplankton feeding on the phytoplankton, filter-feeding animals sifting the plankton and particles from the water, snails and other grazers scraping the algae off all available surfaces, collectors gathering debris from the substratum, and carnivores feeding off everything else

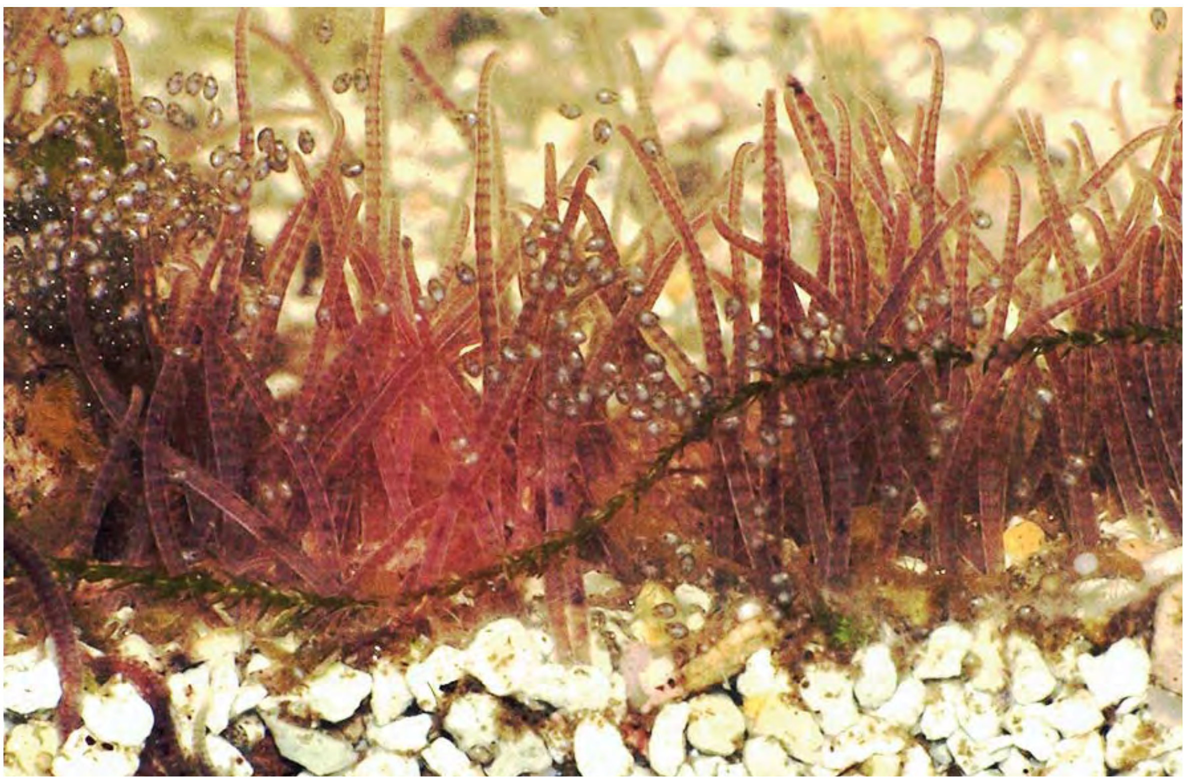
Although we, at the southernmost end of Africa, are accustomed to thinking of freshwater fishes as small and rare (see Chapter 11), the kinds and numbers of fish are considerable in the lower reaches of larger rivers. Sturgeon (sturgeon roe makes the best caviar) in some north-eastern European rivers may reach a length of 3 m or more and giant catfishes of at least this size are known from the lower Amazon and Mekong rivers. As you may imagine, most of these giant fishes are severely threatened by habitat destruction, pollution and hunting.

Erwika/123RF

Sturgeon are becoming increasingly rare in the wild. The largest individual on record was more than 4 m long.

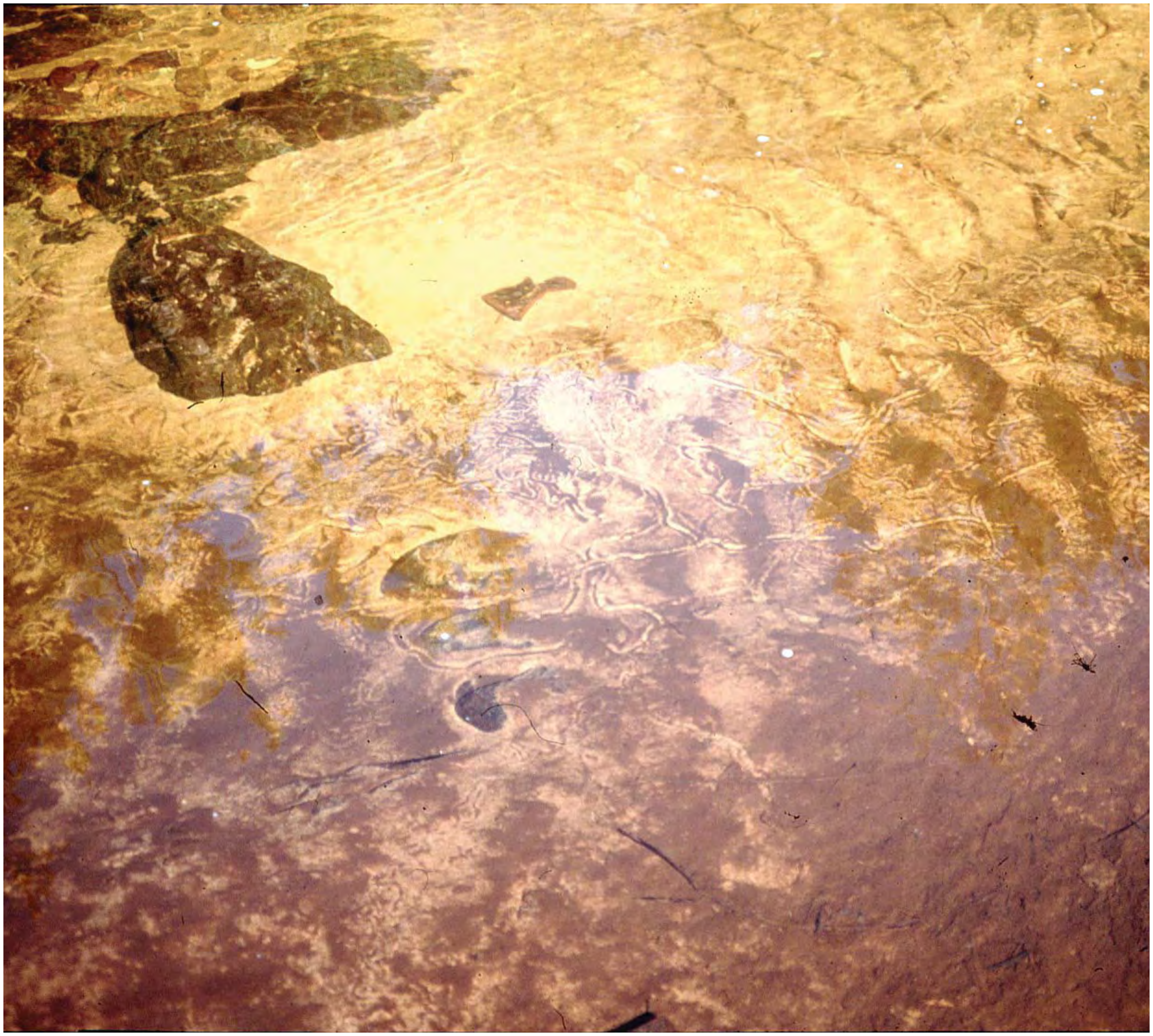
The waters of most lower rivers are turbid because of the load of suspended material in the water. Thus, the amount of light penetrating to the bottom of a large river is too low to allow much algal growth on the bottom, while the organic content of the deposits on the bed encourages microbes to break this material down. These factors combine to push the system in favour of respiration relative to production, so that the P:R ratio is less than 1, as was the case in the headwaters of the river. So, like the headwaters, the lower reaches are heterotrophic, but for different reasons.

If the water is extremely rich in nutrients (as, for instance, when autumn leaves fall into the water and lose their soluble contents, as tea leaves do in a teapot), the phytoplankton may occasionally reach 'pea-soup' proportions. Such algae quickly outrun their nutrient supplies and die, so dead algal cells constantly 'rain' onto the bottom, adding further to the richness of the sediments. Sometimes these are consumed by deposit-feeding organisms but, where large amounts of organic matter encourage microorganisms to thrive, and oxygen is limited, noxious substances such as hydrogen sulphide (see Chapters 3 and 7) and methane may be generated in the river bed. Under these circumstances very few species of animal can survive. Those tough enough to withstand the harsh conditions often have the pigment haemoglobin in their blood to assist in the uptake of what little oxygen is available. These extremely tolerant organisms may, however, occur in astronomical numbers in very nutrient-rich environments.



A mass of oligochaetes, Tubifex tubifex*, densely packed together; the dark colour is caused by haemoglobin.*

Obviously, life in the mature river is very different from that in a mountain stream. Hooks and claws are of little advantage in soft substrata, and sand is such an inhospitable habitat, owing to the grinding and smothering action of the grains, that few species occur on sandy riverbeds. More are found on muddy bottoms and usually occur in relatively large numbers. Burrowing worms (Oligochaeta), midge larvae (Chironomidae), mussels and clams (Bivalvia) and roundworms (Nematoda) are common here, as are a myriad single-celled protists. The main refuge of the more usual aquatic forms is the semi-submerged bankside vegetation, and woody debris, where predators and prey alike find shelter.



Jenny Day

The sandy bottom of the Rondegat River in the Cederberg – the sediments of a river seldom look like this, being very unstable and stirred up by even a slow current.

In the case of small animals, feeding is largely a matter of filtering food particles and plankton from the water column, filtering resuspended sediments, or consuming the mixture of soil and organic particles deposited on the riverbed. In other words, the invertebrate assemblages of this reach are dominated by collectors, although again the species will probably be different from those occurring further upstream. Breathing adaptations are usually elaborate: large, often feathery gills may be protected by flaps or may be tucked under the body to keep silt away from the delicate respiratory surfaces. Oddly, unlike their land-based equivalents, the partly-submerged macrophytes are seldom eaten; instead they provide a surface for the growth of the epiphytic algae so sought after by grazers, as well as contributing to the energy input to the river when their own tissues die and decompose.

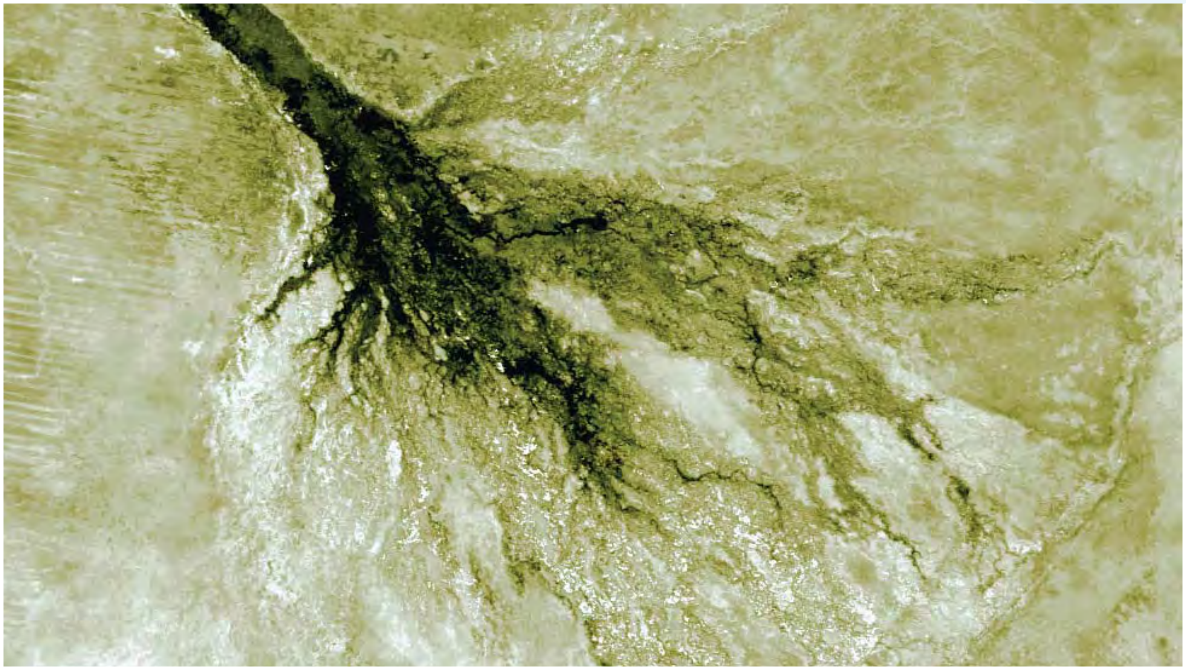
In the very lowest reaches, just above the estuary, the substratum is very muddy and rich in organic matter, as by now even the finest particles of silt and organic matter are dropping from suspension as the current continues to slow. Benthic (bottom-dwelling) invertebrate taxa increase in numbers in these reaches, many tending to be worm-like burrowers into the substratum. These reaches are rich in other kinds of animal life too, for a variety of birds shelter in riverside reeds and feed on the abundant aquatic life, while bottom-feeding fish increase the diversity of the fish fauna. Where the habitat is diverse as a result of submerged and emergent macrophytes, rocky outcrops and dead trees, for instance, biodiversity of invertebrates and fishes may be very high.

THE RIVER AND ITS FLOODPLAIN

Not all rivers are always confined to their channels. Some will overflow only on rare occasions when exceptional floods occur, while others spill water over their banks every year during the wet season. The parts of the landscape that are inundated by rivers in this way are known as the ***floodplain*** of the river. This aspect was not factored in to the RCC in its original form, by the way, probably because the rivers familiar to the authors were mostly mountain streams. Floodplain soils are frequently exceptionally rich in nutrients, providing ideal land on which humans can raise crops, sometimes two or three per year. Examples are the Niger, Nile, Senegal, Zambezi, Okavango and Phongolo rivers in Africa, and the Bramaphutra, Ganga, Irrawady, Narmada and Mekong rivers in Asia. As major sources of nutrients, human-river-floodplain interactions assume enormous importance. Floodplains as wetlands are discussed in chapter 5 and the effects of large dams on floodplains in Chapter 9.

Lani van Vuuren

Sugarcane being grown in the Pongola valley, with water from the Phongolo River.



SeaWiFS Project / NASA

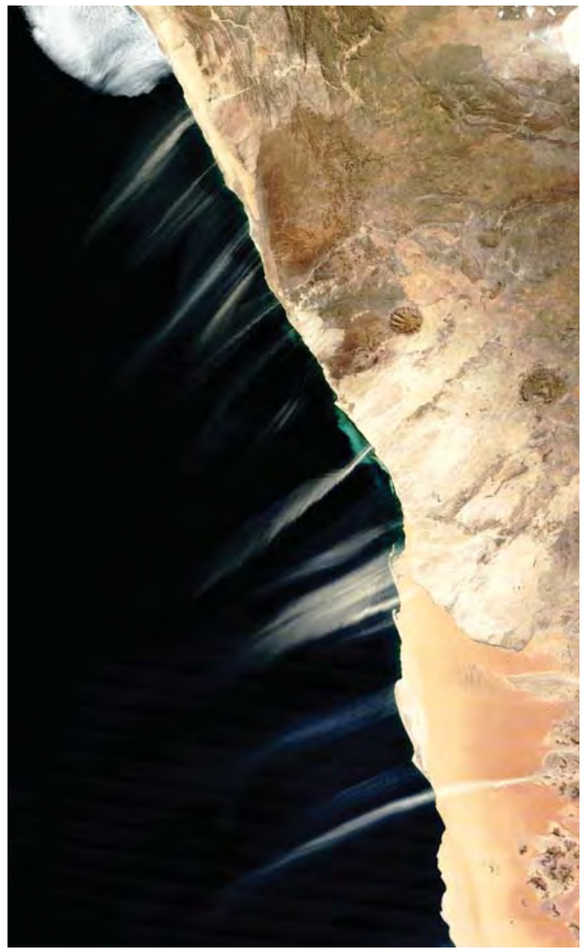
Satellite image of the Okavango Delta, an enormous floodplain that receives its water from the Cavango River that arises way upstream in Angola.

RIVERS AND THE COASTAL ZONE

A soil conservation slogan once quipped that '…top soil is South Africa's greatest export', highlighting the appalling results of agricultural malpractices throughout our region. In fact, many South African soils are susceptible to erosion and our rivers have been removing them to the coastal zone for aeons. It seems, for instance, that the sand dunes of the Namib sand sea originated in the Drakensberg highlands and were transported by the Orange River to the coast and up the coast by the Benguela Current. Such transport has profound significance for the functioning of our coastal ecosystems since every year, millions of tonnes of nutrient-laden sediments enter the sea through our rivers and these sediments provide rich feeding for the myriad marine invertebrates that live inshore (see, for instance, the discussion on Mozambique prawns in Chapter 9) and that themselves provide food for commercially important species of fish.

The Orange River floods of the late 1980s give us a glimpse of the importance of this continual supply of sediments to the marine environment (see Bremner ***et al***., 1990 for details). Four clear flood pulses were studied by Bremner and his colleagues from the University of Cape Town. Their conclusions are interesting. First, they confirmed historical and anecdotal information that the average gap between major floods in that part of the world is somewhere between 10 and 15 years. Surprisingly, though, peak concentrations of total suspended solids (TSS) were not '…too far removed from those reported for the world's most turbid river, the Hwang Ho (Yellow) River in northern China…'. Secondly, they noted that during just the three months of their study in 1988, more than twice the mean annual runoff (MAR) from the river was discharged through the mouth. Thirdly, the concentration of sediments in the river water declined steadily over time, Lastly, the sediment load transported by the river in March 1988 was very similar in magnitude to the mean annual load measured at Prieska/Upington between 1930 and 1969, before the van der Kloof and Gariep dams had been built. The researchers speculated that the decrease was probably '…due to easily erodable topsoil having been stripped from the Upper Orange catchment during the early 1930s and to a rapid increase in the number and size of dams that were constructed in the early 1970s.' The researchers backed up this remark with the fact that the suspended-sediment load had changed from silt dominance before 1970, to clay dominance in the 1988 floods. Most of the load transported during the floods of 1988 came from scour immediately below the many dams on the system, and from bank erosion, whereas before the dams had been built the transported sediments came from poorly managed farms in the form of topsoil. That same soil is now being retained by the reservoirs – an expensive way of retaining topsoil, and not particularly useful since the soil cannot be used if it is caught up in a reservoir, and of course it also fills up space in reservoirs that could otherwise be used for storing water (see also chapter 9).

NASA



(Left) Orange River discharging sediment into the Atlantic Ocean at a much reduced rate than before the river was dammed. (Right) Plumes of sand being blown off the shore of the Namib Desert in Namibia.

Utopia88 / 123RF

The Luvuvhu River in Pafuri, Kruger National Park. The silt in the river can clearly be seen. South African rivers transport millions of tonnes of silt a year.

VARIATIONS ON THE THEME OF RIVER

Not all rivers conform to the basic patterns described earlier. Some arise as seeps from low-lying areas, rather than in mountains, while others arise high above the tree line in alpine zones. Biologists in New Zealand have found, for instance, that shredders do not occur in their alpine streams. This is to be expected, of course, considering the paucity of externally-produced leaf material that might fall into such high-altitude streams. Those rivers that rise in coastal mountains may change from mountain stream to estuary with no intervening zones, as do those along the more precipitous parts of the southern Cape coast (for example, the Steenbras, the Rooiels and the Storms rivers). On the other hand, mature rivers are sometimes 'rejuvenated' by cascading down a second mountain range nearer the coast, as does the Orange River at Augrabies Falls, or the Zambezi River at Victoria Falls and (prior to the construction of the dam), at the Cahora Bassa Rapids in Mozambique. The river below such cascades frequently shows all the characteristics of headwater or middle-reach streams, even though it may be close to the mouth.

We have already discussed intermittent rivers in chapter 2.

Chemically, rivers also vary very widely in mineral content and silt load, depending upon the types of rock and soil over which they flow. For example, as we outlined earlier, it is more than likely that the Orange River naturally carried a heavy silt load even before humans increased that load through agricultural malpractices. (Ironically, the name 'Orange', first coined by Colonel Robert Gordon in 1779, was chosen in honour of the then Prince of Orange rather than because of the orange colour resulting from the river's striking silt load.) See Chapter 7 for more on the water chemistry of rivers.

Despite these variations on the theme, the processes and organisms that we have described so far for our imaginary river occur in every river unless it has been so abused that it no longer supports living organisms. By 'reading' the aquatic life, a river biologist can tell whether or not the river in question is functioning normally, or if unnatural physical or chemical changes are taking place.

The Steenbras River mouth: the river is very short and flashy and has no estuary to speak of.


Erwan Deverre / Flickr / CC BY-SA 2.0

The Augrabies Falls on the Orange River in flood in 2010.

RIVERS AND CATCHMENTS

Let us now briefly consider some of the more specific effects of a variety of activities on rivers and their catchments. A catchment or drainage basin (or watershed, in American terminology) is defined as all the land, from the mountains to the sea, drained by one river system. Although it may not be obvious at first sight, the physical, chemical and biological characteristics of any river are determined almost entirely by the nature of the catchment and the activities, both anthropogenic and natural, that take place in it. We have already shown, for example, that the chemistry of the river depends on the chemical nature of the rocks in its catchment (also see Chapter 7) and that the invertebrates living in its upper reaches are often dependent on trees growing on its banks. But that is not all. Reducing the vegetation cover, especially on steeply-sloping land, means that less water is intercepted or held in the soil by plants during rains. Further, the removal of flow-regulating fringing wetlands will also impinge upon the rate and the way in which rainwater running off the catchment will be delivered to the river (see Chapter 5). When wetlands have been removed, not only does more of the rain run directly into the river but flash flooding may become more prevalent. At the same time, less water is stored in the wetland soils and the river may consequently dry up in summer. Furthermore, enormous amounts of topsoil are washed from poorly vegetated land during flash floods, while riverbanks that have either been cleared of vegetation, or are covered with a motley array of shallow-rooted, inappropriate (and often exotic or alien) plants, may collapse, contributing to erosion. Conversely, the afforestation of headwaters with monocultures of pines or eucalypts can severely reduce available water for the remainder of the catchment, because trees, especially pines, use and transpire vast amounts of water. The Sabie River in Mpumalanga (as seen from the Long Tom Pass) is a good example: about 30% of the MAR is lost from the system by evapotranspiration from these vast green 'cancers' that creep across the countryside and that are almost devoid of other life forms. (See a discussion on the Working for Water programme in Chapter 8.)

Essentially, rivers are mirrors of the landscape, giving us insights into, or reflecting, the environmental condition of their catchments. Understanding this relationship is essential for water resource managers, and will go a long way towards assisting future ethical management of the resources so vital to South Africa's continued wellbeing. Whatever happens within a catchment ultimately affects the river draining it and will eventually rebound on us, the users and abusers of our rivers and the water they carry. We were delighted to see in 1998, in the new South African National Water Act, that one of the major tenets requires water resources to be managed at the catchment level (see more in chapter 10).

IN CONCLUSION

Rivers are complex self-regulating systems supporting arrays of fascinating and important communities of microbes, plants and animals. But the combined influences of deforestation (and, ironically many forms of afforestation), urban development, pollution, bank erosion and poor agricultural practices have so degraded our rivers that they are under severe threat. We suggested, in the first book we wrote together in 1986, that rivers and water resources should be managed at catchment level. Happily, South Africa's National Water Act of 1998 requires exactly this (see Chapter 10). The tasks ahead are daunting (Chapter 11) but at least a sensible legislative framework is available to allow rational planning and management of our rivers, wetlands and groundwater resources.

Long Tom Pass. Most of the hillsides are covered with dark green pine plantations.

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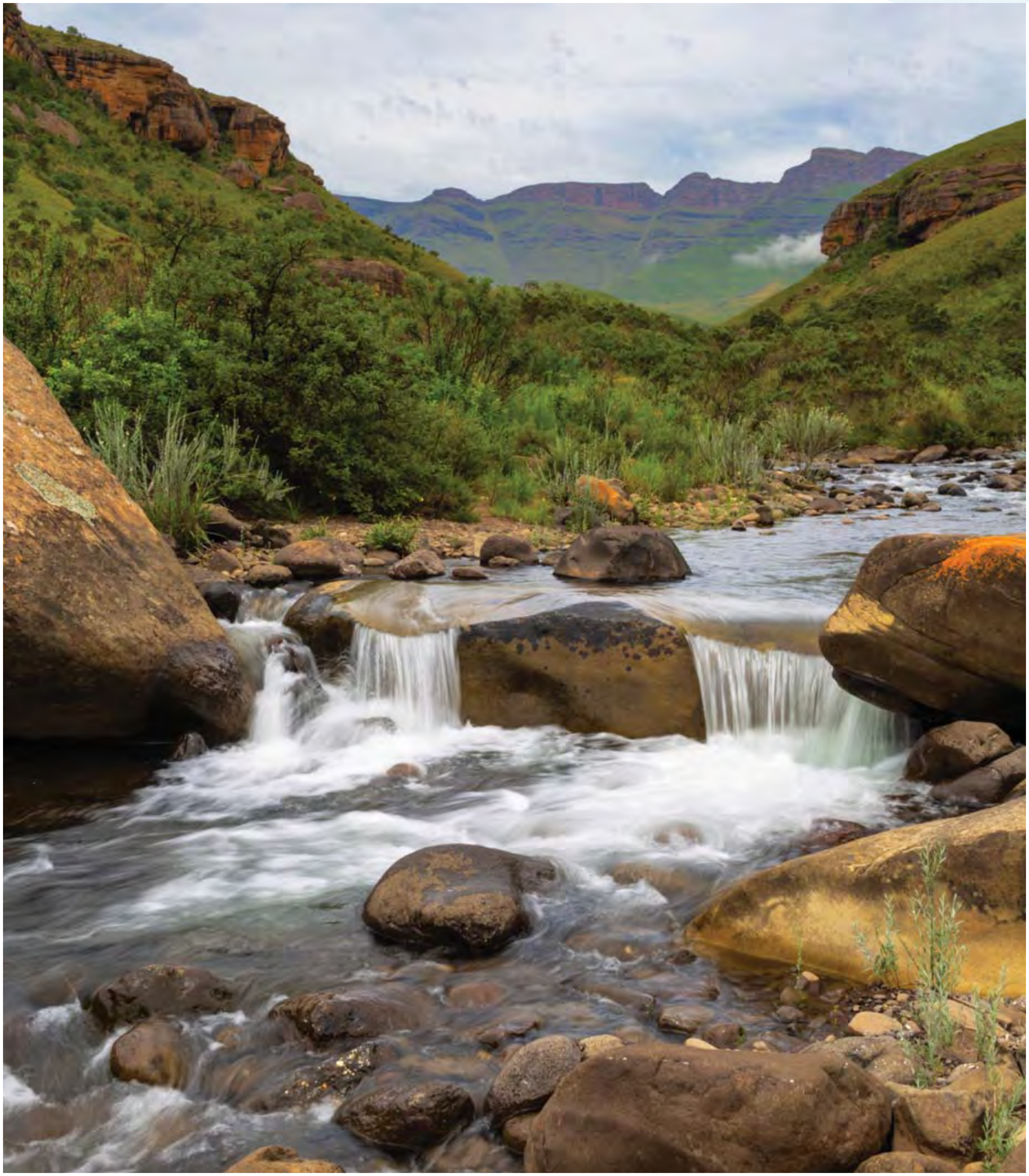


Hannes Thirion / 123RF)

The rocky Bushmans River in KwaZulu-Natal.

CHAPTER FIVE

Jenny Day

Wetlands

What would the world be, once bereft
Of wet and of wildness? Let them be left,
O let them be left, wildness and wet;
Long live the weeds and the wilderness yet

Gerard Manley Hopkins, Inversnaid

WHAT IS A WETLAND?

A wetland is much easier to recognise than to define. After all, if a bit of land holds water and is neither a river nor a lake, it is still wet land. What about a stretch of riverside that becomes inundated once or twice in a hundred years? Or a pool that develops every year in the rainy season, but is a dry grassy depression for the rest of the year? Because wetlands encompass many different kinds of water bodies, even when they hold no water, the definition most widely used is that a wetland is:

a region in which the soils show evidence of waterlogging.

If one is familiar with soils, waterlogging is easy to recognise: soils tend to be grey or black, and often have a characteristic 'muddy' smell of anoxia (lack of oxygen) or even of hydrogen sulphide ('bad egg' gas). Less technical definitions are to be found in the literature, though. The Ramsar Convention defines wetlands very widely as:

areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.

Note that this definition includes coastal seas, rivers and man-made waterbodies – too broad for our purposes. South Africa's National Water Act (1998) defines wetlands as:

land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which under normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

While generally useful, this definition does not include many naturally unvegetated temporary waterbodies, often called pans, in arid areas (that sneaky little word 'and' is the culprit). Perhaps the most useful definition for southern Africa, which includes so much arid land, is that used by the Directorate of Environmental Affairs in Namibia: wetlands are:

the interfaces between aquatic and terrestrial ecosystems, whether permanent or ephemerally inundated, with fresh or salt water.

DWAF

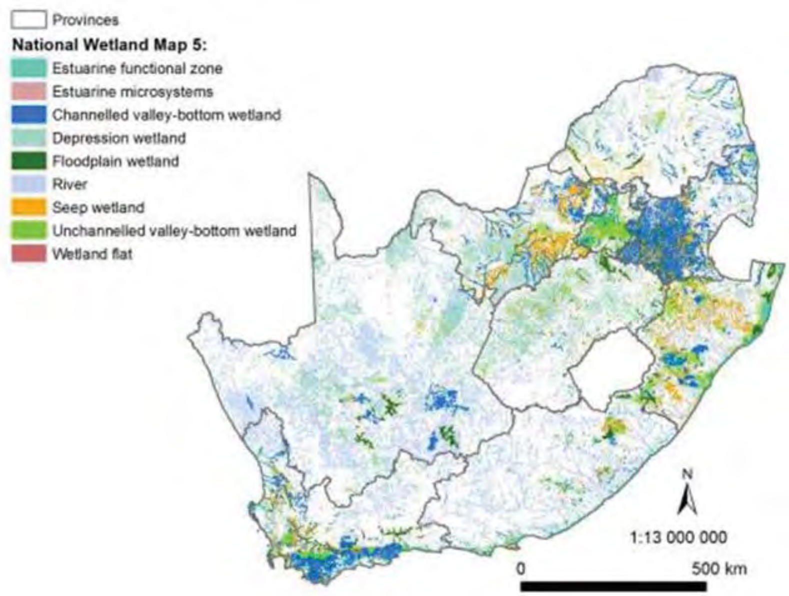
Wetland soils tend to be black or grey in colour and often smell of hydrogen sulphide.

Note that in this definition nothing is said about vegetation because many Namibian wetlands do not support vegetation of any sort. Nonetheless, the most characteristic feature of wetlands, other than the fact that they are always or sometimes wet, is that they are ***depositing*** systems. While the flowing waters of rivers tend to abrade the bed and banks, removing material and carrying it downstream, wetlands tend to aggrade or accumulate material on the bottom. This difference between rivers and wetlands makes for some fundamental differences in the ways that the two kinds of systems function. Wetlands (and lakes) tend to be short-lived, accumulating sediment and filling the basins in which they occur, while the scouring action of rivers digs them deeper and deeper into their beds. A major consequence of the depositing nature of wetlands is that they accumulate materials of all kinds, including organic debris and, in those affected by human activities, toxins of various kinds.

Regardless of definition, though, an area can normally be recognised as being a wetland if it is periodically or permanently saturated with water. Further, drainage is impeded to a greater or lesser extent, and chemically reducing (anoxic) conditions prevail in the soils of most wetlands when they are inundated. While distinctive plant assemblages are characteristic of seasonal and permanent wetlands, ephemeral and saline wetlands are often entirely without vegetation. Their waters are seldom anoxic, therefore, because there is little organic matter to be decomposed, and so there are few decomposer bacteria to use up the oxygen.

KINDS OF WETLANDS

Depending on definition, wetlands are thought to cover somewhere between 6% and 9% of the Earth's terrestrial surface. People who work on ecosystems like to be able to fit them into convenient categories, but wetlands vary so much in size, chemical character and period of inundation that classifying them is really rather tricky. Many countries have developed systems for classifying their wetlands, those for the USA, Canada, Australia and the countries around the north of the Mediterranean being best known. Recently, a classification system has been developed for South African wetlands by Dean Ollis and colleagues (Olllis ***et al*** 2015.) The trickiest part of any classification system is deciding on the fundamental divisions between categories. For instance, in the case of children's building blocks, would one start with colour, or shape, or maybe surface texture? In several cases wetlands are classified first on hydrological features,



Van Deventer et al / https://doi.org/10.17159/wsa/2020.v46.i1.7887

The South African wetlands map Version 5 as of 2022.

although the presence of water is dictated by landform – the shape of the land. The South African team decided on a hydrogeomorphological approach. This big word refers to water ('hydro') and land ('geo') form ('morphology'): landforms allowing the accumulation of water and consequently influenced by its presence. At the highest level, a distinction is made between inland, estuarine and shallow marine systems, followed by features determined by the shape of the land: rivers, floodplain wetlands, depressions, seeps, etc.

Mapping wetlands is also tricky, especially in a large semi-arid country such as South Africa, where many tracts of land are inaccessible, and wetlands seem to come and go depending on rainfall. Namhla Mbona and her team at SANBI therefore decided to use remotely-sensed data to construct a wetland map for South Africa. Of course, there are snags when doing this. It is not always possible even to identify with confidence areas that contain standing water, so there is an intrinsic degree of error in the maps. Furthermore, very small wetlands, even if they occur in clusters, are often too small to be recognised by a satellite camera. Nonetheless, the latest version has incorporated various fine-scale and ground-truthed maps (see the 2020 paper by Heidi van Deventer and colleagues on the National Wetland Map) and is a huge step towards a complete inventory of our wetlands. A total of 4 596 509 ha of inland aquatic ecosystems has now been mapped. No doubt a few more are still to be identified but this is probably close to the actual areal extent of South Africa's wetlands.

Let us look briefly at some of the different kinds of wetlands found throughout the world. It is worth noting that in the following section we use common names for different kinds of wetlands, while the official classification system necessarily uses a far more complex terminology. For details the reader is referred to the very extensive glossary in SANBI's User Manual (Ollis ***et al*** 2013).

Wetlands vary from minute, water-filled depressions in a single rock, to swamps thousands of hectares in extent. They may support magnificent stands of a diverse array of plants, including trees, or may be entirely lacking in plant cover.

They may include large expanses of open water or may be entirely vegetated. The waters of some wetlands are pure and sweet, of others black and acid, and of others hypersaline. Some wetlands are lotic in nature, and others lentic; some are sometimes one and sometimes the other. Note that chapter 6 deals with coastal lakes and estuaries, so these systems are not dealt with here.

Of the smaller wetlands, ***pools*** and ***ponds*** are small bodies of standing water. If there is a difference between them it is probably that pools dry up now and then, while ponds tend to be permanent, or nearly so. Ponds are more likely than pools to support vegetation. A ***tarn*** is an isolated, high-altitude pool or pond in a sediment-filled basin, often supporting some submerged vegetation, and sometimes holding no water in the dry season. Several are to be found in the Drakensberg Mountains.

Sponges and ***seeps,*** which are usually high-altitude wetlands, are often the sources of rivers. The ground may be soft and boggy, or may support low grasses, thus providing valuable grazing in the mountains, in Lesotho, for instance. Excessive grazing, though, has resulted in trampling of the wetland soils by the hooves of sheep and goats. Soil erosion is so pervasive that nowadays virtually none of the rivers of Lesotho run crystal clear; instead; their waters have taken on a pearly glister imparted by fine soils in suspension.

Jenny Day

Several minute rainpools on a granite headland overlooking Langebaan Lagoon.

Jenny Day

Seeps on steep slopes in the Riviersonderend Mountains are indicated by swathes of bright green vegetation.

Jenny Day

Farm dams, such as this one in the Krom-Antonies valley in the Western Cape, can be fairly substantial.

Although the word 'dam', when used correctly, refers to a structure that impounds a river, in southern Africa it often also refers to the lake that is formed as a result of impoundment. In southern Africa, and also in Australia, the term '***dam'*** further refers to small (usually a hectare or less), man-made reservoirs on farmland. Filling with water in the wet season, farm dams are used as watering holes for stock animals, and sometimes for irrigation. In some of the more arid areas, in the Karoo for instance, these dams are often positioned on sites of natural seasonal pools. Since farm dams constitute the most common aquatic habitats in many parts of southern Africa, ecologists are beginning to study various aspects of their limnology and biology. In particular, we are interested in the contribution that these artificial systems make to aquatic biodiversity. Ironically, while farm dams may have detrimental effects on the hydrology of an area by capturing a significant proportion of stream flow, in arid areas they frequently represent the only permanent aquatic habitats in thousands of hectares of farming land. In the wheat belt of the south-western Cape, with its naturally dry summers, for instance, small permanent bodies of water were virtually non-existent under natural conditions, so farm dams constitute an entirely new kind of ecosystem. See also chapters 2 and 9.

Swamps are wetlands with trees. They may be permanent or semi-permanent, and their waters may be slow-flowing or still. The largest and best known freshwater swamp in southern Africa is the Okavango Delta in Botswana. Less well known are the enormous swamps of Barotseland, Lake Banguelu and the Kafue floodplain in Zambia. Compared with these, South Africa's largest swamp – the Mkuzi Floodplain in KwaZulu-Natal – is a mere puddle.

Marshes are tracts of spongy land that support low-growing macrophytes like reeds and sedges. Most estuaries have tidal salt marshes, sometimes very extensive ones, on their banks (see chapter 6). The Cederberg in the Western Cape supports some high-altitude, seasonal freshwater marshes, while most of our coastal lakes are fringed with permanent freshwater or brackish marshes. Because of the extreme differences in precipitation from season to season in southern Africa, some swamps and marshes may dry out, but not necessarily every year.

Dean Ollis

The marshy valley-bottom wetlands of Driehoeks in the Cederberg Mountains.

A few vernacular terms for wetlands are evocative of generally negative attitudes to wetlands. ***'Mire'*** and ***'morass'*** are European words for boggy or marshy areas and a '***quagmire'*** is a soft area that gives way under the feet. In Ireland, ***'slobland'*** is boggy or marshy ground and in the United States, a ***'slough'*** is a hollow filled with mud, a hole where water collects, or a marshy saltwater inlet. ***'Vlei'*** is a commonly used word in southern Africa. In the south-western Cape it is a general term for almost any kind of wetland, large or small, temporary or permanent. Examples include the relatively large Zeekoevlei and Soetendalsvlei and the minute Tumbleweed Vlei and Bamboesvlei. In most of the rest of the country, though, the word has a much more restricted meaning, referring to a reed-bed associated with a river course. Examples are Nylsvlei in Limpopo and Franklin Vlei in KwaZulu-Natal. It seems that the word 'vlei' stems from the Old Norse 'floi', meaning 'wet marshy ground'.

Floodplains are areas where rivers overtop their banks. Overtopping may occur only after extreme flood events, in which case the flooded area is not really a wetland at all. More commonly, though, floodplains are inundated seasonally, often filling depressions that may persist for months or years after filling. These are ***floodplain pans,*** depressions along riverbanks that retain part of the flood waters, sometimes for long periods. Examples include the pans of the floodplain of the Berg River in the south-western Cape. If they hold water permanently, or almost permanently, as do the pans of the Phongolo River in KwaZulu-Natal, they are perhaps better referred to as 'floodplain lakes'. The strangely named billabongs of Australia are seasonally inundated, oxbow-shaped, floodplain pans and lakes. They are commonly associated with Australia's large inland rivers like the Murray.

Jenny Day

Zeekoevlei, a small urban vlei on the Cape Flats, Cape Town.

NASA

Aerial view of part of the massive Kafue floodplain in Zambia.

Jenny Day

Nyamiti Pan on the floodplain of the Phongolo River in the Ndumo Game Reserve, close to the Mozambique border.

As an aside, we also mention that enormous arctic wilderness, the ***tundra***. Covering more than 11 million km^2, ten times the surface area of South Africa, the area is generally flat and featureless. Because it is situated far into the Arctic Circle, the tundra is permanently frozen in winter and even in summer the surface thaws to a depth of only about 50 cm. (This is permafrost.) When it thaws, however, much of the surface becomes waterlogged, since little evaporation takes place because of the cold conditions. Enormous quantities of organic material are buried in tundra soils. Overall, it has been estimated that a third of the Earth's soil-bound organic carbon occurs north of the Arctic Circle. The implications of global warming for the thawing of the tundra are frightening. Until recently it had been estimated that this area was a net sink for carbon but recent studies in Alaska suggest that, because of warming, the tundra had become a source of carbon in the form of both methane and carbon dioxide.

Autumn colours of miniatiure trees on the tundra near Nunavut in the far north of Canada.

NON-PERENNIAL WETLANDS

'Pan' is a South African vernacular term for a closed basin and generally refers to any moderately large (often >1 ha), flat, sediment-filled depression that holds water after rain. Two major types are recognised in southern Africa. The first, the terminal water bodies of endorheic or inwardly-draining drainage systems in arid areas, are also known as 'playas' in North America. Because they are inward-draining and occur in arid areas, they may accumulate salts, in which case the lakes that develop in them are highly saline. Examples include the massive endorheic pan system of the Kenhardt district of the Northern Cape, as well as the freshwater grass-bottomed pans of the Free State and the numerous but much smaller salt pans scattered across the southern African countryside. The second type, ***floodplain pans***, are described briefly above.

A couple of other terms should also be explained here. The water of wetlands may contain appreciable amounts of salt. The term '***brackish'*** is a useful, if imprecise, term for 'somewhat salty' water, probably with salt concentrations between about 3 000 and 12 000 mg/L (up to about a third of the salt content of sea water). Water containing less than 3 000 mg/L of salt (or total dissolved solids; TDS) can be considered to be fresh, while all waters with TDS values greater than 12 000 mg/L are said to be saline. The term ***'salina'*** is a vernacular term for a salt marsh or salt lake in the Americas.


Jenny Day

A pan in the Free State.


Jenny Day

One of the enormous pans of the Northern Cape, often dry for years on end. When water is present after rain it is more or less fresh.


Jenny Day

Salar Uyuni, Bolivia, is the largest salt flat in the world, covering an area of some 10 000 km^2.

PEATLANDS AND CARBON STORAGE

Peatlands are wetlands where organic material builds up in the soil, sometimes forming thick deposits known as peat. Worldwide, peatlands are estimated to cover about 3% of the Earth's total land mass, and to contain a third of the global pool of carbon in the soil. Clearly, peatlands are of great significance, particularly when it comes to carbon stores and climate change. But what is peat, and why is there so much of it? Well, most wetlands are characterised by a lack of oxygen as a result of the activities of decomposer bacteria; and where oxygen is lacking, organic matter tends to accumulate. The amount of peat that builds up depends on the ratio of production to decomposition of plant biomass and this in turn is controlled by temperature, wetness and nutrient levels. Generally where there is a lot of water, and temperatures are high, decomposition exceeds production, so extensive accumulations of peat are rare (although huge areas of Indonesia are covered with massive peat deposits to a depth of 20 m). The Florida Everglades also used to have extensive peat deposits but much of this material has decomposed as a result of draining of the swamps. In contrast, peatlands in colder climates store massive amounts of carbon. It has been estimated that the peatlands of the far north (northern Canada, Europe and Siberia) contain about 550 Gt (billions of tons) of carbon. Siberian deposits are up to 11 m deep and even areas of permafrost have layers of peat up to a metre deep.

Kevin Scannell / Wikimedia / CC BY-SA 4.0

Piet-Louis Gründing

Jenny Day

Wilson 44691 (CC0 1.0)

A) Peat sods in Ireland laid out in the sun to dry before being used in kitchen fires. B) Peat augured from the Mfabeni peatland, iSimangaliso. C) A peat bog in the Scottish highlands: all the low-lying areas are deep in peat. D) Sphagnum *moss from a bog in Ohio, USA.*

Virtually any plant remains can become peat if they are subjected to anoxic, waterlogged conditions. In southern Africa, for instance, peat consists mostly of common macrophytes like reeds and sedges. In the colder latitudes of the northern hemisphere, however, mosses of the genus ***Sphagnum*** form by far the greatest bulk of peat. ***Peat*** bogs are wetlands consisting mainly of decaying peat moss (***Sphagnum***) and other vegetation. Bog waters are characteristically acidic (pH values as low as 3.5 are not uncommon) and dark in colour. Why? Because ***Sphagnum*** is a remarkable plant. The surfaces of its cells are coated with polyuronic acid, a substance that is able to adsorb cations (e.g. Ca^{2+} and Mg^{2+}). In a process known as ion exchange, polyuronic acid exchanges calcium ions for hydrogen ions, which escape into the water and decrease the pH. (For a brief explanation of pH, see chapter 7). ***Sphagnum*** also contains polyphenolics which, when they leach into water, colour the water a dark brown as well as contributing to the low pH. The waters of ***Sphagnum*** bogs, then, are cold, dark in colour, very acidic, and virtually anoxic. It is no wonder that decomposition is retarded. It ***is*** a wonder though, that bog water makes the most superb whiskies.

Of course, it is not only plant material that is prevented from decaying in very peculiar chemical conditions of many wetlands. Hundreds of 'bog bodies' have been found in bogs throughout northern Europe. There is evidence to suggest that many of them were human sacrifices and most are of Neolithic or Roman age, which means that they have been preserved for two thousand years or more. If ritual sacrifice was indeed involved, it may be that the people of the time were aware of the preservative properties of the bogs in which they disposed of their victims.

The hand of the 'Old Croughan Man', found in a peat bog in Ireland. The body is thought to be more than 2 000 years old, illustrating the remarkable ability of peat to preserve organic remains.

Although southern Africa does not generally have large peat deposits, many of our wetlands do have very peaty soils. The most extensive peatlands in South Africa are in Maputaland in northern KwaZulu-Natal. Recent studies by Piet-Louis Grundling and colleagues have identified more than 250 individual peatlands in the area, varying from less than a metre to 10 m in depth. The largest are nearly 10 000 ha in extent and the total quantity of peat in the area has been estimated at nearly 160 million m^3 – some 60% of South Africa's total peat reserve.

The sediments of large wetlands elsewhere in southern Africa almost certainly contain a great deal of peat, although not much has been published on them. An exception is an article by Fred Ellery, now of Rhodes University, and some of his colleagues, who in 2008 described the peatlands of the Okavango Delta in Botswana, and a fire in the peat that may have been burning for weeks or even years. No doubt other massive wetlands, like those of the Barotseland and Banguelu floodplains in Zambia, can also lay claim to being peatlands.

Like most other ecosystems on Earth, peatlands are under threat. For thousands of years, the peasants of northern Europe and Britain unwittingly completed the carbon cycle (see chapter 3) by burning peat as their major source of fuel for heating and cooking. For centuries, too, the quantities of peat available, relative to the amount used by humans, was so great that exploitation did not really have much of an impact, except very locally. That situation did not last. Finland, Estonia, Russia and the Republic of Ireland have constructed peat-burning power stations (clearly the amount of peat must be enormous to make these economically viable). Ironically, if these peat deposits were to be left alone for long enough, they would at some point in the distant future be 'fossilised' and transformed quite naturally into another kind of fuel – coal – which is literally the fossilised (and highly transformed) remains of peat generated in bogs in the Carboniferous period some 350 million years ago. Burning peat is much more polluting than burning coal, and so the countries where peat is used in power stations are removing subsidies or actively discouraging the continuation of these powerplants in order to meet EU targets for carbon emissions. Russia now has a single peat-fired power station; the number in Finland has been reduced to three (but see the following website for a discussion of the politics of peat in Finland: https://en.wikipedia.org/wiki/Peat_energy_in_Finland). Most peat-fired power stations in the Republic of Ireland have closed down in the last few years, although the Edenderry Power Station has not. As of 2020, the plant has been co-fired with biomass, including grass, olive pits, almond shells, palm kernel shells, and beet pulp, much of it imported. At what fuel cost, one wonders. The intention is to replace peat entirely by other forms of biomass. On the other hand, believe it or not, Rwanda has two new peat-fired power stations.

Despite only covering around 3% of the Earth's surface, peatlands contain about a fifth of its soil carbon. (Wetlands in general cover approximately 7% of the Earth's surface and yet they contain about 35% of soil carbon on Earth.) In Europe, these ecosystems store five times as much CO_2 as forests do. Many peatlands are under threat, however, partly because mining the peat damages the soil structure and allows water and oxygen to enter, causing rapid decomposition and loss of CO_2. It has been estimated that damaged peatlands release as much 3.5% total global anthropogenic CO_2 every year.

One of the greatest challenges in the world of today is reducing the amount of carbon dioxide in the atmosphere. The fate of our peat deposits is therefore of utmost importance. If they grow as the world warms, then they will sequester carbon and assist in controlling CO_2 levels. If they shrink, they will 'outgas' and contribute to global warming. Research programmes around the world are examining this problem: are wetlands net sources or sinks of greenhouse gases? The results are not yet in, but the answer seems to be 'maybe', depending on the balance of temperature, the degree of wetness and nutrients levels, the species of plants making up the peat, and the species of bacteria doing the decomposing. At best, though, peat accumulates very slowly, usually not more than a millimetre or two a year, so we can't expect climate redemption from this route alone, if at all. Furthermore, because of the reducing conditions in many wetland soils, a good deal of the carbon emerging from wetland soils does so in the form of methane, which is a much more effective greenhouse than CO_2.

We also need to give a nod to the far northern countries where fuel of any kind is scarce. There are few trees, and those grow very slowly; sunlight is limited, so solar power is of limited use; winters are cold, so a reliable source of energy for warming homes and other premises is essential; and even coal deposits are very limited in the areas we are talking about. So, it is understandable that peat burning is an attractive source of electric power: another complex environmental conundrum with no simple solution.

THE VALUE OF WETLANDS

The tiniest ephemeral pool in a rock crevice can hold water that becomes the home of short-lived organisms like protozoans or bacteria, or even mosquito and midge larvae. Slightly larger pools on soft sediments may retain water for at least a number of days, providing a habitat for plants, as well as for a variety of invertebrates. But really big, vegetated wetlands are far more important than mere habitats for wetland organisms. Indeed, they can have profound effects on the functioning of entire catchments. Generally, these effects are beneficial from a human point of view, and so wetlands are some of the most valuable types of ecosystems worldwide. Some of the 'services' they provide are described in Chapter 11, together with an analysis of the monetary value of wetlands worldwide.

A WORD OF WARNING

While wetlands are undoubtedly of great value to the planet, we should not lose sight of the fact that they can sometimes be detrimental to the people living near them. Malaria and other diseases are transmitted from person to person by mosquitoes, and the young stages of mosquitoes live in standing or very slowly flowing water – in wetlands, in other words. The young stages of bilharzia parasites live in aquatic snails, which require still or very slowly-flowing water – where other than wetlands? Water-related diseases are discussed in more detail in Chapter 8.

WETLANDS PERENNIAL, SEASONAL AND EPHEMERAL

By and large, permanent wetlands are more similar to standing waters (see Chapter 3) than to rivers (Chapter 4). Obviously, the details vary, but permanently inundated wetlands function in very similar ways to shallow lakes or very sluggishly-flowing streams. Temporary waters are another matter altogether, though. The fact that water appears and disappears from time to time means that their aquatic organisms can thrive there only if they can survive being inundated or desiccated, sometimes predictably (at the beginning and end of a wet season, for instance) and sometimes unpredictably – in very dry deserts, for example. Below we discuss a variety of wetlands subject to different hydroperiods (cycles of wetting).

FLOOD PLAINS

When most rivers overtop their banks, the water soon filters into the ground and disappears. But some rivers flowing through low-gradient landscapes inundate huge areas when they flood. Annually the Amazon, for instance, floods 50 000 to 60 000 km^2 of ***várzea*** or flooded forest. The flood waters rise 10-15 metres above the dry-season level so that tree trunks and parts of the canopy are entirely under water for a couple of months each year. It seems that this pattern has been in existence for many thousands of years at least, since the teeth of some Amazonian fishes are adapted to feeding on fruit and leaves that they feed on high in the canopy. Some human populations wait out the flooded months in floating villages anchored above their usual homes. This degree of inundation is not common, although similar 'drowned forests' are also found in some parts of south-east Asia. More commonly, the flood period is shorter, river waters extending over the floodplain and filling floodplain pans, but then soon retreating to within their dry-season banks. In southern Africa, immense floodplains of this second kind are associated with the Kafue, Zambezi and Limpopo rivers (the Kafue floodplain is about 650 km^2 in extent, for example). South Africa's largest floodplains – the Phongolo and Mkuzi (450 km^2) rivers in KwaZulu-Natal and the Berg River in the south-western Cape – are puny by comparison, extending for no more than a couple of square kilometres. Botswana's enormous Okavango swamp, in contrast, is like a shallow grassy várzea, a meter or two of water remaining on 16 000 km^2 of floodplain for many weeks or months.

Floodplain lakes or pans may have started off as old meanders, like the billabongs on the Murray River in Australia, or as old lakes, like those on the floodplain of the Phongolo (also spelt Pongola) River. Whatever their origins, floodplains are lentic ecosystems directly dependent on rivers for their water – and usually for sediments and nutrients too. Floodplains occur where rivers flow through flat land. The speed of the current is slow, so that the river is less able to carve a deep channel here than it did in the steeper reaches upstream. It tends instead to become wide, sinuous and sluggish, and to deposit the sediments it carries. During floods, however, sediment is scoured from the bed and, as the flood waters spread out, it is deposited across the floodplain. This material is rich in nutrients and is ideal for planting crops, or for the growth of natural floodplain vegetation. Famously, Egyptian agriculture has relied for millennia on the water and silt deposited by the Nile River on its floodplain (see Chapters 1 and 9). A similar phenomenon, at a much smaller scale, can be seen on the Phongolo River in northern KwaZulu-Natal and is discussed in more detail on page 161.

In Chapter 4 we alluded to the Flood Pulse Concept (FPC), which deals with the seasonal recharging of floodplains by

Várzea forest of the Rio Negro, a tributary of the Amazon River, during the annual period of inundation. Flood waters reach a depth of 10 m and cover the floodplain for 2 to 3 months each year.

Lani van Vuuren

Maize under irrigation on the Makatini Flats, below Pongolapoort Dam.

pulses of water and nutrients. Wolfgang Junk, chief author of the FPC, considers that water and material brought in on the flood will determine the timing and extent of processes such as colonisation of the floodplain and associated pans by mobile organisms like fish, and seasonal destruction of terrestrial plants through drowning. More than this, though, the biological processes that go on in the floodplain are dependent on the quantity, quality and timing of material brought in on the flood. The concept was developed from Wolfgang's extensive knowledge of the Amazon but has proved to be more widely useful, even for smaller systems.

The hydroperiod (the length of time, and when, water remains on the floodplain) has an enormous influence on the processes of decomposition and nutrient cycling, and therefore on the biomass and productivity of floodplain plants and animals. Further, the frequency of inundation (every year, or perhaps every four or five years) may be significant. For instance, chemical substances may accumulate or be flushed out of the system depending on the flood cycle, which may also determine whether or not aquatic organisms like plants, fish and invertebrates are able to breed successfully. The amount of water that arrives over a season, or even in a single flood, may also be important. In some species of fish, recruitment of juveniles into the population is enhanced by flooding, so even minor floods may sustain low but significant levels of recruitment in the years between major floods. This phenomenon may explain declines in the populations of native fish on certain floodplains worldwide, where dams prevent small floods from inundating their floodplains (see Chapter 9). The frequency of major floods remains little changed in these rivers, though, because impoundments are seldom large enough to store really massive floods. Major floods may flush accumulated sediments and debris from the floodplain but may also introduce large amounts of new material, including newly fallen wood, that provides essential refuges for riverine plants and animals in the main channel.

Floodplains are characterised by diverse biotopes ('living places': Gr ***bios*** = life; ***topos*** = place) and also by fast rates of production and large biomasses of both plants and animals. Production of biomass is usually considerable because of the nutrient-rich silt that the river spreads over the floodplain as flood waters advance. At the same time, terrestrial plants are inundated and may die, contributing their decaying remains to the rich humus covering the floodplain. Enormous amounts of food become available for the small aquatic invertebrates that colonise the flooded areas in vast numbers and that in turn form a superb food source for the larger animals like birds, reptiles and fish. At the end of the wet season, the river is once more confined within its banks and, except for the now-isolated pans that may persist throughout the year, the floodplain starts to dry out. Aquatic animals retreat into the main channel or into peripheral wetlands, while on land the terrestrial vegetation (trees, shrubs and especially grasses) grows again. Because of the very rich alluvium that has been deposited in the area, plant growth is rapid. Terrestrial grazers and browsers, such as antelope and rhinoceros, are attracted to the new growth, and much of their food is recycled within the system in the form of urine and faeces.

The flood pulse in dryland rivers is often far less predictable in time, and much more variable in quantity of water, than it is in rivers in more mesic (moderate/wetter) areas. This means that consideration must be given to the responses of floodplains to drought, as well as to flood. In addition to unpredictability of timing, the flood pulse may arrive quickly or slowly and, equally, may recede rapidly or over a long period. The timing and rate of arrival of the flood in a floodplain river can influence the responses of the biota. Fish, for instance, may take as a cue for spawning a flood of a certain current speed arriving during a particular season. Human interference, by impoundment of rivers, has almost certainly interfered with fish populations dependent on floodplain wetlands in southern Africa (see Chapter 9).

In summary, floodplains are ecologically complex ecosystems that depend on interactions between the river that inundates them and the land on which they lie. They can be very productive, but this productivity is easily disrupted by human interference, which may change the delicate balance in dominance of aquatic and terrestrial influences.

INTERRUPTION TO THE FLOOD-PULSE: THE CASE OF PONGOLAPOORT DAM AND THE MAKATINI FLATS

The work by Charles Breen and Jan Heeg in the 1980s on the Makatini Flats of the Phongolo River floodplain is a classic study of the FPC in action, considering interactions between the people of a floodplain and the river that fed it. The study was driven by the need to alleviate the potentially harmful impacts of a dam on the people who lived on the banks of the river, and to develop a rational management regime for the floodplain.

From an ecological point of view, the important features of the floodplain are as follows. It supports a mix of floating, rooted and emergent plants which, together with their dense epiphytic communities, provide autochthonous food sources that are added to by the periodic inundation of the grasses and other terrestrial plant communities. The terrestrial vegetation is controlled by the inundation regime. It develops rapidly as the flood waters recede, and is consumed mostly by hippos and cattle. The hippos play an important role in the transfer of material from land to water because they feed on land at night and defaecate in or near the wetlands during the day. As the flood season progresses, about 800 kg/ha of grass is drowned and decomposes, adding to the food supply of the rising flood waters. ***Cynodon*** is a grass favoured as food by hippopotamus. In Namanini Pan, towards the lower end of the river system, hippos cause some 26 000 kg of the 34 000 kg of annually submerged ***Cynodon*** to enter the food web.

Lani van Vuuren

The Phongolo River and the main irrigation canal below the Pongolapoort Dam, with the Makatini Flats in the distance.

In contrast, ***Potamogeton crispus,*** a rooted, submerged plant, forms extensive stands in permanent wetlands. It is very sensitive to desiccation and so it is restricted to pans that never dry out. (This is an important consideration for the management of low-flow conditions caused by the regulation of rivers by dams.) The growth of this and other plants like the water chestnut, ***Trapa bispinosa***, and waterlilies (***Nymphaea*** spp.) reduces turbulence and wave action and, in so doing, allows the development of very dense epiphyton communities. This epiphyton has a high turnover rate (two to three weeks) because it is continually grazed by the snail ***Bulinus natalensis*** (which, incidentally, is a vector of bilharzia). The annual production of epiphyton probably exceeds that of ***P. crispus,*** which itself annually contributes about 27 000 kg dry mass of potentially decomposable plant material to the detritus of the pan.

Ebb and flow of water with the seasons was abruptly halted by the construction of Jozini (Pongolopoort) Dam. The dam, built to store water for a sugarcane irrigation scheme, is situated in the hills just above the 130 km^2 floodplain known as the Makatini Flats. The dam wall was closed in March 1970. In those days no consideration was given to water requirements for social or environmental purposes, so releases of water from the dam were kept to no more than 20 m^3/s. In consequence, the river stopped flowing and dried up to form a series of stagnant pools, resulting in a lack of adequate water supplies for the local people on the Makatini Flats. An outbreak of typhoid ensued. Because it was clear that the amount of water in the river was insufficient for the local people to carry on their normal activities, in December of the same year, the South African Department of Water Affairs (DWA), in the form of their lone limnologist, Charel

Bruwer, arranged for the country's very first 'environmental' flow of water to be released into the river from the Dam. Unfortunately, the dam operator released water so slowly that it had no significant effect on the floodplain. As a result of the experience gained over a number of years, though, eventually the releases became adequate.

Leslie J. Mehrhoff / Wikimedia /CC BY 3.0

Jenny Day

Jenny Day

(A) Potamogeton crispus*, a plant commonly found in the floodplain pans of northern KwaZulu-Natal; B) The floating* Trapa natans*, water chestnut, in a channel in the Okavango Delta, and C)* Nymphaea nouchali*, the blue waterlily, a common inhabitant of wetland ponds and slowly-flowing streams throughout much of Africa.*


Kevin Rogers

Prior to the construction of Pongolapoort Dam, fish was an important source of food for people of the floodplain. Traditionally, fish were caught using weaved baskets known as isifonyo.

That was the end of the story when we wrote the previous edition of this book, but events took a turn for the worse some years ago. Commercial cotton farming began on the Flats in the 1980s and by the 1990s commercial farmers formed a strong lobby. No attempt was made to protect the small subsistence farmers, and indeed the cotton growers threatened to take DWAF to court if the Department released water at times of year necessary for the small farmers, but inappropriate for the cotton crop. In reply to my questions about the management of releases from the dam, a DWS spokesperson commented as follows. "A baseflow release at a rate of 5 m^3/s is released under normal circumstances from Pongolapoort Dam. Socio-environmental flood releases are also made when the dam level is above 60% and these releases have not been made since 2014 due to drought in the area." As I write this (April 2022), however, DWS is deliberately releasing 75 m^3/s, and "notifying all stakeholders and communities downstream to be vigilant and look out for rising water levels along the Phongolo River and surrounding areas". The recent releases were made for purposes of dam safety, because there is insufficient spillway capacity to deal with large floods. Furthermore, the Phongolo River flows from KwaZulu-Natal into Mozambique, where it is called the Maputo River. To prevent flooding downstream, Mozambique has asked South Africa to keep maximum flow in the river to less than 450 m^3/s, which is a lot more than 75 m^3/s. The end of this story has still to be told but once again it looks as if commercial interests, and possibly official apathy, outweigh the interests of the local people – and the river they have depended on for centuries.

SALINE LAKES

When one hears the word 'lake', one usually thinks of the beautiful deep blue of the freshwater lakes of Switzerland or of the massive Great Lakes of central Africa. In fact, though, a significant proportion of the world's lakes hold salty, not fresh, water. Salt lakes are particularly common in the Andes of South America, in parts of North America, China and Africa, and in Australia. Some salt lakes, such as Etosha Pan in Namibia and Lake Eyre in Australia, are inundated only episodically (in which case they should, by rights, be called 'pans' or 'playas'), but many contain water permanently.

Their waters may vary in salinity from a few grams of salt per litre of water through to almost-saturated salt solutions containing about 350 g/L of salt. (In contrast, sea water contains 35 g/L). Because of the peculiarities of solubility of different salts in water, the 'salt' normally found in saline lakes is almost pure NaCl or sodium chloride, the 'common salt' used to season food. The waters of some saline lakes are dominated by rather odd salts, though. Lake Naivasha and some of the other salt lakes of Africa's Rift Valley are very rich in sodium carbonate (Na_2CO_3), while some of the salt lakes of the Andes contain particularly high concentrations of arsenic or boron. (The highest-altitude mine in the world is a borax mine at nearly 5000m in the Andes in southern Bolivia.)

Some salt lakes have waters of most spectacular colours. At salt concentrations around 120 g/L, a minute alga (≈10μm in diameter) called ***Dunaliella salina*** may occur in enormous numbers. To counteract the effects of the high salinities, ***Dunaliella*** sometimes contains large amounts of a pigment called β-carotene, which helps to protect the algal chlorophyll from the damaging effects of intense solar radiation. This pigment is found quite widely in nature – when combined with a particular protein it provides the red colour of tomatoes, for instance, and the yellow colour of butter. Some saline lakes look as if they contain tinned tomato soup, not water, but in fact they merely support dense populations of ***Dunaliella.*** Bolivia's Laguna Colorada (the Red Lake) is a most spectacular and surreal sight. The surrounding peaks of the Andes are purple, tipped with white snow, and the marginal vegetation is a vivid, if not sickly, lime green. Blindingly white islands of ice, covered with precipitates of chalk, contrast weirdly with the tomato-red water.

Jenny Day. Insert: Mike Dyall-Smith / Wikimedia / CC BY-SA 4.0

Laguna Colorada, at 4 300 m in the Bolivian Andes; the red water is coloured by the unicellular alga Dunaliella salina (inset).

The waters of some other saline lakes are pinkish or purplish rather than tomato-red, usually indicating that the water is too salty to support *Dunaliella*. The colour is, in fact, the result of massive populations of bacteria in the water. Some of them are purple chemoautotrophic 'sulphur bacteria', which use chemical energy to fix carbon. These bacteria contain bacterioruberin, a purple pigment chemically similar to β-carotene, which also acts as protection against intense solar radiation. Members of another group of halophilic (salt-loving) bacteria are ***Halobacterium*** and ***Halococcus,*** which also contain a purple pigment. This pigment, bacteriorhodopsin, is entirely different chemically from β-carotene and bacterioruberin, however, and has a most unusual function. It is closely related to the 'visual purple' of vertebrate retinas and,

The mauve colour of the water in this Australian salt lake comes from the halophilic (salt-loving) purple sulphur 'bacteria' (Archaea) living in it. The salinity is close to 300 (i.e. 300 grams of NaCl) per litre.

like them, converts light energy to chemical energy (i.e. carries out photosynthesis). This is one of the very few examples in nature of light energy being fixed by any substances other than chlorophyll.

Because high concentrations of salt prevent most plants and animals from living in salt lakes, the biodiversity of these systems is low. Apart from a few species of nematodes (roundworms), rotifers and protozoans, most of the invertebrates that can survive at least to salinities around 60 g/L are gastropods, crustaceans and a few insects. Very similar genera of snails, ***Coxiella*** and ***Tomichia,*** live in Australian and South African salt lakes respectively. At higher salinities still, Australian systems support several genera of crustacean, including the copepods ***Calamoecia*** and ***Boeckella,*** the water flea (a cladoceran) ***Daphniopsis*** and the brine shrimps ***Artemia*** and ***Parartemia.*** Oddly, the only one of these to be found in southern Africa is ***Artemia.*** It is not clear why this should be so, but perhaps it has something to do with a period or periods of extreme aridity in southern Africa in the last 70 million years or so, after Africa had separated from Gondwanaland. (This theory, suggested by Australian biologist Iain Bayley, relates to the fact that ***Daphniopsis*** and some calamoecid copepods occur in South American as well as Australian salt lakes. We know that Australia and South America parted from each other some time after the splitting of Africa from Gondwanaland, so we can postulate that the episode of extreme aridity in Africa did not affect either of the other two southern continents.)

Bronwen Scott

Washed up dead shells of Coxiella *sp. from Australia.*

TEMPORARY WETLANDS

In much of the northern hemisphere, wetlands do not appear and disappear with the seasons. In the more arid southern continents, though, this is often the expected, not a peculiar, thing to happen. The annual 'water surplus' (the ratio of precipitation to evaporation) is less than 100 mm for much of the southern African region. This means that standing waters, particularly small and shallow ones, are unlikely to be permanent, except perhaps in the mountains of the south-western Cape, the Drakensberg and the Zimbabwean highlands. Even in these regions, rainfall is so seasonal that the persistence of standing waters throughout the year is unlikely (see Chapter 2). (This explains why the only perennial inland lake in South Africa is Lake Fundudzi in the far north of Limpopo – see page 47).

From a biologist's point of view, temporary waters are not only interesting ecosystems, but ones from which valuable ecological and physiological information can be gleaned. Because the smaller ones are relatively simple ecosystems, they have been used to examine ecological theories such as those relating to island biogeography, stability and diversity, competition, and disturbance. And the adaptations of their biotas to their 'here today, gone tomorrow' waters are fascinating. Below we look in detail at some of these adaptations, but first we need to mention something about the variety of temporary wetlands.

TYPES OF TEMPORARY WETLANDS

Inundation of temporary wetlands may occur regularly or irregularly. In the more mesic areas of southern Africa, rainfall is generally predictable, occurring annually and seasonally. In drier areas (MAR <250 mm) rainfall, and thus inundation of pools, is usually episodic, occurring in discrete, often unpredictable, episodes rather than seasonally. If the rains have been heavy then the water may remain on the surface for weeks or even for months. But more often the water bodies formed are ephemeral, lasting for a few hours or days only. Obviously the smaller the water body, the faster it will dry out.

Perhaps the most spectacular temporary wetlands of southern Africa are the hundreds of thousands of hectares of pans in the Northern Cape, and the saline Makgadikgadi Pan in Botswana and Etosha Pan in Namibia. All of these are virtually without vegetation (and therefore are not particularly productive) but most support algal growth on their bottoms and some sort of vegetation around their fringes. One of the more unusual plants living in temporary waters is ***Aponogeton,*** the genus of the waterblommetjies. These are unusual water plants, most of which are adapted to living in temporary ponds, and which are found only in Africa, Asia and Australia. Even more remarkable is ***Lindernia intrepida*** (Hyacinthaceae), which is found only in deep potholes in a few isolated granite inselbergs (island mountains) in Namibia. Far more common plants of temporary waters are a variety of grasses, reeds and sedges and, in the saltier ones, glassworts such as ***Arthrocnemum.*** (***Arthrocnemum***, like the alga ***Dunaliella*** and many other salt marsh plants, is pinkish in colour because of the β-carotene that it contains.)

Ronald Flipphi / Wikimedia / CC BY-SA 4.0

The floating-leaved Aponogeton distachyos*; buds and flowers are eaten in waterblommetjie stew in the Cape.*

imagesource / 123RF

Jenny Day

Above and top: The Etosha Pan in northern Namibia is an enormous salt pan.

Anon / Kew Gardens / Wikimedia / CC By-NC-S

The remarkable Lindernia intrepida*, a very rare plant that is known only from temporarily-filled potholes in isolated inselbergs ('island mountains') in the Namib Desert.*

John Day

A glasswort, Arthrocnemum *sp. Note the red colour of some of the segments.*

Although large temporary pans are found on soft sediments, a few smaller ones occur on rocky bottoms. These are usually entirely without vegetation and if the bottom is relatively free of debris, the water is crystal clear. In contrast, the waters of soft-bottomed ponds may be very murky because of sediments kept in suspension, often by large animals trampling the bottom while drinking. For details of a classification system for temporay wetlands, see the paper by Aram Calhoun and colleagues (2017).

LIVING IN A TEMPORARY POND

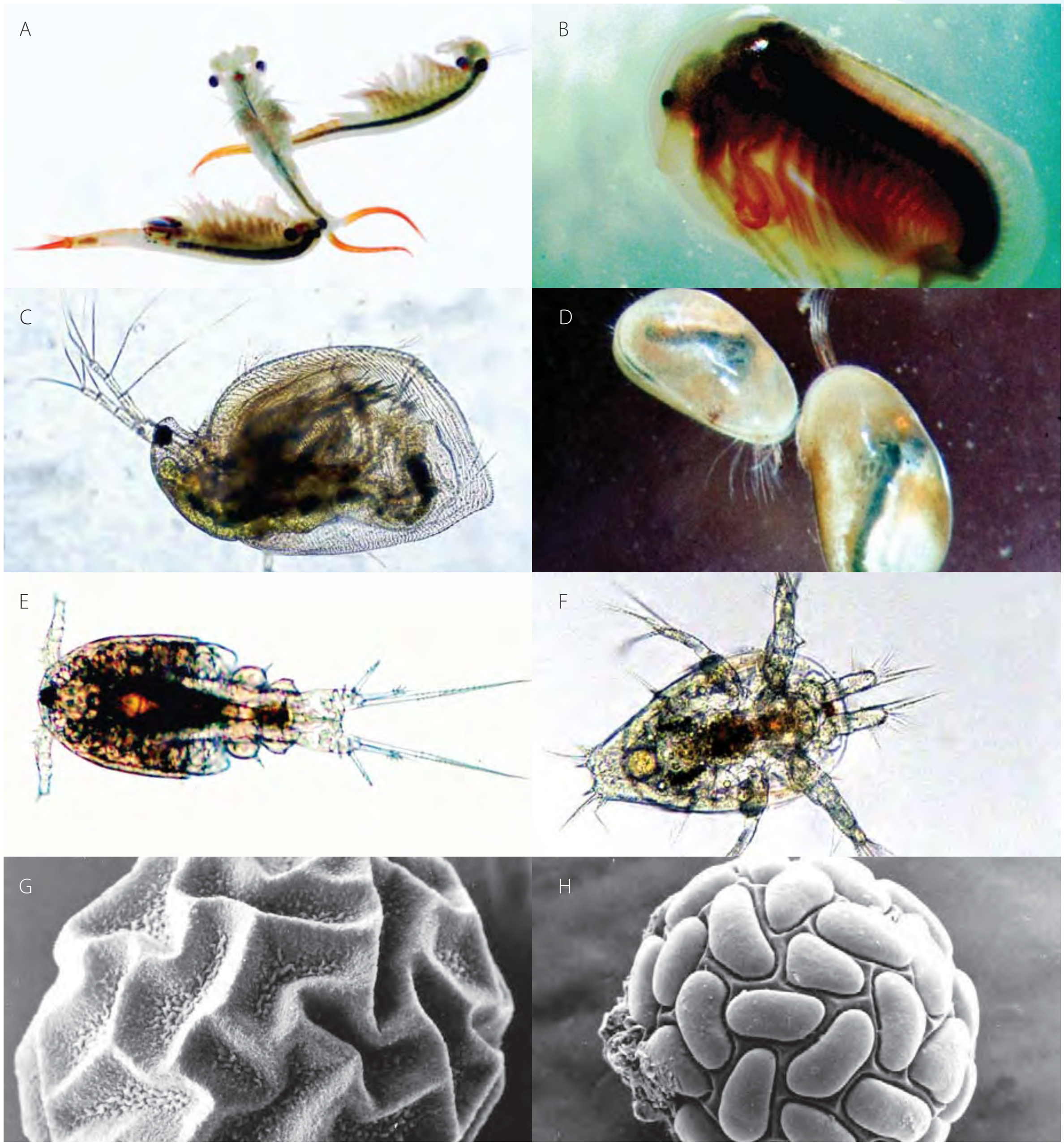
Organisms that survive the harsh conditions of a temporary pond must obviously have a number of very specific adaptations to their peculiar environments. This is particularly so for those who live in ephemeral waters in deserts, where rain may fall no more than once in five or ten years, and where temperatures on the ground may reach 50°C in dry times. Let us look at some of these inhabitants of desert pools, and examine the adaptations that allow them to live in these unlikely places.

When the desert blooms after rain, land that was utterly dry and apparently lifeless is clad in a soft green cloak of young grass plants. Animals, from zebras and gemsbok to bugs and grasshoppers, gorge themselves on the unexpected largesse. Most of the rain is quickly soaked up by the dry soil, but some falls into hard-packed clay depressions, or into hollows in rocks, where it may remain for a week or two, or even longer. These ephemeral ponds burgeon with life. Birds and mammals come to drink. Two species of frogs, ***Phrynomantis annectens*** and ***Poyntonophrynus hoeschi,*** having spent the dry years in protective cocoons buried deep in the dry mud, or in cracks in the rocks, emerge to feed and mate, and lay their eggs. Voracious beetles and dragonfly nymphs prowl the ponds. But the most fascinating inhabitants are the branchiopods: ancient, primitive, distant relations of the crabs and crayfish and other crustaceans. They include ***Triops,*** the shield or tadpole shrimps belonging to the order Notostraca; the clam shrimps (several genera) of the order Diplostraca (previously Conchostraca) and the fairy and brine shrimps of the order Anostraca.

Representatives of all of these taxa are, or once were, found throughout southern Africa from Cape Town to Zimbabwe and from the Namib to KwaZulu-Natal, almost anywhere that temporary pools occur. ***Triops*** is still found here and there throughout its ancestral range. (We know this because nearly every time that floods allow temporary pools to last for some time anywhere in the country, some inquisitive member of the public will find some of these strange animals, and phone to ask us what they are.) Let us look at ***Triops*** itself in some detail.

Phrynomantis annectens*, from deep in the Namib Desert, lives out the dry years in cracks in the rocks.*

As adults, these beasties reach a length of no more than about 60 mm, often less. When viewed from above, the body consists of a rounded carapace or shield covering the head and thorax, followed by a flexible, jointed abdomen ending in two long sensory filaments. The carapace bears three eyes (hence the name ***Triops,*** from the Greek: ***tri*** = three; ***ops*** = eyed), one on either side at the front of the head, and the third between them. The lower or ventral surface of the head bears rudimentary antennae and a pair of heavy jaws, behind which are many pairs of flattened legs of remarkable construction. The basal part of each leg is called the gnathobase (from the Greek: ***gnathos*** = a jaw) and is armed with teeth pointing to the midline and almost touching the teeth of its partner on the other side. Between the pairs of leg bases is a groove, the food groove, up which pieces of food are passed to the mouth, being chewed all the way by the gnathobases. Apart from acting as jaws, the legs are flattened (the technical term is 'phyllopodous', from the Greek: ***phyllos*** = a leaf; ***pous, podos*** = a foot) and form a series of paddles acting in concert to propel the animal forwards. Not content with having legs with two functions, ***Triops*** also uses them for breathing, for feeling, and for carrying eggs. The surface area is large and the



Dirk Ercken; Braam van Schoenwinkel; Cecile Reed; Jenny Day; Cecile Reed; Lithium57 / Wikimedia / CC BY-SA 3.0; Jenny Day; Jenny Day

All these crustaceans (A-E) are adapted to living in temporary waters. Some produce eggs (G, H) that are resistant to desiccation and most go through a development stage, known as a nauplius larva (F). A) Branchipodopsis wolfi, *a fairy shrimp (Anostraca); B)* Leptestheria rubidgei, *a clam shrimp (*Conchostraca*); C)* Moina micrura, *a water flea (Cladocera); D) a seed shrimp (Ostracoda); E)* Cyclops sp *(Copepoda); F)* nauplius *larva of a copepod; G & H) scanning micrographs of anostracan eggs.*

Small pools like that shown in (A) commonly contain tens of individual Triops *(B). (C) shows a pair of strong mandibles on the underside of the head with a tooth-lined groove in the midline. The carapace has been flipped upwards in (D) to show the paired egg sacs containing eggs.*

exoskeleton thin, so that the legs form admirable gills, not very different in appearance from those of a fish. Parts of the first one or two pairs of legs are elongated and particularly hairy and used as antennae, or feelers, since the original antennae are rudimentary. Finally, in the female a single pair of legs, tucked up under the carapace, is modified to form a cup with a lid – the ovisac, where the fertilised eggs are stored while they are developing into minute larvae.

Tadpole shrimps can live only as long as they are covered by water, which may be for no more than a few days. They give the impression of making use of every minute, hurtling around the pond like miniature tanks or trilobites, copulating momentarily in a swirl of bodies, swimming briefly at the surface or bulldozing through the mud. During its short life, each individual *Triops* must hatch from the egg, pass through several larval stages (moulting each time it outgrows its exoskeleton, sometimes more than once a day), grow rapidly to maturity, and mate and lay eggs that will form the next generation. This requires eating as much as possible, as fast as possible. For this reason, *Triops* seem to prefer to live in soft-bottomed ponds where bacteria form the base of the food chain, occurring in countless numbers and coagulating the sediment particles into a thick, spongy mat. Although these bacteria form the staple diet of *Triops*, it will eat almost anything it can lay its many jaws on, not excluding its own cast moult or its smaller and weaker brothers and sisters, particularly if they are soft and vulnerable after moulting.

Closely related species living in rice paddies stand accused of uprooting germinating rice seedlings: it is not certain if they eat the seedlings, or merely uproot them while grubbing for other food in the mud.

A small pool only two or three metres in diameter may contain several hundred ***Triops***, which constitute a concentrated food source for bigger animals. So ***Triops*** does not have things all its own way: it is in turn preyed upon by frogs and birds, and sometimes even by fish. Perhaps this explains why it has the third eye in the middle of its 'forehead', enabling it to look skyward and detect predators descending from above. (The third eye is in no way related to the third eye of vertebrates: it is a persistent median larval or naupliar eye, which can probably distinguish between light and dark but not form an image)

All inhabitants of temporary ponds, in arid areas particularly, have to overcome many obstacles to staying alive and especially in leaving viable offspring. These problems can really be divided into just three kinds:

1. growing rapidly enough to be able to reproduce before the pond dries;
2. surviving the deteriorating conditions in the shrinking pond, at the same time producing as many eggs as possible;
3. hatching at an appropriate time.

Rapid growth is fairly well understood. We have already mentioned that they eat voraciously, but the rate at which they burn up food and oxygen (i.e., the metabolic rate) is also very high, partly because of inbuilt genetic features and partly because the temperature in the pond may be high. ***Triops*** from Namibia can grow to adulthood at a length of 35 – 40 mm in a week at 35°C.

Surviving the deteriorating conditions in a shrinking pond is possible because of a number of adaptations, only some of which are understood. ***Triops*** can live as adults (but not as larvae) in water with a relatively high salt content (this is necessary because as evaporation of the water occurs, the remaining water becomes more and more salty) and can also survive a surprisingly wide range of temperatures, from <15°C to >40°C. But most impressive is their ability to survive very low levels of oxygen in the water. We have already said that they have a high metabolic rate, which means that they consume a great deal of oxygen. Now the physical properties of dissolved gases are such that the higher the temperature, or the more concentrated the salt, the less oxygen (or any other gas) can dissolve in water. Thus, when ***Triops*** is largest and needing most oxygen, least is available because the pond is drying up and the water is becoming hotter and saltier. The large surface area of the gill-like legs does help in respiration, but ***Triops*** does two other things. Firstly, it may cavort around near the surface, or even swim upside down, almost hanging on the surface film, and briefly expose its legs to the air. Secondly, it can produce haemoglobin, almost the same red blood pigment as that found in vertebrates, which assists in extracting greater quantities of oxygen from the water.

Most fascinating of all are the ways in which ***Triops*** (and other branchiopods) synchronise the hatching of their eggs with the highly unpredictable environment of a temporary pond.

But first, we need to say something about the way in which evolution by natural selection happens. We may be tempted to imagine that over aeons, the ancestors of the current generation of ***Triops*** somehow became aware of the adaptations necessary for survival in these difficult conditions, and actively developed them, This is not the case, of course. Instead, we need to think of it in a different way: only those individuals coming from a gene pool in which those adaptations developed, little by little, over thousands of generations, will be able to survive. The rest will die.

Consider the circumstances that allow a species like *Triops* to persist in a pond from generation to generation. A female has laid her fertilised eggs on the mud at the bottom of the pond. The pond dries up, so the female dehydrates and dies, leaving her eggs unprotected on the drying mud. There is no guarantee that the next rainfall will be sufficient to allow a long-lasting pond to form, which would allow the eggs to hatch and grow into adults that could themselves lay eggs. If there is no way that prevents an entire population of eggs from hatching, they may all die before reproducing. But the same rainfall could equally be the best for years, in which case it would be advantageous for at least some of the eggs to hatch. In other words, the chance of the species persisting over time are best if a proportion of the eggs hatches after each inundation How can this be achieved, since *Triops* eggs are no better than anyone else at predicting the future? Then what about the problem of survival of the eggs during the long period of drought, perhaps upwards of ten years? Lastly, how does an aquatic animal living in a desert become dispersed around the countryside?

When deposited by a female, an 'egg' consists, from the inside outwards, of a blob of yolk (which is a single cell, like the yolk of a hen's egg) surrounded by two membranes made of cells, and finally a thick, spongy outer coat. Even before it is laid, the fertilised egg begins to develop to the larval stage known as a metanauplius. (Because the contents of the shell are no longer a mere egg, the correct term should now be 'cyst', but it is often still referred to as an egg.) It is released by its mother after which all development stops: it is totally inert and quite unable to hatch until it has been thoroughly desiccated and then wetted again. When the cyst dries out, the outer spongy coat becomes rock-hard and resistant to mechanical abrasion, attack by bacteria or fungi, and the intense sunlight to which it is subjected during the years of lying inert on the floor of the dry pond. The little metanauplius inside is in a state of ***anabiosis***: there is no sign of life whatsoever.

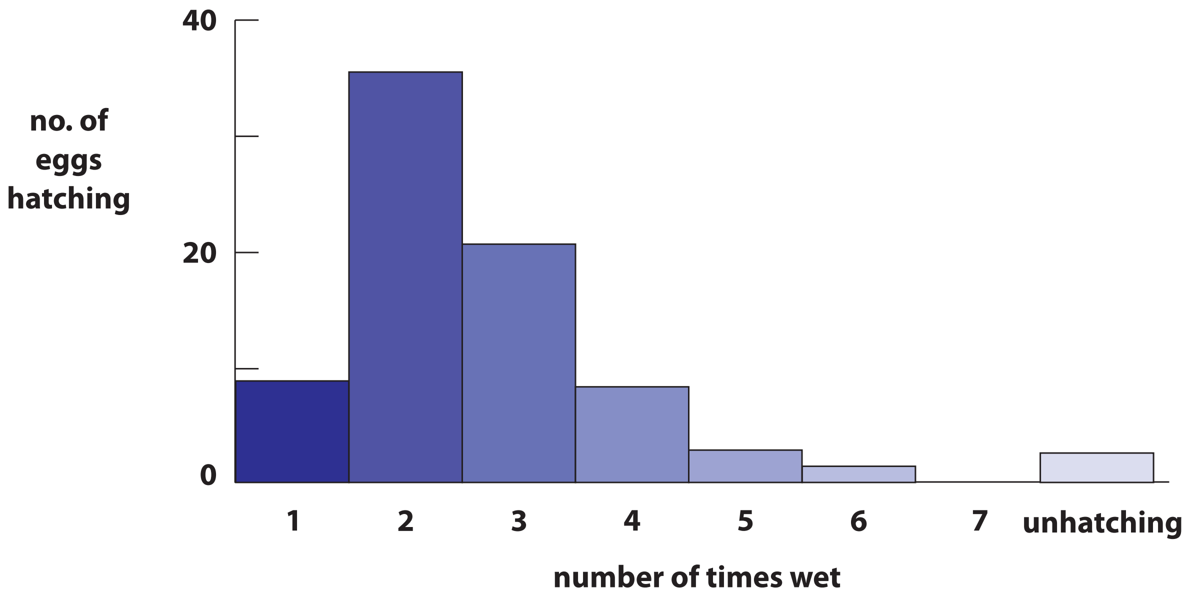
Experimentally, the cysts of ***Triops*** can be subjected to temperatures ranging from below freezing to above 100°C and the metanauplius will still hatch when returned to water at a suitable temperature. A fascinating experiment has shown that the cysts of *Triops granarius* from the Sudan are not killed by temperatures of 98°C when the boiling point of the water is 100°C, or 103°C if the boiling point is 105°C, but that they are killed at 75°C if the boiling point of the water is reduced to 70°C. What does this experiment mean? Simply this: the shell is entirely permeable to water, so that even under normal conditions, the larva becomes desiccated. During the dry phase of the pond, the larva may lose up to 96% of its body water, retaining just that last 4% essential for the structural integrity of its proteins. By subjecting the cyst to any temperature at which the air pressure is low enough to boil water (i.e., boiling it dry), that last water is driven off as steam, and the larva becomes completely waterless and dies. At the ambient temperatures and pressures in the real world of a desert, of course, they are unlikely to lose that last 4% of water.

It is during the dry phase, too, that most dispersal of the cysts occurs. Less than a millimetre in diameter, and as light as a mote of dust, they may be blown about in storms and may land in another depression that also harbours an ephemeral pond when wet. Dispersal of cysts or of adults may also occur during the wet phase, when they may stick to the fur or feathers of animals coming to drink.

The solution to the last problem, that of synchronising the hatching of only some cysts with the filling of the pond, is one that is poorly understood. We do know that the cysts of some species of fairy shrimps will not hatch if they are kept in darkness or in water low in oxygen. Thus, those cysts that are buried in the mud, even under just a couple of millimetres, will be subject to darkness and low oxygen levels, and will therefore be unlikely to hatch. We also know that the cysts of certain fairy shrimps from the Namib Desert, even from a single batch laid by a single female, and kept under identical conditions, do not all hatch at the first wetting. Some hatch 'first off', some after only two, three, or even five or six wettings. The explanation for this versatility is quite unknown: it must be due to genetic variability or to some difference in the way that the eggs are treated within the body of their mother. It will probably prove that the cysts of ***Triops*** behave similarly, but given the very peculiar ways in which these animals have become adapted to their harsh and unpredictable environments, there are no doubt surprises still in store for us.

Apart from ***Triops,*** the crustacean order Notostraca consists of only one other genus, ***Lepidurus,*** and this does not occur in sub-Saharan Africa. ***Lepidurus*** looks very similar to ***Triops*** but it can be recognised by an elongate telson sticking out between the posterior sensory filaments. It may also occur in temporary waters, but the eggs do not need to be desiccated before they will hatch.

Other animals also live in temporary ponds in deserts like the Namib. Most of them are also crustaceans: ostracods (seed shrimps), copepods and cladocerans (water fleas similar to ***Daphnia***). They must all have effective adaptations that allow them to survive in temporary pools, in the same way that ***Triops*** does. We are learning more about them as time goes on.



Eggs from a single female Streptocephalus *were dried and rewetted a number of times (X axis). The number of eggs hatching during each wetting is shown on the Y axis. A few eggs hatched only after going through the wet / dry cycle six times.*

The larvae of many aquatic or semi-aquatic dipterans, particularly in the families Chironomidae (midges), Culicidae (mosquitoes) and Ceratopogonidae ('no-see-ums'), may use temporary waters for raising their young. Species of chironomid such as ***Chironomus imicola*** and ***C. pulcher*** from central and west Africa seem to breed only in small rain pools on rock surfaces, while the famous ***Polypedilum vanderplanki,*** from west Africa, can breed in even the most ephemeral waters because the larvae can become 'anhydrobiotic'. Apparently, the larvae can be dehydrated and, when re-wetted, slowly 'come back to life'. This can occur several times, so in the wild they merely dry out each time the pond dries up. No species of this kind is presently known from southern Africa. Various species of ceratopogonid (biting midges) are known to breed in temporary waters such as leaf axils, and larvae of the genus ***Leptoconops*** are largely confined to desert oases. The adults are bloodsuckers and can be mightily irritating to humans. They seem to be attracted to the sweat around the hairline and, for such minute flies (sometimes no more than 1 – 2 mm long), produce a remarkably painful bite, as well as an exceptionally high-pitched whine just before they attack. Larvae of ***Anopheles*** mosquitoes, which transmit malaria, are commonly found in temporary waters, even in holes in trees, in discarded tyres and small containers like tins and empty bottles.

A non-biting midge of the family Chironomidae – a close relative of the remarkable Polypedilum vanderplanki*.*

A biting midge of the family Ceratopogonidae ('no-see-ums').

FISH IN TEMPORARY WATERS

In southern Africa, only two genera of fish are confined to temporary biotopes, although individuals of others may become stranded, and survive, in pools in drying riverbeds. Members of both genera are confined to the north-eastern parts of the region. ***Protopterus annectens,*** the African lungfish, reaches its southern limit in the lower reaches of the Zambezi system and the coastal plain of Mozambique. They survive drought as adults buried in cocoons deep in the mud. Four species of the genus ***Nothobranchius,*** the annual killifishes, are known from the coastal plain of Maputaland northwards, as well as one each from the Kafue floodplain and the Caprivi. These gorgeous little fishes are normally confined to temporary pans, and their eggs can withstand desiccation while buried in mud.

The tadpoles of many species of frog are known to use temporary waters at least occasionally. Remarkably, given their dependence on water as adults, several species apparently breed only in temporary biotopes. This means that adults must be able to aestivate during the dry season. Members of several southern African endemic genera, including ***Vandijkophrynus, Poyntonophrynus, Capensisbufo*** and ***Phrynomantis*** in the family Bufonidae, breed in temporary pools; ***Phrynomantis annectens*** is found only in the driest parts of the Namib Desert. As adults, giant African bullfrogs, ***Pyxicephalus adspersus,*** stay buried up to a meter deep in the dry mud, emerging to feed and lay eggs in temporary pools formed after rain.

An African lungfish, Protopterus annectens.

'Lord Mountbatten' / Wikimedia Common

Drying habitat of the African lungfish in the Luangwa Valley, Zambia.

CONSERVATION OF WETLANDS

The perception of wetlands, particularly temporary ones, as unproductive mosquito-ridden mires to be drained and obliterated, goes back at least to Roman times. This perception was given further impetus during the attempts to eradicate malaria in the 1960s. Small, temporary waters were major targets for elimination, because it was recognised that these ecosystems are ideal habitats for mosquito larvae and pupae, and that mosquitoes are the vectors of malarial parasites. Only in the last few decades has it become fashionable to conserve wetlands. In the United States, for instance, duck-hunters have recognised the importance of wetlands as habitats for the ducks they shoot. Ironically, funds generated by the duck-hunting fraternity have ensured that wetlands are well protected in many parts of the United States and that money is available for studying and conserving wetlands and their biotas. Further, because people enjoy birds, to look at if not to shoot, the Ramsar Convention on Wetlands was instituted to allow countries to declare wetlands that are major bird habitats as Wetlands of International Importance.

SOUTH AFRICA'S RAMSAR WETLANDS (WETLANDS OF INTERNATIONAL IMPORTANCE)

In 1971, in conjunction with the IUCN, the International Waterfowl Research Bureau held a conference at Ramsar in Iran. At this conference, delegates decided that countries should be encouraged to identify those of their wetlands that are most valuable as bird habitats, and to designate them as Wetlands of International Importance. Such wetlands have since become known as 'Ramsar' sites and it is generally a matter of pride for a country to have wetlands that are so designated. Systems are accepted for listing only if they have a number of attributes, particularly concerning bird populations, and some likelihood of protection against degradation in the future. Today, to be declared a Ramsar site, a wetland has to meet a number of criteria that extend beyond birds.

As of 2022, 170 countries are signatories to the Convention. South Africa was the fifth Contracting Party, listing two sites as long ago as 1975. The country presently has the following 28 Ramsar sites listed (dates in brackets are dates of listing):

- Barbers Pan, North West (1975)
- Berg River Estuary, Western Cape (the latest addition, designated on World Wetlands Day, 2 February 2022)
- Blesbokspruit, Gauteng (1986) (Montreux Record 1996 because mining activities take place upstream and the site is contaminated by large quantities of polluted mine effluent)
- Bot – Kleinmond Estuarine System, Western Cape (2017)
- Dassen Island Nature Reserve, Wester Cape (2019)
- De Hoop Vlei, Western Cape (1975)
- De Mond/Heuningnes estuary, Western Cape (1986)
- Dyer Island & Geyser Island Provincial Nature Reserves, Western Cape (2019)
- False Bay Nature Reserve, Western Cape (2015)
- Ingula Nature Reserve, KwaZulu-Natal / Free State (2021)
- Kgaswane Mountain Reserve, North West (2019)
- Kosi estuarine system, Kwaulu-Natal (1991)
- Langebaan Lagoon, Western Cape (1988)
- Lake Sibaya, Kwazulu-Natal (1991)
- Maluleke wetlands, Limpopo (2007)
- Natal Drakensberg Park, Kwazulu-Natal (1996)
- Ndumo Game Reserve, Kwazulu-Natal (1997)
- Ntsikeni Nature Reserve, Kwazulu-Natal (2010)
- Nylsvlei, Limpopo (1998)
- Orange River Mouth, Northern Cape (1991) (Montreux Record September 1995 following the collapse of the saltmarsh component of the estuary as a result of adjacent diamond mining activities and flow regulation of the Orange River; the Namibian side of the estuary was declared a Ramsar wetland a month before this, in August 1995)
- Prince Edward Island (2007)
- Seekoeivlei (largest floodplain on the Highveld: Upper Vaal), Free State (1996)
- St Lucia system, Kwazulu-Natal (1986); added to the Montreux Record in July 1990 but removed in March 1996 when the threat of large-scale mining for heavy metals abated
- Tongaland's turtle beaches and coral reefs, Kwazulu-Natal (1986)
- uMgeni Vlei Nature Reserve, Kwazulu-Natal (2013)
- Verloren Vallei, Mpumalanga (2001)
- Verlorenvlei, Western Cape (1991)
- Wilderness Lakes, Western Cape (1991).


EcoSnap / 123RF

Traditional fish traps in the Kosi Bay estuary.

Ramsar sites that are degraded in one way or another, or under threat of degradation, are listed in what is known as the Montreaux Record. For instance, when South Africa was considering allowing sand mining in St Lucia, that system became listed but once the Cabinet decided not to allow mining there, the St Lucia wetland was removed from the record. Shamefully, the Blesbokspruit and Orange River Mouth sites, added to the Record more than 25 years ago, are still listed. They, and many other less spectacular South African wetlands, are under increasing threat of damage or destruction. It is hard to estimate the actual area of wetlands that has been irretrievably degraded, but the few studies that have been done at provincial or local level indicate loss of between 35% and 70% of wetlands in the areas examined.

It is worth noting that of the eight World Heritage Sites in South Africa, only one – the iSimangaliso Wetland Park – is based on aquatic ecosystems: those of St Lucia, the Tongaland beaches and reefs, Lake Sibaya and the Kosi system. Refer to Chapter 11 for more on wetland conservation.

MANAGEMENT ISSUES

Despite their value as dampeners of floods, and purifiers and storers of water, wetlands are frequently disturbed. 'Disturbance' can vary from minor physical damage in parts of a wetland, to its complete destruction. Below we describe briefly some of the ways in which wetlands are degraded.

DAMAGE TO WETLANDS

A common fate of wetlands is 'reclamation', either to be built on or to be used for growing crops. Essentially, the land is drained so that the original hydrological functions are eliminated and the land reverts to the terrestrial, rather than the aquatic, condition. This kind of 'reclamation' has happened to enormous numbers of wetlands in southern Africa and may be responsible for the apparent increases in frequency and intensity of floods in catchments where the practice has been particularly rife. Alteration in drainage patterns, often by the construction of canals, is a less drastic form of 'reclamation', although modification of flow patterns by manipulating the amount of water entering a wetland has a similar (if sometimes unintentional) effect. Damming a river may severely alter the character of wetlands downstream of the dam. Because of the dam, less water will flow into the wetland, and so channels may silt up and alter flow patterns. At the same time, wetland plants will be able to grow in the channels and may further clog them. If too little water enters the wetland then its water-loving plants will die and no longer be available to dampen floods or to store or purify the water.

The devastation of New Orleans by hurricane Katrina in 2005 was almost certainly greatly exacerbated by two wetland-related issues. The first is the destruction, mostly for agricultural purposes, of countless thousands of hectares of wetland in the basin the Mississippi River, on whose mouth the city is situated. Second is the fact that the city was built largely on peatland. As it was cut off from its water supply, the peat gradually decomposed, resulting in the city sinking by 2 m or more due to consolidation of the underlying soils as the peat disappeared. The land in large areas of the city is now below sea level. Intricate systems of levees were built to prevent ingress of the sea – and for a long time they were successful. But the combination of high water levels in the river, and a massive hurricane, breached the defences. Wetland scientists such as Bill Mitsch and John W Day Jr consider it unlikely that the city can be entirely rehabilitated, particularly given the continued increased rise in sea level that is expected as a result of global warming. Ironically, all the rehabilitation of the city that has happened since 2005 was unable to prevent new floods in 2010, although rebuilt levees seem to have provided some protection against floods caused by Hurricane Ida in August 2021.

Severe toxic pollution of wetlands is not common, except perhaps where acid effluents from mines drain accidentally into wetlands on water courses. Much more common is pollution by sewage effluents. If the effluents are well processed, then very little degradation will ensue. If, on the other hand, the effluent is still rich in nutrients, phytoplankton blooms or increased rates of growth of macrophytes can be expected. In either case, the rate of accumulation of organic matter will accelerate and may cause shallowing of open waters or increases in the density of wetland macrophytes.

Kyle Nieme / US Coast Guard

New Orleans flooded by Hurricane Katrina in 2005.

REHABILITATION OF WETLANDS

Since wetlands are such valuable features of the landscape, it is clearly useful to be able to restore damaged ones. It may not be possible to return a wetland to its pristine condition but it is usually possible to restore it at least to the point at which it is once again functional. Two South African enterprises are particularly worth mentioning in regard to wetland restoration or rehabilitation. The first is 'Working for Wetlands' (WfW), a programme of the South African Department of Forestry, Fisheries and the Environment (DFFE). Like the 'Working for Water' programme (see Chapter 10), Working for Wetlands is valuable both environmentally and socially, in that it employs unskilled labourers in the physical restoration of damaged wetlands. In this way, wetland function is re-established, while people learn new skills and are sometimes even able to develop small WfW-related businesses, such as cultivating the plants needed for rehabilitation projects. Secondly, in conjunction with WfW, the WRC recently funded a three-year wetland rehabilitation programme designed to provide the information needed for successful rehabilitation of wetlands. A series of documents emanating from this work is available on the WRC website (see the list of references and useful websites at the end of this chapter).

A note on terminology: some people get hot under the collar by the incorrect use (according to them) of the words 'rehabilitation' and 'restoration'. Since it is virtually impossible to restore a wetland exactly to its previous state, the distinction is really semantic, although the term 'restoration' usually implies an attempt to return a system to (something like) its original state, while 'rehabilitation' is intended to re-establish some degree of natural structure and functioning to the system.

ARTIFICIAL WETLANDS

Ironically, while many landowners have been spending time and money in efforts to destroy wetlands, others are beginning to spend even more in efforts to create artificial ones. In the United States it has become normal practice, and in some states a legal requirement, that if a wetland is to be damaged by development, a new wetland of equal size should be created, or an existing degraded wetland restored, at the expense of the developer to replace the lost one: the concept of "no net loss". Perhaps in places where all wetlands are much the same this is a perfectly reasonable thing to do. It seems strange to us, though, because wetlands have developed naturally where they have because of some combination of hydrological and landscape features. A new hole dug and kept filled with water cannot possibly have the same effect in the landscape as the original wetland did, nor is it likely to be able to support the same community of organisms. The reason that 'wetland replacement' is not acceptable is that the quality and kind of wetland is every bit as important as quantity. The impetus for the American legislation arose very largely through associations of duck-hunters throughout the USA. To them, presumably, any wetland with ducks is 'good', and certainly 'better' than one with no ducks: a matter of quantity rather than quality. On the other hand, we have to admit that a lot of different organisms colonise human-made wetlands, not seeming to 'care' whether the wetland originated naturally or as a result of human activities.

Artificial wetlands are also being developed for far more practical reasons. It is evident that the purification of water by wetlands can be of great economic benefit. The Aloeboom wetland, 134 ha in extent, on the Black Mfolozi River in KwaZulu-Natal, is an example. It was estimated as long ago as 1992 that the cost of cleansing effluent water from local coal mines was R2.6 million a year. The Aloeboom wetland performed the same task at no cost at all. This sort of calculation has resulted in developers, local authorities and landowners becoming keen on building artificial wetlands for purifying effluents of various kinds. So far, most extant artificial wetlands are being used for purifying sewage effluent and, by and large, they are very successful. The principle is simple. Stands of vegetation in natural wetlands and the associated wetland soils can cleanse water of nutrients and particulates, including bacteria. If we can provide the right conditions for the right plants, then artificial wetlands should be able to do the same. A great deal of research has been done on the topic and we already have many successful artificial wetlands cleansing effluents for communities that are isolated from regular sewerage systems. It should be noted, however, that constructed wetlands are unable to function under the freezing conditions found in colder parts of the world, and that there is a limit to the efficient size at which wetlands can be used for sewage treament. The use of constructed wetlands for processing acid mine drainage (see Chapter 7) is currently being investigated.

Constructed wetlands in Fuzhou, China, use fish and bacteria as well as wetland plants to purify sewage.

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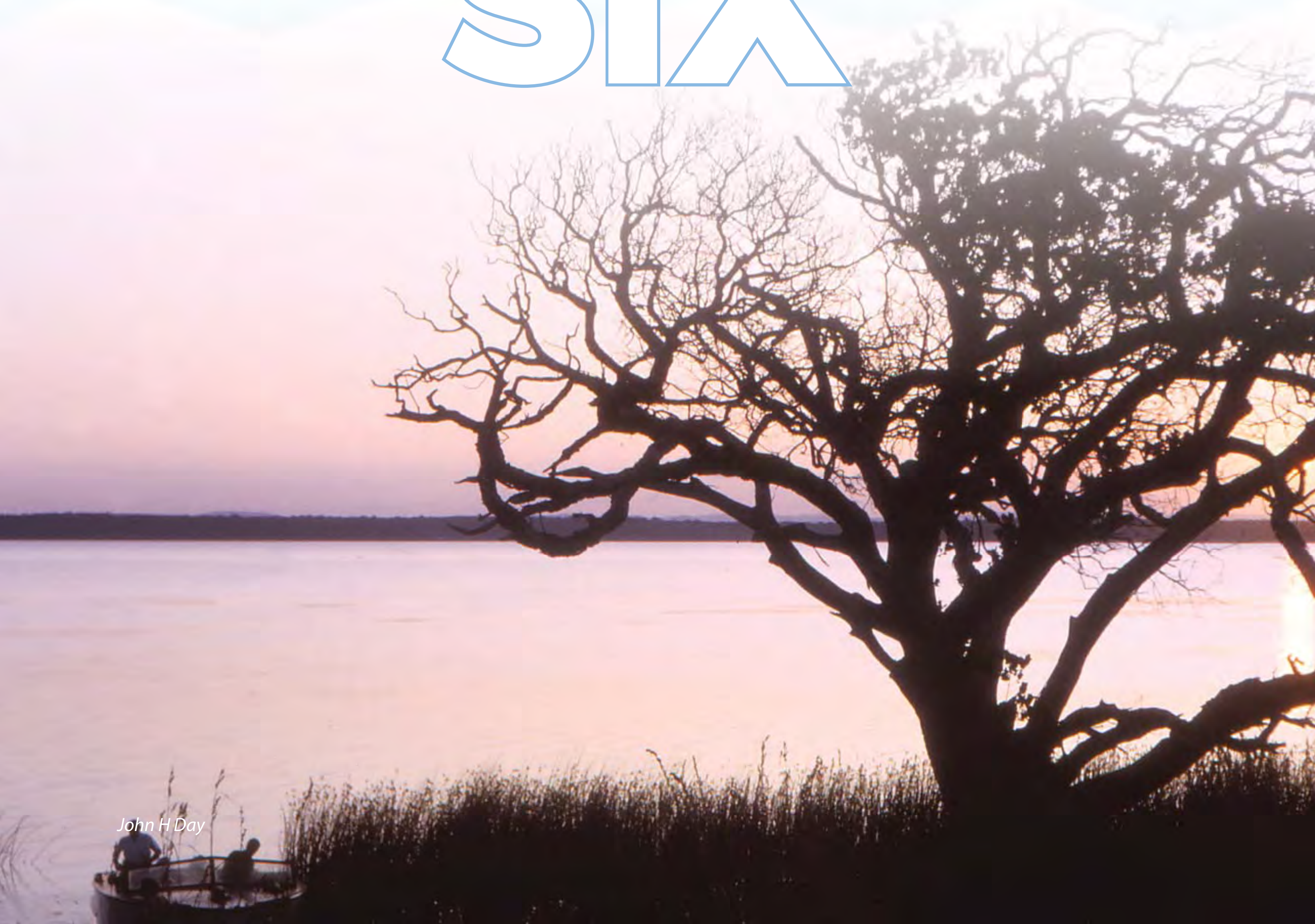
CHAPTER SIX



John H Day

Coastal lakes and estuaries

Naturae enim non imperatur, nisi parendo.
(We cannot command Nature except by obeying her.)

Francis Bacon

INTRODUCTION

This book is really about inland waters and not about the sea or about estuaries, which are strongly influenced by the sea. We include some information about estuaries in this chapter, though, because the histories of our coastal lakes are essentially the histories of estuaries. A number of books on South African estuaries have been written over the years. John Day's ***Estuarine Ecology with Special Reference to Southern Africa***, although published in 1981, contains valuable information on individual systems. Other comprehensive volumes are Brian Allanson and Dan Baird's ***Estuaries of South Africa*** and Alan Whitfield's recent ***Fishes of Southern African Estuaries.*** Other useful works on South African estuaries are listed at the end of this chapter.

Although inland lakes are rare in South Africa, estuaries and coastal lakes or vleis are well represented. Estuaries occur right around the coastline, mainly in the south and east. Many are small in area and seasonally closed, while others, such as Knysna Estuary on the south coast, and Morrumbene in Mozambique, are large and deep, and their mouths are permanently open to the sea. The best-known and most extensive coastal lake systems in South Africa are those of KwaZulu-Natal (the estuarine Kosi Bay and St Lucia systems, and Lake Sibaya), the southern Cape (the estuarine Wilderness Lakes and the Agulhas vleis), and the Cape Flats (Zeekoevlei, Princessvlei and Zandvlei). The coastal plain of central Mozambique also supports a marvellous array of coastal lakes (an example is Lagoa Poelela at Inharrime), however, we know very little about them.

Estuaries are the places where rivers reach the sea. They are normally influenced by the twice-daily rising and falling of the tide, having wide sand- or mudflats that are alternately covered and uncovered. Their waters are chemical mixtures of sea water and river water, the proportions of each changing with the tides. Their biotas are often rich in biomass and sometimes in species too. Estuarine organisms are adapted to these changing conditions, and many are found only, or largely, in estuaries. George and Margo Branch's book ***Living Shores*** has an excellent chapter on estuarine organisms.

Coastal lakes lie on flat, sandy, coastal plains and are either associated with extant estuaries or are themselves relictual estuaries. They are normally permanent systems and their biotas often include a typically estuarine element. In fact many, but not all, coastal lakes seem to represent a series of stages in the ageing of some estuaries, which is why we deal with both coastal lakes and estuaries in this chapter.

When rivers are large and carry a strong flow of water, their estuaries are characteristically wide, often with extensive mudflats exposed at low tide, and one or more fast-flowing channels carrying most of the water to the mouth. If discharge from the river should be reduced as a consequence of human intervention, or even because of an event such as a decrease in rainfall, then the scouring action of the water will also decrease and the estuary will become smaller because of the increased deposition of silt from upstream, or of sea

Jenny Day

The Knysna Estuary from the eastern head, with the mouth to the bottom left.

Jenny Day

An elevated view of Zandvlei in Cape Town.

sand coming in through the mouth. Eventually, if the process continues for long enough, the mouth will become blocked by sand and the estuary will close. At first this will be a rather unusual event (as it used to be, for example, at St Lucia) but later the mouth will close annually during the dry season (as it does in the Bot River and many other South African estuaries). Each time the mouth closes, sand builds up from the seaward side and so it takes a greater and greater flood of river water to open it again. Sooner or later opening of the mouth will become the unusual rather than the expected event, and the system will behave like a coastal lake rather than an estuary for most of the time. The Bot River and Verlorenvlei estuaries in the south-western Cape are typical examples of this stage of estuarine 'development'. Estuarine ecologists call these on-again-off-again systems 'temporarily open-closed estuaries' or TOCEs – a bit of a mouthful, but a clear description of what they are. Finally, the mouth closes permanently. If the estuarine basin is large, then fresh water from the river will accumulate here to form a shallow vlei separated from the sea by sand dunes, which eventually become vegetated and even more unlikely to be breached by floodwaters. The water will be brackish at first because of the trapped sea salt but later, as this is washed through the sediments, the water may become quite fresh. These are true coastal lakes and include systems such as De Hoop Vlei, Soetendalsvlei and Zeekoevlei in the south-western Cape, and Lake Sibaya in KwaZulu-Natal. Often the only direct evidence we have for the estuarine origin of such systems is the presence of certain species of invertebrates which, although they live quite happily in these waters, elsewhere live only in estuaries (see page 199). This process may be one-way from estuary to coastal lake, but it is also possible that cyclical changes in rainfall patterns may result in sediments in coastal lakes being breached and the lake returning to estuarine conditions. Alan Whitfield notes that "the pristine St Lucia system may well have closed off from the sea on a fairly regular basis in association with changes in decadal rainfall regimes."

EcoSnap / 123RF

A closeup of the artisanal fish traps constructed in Kosi Bay.

Jenny Day

Palmiet Estuary, south-western Cape, in the spring.

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De Hoop Vlei on the south coast.

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Verlorenvlei mouth open to the sea (mouth directly ahead), 1981.

Jenny Day

Verlorenvlei mouth now closed by a huge build-up of sand (one-time mouth left of centre), 2018.

Jenny Day

Lake Sibaya.

When the mouths of large estuaries close permanently, coastal lakes normally form. If, on the other hand, the estuary is small, or river inflow reduces because of reduced rainfall or abstraction of water, then it may silt up completely, becoming at first a marsh or swamp with a narrow channel to the sea (the Onrus Lagoon near Hermanus, for example), finally silting up completely and disappearing if river flow is small enough. Of course, in this instance no lake will form. In some cases, particularly in more arid areas, blind estuaries are occasionally breached by the sea. The accumulated water eventually evaporates each time and so, over long periods, considerable quantities of salt may accumulate.

This is probably the origin of a number of coastal salt pans like Rocher Pan on the west coast and Yzerfontein near Langebaan, and a number of salt pans scattered amongst freshwater wetlands on the coastal plain in the Cape Agulhas area.

Langebaan Lagoon, that magnificent stretch of sand flats and channels near Saldanha Bay on the west coast, is unusual in that it does not fit any of these categories. According to geomorphologists, millions of years ago the Berg River opened to the sea here, so that the lagoon was in fact the estuary of the Berg River. Nowadays no rivers enter the system, so it is essentially a partially land-locked arm of the sea. It behaves like an estuary, though, with its wide tidal mudflats, extensive salt marshes and typically estuarine fauna. It does not become excessively salty, despite the high rate of evaporation in the area, because of seepage of fresh water from aquifers beneath the landward slopes to the east.

Jenny Day

A tiny unnamed outlet to the sea on the Wild Coast near The Haven.

Jenny Day

Wadrif Soutpan, a saline lagoon at the mouth of the intermittent Langvlei River, north of Lambert's Bay.

Jenny Day

Field-collecting in the Soutpan, a saline coastal pan on the Agulhas Plain.

John H Day

Sand flats at Langebaan Lagoon looking north-west towards Saldanha Bay.

Jenny Day

Langebaan Lagoon with Schaapen Island and Langebaan village in the distance.

ESTUARIES, ESTUARINE PROCESSES AND ESTUARINE BIOTAS

In geomorphological terms, estuaries usually consist of a relatively deep permanent channel bordered by flat expanses of mud and sand that are inundated and drained by the rise and fall of water resulting from tides in the sea. Tidal fluxes, which are caused by the gravitational pull of the Moon, occur twice daily: the tide rises, covering sand- and mudflats, then falls, exposing them to the air, in concert with the orbiting of the Moon around the Earth. Chemically, they are dependent on the tidal movement of water: as water drains out of the river on the ebb tide, the water may be fresh or nearly so, while on the flood tide, seawater may reach some distance inland. Because seawater is denser than fresh water, water entering from rivers usually forms a layer of fresh water covering the heavier seawater, so that deeper waters of estuaries may be saline, while the upper layers are fresh, or nearly so.

The biota is mostly associated with the tidal flats and the waters above them. Where the force of the current is not overwhelming, the mud flats may be colonised by sea grasses or, nearer to the shore, by salt-marsh plants. Although any species living in an estuary must be able to cope with the salinity changes brought about by the tides, in all other respects estuaries are particularly favourable places to live. This is reflected in the large numbers of species, particularly invertebrates, living within the sediments – the so-called 'infauna' – and the high biomasses of zooplankton and fish supported by many estuaries. Southern African examples of very rich estuaries are Knysna on the south coast and Inhambane in Mozambique. Oddly, and for reasons as yet unexplained, large west coast estuaries like those of the Orange and Olifants rivers are depauperate in comparison with those further east, despite the fact that the sea on the west coast is particularly rich in nutrients and biomass, if not in species.

Mangrove swamps, characterised by a number of species of mangrove trees, develop on tidal flats in warmer seas and estuaries. The southernmost mangroves in South Africa occur at the mouth of the Mbashe River on the Wild Coast in the Eastern Cape.

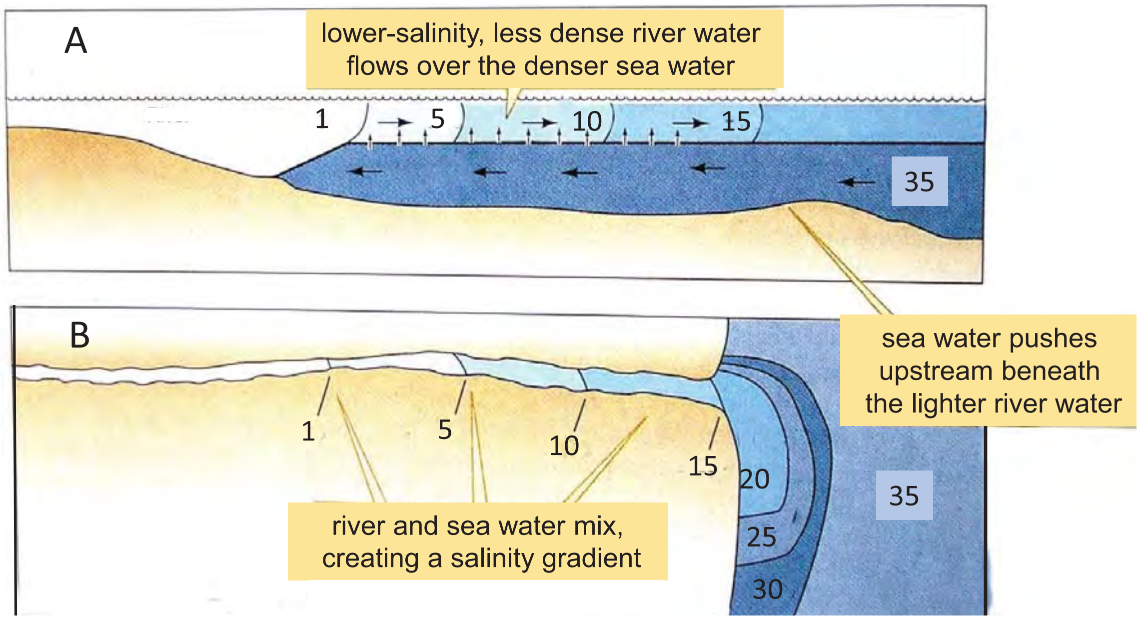


Diagram showing the 'salt wedge' in an estuary caused by less dense river water flowing over denser sea water. A) vertical profile and B) view from above. Numerals refer to salinity values.

Andrea Willmore / 123RF

An aerial view of Milnerton beach and lagoon, Cape Town.

A variety of invertebrates that lives on or in the sediments of sandy shores and estuaries. A) The parchment worm Chaetopterus variopedalis *(Polychaeta), which makes a tough parchment-like tube in which it lives and filter-feeds; B) Head of a large specimen of* Eunice aphroditois*, a carnivorous polychaete that lives under rocks and in shallow burrows; C) A burrowing bivalve* Lutraria lutraria*; D)* Polinices didyma*, a predatory gastropod that remains shallowly buried except when hunting; E) Fiddler crabs of the genus* Uca *dig burrows in firm sand and feed on surface particles; F) Pansy shells,* Echinodiscus bisperforatus*, burrow just under the surface of the sand and feed on small particles. These are dead shells but living ones are covered with a mat of pale brown spicules.*

The Orange River Estuary: its unimpressive size reflects the many upstream dams.

The Olifants River Estuary, looking north.

Sampling in mangroves, Merimbula, Australia; note the enormous prop roots that allow tidal currents to pass through without uprooting the trees, and that assist with oxygen exchange.

COASTAL LAKES AND THEIR FAUNAS

Some of South Africa's coastal systems, such as those of St Lucia, Kosi and Wilderness, are really estuarine lagoons. Exchange of sea water occurs throughout most or all of the year, but the very large sizes of the basins, relative to the channels feeding and draining them, means that they behave much as vleis and lakes do, although their organisms are essentially estuarine.

Unlike the lifecycles of most freshwater animals, those of many estuarine animals include marine planktonic larval stages: fertilised eggs hatch into minute, free-swimming larvae that live and feed in the plankton. This means that the estuarine lake fauna can maintain itself only if there is adequate connection with the sea at appropriate times of the year. Superimposed on their normal functioning as lakes, estuarine lagoons receive water from inflowing rivers, and exchange water with the sea. Both of these interactions may be very seasonal, so that water levels and nutrient regimes, and connections with the sea, may also vary from season to season. In estuarine lakes, stratification may also be more extreme than in freshwater lakes because a salinity gradient is often present.

Coastal lakes such as Lake Sibaya, De Hoop Vlei and Soetendalsvlei, with no interchange with the sea and with limited inflow from rivers, essentially function as freshwater lakes (see Chapter 3). The faunas of de Hoop and Soetendalsvlei on the South Coast are typical of freshwater lakes, if rather depauperate, while the fauna of Lake Sibaya is rich in both diversity and biomass. The fauna of Lake Sibaya, which was intensively studied in the 1970s by a team of biologists from Rhodes University led by the late Brian Allanson, is particularly interesting. Apart from typically freshwater insects and representatives of some minor groups like rotifers and flatworms, the lake supports a number of species of crustaceans and molluscs. While the molluscs are mostly of freshwater origin, and the decapods include the freshwater crab ***Potamonautes sidneyi,*** most are marine or estuarine species that have become adapted to living in the lake. The crab ***Hymenosoma projectum*** for instance, has close relatives living in most estuaries around the coast of South Africa, as do the tanaid ***Apseudes digitalis***, the amphipod ***Grandidierella lignorum*** and the isopods ***Cyathura estuaria*** and ***Exosphaeroma hyelocoetes***. ***Hymenosoma,*** like most other crabs, has planktonic larvae. Unlike the larvae of most crabs, however, those of ***H. projectum*** from Lake Sibaya do not need to go to sea and are able to survive entirely in the fresh waters of the lake, which other populations of ***Hymenosoma*** are unable to do.

When the previous edition of this book was published, ***Hymenosoma*** was considered to consist of one morphologically variable species – ***Hymenosoma orbiculare*** – that occurred in estuaries and along the coast of most of South Africa. As long ago as 1969, Burke Hill and Ticky Forbes, then of Rhodes University, noted that the larvae of ***Hymenosoma*** were unable to survive in fresh water and postulated that, since those from Lake Sibaya clearly can survive in fresh water, they might belong to a different species. Lo and behold, more than 40 years later Jessica Dawson from the Zoology Department at UCT showed that ***Hymenosoma*** does, in fact, consist of several species. ***H. producta,*** the one found in Lake Sibaya, occurs only from the Mzimvubu Estuary to Lake Sibaya and Kosi Bay. It would be instructive to see if larvae of this species are able to survive in fresh water in Kosi Bay, for instance, or if this physiological

Charles Griffiths

The Lake Sibaya crab Hymenosoma projectum.

Charles Griffiths

The freshwater shrimp, Caridina nilotica*, is found in Lake Sibaya.*

adaptation to fresh water occurs only in the population living in Lake Sibaya. Isopods, amphipods and tanaids never have planktonic larvae but, unusually for shrimps, neither does *Caridina nilotica,* a freshwater shrimp found in Lake Sibaya but also in rivers and lakes throughout the warmer regions of southern Africa. In summary, the crustacean fauna of Lake Sibaya, and of many other coastal lakes too, consists of species with no larvae, those in which larvae are suppressed, and those in which larvae are adapted to living in the restricted waters of coastal lakes.

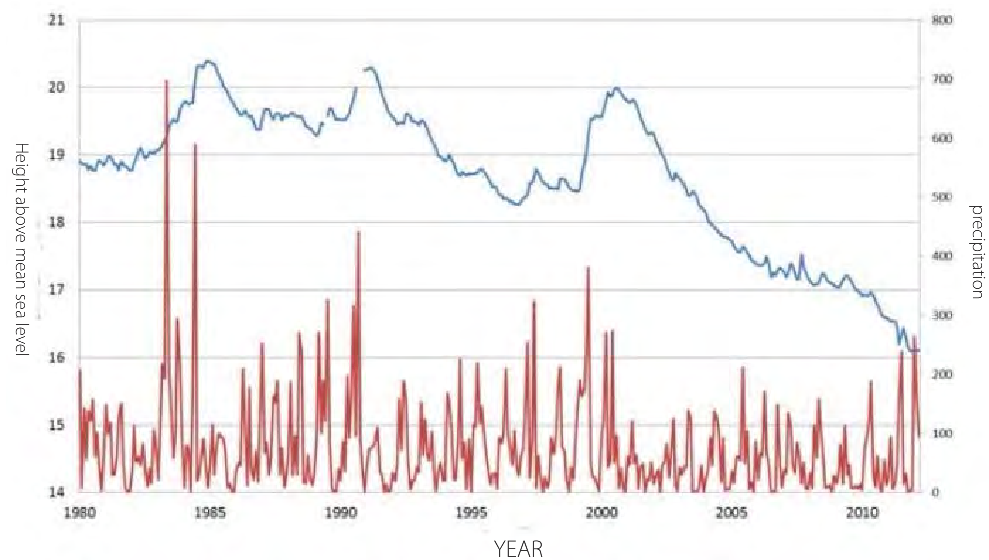
THE EFFECTS OF HUMAN ACTIVITIES ON COASTAL LAKES AND ESTUARIES

Coastal lakes are delicately balanced stages in the ageing of estuaries. As we saw in chapter 3, human manipulation tends to increase the rate at which lakes age, and this is true for estuaries too. The first indication that human activities are altering the balance can usually be seen in the accelerated silting of the mouth of an estuary as a result of agricultural activities in the catchment area. Most commonly, ploughing results in increased soil erosion, the displaced soil being washed down the river towards the mouth. If the river has also been dammed upstream for irrigation or domestic purposes, then the amount of water coming down the river is reduced, contributing to the rate of sediment build-up at the mouth. Even in those systems that (like Zeekoevlei, for instance) no longer have any pretence to estuarine status, premature ageing is very evident and is largely due to a second feature of human interference: eutrophication (see page 205 for details). Nutrients are taken up by plants (often phytoplankton) that sink to the bottom when they die and accumulate as organically-rich sediments. In extreme cases, organic sediments can be deposited at the staggering rate of nearly a metre a year. Obviously, as long as excessive quantities of nutrients enter the system, phytoplankton will continue to bloom and sediments to accumulate. Ultimately, the basin will silt up completely and the lake will cease to exist. This process may reduce the lifespan of a coastal lake from hundreds or thousands of years under natural conditions to perhaps a few

Jenny Day

Zeekoevlei – a paradise for freshwater yachtsmen.

Weitz & Demlie 2013



Declining water level (blue) in Lake Sibaya and precipitation (red) from 1980 to 2010.

decades where human interference is extreme.

In essence, closed coastal lakes have shifted from being open estuaries to being endorheic (i.e. closed) basins with inflow of water but little or no outflow. Of course, if inflow is restricted further by human activities, then the lake is likely to decrease in size, as seems to be happening to Lake Sibaya right now. According to Prof Mike Bruton, the lake is drying up because huge eucalyptus plantations are causing massively increased evapotranspiration in the catchment. (Much of the wood pulp derived from these trees is exported.)

An important consequence of a shift to a closed system is that pollutants accumulate instead of being washed away. This in turn means that coastal lakes are particularly prone to human influences and are particularly difficult to maintain in a natural or near-natural state. In the rest of this chapter, we address some of the effects of human activities on our coastal and estuarine lakes. The lakes of northern KwaZulu-Natal are mostly in protected natural areas and so are probably least disturbed, although there is a long history of mismanagement of the hydrology of St Lucia. The Wilderness lakes on the south coast are affected mostly by the abstraction of water for agricultural purposes, and by some degree of eutrophication. The lakes of the Agulhas plain lie in a marginal area for agriculture and are moderately disturbed. Those of the Cape Flats, though, are in the middle of the dense conurbation of Cape Town and are therefore severely polluted. It is mostly these last that we will discuss below.

POLLUTION AND ITS CONSEQUENCES

Development of waterside land for agriculture, recreation or housing virtually always results in pollution of one sort or another. Urban litter such as plastic bags, tins and bottles is unsightly, but unless it is excessive this sort of garbage does not have serious consequences for the functioning of an aquatic system. (Individual water birds, fish, hippos, and so on can be affected if they eat discarded plastic or become entangled in fishing line, of course) We humans are conscious of litter because it is the most obvious evidence of human care-less-ness. Clearing it may improve the appearance of our favourite vleis and rivers, and soothe our consciences, but its presence is often little more than a clue to other, invisible, forms of pollution. Pollution by toxic substances such as oils and heavy metals is extremely damaging when it does occur, but it is not at the moment a feature of most southern African coastal lakes, not least because heavy industry is unsightly and therefore seldom permitted in close proximity to areas used for recreation and housing.

The smaller estuaries are probably not seriously at risk from this kind of pollution, except when they are subject to unintended spills of toxic materials. The worst such case in South Africa occurred during the unrest in KwaZulu-Natal in mid-2021, when looters set fire to a warehouse storing agrichemicals, including herbicides and pesticides, on the banks of the Ohlanga River just north of Durban. Water sprayed onto the flames, mixed with the unburnt and partially burnt chemicals, sent a toxic mass down stormwater drains, into the river, and from there into the uMhlanga Estuary, destroying the biota and sending toxic debris into the sea and along the coast. 'Accidents' of this kind are inevitable but would be much less devastating if proper disaster-management plans were in place – and followed during a crisis.

Larger estuaries, like Knysna, with industrial and urban development on their banks, are probably not yet heavily polluted, but are cause for concern. The Knysna lagoon did receive chemicals such as creosote and chromated arsenicals dating back to the days when production of timber was the major industry in Knysna, but there is currently no evidence of pollution from this source. According to Ian Russell of South African National Parks (SanParks), the issue of greatest concern is nutrient enrichment: the lagoon receives effluent from the local wastewater treatment works and from contaminated stormwater from informal and poorly serviced settlements. Eutrophication is always a danger in estuaries with a preponderance of residential areas, particularly where sewage treatment services are not available, as is the case with many smaller estuaries. See the list of references for details of the large Knysna Basin Study lead by Prof Brian Allanson a few years ago.

The Buffalo Estuary is now the port of East London, and Durban Bay, once the delta-like estuarine bay formed by the Umbilo and Mhlatuzana rivers, has been expanded to form Durban harbour. Neither of these presently functions as a normal estuary, and must be at risk from long-term pollution, JMK / Wikimedia / CC BY-SA 3.0

Ohlanga lagoon.

Thabisa Goba / The Witnes

Ruins following the fire on the banks of the Ohlanga River.

as well as from accidental spills. The threat of spillage is always present in industrial areas. For example, some years ago, 4 000 litres of highly toxic chromic acid was accidentally spilled from a factory yard into a river flowing into Zandvlei, near Muizenberg on the Cape Flats. No obvious consequences have resulted, although at least some of the chromium must have entered the sediments, where they will remain until released by some future perturbation.

Furthermore, coastal development is leading to rapid urbanisation along the banks of many estuaries and coastal lakes. These banks are desirable places to live near, to retire to and to holiday in, but they are sensitive to many of the effects of urbanization. Effects of peri-urban development vary from habitat fragmentation and the interruption of migratory corridors for animals, to increased stormwater runoff into estuaries and coastal lakes, and the destruction of wetlands and salt marshes. A brief look at lakes like Zandvlei and Zeekoevlei, and the estuaries of the Eerste and Lourens rivers on the Cape Flats, bears ample testimony to these remarks. Even the tiny Buffels Estuary at Pringle Bay, where Bryan Davies lived, is subject to stormwater discharges from the village. In this case, as in many others, no environmental impact assessment (EIA) was ever carried out by the relevant municipal authority or the consulting firm concerned, despite the existence of national legislation that requires impact assessments to be performed in cases of this kind. The only saving grace is the fact that the Buffels system opens in winter during high discharges, allowing stormwaters to be flushed to the sea.

Obviously, all rivers are potentially subject to pollution from their catchments. Particularly severe effects of pollution arise, however, when the rivers empty into coastal lakes because the pollutants are retained here temporarily – or even permanently if there is no connection to the sea. Nutrients are often major pollutants, and eutrophication the major outcome.

EUTROPHICATION

Although pollution by toxins is not generally of major concern in coastal lakes and estuaries, eutrophication (refer to page 253) is an almost inevitable consequence of human activities. The nutrient loads that cause eutrophication may come from runoff from farms in the catchment area, from wastewater treatment plants, from gardens and septic tanks, and simply from untreated human and animal waste. Except in the case of sewage effluents, nutrients seldom arise from a single discharge point. Instead, they leach through the soil and into the ground water and thence into water bodies; for this reason are given the rather inelegant title of 'non-point-source' discharges. Because it is difficult to control or eliminate nutrients entering in this way, eutrophication will probably always accompany humans wherever they live. And, because nutrients constitute an invisible menace, we often take a while to identify eutrophication as a problem, and a much longer time to rectify it – if we can.

The consequences of eutrophication are predictable. In coastal lakes the plants normally include large rooted macrophytes (for example, the sago pondweed ***Stuckenia pectinata,*** previously ***Potamogeton pectinatus***), which are completely submerged in the water; emergent plants such as the reed ***Phragmites australis,*** the bulrush ***Typha capensis*** and the rush ***Juncus kraussii*** at the water's edge; minute phytoplanktonic algae and bluegreens suspended in the water column; and filamentous algae such as ***Cladophora*** floating on the surface. Under natural conditions, these plants use up most of the free nutrients in the system and so the extent of plant growth is limited by the quantity of nutrients available to them. Plants may replace each other in cycles, so that the suite of species in any system may vary from season to season or from year to year. Phytoplankton may bloom for a while, cutting down the light that submerged plants need in order to grow. The submerged plants therefore die back, releasing their nutrients that are then taken up by the phytoplankton and filamentous algae. Eventually the algae outgrow the nutrient supply, perhaps at a time when the temperature is unfavourable, so that they begin to die, and their rotting remains settle on the bottom. The water is now clear, so when nutrients are released from the decaying algae, the submerged plants may grow again.

This sort of cycle is natural and normal, but two things may happen to disturb it. On the one hand, when nutrients are always in good supply (in other words, in eutrophic systems) the algal blooms do not die down completely and so the cycle is broken: algae continually dominate the system so that the water may be as green as pea soup or covered with a thick green scum. ***Cladophora*** is the filamentous alga most commonly responsible for lime-green, bubbly scums on the surface of the water and must be well-known to those who frequent Milnerton Lagoon, Zandvlei or the Klein River Lagoon at Hermanus, or indeed any of the thousands of eutrophic wetlands thoughout the country. When it dies and dries it forms a thick, greyish felt-like mat on the banks. When single-celled algae die, however, they fall to the bottom, and build up there if oxygen concentrations are low. On the other hand, humans may interfere with the natural cycle by removing rooted plants because they are a nuisance: the plants become entangled in the propellers of outboard motors and in fishing lines; they choke channels so that sailing or canoeing is difficult; they may become uprooted and drift ashore, where they die, rot and form a noisome (smelly!) mess. Also, reeds may encroach onto the properties of shoreside homeowners, sometimes preventing access to the water. When we break these cycles by killing off the large plants, though, we are always in danger of invoking the 'Law' of Unintended Consequences. The entire history of human manipulation of the environment, and much of economics too, is an illustration of this law, which says that manipulation of complex systems usually leads to unexpected, and often unwanted, outcomes. This book is full of examples of that law in action. Here are two more.

Jenny Day

Decaying Cladophora*, a filamentous alga, in the saline Wadrif Soutpan, a lagoon at the mouth of the intermittent Langvlei River, north of Lambert's Bay.*

Dead Cladophora *forms a grey, felt-like mat that smothers any plants that it covers.*

ZEEKOEVLEI: A CASE STUDY

The first case concerns Zeekoevlei on the Cape Flats south of Cape Town. Zeekoevlei was a small estuarine lagoon, discharging into the northern shore of False Bay during the winter rainy season. When it became a popular residential and yachting area in the 1920s, the City Fathers constructed a weir at the outlet of the vlei, stabilising the water level for the yachtsmen and homeowners, cutting it off from the sea and ultimately causing it to become a coastal lake. The vlei lies adjacent to the Cape Flats WWTW and nutrients from the purified effluent seeped into the vlei for decades. In the late 1950s the vlei was affected by a massive growth of the pondweed ***Stuckenia pectinatus.*** This stringy, rooted, cosmopolitan weed gets tangled in rudders and propellers and is generally a nuisance for boaters, although it is a useful source of food for some ducks, and a refuge and food supply for numerous species of small aquatic invertebrates and the fish that feed on them.

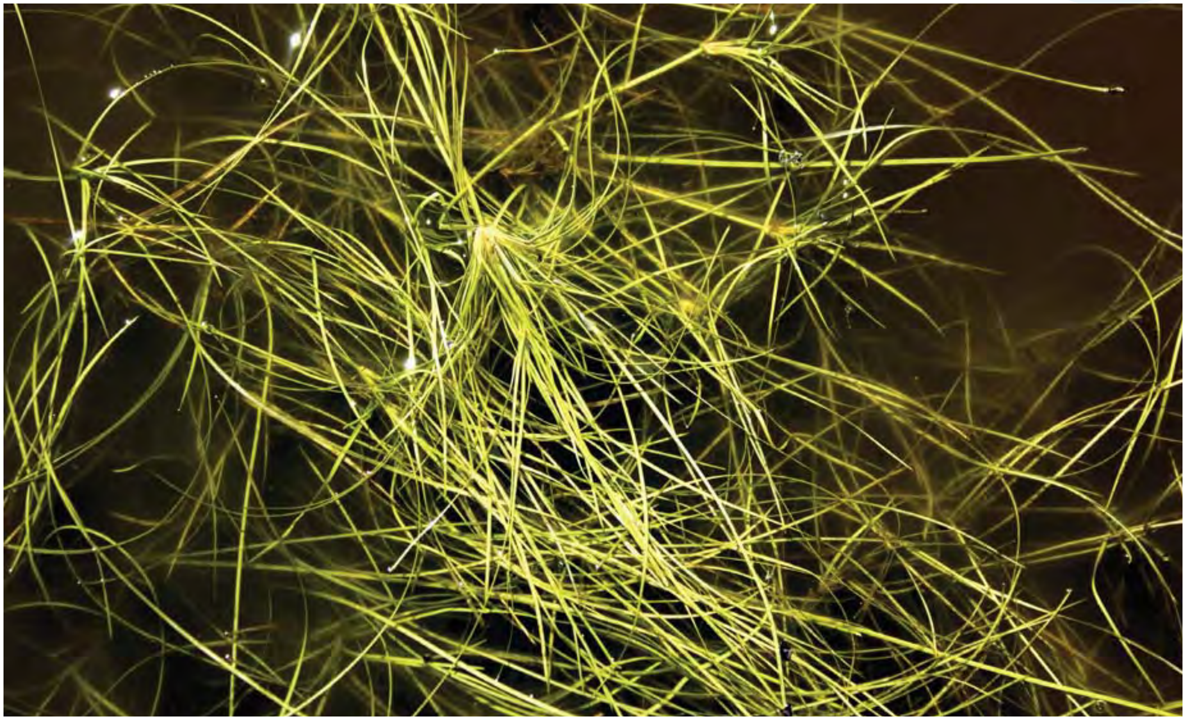
Unbelievable to us today, the vlei was treated with sodium arsenate, a salt of arsenic, to kill off the pondweed. This procedure was effective: ***Stuckenia*** did not appear in the vlei for decades and even today is found only sporadically and in small patches. And today, more than 70 years after it was introduced to the vlei, the arsenic lies well and truly buried in the mud (arsenic, being an element, does not decay). This would have been a masterly, if questionable, solution to the pondweed problem were it not for the fact that large quantities of nutrients still entered Zeekoevlei, and other organisms – members of the phytoplankton – were just waiting to take over. Algae usually dominate eutrophic systems to the extent that rooted plants cannot become established, and this is exactly what happened in Zeekoevlei: its waters have supported massive blooms of green-pea-soup-like algae on and off ever since the ***Stuckenia*** was killed by the arsenic. In essence, when conditions are eutrophic we have a choice (if we are lucky) between massive growths of weeds or massive algal blooms, or sparkling clean, chemically-treated, aseptic water with no plants and no animals. (But for how long would the water stay sparkling if there were no organisms to clean up the organic material inevitably entering the vlei?)

Sidney Jacobs

The banks of Zeekoevlei, looking south, with Rondevlei in the middle distance.

That is not the end of the story. A particularly villainous kind of organism adds a further complication to the saga of Zeekoevlei (and of many other eutrophic systems throughout the world). This is ***Microcystis,*** one of the blue-greens. The blue-greens, or Cyanobacteria (see page 209), used to be known as 'blue-green algae', because they are a darkish blue-green in colour, and look very like algae. They are, in fact, photosynthetic bacteria and not algae at all, although they behave (or misbehave) very much as algae do in eutrophic waters. The dominant species of phytoplankton in Zeekoevlei is ***Microcystis aeruginosa***. Because of its ability to bloom in eutrophic conditions, ***Microcystis*** has produced bothersome 'pea soup' conditions in Zeekoevlei for many years.

Cyanobacteria have a number of other nasty characteristics, too. They can float to the surface, where they may be gathered as windrows into thick scums that look as if someone has spilled vivid green paint on the surface of the water. (In the 1980s, 20 cm-thick scums of ***Microcystis*** covered large areas of Hartbeespoort Dam in North West.) The surface of the scum eventually dries out, forming a crust, and the cells below die and decay, producing revolting smells. Decay of large blooms can use up all of the oxygen in the water, and result in fish dying. They may also clog water-purification plants as well as producing unpleasant tastes and odours in the water. Some years ago, Bill Harding produced an elegant PhD thesis on the phytoplankton of Zeekoevlei. Some of the papers he wrote on this work are listed in the Reading List at the end of this chapter.



The pondweed Stuckenia pectinata *(previously* Potamogeton pectinatus*).*

An awkward feature of the blue-greens is that many of them can produce toxins (see Chapter 7). This fact has been known for a long time but, except for isolated incidents (the first report being from Australia in 1878), cyanobacterial blooms had not been noticeably toxic, even under severely eutrophic conditions. In recent years, though, toxic blooms have been recorded from various parts of the world. The most sensational was in Australia where, in 1991, more than 1 000 km of the Darling River supported a bloom of toxic cyanobacteria of the genus ***Anabaena.*** Drinking water had to be trucked to towns along the river, for both humans and their stock animals. The deadliest bloom reported so far resulted in the deaths of 43 people in Brazil after water contaminated by toxic blooms was used in kidney dialysis machines. How's that for an Unintended Consequence?

More recently, toxins from ***Microcystis*** have been identified in Zeekoevlei, and in 1996 several pet dogs died from drinking the water although to date, the water of Zeekoevlei seems to have posed no danger to humans. Of more concern is the presence of ***Anabaena*** toxins in Theewaterskloof, one of the major sources of drinking water for Cape Town. We should point out that the authorities are intensely aware of the potential danger from these blooms. Water from all of Cape Town's major supply reservoirs is regularly tested for cyanobacteria and, if these are detected, for toxins. If toxins are present, the water is filtered through activated charcoal, an expensive process that effectively removes the toxins before the water is distributed to the city. These toxins clearly represent a major headache for managers of the City's water supply.

Cyanobacterial toxins also represent a biological conundrum. Firstly, no-one has yet figured out exactly what advantage the toxins confer on the cyanobacteria themselves. (From an evolutionary point of view, it does not help a particular algal cell to produce a toxin, no matter how virulent, if the cell itself is not protected by its toxins from being consumed by some larger organism) It is, of course, possible that some of the toxins have normal metabolic functions within the cyanobacterial cells, and recent work by Kaplan and co-authors (Kaplan ***et al.,*** 2012) certainly indicate that this is so. Many species of cyanobacteria produce one or more types of chemical that are super-toxic (a real case of overkill) to a wide variety of other organisms, including insects and fish. Some of the major types are the hepatotoxins (which damage the guts and livers of vertebrates, and are implicated in liver cancer as a result of chronic exposure), neurotoxins (which damage the nervous systems and brains of vertebrates) and endotoxins (which cause respiratory and skin problems in humans).

Jenny Day

A scum of the blue-green Microcystis aeruginosa *in Zeekoevlei.*

A species of the filamentous blue-green, Anabaena.

Although few human deaths have yet been attributed to cyanobacterial toxins, it is known that some of them are powerful carcinogens (promoters of cancer), even in minute doses. Several studies have shown an alarming correlation between the high incidence of liver cancer in parts of China and the consumption by the local people of untreated, eutrophic water contaminated with cyanobacteria. It seems that they have been consuming minute doses of the toxins over long periods, and are therefore suffering from chronic effects. Secondly, we do not know if certain strains are always toxic and others are not. It seems that some strains are unable to produce one or more of the toxins regularly produced by others, but it is not clear if those that are able to produce toxins can switch the relevant gene on and off and, if they can, what the trigger might be. Thirdly, it appears that more toxic strains exist now than in the past. This trend might be an artefact resulting from an increased interest in cyanobacterial toxins, and our increased ability to detect them. Then again, it might not.

Clearly, it is the accumulated nutrients in the water and sediments of Zeekoevlei that continue to encourage the growth of blue greens. Thus a few years ago City officials began an annual drawdown of the water in the vlei by opening the sluice gates and allowing water (and accumulated nutrients) to flow out to sea. For the first couple of years this was remarkably effective: the remaining water became much clearer; pelicans came to the vlei in large numbers; and much of the water hyacinth was left high and dry. The effects of drawdown have been less impressive in recent years, perhaps because of the relatively short period of drawdown, the very flat nature of the terrain (which means that flushing is inadequate) and decreased rainfall. In 2008, the sluices were enlarged so that deeper water and more of the sediments could be flushed out, and more recently still, nutrient-rich seepage from the waste-water treatment plant on the south bank has been controlled. Even this is not providing the result required, and the Council is considering removal of the accumulating sediments by dredging. Dredging is a common management strategy for shallow lakes, but is not always physically easy to do. It is also expensive, and it is merely a short-term solution, because sediments will continue to accumulate as long as nutrients keep being added to the system. A relatively small dredging operation in one part of a single bay in Zeekoevlei cost several hundred thousand Rand in the mid-1980s. (The present-day cost of removing sufficient sediment to make a significant difference has been estimated at something like R80 million.) Furthermore, after the original dredging operation, water currents within the lake soon redistributed sludge from undredged areas so that, after a few months, the dredged section had received a new layer of sludge up to half a metre thick.

And what is to be done with the enormous quantities of spoil? In several dredging operations in the Western Cape, the dredged sediments have been dumped into specially-dug holding basins on the sides of the vleis concerned. Such areas may become extremely dangerous, forming quicksands that stay unstable for years, and requiring fences and warning signs to ensure that neither people nor their animals stray onto them. Dumping spoils too close to the edge of the vlei being dredged may also negate the effects of removing the nutrient-rich sediments, since those very nutrients can leach straight into the ground water, and from there back into the vlei from which they were expensively removed, and within which they caused the problem in the first place.

Siltation has other effects, also evident in Zeekoevlei. Emergent macrophytes include reeds such as *Phragmites australis,* bulrushes like *Typha capensis*, and sedges like *Schoenoplectus littoralis* (previously *Scirpus littoralis*) and *Juncus kraussii*. Like any other plants, reeds need nutrients in order to grow. Unlike most others, however, they can become established in very shallow water. Now the shores of

Jenny Day

Drawing down the water level in Zeekoevlei by removing wooden sluices; note the green colour of the water, which is mostly due to Microcystis.

Zeekoevlei are becoming increasingly shallow as a result of siltation while, as we have seen, nutrients continue to build up. These are ideal conditions for the reeds, which 'march' into the vlei, taking up nutrients, growing rapidly and gradually encroaching lake-wards in the ever-increasing shallows. Few people particularly like reeds because they can become impenetrable: the water's edge is unreachable, boats cannot be launched, and the reeds get in the way of powerboats, fishing lines and swimmers. They also obscure the view of the water.

But is the solution to get rid of the reeds? For one thing, this is easier said than done because reeds have a tenacious grip once they have become established. But far more important is the fact that reedbeds form a natural filter, not only for beer bottles and Coke cans but also for sediment and nutrients: water filtering through a reedbed drops most of its sediment and, by their own growth, the reeds remove a high proportion of incoming nutrients. Thus, dense reedbeds in appropriate places can protect a vlei very adequately from the effects of nutrient-rich water entering *via* rivers and drainage canals. (Reedbeds are the basis of artificial wetlands, which are increasingly being used as a cheap and highly effective method of purifying sewage or sewage effluent and for protecting aquatic ecosystems from the effects of excessive loads of nutrients: see Chapter 5.) Is it, then, such a good idea to remove the reed-beds? The answer is often 'no', although waterside homeowners would disagree.

Jenny Day

Fluitjiesriet, Phragmites australis*, a very common reed in much of southern Africa; note that 'australis' refers to 'southern' not Australian!*

In summary, in many places *Typha* (bulrushes) has replaced ***Scirpus*** and other macrophytes around the margins of the vlei, while algae have replaced ***Stuckenia*** in the more open waters. Dead algae form the bulk of the accumulating sludge on the bottom and the reeds take advantage of the ever-increasing areas of shallow water where they can become established. A vicious cycle has been set up. To conclude the story of Zeekoevlei, we should mention its close neighbour, Rondevlei. Rondevlei is now a separate vlei but until early last century, it was a westerly arm of Zeekoevlei, the two being connected by a shallow and fairly narrow channel. By the 1940s, but before Zeekoevlei became dominated by phytoplankton as the result of the assault on ***Stuckenia*** with arsenic, the narrow neck of land between the two had become vegetated by acacias, a road was built on it, and the two vleis have been separate since then. Rondevlei was declared a bird sanctuary in 1952 and has been managed as a natural area ever since. It, too, receives massive loads of nutrients from its influent rivers. Whereas Zeekoevlei has been phytoplankton-dominated, for decades until the early 1990s Rondevlei maintained large beds of ***Stuckenia***. But fringing reed-beds, which had until then largely comprised the relatively well-behaved sedge ***Schoenoplectus littoralis,*** began to be dominated in some places by the finger grass, ***Paspalum vaginatum,*** and in others by ***Typha capensis,*** the bulrush – or cat-tail, as the Americans call it.

In the Western Cape, *Typha* is a typical pioneer plant, finding its way into almost every perennial patch of nutrient-rich water and soon colonising most of the shoreline. It did this in Rondevlei, and soon birdwatching became difficult because it was impossible to see the wading birds over the tops of the bulrushes. The managers built elevated hides, and all was well for a while. Then more of the shallows, where the waders feed, became colonised by ***Typha*** and ***Paspalum,*** and the waders began to disappear. In 1981, two hippos were introduced to the vlei to control the ***Paspalum.*** This has been a great success story: ***Paspalum*** has virtually been eliminated and the hippos have bred. Some have been sold to defray expenses and the remaining ones continue to keep the grass under control.

In the mid-1980s, Debbie Hall, a PhD student in the Freshwater Research Unit at the University of Cape Town, investigated the control of ***Typha*** in Rondevlei. Among other things, she found that the plant was spreading lake-wards at a mean rate of 1.5 m a month. Interestingly, the most effective, and also the most environmentally friendly, method of control was to cut the rushes below the water line. Today, ***Typha*** continues to encroach in Rondevlei but is controlled by cutting and bulldozing. As for ***Stuckenia,*** it disappeared for many years, but the water is currently clear and the weed is back in some quantity It will be interesting to see if the old cycle of weed and phytoplankton reasserts itself, or if the weed will be able to maintain itself.

Eutrophication is a problem in lakes and reservoirs throughout the world. Some years ago, Lindah Mhlanga completed a PhD thesis on the hyper-eutrophic Lake Chivero, a reservoir that holds the water supply for the city of Harare in Zimbabwe. Ironically, just as she was starting her work, ***Microcystis*** almost disappeared from the lake and was replaced by other algae, even though nutrient concentrations were as high as ever. We still do not really know why this happened. Until more work can be done on the system, we have to file it under 'unexpected results' – yet another unintended consequence of too many nutrients in a confined space.

SWARTVLEI: ANOTHER CASE STUDY

The second example of coastal lakes resulting in management 'headaches' comes from Swartvlei, an estuarine lagoon that is one of the Wilderness Lakes in the southern Cape. During the 1970s, and indeed for many decades before that, the lake supported very dense and ecologically important stands of ***Stuckenia pectinata***, which stretched right around the shallow margins of the lake, down to a depth of about three metres. The depth limit was dictated both by the lack of light (true to its name, Swartvlei is a black-water coastal lake), and by a halocline (fresh water on top, salty water at the bottom) in the deeper waters because it is an estuarine lagoon. The plants form a substratum for the invertebrates of the system (interestingly, several are the same species as those found in Lake Sibaya), which in turn provide food for more than 30 species of fish. Controversy arose in the local community when a report (written by an engineer) claimed that the plant was encroaching upon the vlei – which it was not – and should be controlled. Ironically a very few years before, in the early 1980s, the same beds of ***Stuckenia*** disappeared from the lake, for no apparent reason. Associated with the decline in ***Stuckenia*** was a collapse of the invertebrate assemblages that were dependent on the plant, and that formed the major food source for many of the fish in the lake. Indeed, the invertebrate biomass declined by an order of magnitude in summer and by two orders of magnitude in winter, representing a loss of approximately 250 tonnes dry mass of invertebrate tissue from the littoral zone of the lake. Of course, the number of fish in the lake, including popular angling species, decreased. Human activities may have had some effect on ***Stuckenia*** in the Wilderness Lakes; it seems, though, that ***Stuckenia*** is one of those water plants (the sea grass ***Zostera*** is another) that come and goes in cycles, for reasons that we still do not understand. So, the decline was probably due to natural long-term fluctuations in the physical environment and in the biological interactions within the system. Who knows? We still have a lot to learn about the responses of plants and animals to natural cycles and to human interference.

At about the same time, still in the bad old days, a Very Important Politician, PW Botha, was sailing on Eilandvlei, one of the Wilderness lakes, and became firmly stuck in the weed-beds. He and his entourage were eventually rescued from their predicament, and a few weeks later a call was made from very high office to eradicate the 'nuisance weed' as it was a menace to recreation. Despite considerable pressure, the advice of ecologists – leave the weed alone – prevailed; this was probably the only time in this politician's career that he was foiled by science. He was also foiled on another occasion, this time by brave nature conservationists. The story is told by John Allen himself, then a conservationists with SanParks. It seems that one evening John was patrolling along the shore of one of the Wilderness vleis when a large black car towing a boat trailer drew up at the edge of the vlei in order to launch the boat. John very politely pointed out to the boatsmen that it was not legal to launch a boat into that vlei. He was clearly not going to allow it to happen, so the back door of the car opened, and a large man emerged, saying, "Do you know Who I am?" "Yes I do, Mr Prime Minister", said John. "And even you, Sir, are not permitted to have your boat on this vlei." Nonplussed, Botha got back into the car and they all drove off. Sure enough, a couple of days later, Robbie (Turkey) Robinson, then head of National Parks in the Province, got a call from On High indicating that John Allen was to be dismissed forthwith.

Robbie informed the caller that if John were to be dismissed, Turkey would resign too. Both kept their jobs. And I can't resist mentioning that in 1990, when Turkey was appointed as CEO of National Parks, one of his first actions was to oust the South African army from the Kruger National Park. They had built a rest camp for themselves and their political masters, who used the camp as a free, private holiday resort. Remember that this was still in apartheid days. Turkey Robinson was a very brave man.

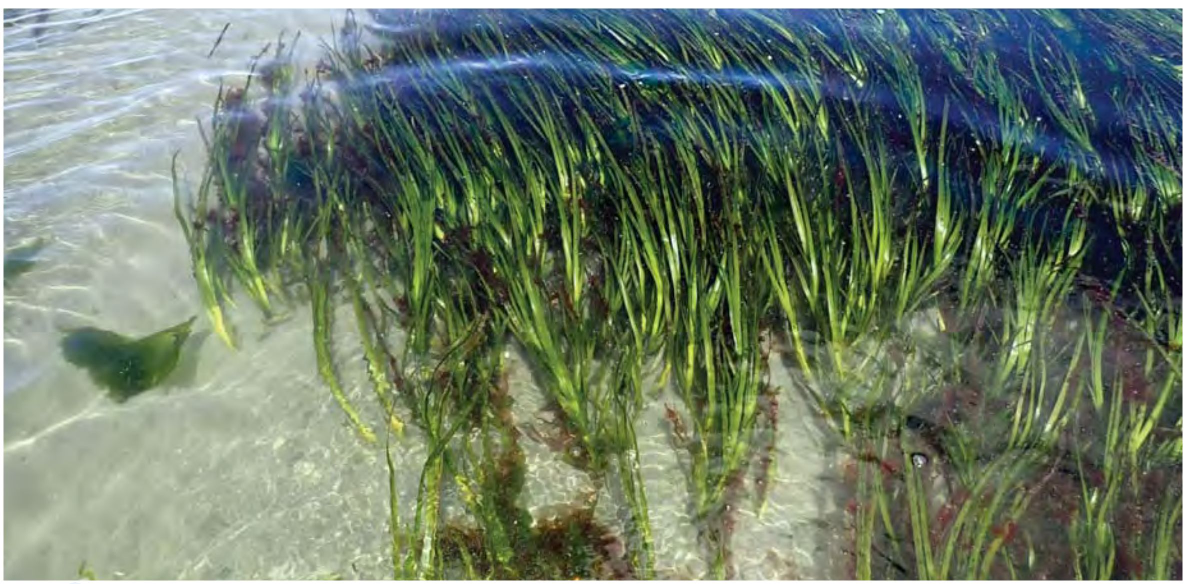
dpreezg / 123RF

Swartvlei, the largest of the lakes in the Wilderness Lakes area.

John H Day

A bed of the sea grass Zostera capensis *on the shore of Knysna lagoon.*

John Brew / Wikimedia / 4.0 International CC BY 4.0



Zostera marina *under water.*

MANAGEMENT OF COASTAL LAKES AND CATCHMENTS

Our coastal systems are very heavily used in a variety of ways: as residential areas (Zandvlei, Knysna, Swartvlei, the lower parts of Lake St Lucia and the estuaries of southern KwaZulu-Natal, for instance), including marina developments and holiday homes; as nature reserves and national parks (Rondevlei, Langebaan Lagoon and St Lucia); and as recreational centres for fishing, sailing, windsurfing, canoeing, rowing, power-boating, swimming, picnicking, bird-watching, having a braai or simply walking the dog. So, these natural systems are coming under extreme pressures from various groups of people, many of whom have conflicting aspirations, some of which are in direct conflict with the needs of the lakes and estuaries themselves. (There is nothing scarier than a 'discussion' among Concerned Citizens, each of whom knows that he or she is right and that the others are idiots with nasty hidden agendas.) Furthermore, many early developments were ill-conceived, badly planned and poorly executed – often for short-term profit but sometimes out of ignorance. The situation has been greatly improved by the National Environmental Management Act (NEMA: Act 107 of 1998) and its subsidiaries, which act as watchdogs and controllers of developments. The NEMA legislation opens with the statement, "In terms of the Bill of Rights included in the Constitution of the Republic of South Africa, 1996 … the citizens of South Africa have … the right to have the environment protected and to live in an environment that is not harmful to human health or wellbeing." NEMA, particulary the provisions with regard to Environmental Impact Assessments (EIAs) has certainly been effective, although there are still loopholes and ways of ignoring (or wilfully misreading) the recommendations from EIAs. (See chapter 11 for more on environmental legislation in South Africa.)

Jenny Day

Zandvlei: Marina da Gama (upper reaches of the Zandvlei estuary) under development in 1979.

When we wrote the previous edition of this book, we noted that "no single agency has an overview of, or authority to act on, the overall management and planning" of Zeekoevlei and we made a plea for management of aquatic ecosystems at the catchment level. Soon afterwards, late in 1998, the new National Water Act (Act 36) was promulgated, making provision for management of aquatic ecosystems ***at catchment level*** (see chapter 11 for more detail). Indeed the City of Cape Town now has a Catchment Management branch. We have come a long way in the last 20 years or so and the piecemeal management of the last few decades is a thing of the past. This does not mean, of course, that the actual challenges to good management are any less than they were, but they are perhaps less difficult to handle.

Management of the water bodies in any large city is a major challenge. It helps that those of Cape Town are under the control of either the City of Cape Town or the Table Mountain National Park. It also helps enormously that the metropolitan area is virtually a mountainous island. Why should this be significant? It is because, unlike many other cities, Cape Town does not have rivers that originate elsewhere, so the local authorities can now control what goes on in their entire lengths. (Of course, this also means that the management buck cannot stop elsewhere than with the City managers!)

WHY WE NEED TO KNOW MORE ABOUT ESTUARINE AND COASTAL LAKES

Let us return to Zandvlei and other coastal systems to make another point. Ecologists are still far from understanding the fundamentals of the ways in which aquatic ecosystems function. This is not merely a gap in our esoteric knowledge, but it is of real practical concern. Until we clearly understand how such systems work, it will not be possible to provide adequate advice to planners or managers. We have even less idea as to how increased temperatures and sea levels, reduced rainfall, and more extreme weather events, will affect these systems. An example will illustrate the point.

The canals of Marina Da Gama in Zandvlei, and the main body of the vlei itself, were regularly choked with ***Stuckenia,*** which made it difficult to get watercraft to and from the shore and to sail, row or windsurf. Furthermore, the weed acted as a substratum for nuisance algae such as ***Cladophora*** and ***Enteromorpha,*** which began to grow in abundance. In the late 1970s, Cape Town City Council, which was primarily responsible for the management of the vlei itself, purchased a mechanical weed-harvester and began to remove massive amounts of ***Stuckenia.*** In the early 1990s, the weed began to disappear from parts of the vlei but by 1996 it was present again. As we mentioned above, a similar thing seems to have happened in Swartvlei in the 1980s. No-one yet really understands why it appears and disappears. Is this disappearance part of a natural cycle, or one imposed by some undetected climatic change or by human-induced perturbation? By the same token, no-one had any real idea of the importance of the weed in maintaining water quality within Zandvlei and its adjoining canals.

Experiments carried out by our group in the Freshwater Research Unit at the University of Cape Town, in conjunction with staff of the Scientific Services Branch of Cape Town City Council, provided at least part of the answer. The beds of ***Stuckenia*** provide a substratum for fairly dense populations of invertebrates consisting predominantly of filter-feeders – animals that derive their food by sifting particles from the water column – such as ***Ficopomatus enigmaticus***. As they feed, they strain particles of silt as well as food, and so clarify the water. It has been shown that cutting the weed right down to its roots does not improve water quality because the filter-feeders have no weed on which to live, and so their populations crash. Considerable improvements can be achieved by 'trimming' the tops of the plants to a depth that does not interfere with the passage of boats. The plants themselves remain in a reasonably healthy condition and they still provide physical support for the filter-feeders, while the plants' own photosynthetic activities oxygenate the deeper water of the canals and keep it relatively clean.

Good news on the estuarine front is that Zandvlei, after 50 years or so of inadequate management, is once again a beautiful estuary. It only needed a clear understanding of how the system would work naturally, and clever management of the mouth, to achieve what once seemed unachievable. It now has a tidal regime; it is a nursery for juvenile fish; the sand prawns are back. Applying science to management challenges really does work.

Jenny Day

Open mouth of the Zandvlei estuary.

And just how important are the reedbeds to the north and west of the vlei? How much do they assist in the cleansing process that goes on before the inflowing waters reach the vlei? How important is it, for the biota of the system, to widen the connection with the sea? To what depth, and how often, if at all, should the vlei be dredged? Questions relate to other systems, too. When, and how often, should coastal systems like Swartvlei and the Bot estuarine lake be opened to the sea? Should we interfere at all or should we let nature take its course, given that we have already interfered with the systems so that they are no longer natural? What are the consequences for the fish in these lakes if the mouth is opened before they are ready to leave for the sea? What are the consequences for juvenile fish in the surrounding sea if the mouth is not opened? What will happen if floods are larger than at present, or more frequent? What will happen to coastal lakes as sea levels rise? Can we do anything to protect these systems as nursery areas for juvenile fish? These are just a few of the many questions that need to be answered in order to understand how coastal lakes and estuaries function and, therefore, how they can best be managed.

WHAT DO WE WANT OUR COASTAL SYSTEMS TO BE LIKE?

It is no good understanding how systems work if we do not know what we want to do with them. And, given that virtually every aquatic system in southern Africa has been, or soon will be, affected by human activities, we cannot realistically sit back and leave them to look after themselves. The all-important questions become, ***how*** should they be managed, and to what ends? We ecologists tend to think that we know best. That is probably true, if the decision is made to keep a system as natural as possible. In real life, though, in a country with a massively expanding population, we will be lucky if we can keep just some of our aquatic gems in a reasonably pristine state. The others will be affected by abstraction of water, or inflow of pollutants, or excessive pressure for housing or recreation or, most likely, all of these. Thus, we have to begin any management plan by asking, "What do we want the system to be like?" Do we want merely to avoid it being a health hazard, or do we want it to retain its ability to provide us with ecosystem goods and services? If so, what do we need to preserve? And the answers must come, at least to some extent, from the citizens at large who ultimately foot the tax bill that pays for managing the system.

Some aspects of management are fairly self-evident. Obviously, it is possible, and sensible, to separate pursuits such as powerboating, which creates considerable disturbance, from more passive recreational pursuits such as bird-watching, sailing, canoeing and nature rambling. Similarly, the traditional South African braaivleis and blue-tooth speakers are not necessarily compatible with the desires of birdwatchers. It is clear that there is a need to separate certain activities from others in order to avoid conflict. Apart from the partitioning of individual systems for various uses (one end for passive pursuits and the other end for 'active', noisy pursuits, for example), it might be useful to assign certain systems that are already of minimal ecological value to activities incompatible with conservation goals, while setting aside other, more sensitive, systems for greater protection and conservation. Who, for example, needs powerboats on a narrow, easily erodable natural waterway that harbours purple gallinules, spoonbills and fish eagles? By the same token, birdwatchers are unlikely to be interested in a reservoir that has a large, regular draw-down and in which waterweeds that support invertebrates and fish, and therefore birdlife, cannot survive. By judicious management we will not only reduce conflict, but we will also earn more money, for the maintenance of a wider variety of ecosystems, from a wider variety of people with a wider variety of interests. What finer conservation opportunity can there be than provision of money to support our most basic goal in life: the survival of all species, including *Homo sapiens*?

Some systems are so badly degraded that it would be flying in the face of sense to expect them to be rehabilitated. We have previously suggested, for instance, that the Black River in Cape Town was such an example, and that the best we could expect would be an attempt to ensure that it would not be a health hazard. But maybe we were wrong: the upgrading of the Athlone WWTW resulted in a marked improvement in the river for some years, allowing it once again to support fish and birds and ***Stuckenia.*** On the other hand, though, the WWTW is again overloaded and the river is once again seriously degraded. (The lesson to be learnt from this is probably that if there is enough money, virtually any system can be rehabilitated and maintained in good condition. Since there is never enough money to do everything, we need to develop a system of ***triage:*** decide which ones to look after and which to abandon.)

At the other end of the scale, some time ago we followed with interest and alarm the controversy over St Lucia, a system that should have been so well protected that it would be inviolable. An estuarine lake system on the coast of KwaZulu-Natal, St Lucia is the largest such system in the country, and renowned for its beauty as well as for its biodiversity and the abundant populations of birds, fish and prawns that it supports. It had been run for many years by the then Natal Parks Board as a nature reserve when Richards Bay Minerals, a subsidiary of Rio Tinto Zinc, applied for the right to mine rutile, a titanium-bearing ore, from the sand dunes between Lake St Lucia and the sea. The story is too long to be retold here in detail; suffice it to say that the environmental consulting community was ineffectual, the submissions of the then Natal Parks Board were more or less ignored, and we very nearly landed up with a surface sand mine in the middle of one of the most valuable coastal systems in southern Africa. The resultant uproar was unedifying, and the only organisation to come out of the proceedings with some respectability was, ironically, the mining company itself. The important lesson to be learnt from the debacle is that, regardless of how reasonable a proposal for development may be, there should be certain areas that are sacrosanct. They should not be sacrificed for expediency of any kind, because we have too few natural wonders left, and we have no right to debase them. We owe it to our children's children to leave some of the earth's wild places wild. A "sense of place" is intangible and invaluable.

John H Day

Aerial view of St Lucia mouth in 1964.

Tony Carnie

Sand-mining for rutile, zircon and ilmenite on the eastern shore of St Lucia.

Remarkably, the estuarine and coastal lakes of KwaZulu-Natal have now been declared a World Heritage site as the iSimangaliso (formerly St Lucia) Wetlands Park. We will have to see what the future holds but if anything can protect natural areas from degradation due to development, it must surely be this very prestigious appellation.

What of the protection of other estuaries and coastal lakes? 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 main 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 'insurance' against the failure of other stock management techniques; and to simplify policing and law enforcement. Yet 'Estuarine Protected Areas' simply do not exist! Given our extensive knowledge of the nursery role of estuaries in terms of coastal fish stocks, and the maintenance of biological diversity (not simply of fish, but of the plant and animal communities that support them, and their predators such as birds), it is amazing that so many of our estuaries are ignored in terms of blanket protection as seen in MPAs. Had it not been for a very hard and expensive fight we would have lost St Lucia completely. It is high time for other coastal systems to be earmarked for serious protection – before it is too late.

READING LIST

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https://resource.capetown.gov.za/documentcentre/Documents/Bylaws%20and%20policies/Environmental%20Strategy.pdf

IsiMangaliso (St Lucia) Wetland Park World Heritage
http://whc.unesco.org/en/list/914

Friends of Rietvlei ***(Potamogeton)***
https://friendsofrietvlei.co.za/ecobites-potamogeton.html

Ohlanga River spill
https://www.news24.com/news24/southafrica/news/upl-disaster-it-smelled-like-guy-fawkes-residents-kept-in-dark-about-dangers-on-their-doorstep-20210921

deyandenchev / 123RF

Storms River mouth.