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WATER QUALITY OF THE UPPER ORANGE RIVER

by

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CHAPTER 1

GENERAL INTRODUCTION

1.1 WATER RESOURCES IN SOUTH AFRICA

The Witwatersrand took its name from a range of hills known as the “ridge of white waters”, Amanzimtoti is the Zulu word for “sweet waters” and Bloemfontein is the “fountain of flowers”. These picturesque names indicate the respect that the country’s indigenous people once accorded to South Africa’s rivers. Today, however, there is increasing concern amongst scientists and ecologists that, under the twin impact of industrialisation and rapid population growth, our rivers are becoming among the most polluted in Africa.

South Africa is well endowed with natural resources, but unfortunately abundant rainfall and surface water are not among these resources. Of the average total of 500mm yearly rainfall (Balance & King, 1999), only 11 % reach its rivers. The total surface run-off in South Africa is 51 billion $m^3.a^{-1}$. The largest, and thus most important river in South Africa is the Orange River, with 600 000 km^2 of its catchment within South African borders. The country’s industrial heartland is located in the Witwatersrand and Mpumalanga, and the farming communities in the central western and south eastern areas. Organised agriculture consumes 62 % of the country’s water supplies, mining and industry takes 8 %, urban and domestic purposes use 10 % and environmental functions, like instream flow requirements, receive the remaining 20 % (Ballance & King, 1999).

The population in South Africa was estimated to be about 45.2 million in the mid-1998’s (SA Focus, 2000), and is growing at 2 % per year (Ballance & King, 1999).

Although this rate is declining, the population will continue to grow for several years. Roughly half of all South Africans live in towns and cities, and less than 60 % live in informal dwellings (Ballance & King, 1999). In cities and towns we turn on the tap and expect the water from it to be clean and drinkable. In rural South Africa, things are very different. Only 45 % of all households have a tap inside the dwelling (Ballance & King, 1999). At best, water has to be fetched from a tap in the street. More commonly, people have to go to a distant spring or stream to fetch some water. On average, 45 % of South Africans do not have access to clean water (Ballance & King, 1999). The new National Water Act (36) of 1998 recognizes that water is a scarce and unevenly distributed national resource and that the ultimate aim of water resource management, both quality and quantity, is to achieve sustainable use of water for all user groups (Scotcher, 1998).

According to the Orange River Replanning Study (ORRS) (1998), all freshwater resources in South Africa will be fully used between 2025 and 2030. The executive director of the Water Research Commission, Piet Odendaal, theorised that South Africa will probably have to import water within the next few decades, as our water resources will become limited by 2020 to 2030 (Grobler, 1999).

1.2 WATER QUALITY IN SOUTH AFRICA

Water quality is a broad term referring to the chemical composition, content of trace elements, flora, fauna, microbial populations, dissolved oxygen, temperature, suspended particulate materials and other physical properties of water (Grobbelaar, 1998). According to Du Plessis and Van Veelen (1991) the quality of water is not an inherent property but is determined by the purpose for and the circumstances in which the water is used. In spite of the effluent quality regulations, the main water quality problems experienced in South Africa are due to salinisation and eutrophication (Du Plessis & Van Veelen, 1991).

One of the most serious problems in several South African rivers is the increase in inorganic salt concentration of the water associated with excessive irrigation under arid conditions. The importance of salinisation as a measure of water quality lies in the fact that the usefulness of water for most purposes diminishes with increasing salt concentration. The salt content of soil can be vastly concentrated by irrigation. Crop yields decrease when irrigated with saline water. Du Plessis and Van Veelen (1991) calculated that an increase from 300 to 500 mg l^{-1} in the salt concentration in the Vaal River could cost Rand Water Board users R76 million per annum in terms of drinking water treatment. A further increase to 800 mg l^{-1} could cost an additional R63 million per annum. The agricultural and economic effects of salinisation are thus considerable.

Nutrients (such as phosphates, nitrates, ammonia and potassium from fertilizers) eventually are washed into rivers. Another major source of these nutrients is effluent from sewage treatment works. The enrichment of a water body with nutrients is called eutrophication. The Organization for Economic Co-operation and Development (OECD, 1982; cited in Cooke *et al.*, 1993) defined eutrophication as: "the nutrient enrichment of waters which results in the stimulation of an array of symptomatic changes, among which increased production of algae and macrophytes, deterioration of water quality and other symptomatic changes, are found to be undesirable and interfere with water uses." Eutrophication is a world wide problem, and in South Africa, this phenomenon could be observed in numerous rivers and impoundments. The Hartbeespoort Dam (Robarts, 1984) and the Vaal River (Roos, 1991; Roos & Pieterse, 1996), are just two examples of many.

During eutrophication, the biotic compartments change in composition as well as increase in biomass. As an example, the number of desmids (green algae) such as *Cosmarium* and *Staurastrum*, are diminishing from the phytoplankton (Gower, 1980). Diatoms, especially *Asterionella*, first become conspicuous, and are later replaced by Cyanophyceae (Cyanobacteria or blue-green algae). Dense populations of the latter may appear at the surface of lakes and reservoirs during calm and warm weather, forming 'blooms'. An interesting characteristic of some blue-green algae (e.g. *Anabaena*, *Aphanizomenon*, *Gleotrichia*) is their ability to fix atmospheric nitrogen (Carter-Lund & Lund, 1995).

Nitrogen fixation by blue-green algae can introduce substantial amounts of nitrogenous compounds into the water during blooms, which ultimately become available for other species including non-nitrogen-fixing blue-green algae such as *Microcystis* and *Oscillatoria*. *Cladophora* is a benthic filamentous green alga that is attached to stones and other hard surfaces. In eutrophic waters, it grows rapidly and manifests for most of the year (Pitcairn & Hawkes, 1973).

During eutrophication zooplankton also becomes more abundant. There are changes in the relative dominance of some of the species. There is evidence, for example, that the cladoceran *Chydorus sphaericus* increases in association with 'blooms' of blue-green algae, perhaps using the latter as a nutrient source (Pitcairn & Hawkes, 1973).

The importance of eutrophication lies in its effects, namely, impaired aesthetics of water bodies, increased water treatment costs, taste, odour and colour problems, as well as potential health risks (Hynes, 1970; Westlake, 1975; Du Plessis & Van Veelen, 1991). These risks arise from waterborne diseases, pathogenic organisms causing skin and ear infections, carcinogenic risks, etc. Hippocrates had already noticed in 460 BC that human health was very much dependent on the water that they drink (WRC, 1987).

1.3 RIVERINE ECOSYSTEMS

Rivers can be regarded as the natural water reticulation system of any land mass, draining the land, concentrating runoff and seepage into water masses usable by human populations and transporting such water on the surface from often inaccessible high rainfall areas to other regions where it is less plentiful (Appleton *et al.*, 1986). By virtue of their self-cleansing ability rivers are capable of delivering water of a high quality, provided that the system's ability to clean itself is not overloaded.

The rapidly increasing population of South Africa has resulted not only in an increased water demand, but also greater human impact on the country's river-borne water resources. This impact has given rise to rapid lowering of the conservation status of many rivers through partial or total destruction of the natural river biota, alterations to river functioning, overloading of self-cleansing mechanisms and a drastic lowering of water quality (Appleton *et al.*, 1986).

Rivers are intricate systems because they usually exist between multiple geographical boundaries (Pitcairn & Hawkes, 1973). This fact introduces numerous factors such as altitude, climate, topography, geochemistry, hydrology and catchment land utilisation. This in turn, influences the distribution of species, communities and habitats.

1.4 MANIPULATION AND USES OF WATER IN RIVERS

Rivers provide South Africa's most important large-scale resource of freshwater. The topography of the country is such that there are virtually no natural standing waters that can supply water for potable use, irrigation, stock or industrial use. Rivers have to be dammed in order to use their water effectively. In doing so, the characteristics of rivers are inevitably altered: their flow rate, their volume and their temporal features, their temperature, erosive nature, particulate material and their chemistry. The ability of river systems to clean themselves, to adapt to additional perturbations, to support fisheries, to supply water to floodplains and estuaries, to flush pollutants and sediments from lower reaches and to fertilize estuaries, floodplains and coastal regions are therefore profoundly altered. Essentially, the water of a river can be deliberately manipulated by impoundment, extraction and transfer from one catchment area to another (Davies *et al.*, 1993).

1.4.1) Impoundment of rivers and river regulation

Rivers can be divided into different zones, based on numerous physical, chemical and biological factors. Kimmel and Groeger (1984) distinguished between three zones, namely the riverine zone, transitional zone and lacustrine zone (cited in Cooke *et al.*, 1993). This postulated zonation was based on the water quality of the river (lotic system) before it enters the reservoir (riverine zone) and the quality of the lenthic water in the reservoir (lacustrine zone).

Vannote *et al.* (1980) had a different approach and their three major riverine zones consist of fast-flowing erosive headwaters; slower-flowing, partly erosive, middle reaches and slow-flowing, low-lying, mature reaches where materials eroded in the upper reaches are deposited. This zonation was part of their river continuum concept. Both these zonations will be discussed in Chapter 7.

The flow of regulated streams is strongly influenced by the type of impoundment retaining the water (Ward & Stanford, 1979; Ward *et al*., 1984). Hydroelectric and irrigation dams can lead to short-term fluctuations in the flow of the river below the dams. The major result is reduction in the natural annual variations in flow of South African rivers. Where once there were winter low flows and summer floods (or vice versa), the original flow peaks have been evened out, while there is a general reduction in the annual flow in rivers below storage dams, as well as in the sediment carrying capacity of the water.

The low sediment loads in water released from many impoundments increase the erosive capacity of the water (Simons, 1979) and, together with a modified flow regime, lead to degradation of the river channel downstream of the impoundment (Ward *et al*., 1984). Decreased turbidity also leads to greater water clarity, with a possible consequent development of benthic algal mats (Chutter, 1968). While permanently turbid waters in some South African and Australian impoundments lead to perennially high turbidity levels in the downstream regions, a factor that might not have been encountered prior to impoundment.

1.4.2) Agriculture

The agricultural sector makes the greatest demand on the country's water resources, with an estimated abstraction of 62 % of the total volume of water used in South Africa. Crop irrigation and stock watering account for a large quantity of this water resource (around rivers), with some multiple use in the form of fish culture being practiced on a limited scale.

Rivers are essential to agriculture for maintaining food production on a sustainable yield basis and can only fulfil this function by an adequate yield of suitable quality water. In areas of highly seasonal rainfall, which includes the whole of South

Africa, this depends on land-use practices within the catchment, which are most often under the direct control of the agricultural industry. Runoff carries excessive agricultural fertilisers into rivers and leads to eutrophication of the river system (Benade, 1986). A disregard of the principles of sound catchment management and river conservation, whether through ignorance or willful neglect, has an immediate detrimental effect on downstream users. This causes irreparable damage to catchment regions and rivers (Appleton *et al.*, 1986).

Natural riparian vegetation, which forms an integral part of any river ecosystem, plays an important role in riverbank stabilization. It is frequently destroyed in order to extend grazing or to allow the planting of crops (Appleton *et al.*, 1986). Apart from the direct effect of these practices in destroying a wildlife refuge, they also deprive the riverine fauna of its primary energy resource, particularly the upper and middle reaches. The effect on downstream users is, however, much more tangible. Shallow rooting grass and crops such as sugarcane cannot stabilize riverbanks even against normal summer flow and the effects of floods become disastrous. The result is continuous bank erosion with considerable siltation and also substantial soil losses during floods (Appleton *et al.*, 1986).

1.4.3) Industries

Industrial development is dependent on energy, labour and water. No matter how abundant the raw materials may be, without these resources little growth in the industries of a region is possible. Industry sites are currently independent from the location of coal regions as primary energy source. This is ascribed to an efficient electricity supply grid nationally. However, industry sites are dependent on water resources. Therefore, industrialisation and urbanisation become almost synonymous with water resource areas with resulting labour force settlement. Industry accounts for some four to six per cent of the total national water consumption, but its impact is disproportionately high because of the discharge of effluents containing toxicants and other pollutants (MacDonald *et al.*, 1984).

Although many industries utilise water directly for the processing of commodities, and river systems provide avenues of supply, an additional value of a river to industry is that of disposal of solid, liquid and heat wastes. Such waste discharges vary from large volumes of cooling and rinsing effluents to small concentrated effluents containing organic wastes and heavy metals (zinc, copper, iron, lead, nickel etc.).

1.4.4) Hydro-electrical power generation

Most of South Africa's power supply is generated in coal based power plants, which require water for their cooling towers. Water is abstracted from nearby rivers, passed through the towers and returned to the river with an increased heat load, thus raising the temperature of the river by several degrees. Such maintained elevated temperatures could have a marked effect on the river biota, particularly if the river is already perturbed in other ways (Appleton *et al.*, 1986).

Hydroelectric power generation can, through wide unpredictable fluctuations in downstream flow, create a maximally disturbed environment, greatly reducing the diversity of the biota (Ward & Stanford, 1979). Although limited in South Africa at present, this happens particularly when serving the national grid on high demand.

1.4.5) Mining

Mining is one of South Africa's major industries and the economic gains from the exploitation of mineral resources (gold, platinum, manganese, coal, diamonds, etc.) far outstrip other natural resources in terms of contribution to the gross national product. The provision of water to mining is therefore vital to the South African economy, not only because of the revenue derived from the sale of minerals but also provision of employment.

Most mining concerns require water as a medium for mineral extraction processes, which often involve highly toxic chemical compounds. This renders mining effluents extremely hazardous in terms of their pollution and toxicant status. Seepage water from mines, particularly coal mines, can have extremely detrimental effects if it enters river systems (Koch *et al.*, 1990). For example, it was reported in 1987 that coal-burning power stations and factories in Mpumalanga and in the heavily industrialised Vaal Triangle south of Johannesburg were pumping sulphur dioxide, and other chemicals that cause acid rain, into the atmosphere at levels that were twice those in East Germany, the country with the world's most serious acid rain problem. Emission from twelve power stations and two of Sasol's fuel-from-coal plants in Mpumalanga dumps 58 tons of sulphur dioxide per square kilometer into the atmosphere each year. The Council for Scientific and Industrial Research (CSIR) had already in 1988 warned that forests in Mpumalanga were showing some of the scars of acid rain damage and that maize and other crops in the fall-out area could be affected (Koch *et al.*, 1990). Half of South Africa's fertile agricultural land and forest resources are concentrated in the area and the rivers that drain out of it provide nearly a quarter of the country's surface water (Koch *et al.*, 1990).

1.4.6) Recreation

The recreational industry in South Africa is substantial, with considerable investment in boats, fishing, caravans, tents, and supports a large number of hotels, caravan and camping sites. This can only be sustained by sufficient acceptable venues. Much recreational activity is centered on inland waters, and these activities require high quality water for obvious aesthetic and health reasons. Favoured recreational sites are impoundments which, as modified rivers, are directly affected by the state of their river inflows (Appleton *et al.*, 1986).

1.5 RESEARCH, CONSERVATION AND MANAGEMENT OF FRESHWATER SYSTEMS

Limnological research in South Africa has changed emphasis from reservoir studies to river ecosystem studies in the 1980's (Awachie, 1981). Since then, the knowledge of South African rivers has been increasing. However, there are several weaknesses and threats with regard to the capability of the scientific community to provide an adequate input into river ecosystem research. The most important of these are insufficient manpower, a lack of funding, an uncertain future with regard to co-ordination of research effort and a weak interaction with resource agencies (Walmsley & Davies, 1991).

Inland water research thusfar has been dominated by ecologists, mostly with zoological interests. A great deal of research has been concentrated on the biota, particularly fish and invertebrates. There has been little input from chemists, botanists, geomorphologists and hydrologists (Walmsley & Davies, 1991). However, the problem of quantifying the quantity of water required for environmental management demands a multi-disciplinary team approach. Such an approach requires the input of research specialists from numerous disciplines. Thus, a research effort that involves all the expertise necessary will have to be developed.

It is important to take a holistic or all-embracing view of water management (integrated catchment management), in which a comprehensive spectrum of demands are recognized and evaluated to assess their priority. Integrated catchment management agencies must address all the elements of the physical catchment, including the impacts on the catchments' water bodies and their users (Pegram *et al.*, 1997). This has led to a precautionary approach to water quality management, beginning with options to prevent and minimize pollution, followed by receiving water quality objectives and keeping remediation of water bodies as a last resort. The National Water Act (Act 36 of 1998) states that the functions of the catchment management agencies are to: a) investigate and advise interested persons on the protection, use, development, conservation, management and control of the water resources in its water management area; b) develop a catchment management strategy; c) co-ordinate the related activities of water users and of the water management institutions within its water management area.

The International Union on Conservation of Nature and Natural Resources (IUCN) (1980) defines conservation as: "The management of human use of the biosphere so that it may yield the greatest sustainable benefit to present generations, while maintaining its potential to meet the needs and aspirations of future generations" (cited in O'Keeffe, 1986). Thus, conservation is positive; embracing preservation, maintenance, sustainable utilization, restoration and enhancement of the natural environment. The important implications of this statement are that conservation is for people, and that it is a holistic concept, embracing use of resources as well as their preservation, while maintaining ecological integrity. The National Water Act (Act 36 of 1998) takes the following into account in the classification of water resources and resource quality: a) the reserve; b) the instream flow; c) the water level; d) the presence and concentration of particular substances in the water. It also deals with the ecological reserve, which consists of two parts – the basic human needs reserve and the ecological reserve. The basic human needs reserve provides for the essential needs of individuals served by the water resource in question and includes water for drinking, food preparation and for personal hygiene. The ecological reserve relates to the water required to protect the aquatic ecosystems of the water resource. The reserve refers to both the quantity and quality of the water in the resource and will vary depending on the class of the resource (National Water Act, 1998).

The IUCN statement also emphasizes a range of conservation priorities, from the preservation of pristine habitat in areas of special nature conservation importance, to the wider view of conservation, which can be summed up as the maintenance of diversity of function in rivers. This implies a recognition that water supply is and will continue to be the main priority for river management and that rivers will also continue to be used for effluent disposal and recreation. Within this framework the important conservation aims are to ensure that rivers are not overexploited to a stage where essential functions such as the supply of good quality water, nutrient recycling processes and recreation potential are lost.

In South Africa, the Department of Water Affairs and Forestry (DWAF) is the custodian of the water resources (DWAF, 1996). In order to maintain long-term sustainability of water use, the DWAF developed the South African Water Quality Guidelines. These guidelines contain information similar to what is available in the international literature. Furthermore, the National Water Act (1998) allows the Minister to regulate activities having a detrimental impact on water resources by declaring them to be controlled activities. Four such activities are: a) irrigation using waste or water containing waste from certain sources, b) modification of atmospheric precipitation, c) altering flow regime of a water resource as a result of power generation and d) aquifer recharge using waste or water containing waste.

It has by now been generally accepted that passive preservation of habitats is not possible because of the influence of adjacent areas and this is particularly true for stretches of river, which are subject to influences from upstream, and which reflect events in their catchments. The emphasis must therefore be on active management to conserve rivers and catchment ecosystems. Parts of the most vulnerable ecosystems in South Africa have been declared as Ramsar sites. Ramsar sites are sites with high conservation priority status and only 16 of these sites have been declared in South Africa (Balance & King, 1999). The Orange River Mouth Wetland at Alexander Bay in the Atlantic Ocean is one such Ramsar site (Balance & King, 1999).

Sound conservation practices, based on current knowledge of river ecosystem functioning and reinforced by the results of ongoing research on South African river systems, hold benefits for all users (Appleton *et al.*, 1986). However, this implies that the following requirements be met:

1. Ensuring the integrity of the river course by maintaining riparian vegetation, which stabilizes riverbanks.
2. Ensuring continued flow on a normal seasonal pattern through controlling abstractions of water along the course as well as maintaining wetlands.
3. Ensuring that catchments are managed in such a way as to minimize impacts on river systems.
4. Ensuring continued inputs of allochthonous organic material, particularly in the headwater regions.
5. Ensuring that the quality of return flow into the river, whether through runoff, seepage or canalised disposal, is of a quality which will have minimal effect on the biota and on downstream users. This involves the improvement of all land-use practices.

6. Ensuring that the self-cleansing ability of rivers are maintained in order to restore water quality where degradation from the above mentioned sources is inevitable.

If these requirements are met, it holds advantages for all water users, which ultimately implies the whole population of the country. This country's water resource must be regarded as its primary national asset, and thus, cannot be regarded as the property of any one sector or individual, nor can the actions of any user or user agency be allowed to impinge on others in a detrimental manner.

Even though the importance of rivers as main suppliers of freshwater in South Africa can not be over emphasized, very little information is available on the ecological aspects of South Africa's major rivers. Due to this void in information on major rivers, this study was conducted on the Upper Orange River. The water quality of the Upper Orange River was analysed based on physical, chemical and biological parameters.

CHAPTER 2

THE ORANGE RIVER – A REVIEW

2.1 BACKGROUND INFORMATION

2.1.1 The Orange River basin

Archaeological evidence suggests that the larger part of the Orange River (approximately from the Gariep Dam to the mouth at Alexander Bay) was populated by *Homo erectus* 1,5 million years ago, later by the San people and 1 200 years BP, by sheep-herding Khoi-khois. The first Iron Age people probably settled in southern Africa about 1 000 years ago and during the 1800's the land next to the Orange River was populated by Koranas, who farmed with cattle, sheep and goats (ORRS, 1995). During July 1760 an elephant hunter, Jacobus Coetsè Janz, came across a wide river in the north of Namakwaland, which he named the Great River. The river was known to the native Khoi people, as the Gariep. Colonel Robert Jacob Gordon, the commander of the garrison of the Dutch East India Company (Cape Town), named the Orange River as such in 1779 in honour of the Dutch House of Orange (De Korte, 1982).

The Orange River is the largest river in Southern Africa south of the Zambezi, with a total catchment area close to a 1 000 000 km^2. Almost 600 000 km^2 of its catchment is within South Africa's borders (McKenzie & Schäfer, 1990), with the remainder in Lesotho, Botswana and Namibia (Edwards, 1974). The Orange River drains approximately 47 % of the country's total surface area (Roberts, 1965). The effective catchment area is difficult to determine since it includes many pan areas and also several large tributaries, which rarely contribute to flows in the main river channel. According to Benade (1993) the river has a total length of 2 300 km. It originates in the Lesotho Highlands at about 3 300 meter above mean sea level and receives most of its run-off from the pluvial eastern region of the continent. It passes through the southern Free State and the more arid Northern Cape, to its mouth in the west at Alexander Bay in the Atlantic Ocean.

The Orange River is of great importance to South Africa since the natural flow represents more than 22 % of the country's surface water resources. By Southern African standards the natural water resources (i.e. water available before any developments took place) of the Orange River are large at approximately 11 500 million m^3 per annum (McKenzie & Roth, 1994). This figure, however, is of purely academic interest since major developments have already taken place in the basin. The remaining available resources of the Orange River are currently estimated approximately at 6 500 million m^3 per annum (McKenzie & Roth, 1994).

As far back as 1928, the idea of diverting the water of the mighty Orange River through tunnels to the Great Fish River valley had been conceived by A.D. Lewis who, at the time, was Director of Water Affairs. The Fish River valley had much greater irrigation potential than the Orange River valley. The preliminary planning of this diversion project had reached an advanced stage by 1947. However, financial difficulties at the time prevented the government from putting this imaginative scheme into practice (Alexander, 1974). It was not until 1960, under the auspices of Dr. H.F. Verwoerd, that the planning of the use of the Orange River was instigated (Simons, 1968).

It was envisaged that the development of the Orange River project would take place over a number of years. The central feature would be the Gariep Dam, as a main storage facility to regulate the flow of the Orange River and provide sufficient storage capacity for silt deposits. A circular, concrete lined tunnel, approximately 83 km long with a diameter of 5.1 m would direct water from Oviston to the Theebus Sprout near Steynsburg.

This tunnel would be used to regulate the water supply for areas along the Great Fish and Sunday Rivers. This development of the project would mark the end of the first construction phase. A second diversion dam, the Vanderkloof Dam, would be constructed approximately 105 km below the Gariep Dam in order to feed water, by gravity or under pressure, to irrigate land and supply water to towns on both sides of the Orange River. A canal system on the left bank would irrigate approximately 12 950 ha below the Vanderkloof Dam down to Hopetown. A second canal, on the right bank, would serve approximately 12 150 ha of irrigation land along the river above Hopetown and in the Riet River valley.

A third high diversion dam at Torquay would be constructed in the second phase, which has not been done yet. A gravity canal system will serve 23 070 ha of irrigation land near the confluence of the Orange and Vaal Rivers, and further down the valley towards Prieska (Kriel, 1971).

There are three main storage reservoirs in the Orange River to date, namely the Gariep Dam and Vanderkloof Dam (formerly known as the Verwoerd Dam and PK le Roux Dam respectively) in South Africa, and the recently completed phase 1*a* of Katse Dam in Lesotho. Katse Dam is situated in the Malibamatso River, that is a tributary of the Senque River that becomes the Orange River. The Gariep Dam forms the largest reservoir in South Africa with a capacity in excess of 5 670 million m^3, while Vanderkloof Dam forms the second largest reservoir with a storage capacity of over 3 200 million m^3. Water is transferred to the Eastern Cape through the 80 km Orange-Fish Tunnel, while the Riet River valley is supplied with water from the Vanderkloof Dam via the Orange-Riet canal.

Although the storage capacity of the Katse reservoir is lower at a modest 1 950 million m^3, it is the highest dam wall in the Southern Hemisphere, with a height of approximately 185 m above foundation. The Lesotho Highlands Water Project (LHWP) is the latest, largest and most ambitious water transfer project to be undertaken in Africa and is currently one of the largest water projects being undertaken in the world. When completed it will enable in excess of 2 210 million $m^3.a^{-1}$ of water (McKenzie & Roth, 1994) to be transferred, through a canal complex, from the upper reaches of the Lesotho Highlands to the Gauteng area in the Vaal River basin.

The Gauteng area is the economic powerhouse of South Africa, producing approximately 60 % of the Gross National Product (De Korte, 1982). Several major strategic industries, numerous large mines and most of the country's power stations are located within its boundaries. As a result of the growing water demands in the area, water must be transferred from various parts of the country where water resources are more plentiful and the demands relatively small.

The Vanderkloof Dam is currently the last main storage structure on the Orange River and effectively controls the flow of water along the 1 400 km stretch of river between the dam and Alexander Bay at the Atlantic Ocean (Figure 1). However, according to the ORRS (1997) basic engineering work on evaluating a possible new dam at Torquay has been completed. This dam will trap the water currently being released from Vanderkloof Dam to generate electricity, so that it can also be used for irrigation and to satisfy downstream environmental needs.

The banks of the Orange River downstream of Vanderkloof Dam are fairly excessively developed in many areas, principally for irrigation purposes. Both the Gariep and Vanderkloof dams are used to regulate the river flow for irrigation, as well as to produce hydro-electricity during peak demand periods. A small quantity of Orange River water is used for domestic or industrial purposes, with the exception of that used in the Vaal River basin.

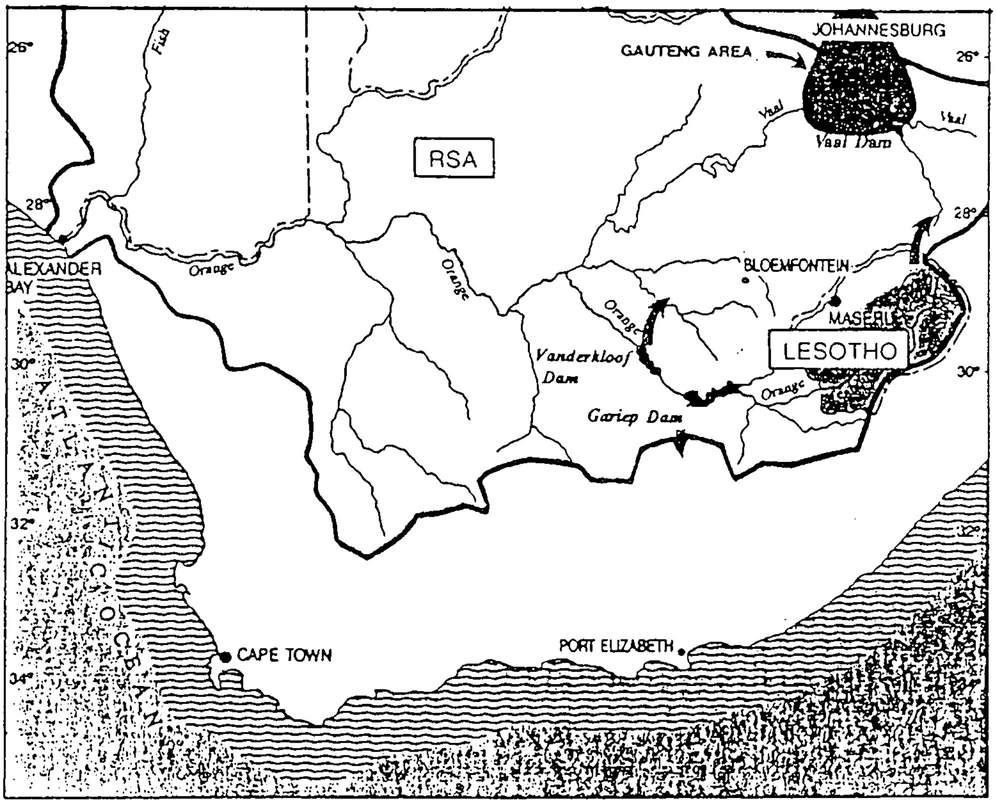


Figure 1. The Orange River catchment

Major impoundments of the Orange River System and their rating amongst the RSA's largest dams are shown in Table 1 (adapted from Benade, 1988).

Table 1. Major impoundments of the Orange River System and their ratings (based on capacity) amongst Southern Africa's largest dams.

Dam	**Completed**	**River**	**Capacity** million m^3	**Rating**
Gariep	1971	Orange	5670	1
Vanderkloof	1976	Orange	3200	2
Sterkfontein	1977	Wilge	2617	3
Vaal	1938	Vaal	2603	4
Katse	1998*[1]	Malibamatso*[2]	1951	5
Bloemhof	1970	Vaal	1264	6
Grootdraai	1978	Vaal	355	10
Kalkfontein	1938	Riet	322	12

*[1] Phase 1*a* completed in 1998, which includes the building of the dam

*[2] Tributary of the Senque that becomes the Orange River

2.1.2 Climate and Topography

The Orange River catchment areas vary dramatically both in climate and topography from east to west. The source of the Orange River is high to the east in the Lesotho Highlands, some 3 300 m above sea level (Grobbelaar & Stegmann, 1987). The precipitation, some of which occurs as snow, can exceed 2 000 mm per annum in places, which together with the relatively shallow soil cover and low evaporation results in significant run-off. As the river progresses towards the west following an average gradient of 1.4 $m.km^{-1}$ (Benade, 1993), the lush pastures of Lesotho gradually change over to harsh, but impressive desert areas. This reaches a climax near Oranjemund where only the most drought resistant plants can grow. The desert areas of the lower Orange River basin are amongst the driest in the world, with an average rainfall of less than 50 mm per annum and high evaporation (Benade, 1993).

Parts of the most vulnerable ecosystems in South Africa have been declared as Ramsar sites (Ballance & King, 1999). The Orange River Mouth Wetland was designated as a Ramsar site on 28 June 1991. The large numbers of birds present, the variety of species involved, and especially the significant numbers of rare or endangered species, support the contention that the Orange River Mouth Wetland is an internationally important coastal wetland. In 1995 the Orange River Mouth Wetland was placed on the Montreux record of the Ramsar Convention following the collapse of the salt marsh component of the system, which was the result of a combination of impacts, both at and upstream of the wetlands. The major threat to this wetland is loss of inflow of water and sediment through human manipulation of water in the Orange River catchment (Ballance & King, 1999).

Except for the Cape clear acidic rivers (Olifants, Breë and Berg Rivers), the Orange River is the only South African river containing all five riverine zones, i.e. mountain source and cliff waterfalls, mountain streams, foothill sandbeds, low and midland streams and rivers as well as an estuary (Noble & Hemens, 1978).

Due to its situation within the summer rainfall region approximately 25 % of the Orange River system's annual run-off occurs from May to October with minimum flow during August (Wellington, 1933 and Chutter, 1973). The remaining approximately 75 % occurs from October to May with maximum flow during February showing erratic flow peaks coupled with high silt loads (Thomasson & Allanson, 1983).

Statistically the Orange River System displays a 1 in 10 - 15 year episodic flood cycle (Benade, 1988), but floods can also occur every 5 to 10 years. Annual flow as well as floods and flow cessations are relatively unpredictable. This is ascribed to extremely erratic rainfall in the catchment and can at times be restricted to only certain sections of the catchment (Benade, 1988).

2.1.3 Geology

The Orange River traverses nearly all the geological systems in southern Africa (Figure 2). The river flows from the basalt of the Drakensberg formation in Lesotho, across the progressively older strata of the Karoo Sequence. This includes; a) the fine-grained massive sandstone of the Molteno formation; b) the interbedded mudstone and fine-grained sandstone of the Beaufort Series; c) the dark carbonaceous shale of the Ecca Group and d) the glacially deposited Dwyka formation, which represents the basalt unit of the Karoo Sequence. Below the Vanderkloof Dam the river traverses mainly andesite of the Alanridge formation of the Ventersdorp Supergroup, and diamictite of the Dwyka formation. Dolomite, limestone, conglomerate, iron formation, shale, sandstone and andesite of the Olifantshoek Sequences are found below Prieska. The river geology is dominated by granite gneiss and granodiorite of the Natal Metamorphic Province from Upington, after which the river flows across dolomite, limestone, quartzite, schist and lava of the Gariep Complex, before entering the Atlantic Ocean at Alexander Bay (ORRS, 1995).

Among the highest sediment yields in the country are those encountered in the cave sandstone formations of the Upper Caledon catchments and along the southern watershed of the Orange River. The Orange River transports on average 40 million ton sediment per annum (Benade, 1986). Most of the erosion occurs naturally, caused by the steep topography and clayey loam soils. However, there are parts where over-utilization of the soil must have led to considerable increases in sediment yields, especially along the southern bank of the Orange River from the Lesotho border. Farming on these slopes, overpopulation and overgrazing cause increased erosion.

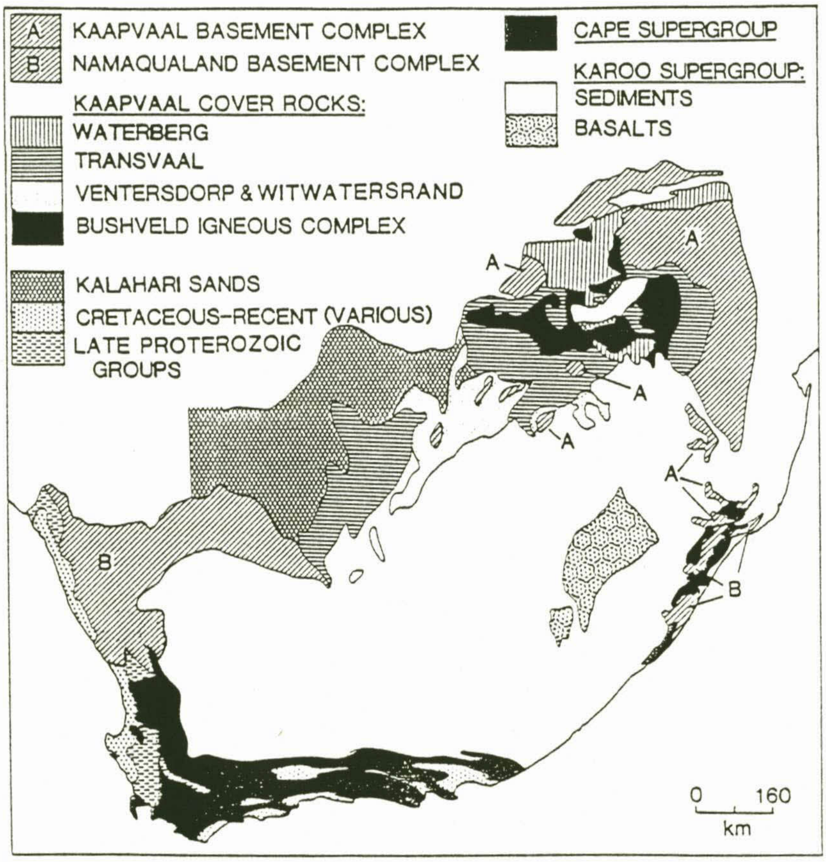


Figure 2. A simplified map of the geology of South Africa (adapted from Dallas & Day, 1993).

2.1.4 Vegetation

The Orange River runs through the southern *Cymbopogon-Themeda* Veld in Lesotho. A mixed sour grassveld is the climax to the *Cymbopogon-Themeda* Veld, resulting in a moderately dense grassveld in the higher-lying portion of the highveld. The vegetation from above the Gariep Dam to downstream of the Vanderkloof Dam is classified as False Upper Karoo. *Tetrechne dregei* is the grass that is generally found in this veld type and the principal shrub is *Rhus erosa* (broom karee).

Below the Vanderkloof Dam to the Vaal River confluence, the river passes through a thin strip of False Orange River Broken Veld, bordered by False Arid Karoo. The False Orange River Broken Veld takes the form of the development of thickets of *Acacia mellifera* (black thorn) and a little *Bascia albitrunca* (Shepherd's tree, Witgat) and *Cadaba aphylla* (Leafless cadaba). The Orange River Broken Veld dominates from the Vaal confluence to Augrabies Falls. Typical Orange River Broken Veld occurs between Prieska and Kakamas. The presence of *Aloe dichotoma* (Quiver tree) and *Euphorbia avasmontana* are the main identifying features of this veld type.

Downstream from Augrabies to below the Fish River confluence, the vegetation is basically Namaqualand Broken Veld, of which the typical form makes up the Richtersveld. It is characterised by *Aloe dichotoma* and *Pachypodium namaquanum* (Halfmens) and is distinguished from the Orange River Broken Veld by the absence *of Euphorbia avasmantana*.

The succulent karoo is present from the end of the Richtersveld to the coast. It is dominated by succulents, mainly *Mesembryanthemum* spp. with few trees or large shrubs. Along the river usually lined with *Acacia karroo* (sweet thorn), *Rhus lancia* (karee) and a few other tree species occur (ORRS, 1995).

Edwards (1974) found aquatic macrophyte communities to be generally absent from, or poorly developed in the Orange River and its major tributaries in the upper catchment outside Lesotho. Exceedingly severe farming activities within this catchment resulted in the extensive conversion of former grassland into secondary

Karroid dwarf shrub type vegetation (Edwards, 1974). This conversion enhanced the water's natural turbidity, which led to South Africa's ranking amongst the world's top soil erosion countries, negatively affecting the macrophyte element of the aquatic ecosystem (Edwards, 1969).

The water hyacinth, *Eichhornia crassipes*, considered by Bruwer (1986) as the most serious macrophyte threat to the lower eutrofied Vaal River, has not yet been recorded in the Orange River. It should be taken into account that the 1988-floods could have expanded its distribution to the Orange River (Figure 3). *Phragmites* reed beds, in especially the middle Orange River, could provide the required niche for settlement of this species.

The river reed, *Phragmites australis*, is the dominant semi-aquatic plant along the Orange River (Benade, 1993). Reed communities above the Gariep Dam mainly occur on the riverbanks directly upstream of weirs and are still subject to natural control. Reed beds between the Vanderkloof Dam and the Orange-Vaal confluence are controlled to some extent by the strong pronounced pulsating effect of hydropower generation. Plant pioneering communities progressively increase along the riverbanks from the Orange-Vaal confluence to Boegoeberg Dam, on sandbanks and in "Orange-minor-tributaries" confluence, flourishing relatively short distances downstream of the start of irrigation areas. The island-rich river section between Boegoeberg Dam and Aughrabies Falls is characterized by extreme *Phragmites* settlement and encroachment in and along the wider, shallower stretches of the river. This results in the river channel becoming narrower in places with cut-off pools developing, giving rise to the development of instream wetlands (Benade & Gaigher, 1987). Some of these wetlands become completely dry and overgrown with *Phragmites* and this is the cause of some concern in the agriculture sector, in fear of floods (Orange River Environmental Task Group, 1989). Along sections of the lower Orange River similar situations occur generally in association with irrigation. Reed communities, however, are less abundant along this river section, because of the bareness of the riverbanks and desert character of this part of the catchment.

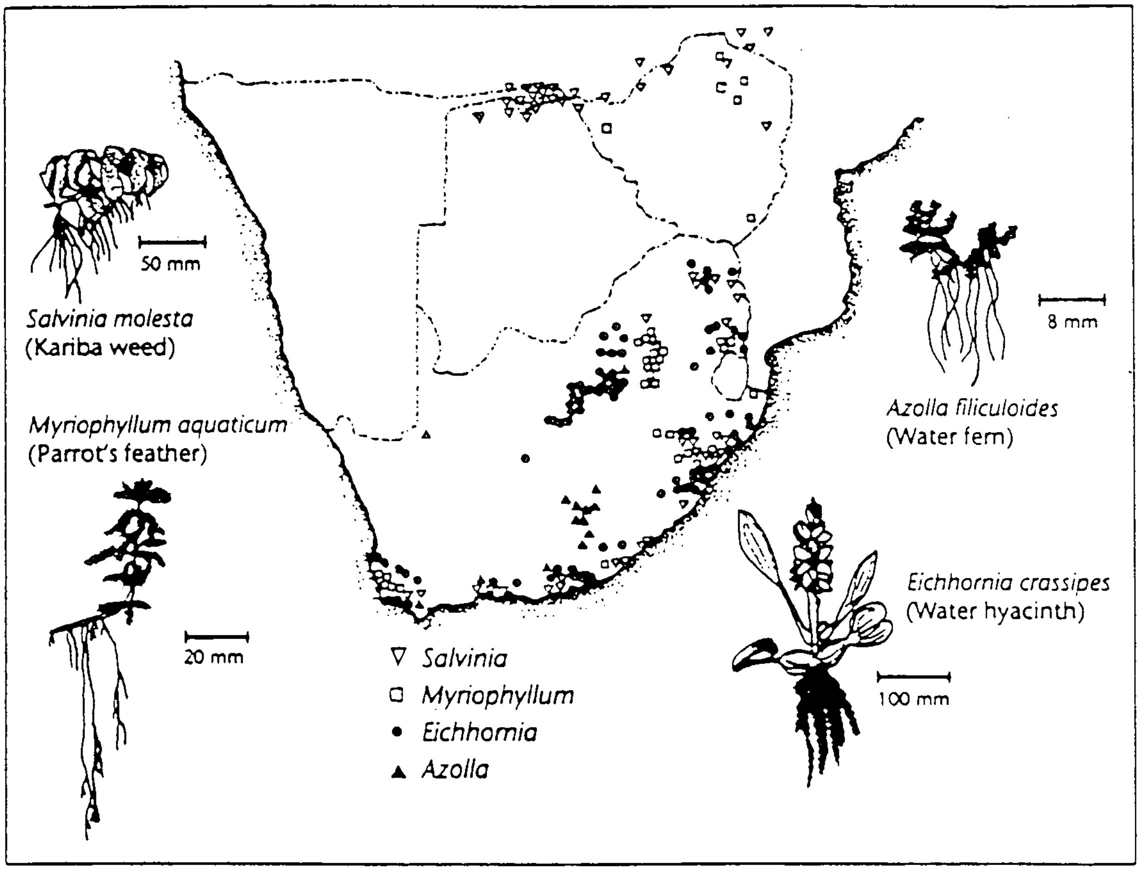


Figure 3. The distribution of four alien macrophytes in South Africa (adapted from Davies & Day, 1998)

The South American floating water fern, *Azolla filiculoides*, related to the pest species *Salvinia molesta* (Kariba weed), grows at its best in sheltered, lightly shaded places (Ashton, 1974). Like *Salvinia* it is capable of rapidly colonizing open water surfaces (Ashton, 1974). Its presence in the tributaries of the Gariep Dam catchment has been reported and studied by Ashton (1974, 1982). It also occurs in the tributaries of Vanderkloof Dam. During seasonal flooding most of the plant aggregations are broken up and washed into the dams, where wave action fragments them further (Ashton, 1974), resulting in their absence from the dam surfaces. Below Vanderkloof Dam, this species is particularly noticeable in the middle Orange River downstream of Boegoeberg Dam, where it commensalistically obtains shelter from *Phragmites* reeds. Otherwise, they appear to be controlled to some extent in the middle and lower Orange River by hydropower generation.

According to Benade (1993), filamentous Chlorophyta (i.e. *Spirogyra* spp.) are fairly abundant in the sidestreams and brooklets in the middle Orange River below Boegoeberg Dam. The blue-green alga (Cyanophyta), *Gloeotrichia natans*, occurs in the lower stretches of the lower Orange River. Allanson and Jackson (1983) found that the most common algal genera in the river were *Microcystis*, *Anabaena* (blue-green algae are dominant), *Scenedesmus*, *Merismopedia* and *Pediastrum*.

2.1.5 Aquatic invertebrates and Fish

The freshwater invertebrates from the Orange River includes 31 species of Chironomidae (non-biting midges), 30 species of Culicidae (mosquitoes), 28 species of Ephemeroptera (mayflies), 26 species of Odonata (dragonflies and damselflies), 23 species of Ceratopogonidae (biting midges), 18 species of Trichoptera (caddis flies), 17 species of Mollusca (snails) and 10 species of Simuliidae (blackflies) (ORRS, 1995). At least 7 Ephemeroptera species are endangered, 1 species of Simuliidae is a serious pest, while 8 Mollusca species are likely disease vectors.

The fish species present in the Orange River, their biogeographical affiliation and their status in the Orange River is indicated in Table 2 (ORRS, 1995). See Skelton (1993) for the common names of the fish species.

Table 2. The status and biogeographical affiliation of the fish species that occur in the Orange River. Species of particular conservation importance are highlighted in bold (ORRS, 1995).

Species	**Biogeographical affiliation**	**Status**
Oreodiamon quathalambae	Endemic to headwaters	Endangered
Oncorhynchus mykiss	Alien (N.America)	Endangered
Salmo trutta	Alien (Europe & NE Africa)	Present
Barbus pallidus	Indigenous	Present
Micropterus salmoides	Alien (N.America)	Present
Lepomis macrochirus	Alien (N.America)	Present
Barbus anoplus	Indigenous	Common
Labeo umbratus	Indigenous	Present
Austroglanis sclateri	Endemic to Orange-Vaal	Rare
Cyprinus carpio	Alien (Europe & Asia)	Rare
Barbus aeneus	Endemic to Orange-Vaal	Abundant
Barbus kimberleyensis	Endemic to Orange-Vaal	Rare
Labeo capensis	Endemic to Orange-Vaal	Abundant
Carius gariepinus	Indigenous	Common
Tilapia sparmanni	Indigenous	Present
Barbus paludinosus	Indigenous	Present
Barbus trimaculatus	Indigenous	Common
Pseudocrenilabrus philander	Indigenous	Abundant
Barbus hospes	Endemic to lower Orange	Common
Mesobola brevianlis	Indigenous	Abundant
Oreochromus mossambicus	Translocated indigenous	Rare
Anguilla mosambica	Peripheral	Rare

2.2 MORPHOLOGICAL IMPACTS OF THE DAMS

The Katse (phase 1*b*) and Mohale Dams in Lesotho (currently under construction) will have a major influence on low flows, small and medium floods. This is due to the fact that 70 percent of the natural runoff of the Orange River at Gariep Dam originates within Lesotho. Most of the new or planned dams are in the basaltic region, while the higher sediment yield region is downstream of the dams in the sandstone region. Sediment supply to the Orange River will therefore not be as drastically lowered as would be the case with runoff from Lesotho.

The building of the Gariep and Vanderkloof Dams, together with an increase in the withdrawal of water, changed the Orange River System into a highly regulated system (Benade, 1986). The fact that the Vanderkloof Dam is the last dam in the eastern half of the Upper-Orange River, regulation from this dam has the biggest influence on the remaining part of the Orange River System. The Vanderkloof Dam is used also for the generation of hydroelectric power. In the Gariep Dam four 90 megawatt turbines draw water for hydro-electric power generation and two 110 megawatt turbines are used in the Vanderkloof Dam (Alexander, 1974). The 600 MW hydropower capability at Gariep and Vanderkloof combined, is worth about R1.2 billion (about R2 000 per kilowatt) (ORRS, 1997). Control of the turbines is automatic and is used for power generation during peak flow periods. Thus, the regulation of the river in the past was dependent on the countrywide electricity demand (Benade, 1986). Presently, other factors than only the electricity demand are also taken into account, e.g. the demand for water for irrigation purposes downstream (Cochrane, pers. comm., 1999).

Chutter (1973) and Day *et al.* (1986) predicted that the generation of hydroelectric power would lead to extremely abnormal pulsating daily flow patterns in a river, especially during winter. Release of water for hydroelectric power generation causes daily fluctuations in the water volume in the river (Foulger & Petts, 1984 and Palmer, 1995a). Such fluctuations in the middle- and lower Orange River have a destabilizing effect on the shallow banks of the river (Skelton & Cambray, 1981).

The unnatural flow pattern that follows the building and implementing of the regulation structures in the river, is an important contributing factor in the out break of the Blackflies, *Simulium chutteri* (Chutter, 1973; Noble & Hemens, 1974; Palmer, 1998). The expansion of swamps and marches in the regulated parts of the river function as breeding places for mosquitoes and snail-intermediates for human- and animal parasites.

The first attempts to control blackflies in South Africa made use of DDT, and although it was successful in controlling *Simulium chutteri*, it also killed fish and non-target invertebrates. DDT was not used again in the control of blackflies in South Africa and became unpopular in other parts of the world because of the rapid development of resistance, its non-specificity, persistence in the environment, accumulation in food chains and undesirability in potable water.

In South Africa the use of DDT to control blackflies was replaced with flow-regulation, which was considered practical, safe and cheap. These methods involved stopping of river flow for periods long enough to dry and kill blackfly larvae and pupae. However, flow regulation was not a practical control option because it is not target-specific. It is feared that an incorrectly timed drop in water levels could be detrimental to certain fish species. Due to the problems associated with flow-regulation, biological control (bacterium BTI and temephos) is now used for blackflies. In 1990 the Northern Cape Agricultural Union estimated that *Simulium* *chutteri* accounted for up to R33 million per annum in lost animal production along a 800 km stretch of the Orange River (Palmer, 1995a).

According to Alexander (1982) simple catchment structures can lead to substantial increases in the concentrations of natural salt contents of the river. The increase in natural salt concentrations, the additional minerals from the agricultural sector and the increasing silt loads in these impoundments, could lead to an increase in water-plants, especially *Phragmites* communities (Edwards, 1969). Such an increase in plant biomass and thus photosynthetic activity could, however, lead to an increase in the pH and oxygen concentration of the impoundments (Chutter, 1973). According to Noble and Hemens (1974) impoundments are important places for the accumulation of toxic pollution in a river. Impoundments in rivers have the advantage that they function as a silt trap and that they stabilize flow and counteract erosion (Chutter, 1973). Furthermore, these impoundments absorb and weaken the smaller floods, which might have been of importance earlier for the maintenance of the physical aspects of the river (Noble & Hemens, 1974).

CHAPTER 3

MOTIVATION AND STUDY SITE

3.1. RATIONALE AND MOTIVATION FOR STUDY

The availability of quality fresh water is clearly emerging as the dominant environmental limitation of the twenty-first century. Most rivers in Southern Africa are over-exploited, degraded, polluted, or regulated by impoundments (Davies *et al.*, 1993). The Orange River is no exception. The Orange River is the largest river in South Africa, however, the flow in the lower river has been substantially reduced, and the amplitude of floods and droughts has also been reduced.

Exploitation of the Upper Orange River in Lesotho could reduce the yield of the Orange River Project further by more than 1500 $km^3 . a^{-1}$. There is also growing concern that water shortages will be experienced in the Orange River when the Lesotho Highlands Water Scheme becomes fully operational (Everson, 1999). This manipulation of rivers is certainly one of the greatest threats to river conservation and management. Such schemes may have major impacts on the biota of rivers and may also influence levels of pollution. Unfortunately, in the past, only limited ecological studies were undertaken on the river.

Some of the first published work done on the Orange River, was by Bruce and Kruger in 1970, on the geology and geomorphology of the Upper-Orange catchment, situated in the Highveld area. Van Rooyen (1971) discussed the soil of the central Orange River basin. Keulder (1973) did some research on the hydrochemistry of the Upper-Orange River catchment area, with special references to the availability of clay-adsorbed cations for algae. In 1974 van Zinderen Bakker, Sr. was the editor of a book: "The Orange River – Progress Report", which was the result of the proceedings of the Second Limnological Conference on the Orange River System. In this book various aspects of the Orange River are discussed. Pitchford and Visser (1975) did important research on the effect of large dams on river water temperatures below the dams, as well as the influence on bilharzia distribution. Ashton (1982) wrote a thesis on the autecology of *Azolla filliculoides* and its occurrence in the Gariep Dam catchment area.

In 1990 McKenzie and Schäfer worked on the hydrological aspects of the Orange River downstream of the Vanderkloof Dam. McKenzie and Roth (1994) did an evaluation of river losses from the Orange River downstream of the Vanderkloof Dam.

Very little was known about the effects that the damming of the river, and thus flow regulation, had on the invertebrates, fish and other organisms further downstream. Farmers downstream of the dams were having a serious problem with blackflies. In 1995 (b) Palmer shed some light on the invertebrates in the Orange River and emphasized conservation and management. In the same year (1995 a) Palmer, together with the Onderstepoort Veterinary Institute, released a report on the biological and chemical control of blackflies. Another report by them was published in 1998, about the principles of integrated control of blackflies.

Recently Seaman and Van As (1998) published information on the fish community at the Orange River mouth. The Department of Water Affairs and Forestry, in co-operation with Ninham Shand, are involved in the Orange River Development Project Replanning Study, in which they give useful information on almost all aspects of the Orange River Catchment area (1995, 1998). Everson (1999) quantifies open water resources by estimating the evaporation from the Orange River.

Recognizing the fact that little research was done so far on rivers in South Africa and the associated problems, it is essential to prepare and implement water management schemes. These are to be designed to aid in the conservation and protection of water quality in sources for maximum consumer benefit. At the same time to ensure that natural systems are kept intact with as little disruption as possible. Therefore, it is considered that scientific knowledge of the target river system should be required as a basis for rational resource management.

Before a river ecosystem can be successfully managed, it must be understood. Assessment of the ecological state of a river cannot be complete without an evaluation of the environmental factors that influence the aquatic ecosystem. These include biotic interactions, chemical variables, flow regime and habitat structure (Uys *et al.*, 1996). Additional environmental factors affecting rivers are hydrology, water quality, habitat availability and geomorphology. Hydrological and water quality indices would give an early warning of widespread, possibly long-term changes in river conditions, especially due to land-use and land management or development. The general objectives of this study is to increase the knowledge of phytoplankton population dynamics in the Orange River system and to gain information on impacts of the dams on the components of river systems.

3.2 OBJECTIVES

The objectives of this study were:

❖ Analysis of historical flow data as well as historical chemical data in order to estimate the effects of the building of both the Gariep and Vanderkloof Dams on the water quality of the Upper Orange River;

- Review and evaluation of the water quality of the Upper Orange River for the different user groups, i.e. recreational and agricultural users;
- Systematic elucidation of the physical, chemical and biological features of the lenthic and lotic environments of the Upper Orange River;
- Statistically qualify seasonal variation and interrelationships between environmental variables and nutrients;
- Investigate the seasonal succession of dominant phytoplankton species as part of the biomonitoring program;
- Determine the health of the river by using the SASS4 biomonitoring program;
- Determine the trophic status of the river;
- Determine the roles of photosynthetic primary producers within the lotic ecosystem and the factors responsible for the waxing and waning of phytoplankton populations;
- Evaluate flow-attenuation problems on the ecosystem such as:
    - General increases in salinity
    - Increased residence time
    - Decreased water quality
- Verify the validity of a river simulation model (EUTROMOD) on the Upper Orange River for future use.

3.3 STUDY SITE

The Orange River, situated in southern Africa, has a total catchment area in the order of 1 000 000 km^2. Almost 600 000 km^2 of its catchment is within South Africa's borders (McKenzie & Schäfer, 1990). This river drains approximately 47 % of the country's total surface area (Roberts, 1965) and according to Benade

(1993), stretches 2 300 km from the source in the Drakensberg (Lesotho) to Alexander Bay in the west.

The Upper Orange River can be defined as the region between the source in Lesotho and the Orange-Vaal confluence. This study was conducted in the Upper Orange River, from the Kraai River (tributary) up to the Orange–Vaal confluence, approximately 456 km (Figure 4).

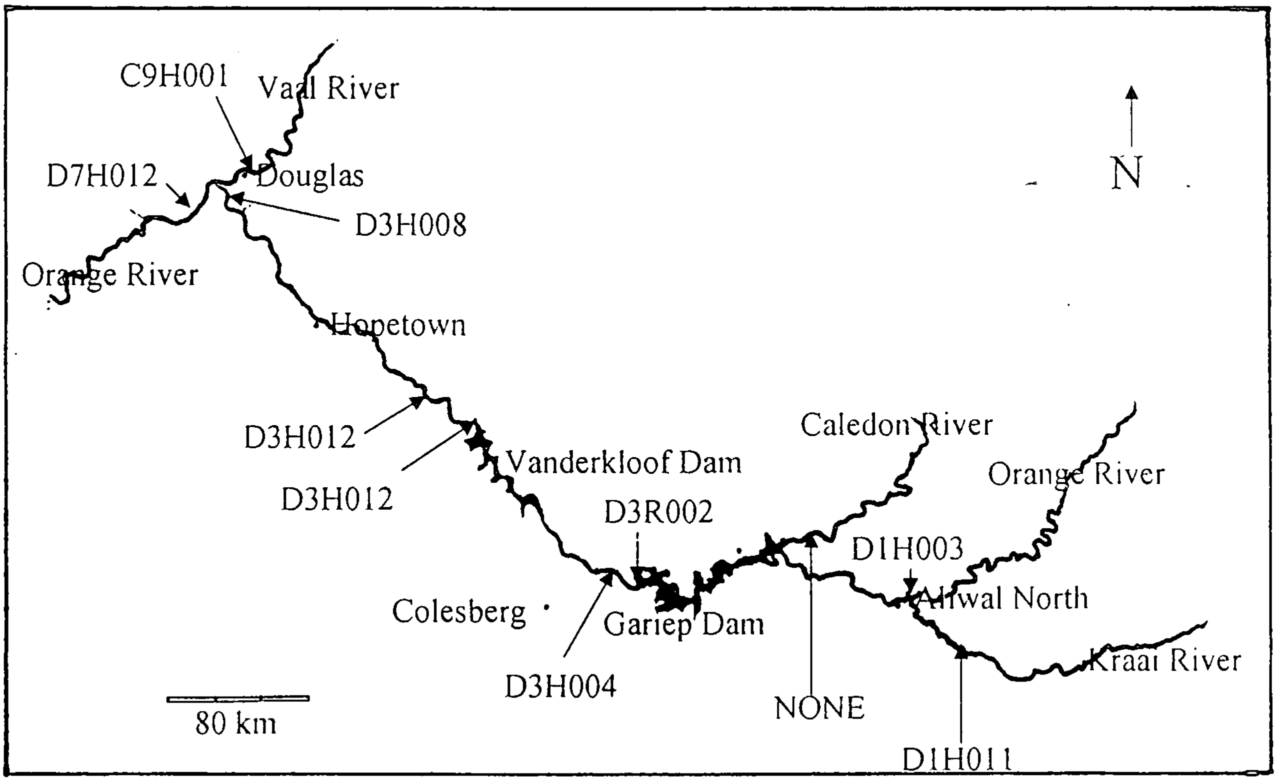


Figure 4. Study area and sampling stations. For explanation see Table 3.

Water samples were taken approximately once every second month, from February 1998 to October 1999, at the sampling points indicated in Table 3. Sampling points are also indicated on colour photographs at the end of this chapter. Weekly data was obtained from the Department of Water Affairs and Forestry.

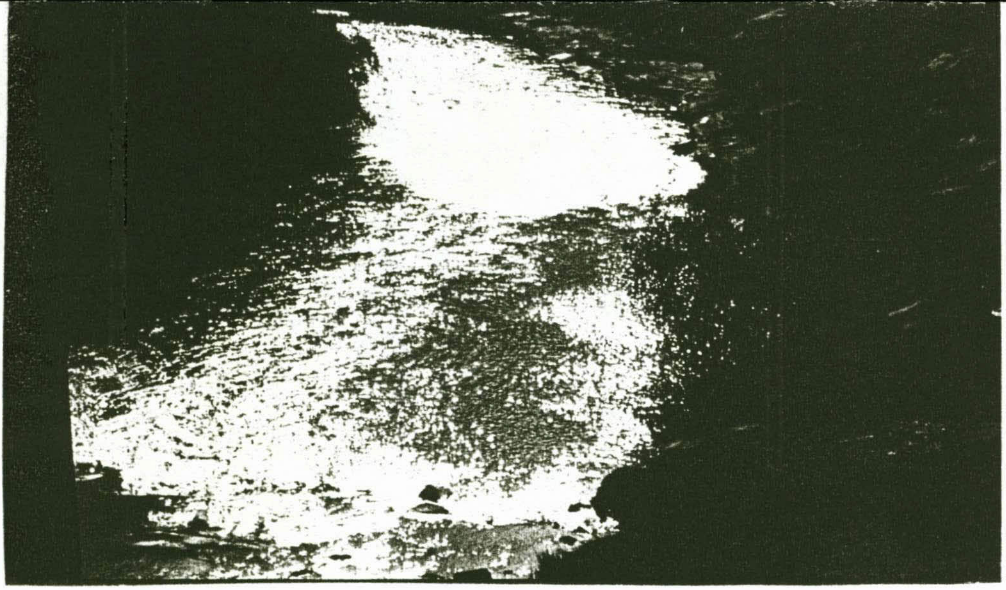
Table 3. Location of Sampling Points

Sampling point	Sampling Station*	Latitude/Longitude
Kraai River (Tributary)	D1H011	30°41' / 26°45'
Aliwal North (Orange River)	D1H003	30°43' / 26°42'
Caledon River (Tributary)		30°26' / 26°18'
Gariep (Dam)	D3R002	31°37' / 24°30'
Norvalspont (Orange River)	D3H004	31°36' / 24°26'
Vanderkloof (Dam)	D3H013	30°05' / 24°45'
Havenga bridge (Orange River)	D3H012	29°37' / 24°07'
Marksdrift (Orange River)	D3H008	29°04' / 23°38'
Vaal River (Tributary)	C9H001	29°03' / 23°37'
Orange-Vaal Confluence	D7H012	29°05' / 23°36'

* DWAF sampling codes (Department of Water Affairs & Directorate of Hydrology, 1990)

The river never ran dry during the study period, although flow cessation sometimes occurred at some of the sampling points during winter periods. The Kraai River is well above the populated area and originates in the mountains, it presumably contains pristine water and was used thus as a reference point.

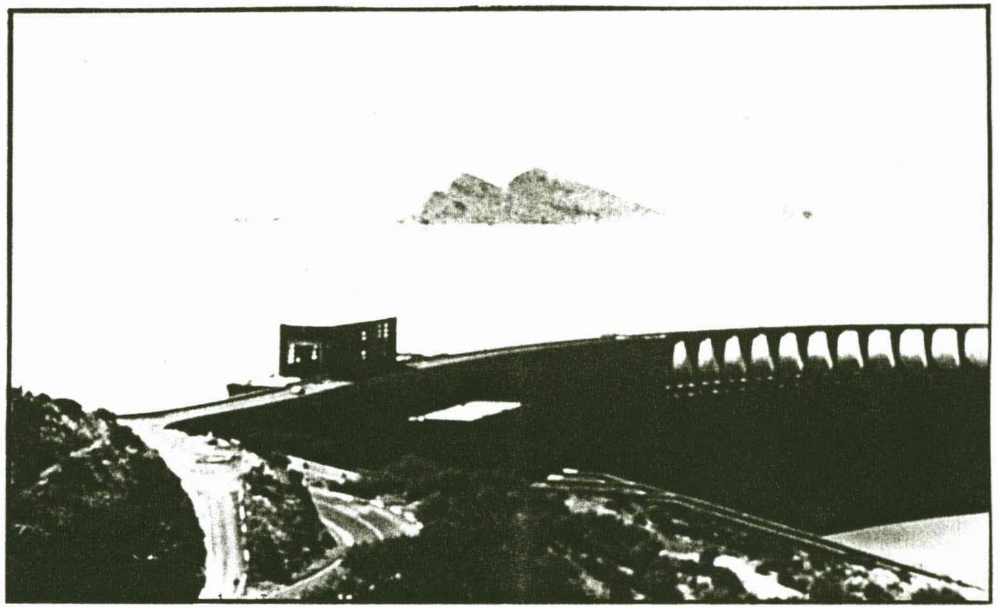
In situ measurements were made of the temperature, depth of light penetration (Secchi), pH, conductivity, oxygen concentration and the percentage oxygen saturation. Subsurface samples (1 liter) were taken and brought to the laboratory for chemical analyses. The analyses were done within 48 hours. Prior to analyses the samples were stored in the dark at 4 °C to limit metabolic processes.



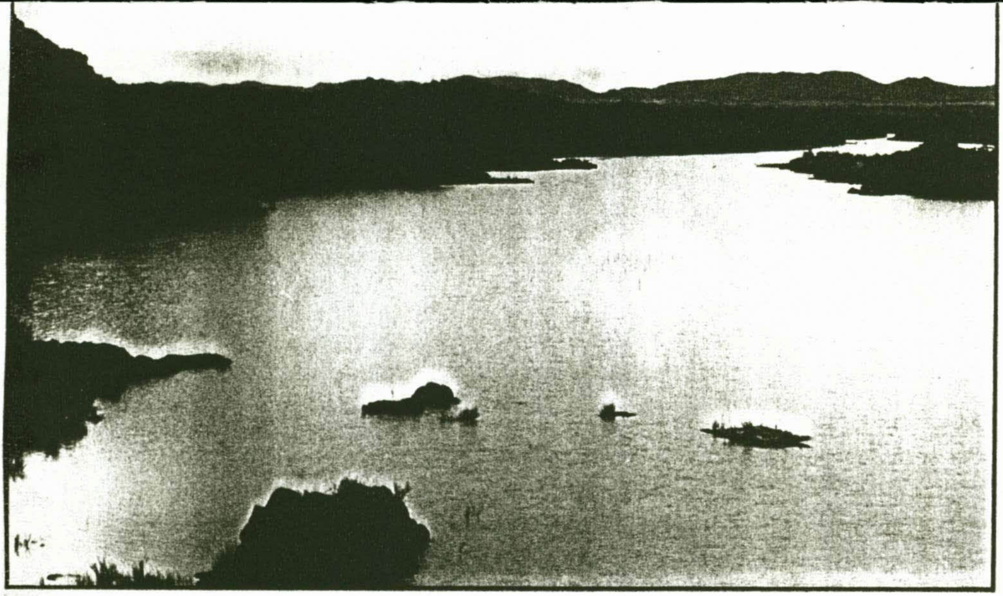
The sampling point in the Kraai River

The sampling point in the Orange River at Aliwal North

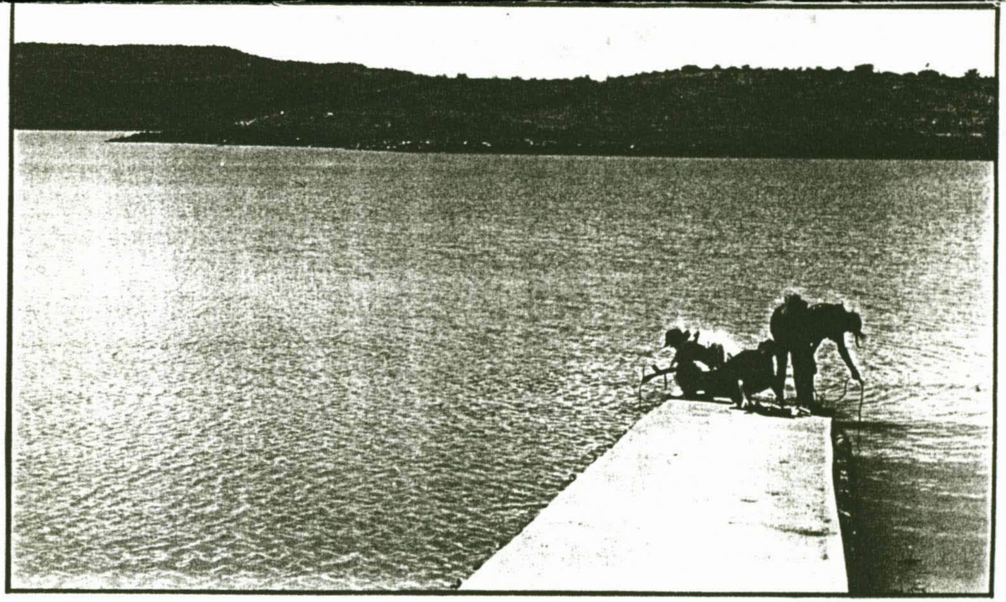
The sampling point in the Caledon River



The sampling point in the Gariep Dam (near the dam wall)

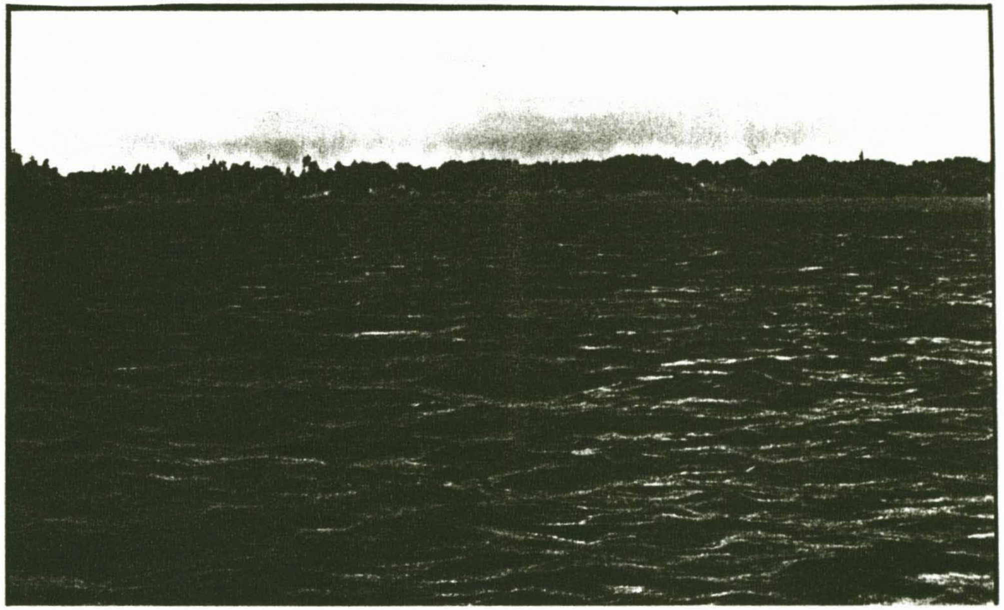


The sampling point in the Orange River at Norvalspont



The sampling point in the Vanderkloof Dam

The sampling point in the Orange River at Havenga bridge



The sampling point in the Orange River at Marksdrift (reached by boat)

The sampling point in the Vaal River (reached by boat)

The sampling point in the Orange River after the Orange-Vaal confluence (reached by boat)

CHAPTER 4

PHYSICAL PARAMETERS

4.1 INTRODUCTION

The sun is the main source of energy and heat for the earth and thus affects many physical phenomena and all the biological phenomena on the earth's surface. Solar radiation is of fundamental importance in the dynamics of freshwater ecosystems. Most light entering water is converted to heat. The penetration of solar radiation can be profoundly affected by light scattering due to suspended particles in the waterbody. The resultant effects on the penetration of solar radiation will have implications for the thermal properties and primary productivity of the waterbody (Roos, 1991).

4.2 MATERIALS AND METHODS

The graphical representations were made with the SigmaPlot 5.0 package. Box plots (data distribution) were frequently used; the box represents the 25th through 75th percentiles (i.e. 50 % of data in box). The 5th and the 95th percentiles are shown as symbols (o) below and above the 10 % and 90 % caps respectively. The solid line in the box represents the median and the dotted line the mean value.

4.2.1 Temperature

Temperature plays an important role in water by affecting the rates of chemical reactions and also the metabolic rates of organisms. Temperature is therefore one of the major factors controlling the distribution of aquatic organisms (DWAF, 1996).

The water temperature (°C) at each sampling site was determined, using a YSI Model 50 B dissolved oxygen meter equipped with a 5739 probe and was done *in situ*. A depth profile, with 1 meter intervals, was done in the Gariep Dam near the dam wall, on 19 February 1999.

4.2.2 Turbidity

Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a water sample. Water turbidity is generally considered to be equivalent to some measure of the concentration of suspended solids (DWAF, 1996).

Unfiltered water was used to measure the turbidity of the water samples in the laboratory. Turbidity is an indicator of the concentration of suspended, inorganic, organic and biological material in the water and was determined with an Aqualitic Turbidimeter AL 1000, expressed as NTU (Nephelometric Turbidity Units).

A Secchi disk (20 cm diameter) was used to determine the transparency of the water-column *in situ*.

4.2.3 Total suspended solids (TSS)

The TSS concentration is a measure of the amount of material suspended in water. The concentration of suspended solids increases with the discharge of sediment washed into rivers due to rainfall and resuspension of deposited sediment (DWAF, 1996).

TSS were determined by pre-weighing glass fibre filter papers and then by filtering a known amount of the sample water through it. These were dried at 70°C for 12 hours and weighed again. The values of the unused filter papers were substracted from the used, dry filter papers and those gave an indication of the TSS in $mg.l^{-1}$.

4.2.4 Flow and Rainfall

Increase turbulence due to increased flow, increases the input and the breakdown of organic matter, which also influences life in the water. In addition, a river is an open system that received allogenic substances through precipitation and rainfall (Prinsloo & Pieterse, 1994).

Flow data was obtained from the Department of Water Affairs and Forestry in Pretoria. Rainfall data was obtained from the Weather Bureau in Pretoria.

4.3 RESULTS AND DISCUSSION

4.3.1 Temperature

As sunlight heats water near the surface, it will form a layer of less dense warm water that overlay a denser cool zone. A layer of water is formed that has a more defined boundary than the illuminated zone. The lake or dam has stratified when this defined boundary forms. Three separate layers can be observed during summer stratification, namely:

The epilimnion – the warmer, less dense upper layer,

The hypolimnion – a cooler, more dense lower layer,

The metalimnion – a layer of intermediate density which lies between the epi- and hypolimnion.

These layers were observed in the Gariep Dam on 19 February 1999 (Figure 5). In the Gariep Dam the epilimnion was approximately the first 25 meters and the

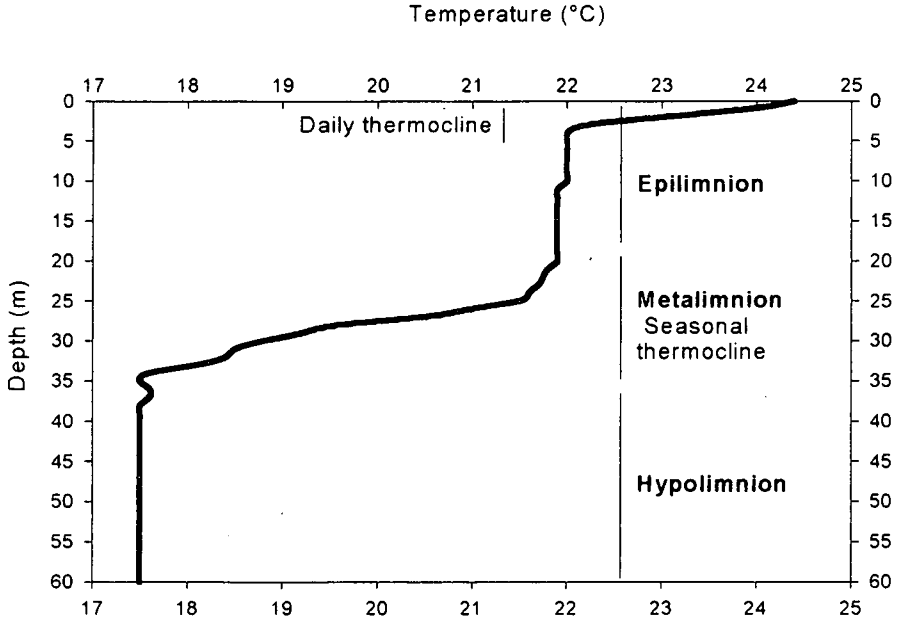


Figure 5. A Temperature-depth profile in the Gariep Dam, on 19 February 1999

hypolimnion stretches from approximately 35 meters to the bottom. However, these layers are dynamic, with some fluctuation in the size of each layer occurring over the season (Horne & Goldman, 1994). The other important zone in the dam is the thermocline, which is the region where temperature changes rapidly with depth. The thermocline can also be defined as the region where the greatest inflection in the temperature-depth curve occurs.

Temporary or daily thermoclines are usually shallow, and on 19 February 1999, it was at the first five meters (Figure 5). The parent or seasonal thermocline lies within the metalimnion, and in the case of the Gariep Dam, it is at a depth of approximately 28 ± 2 meters. Stegmann (1975) estimated the thermocline of the Gariep Dam for October 1971 at approximately 20 meters. The Gariep Dam can be classified as a warm monomictic lake. Warm monomictic lakes occur at temperate latitudes in subtropical mountains and they mix only once during the year, with temperatures that never fall below 4 °C (Thomas *et al.*, 1996).

The thermal regime of the Gariep Dam, as well as that of the Vanderkloof Dam, is very important due to the water being released from the dams for irrigation purposes. Most dams are constructed in such a way that the normal water outflow from them into the river below is from sluices below surface level. This is also the case in the Gariep and Vanderkloof Dams. Both dams have two different types of sluices, namely silt and flood sluices, as well as turbines for hydroelectric power generation. The height of the Gariep Dam wall is 1 313.7 meters above sea level. In the Gariep Dam the silt and flood sluices are respectively 1 204 meters and 1 232 meters above sea level, and the turbines are 1 220 meters above sea level. The height of the Vanderkloof Dam wall is 1 170 meters above sea level. In the Vanderkloof Dam the silt sluices are respectively 1 105 and 1 117 meters above sea level, and the flood sluice 1 146 meters above sea level. The turbines in the

Vanderkloof Dam are 1 142 meters above sea level (Cochrane, pers. comm., 1999). Depending on the depth below surface level, temperatures of the out-flowing water might be very different from the normal water temperatures existing in comparatively shallow rivers.

The average monthly temperatures before and after completion of the dam are illustrated in Figure 6. The average temperature before the building of the dams was 17.5 °C for 1966 – 1969, and for 1971 – 1973 (after the building of the dams), it was 15.5 °C. This figure also shows the delayed thermal inertia of the water mass.

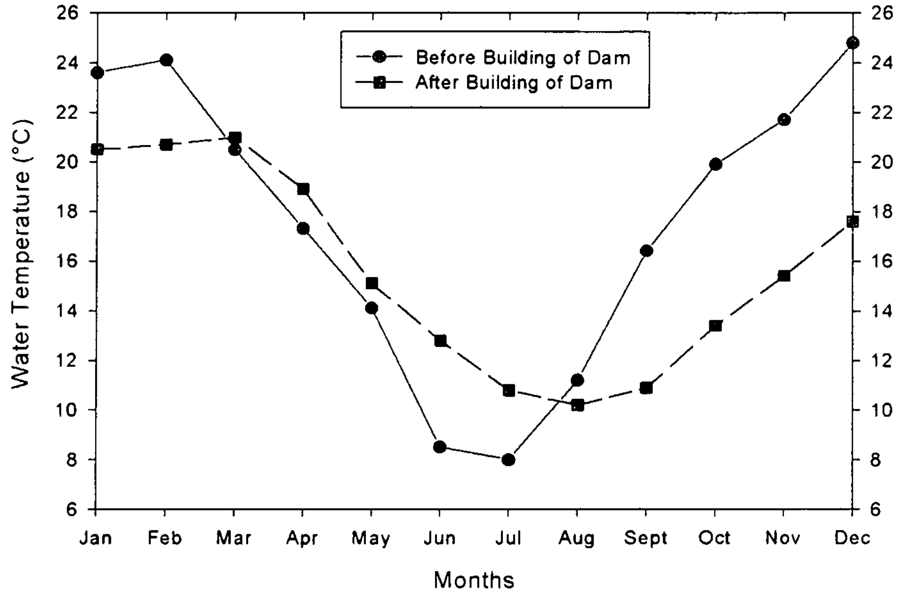


Figure 6. The average monthly temperatures (°C) in the Orange River below the Gariep Dam before (1966 - 1969) and after (1971 -1973) completion of the dam (Redraw from Pitchford & Visser, 1975)

Pitchford and Visser (1975) compared water temperatures 4 km downstream of the Gariep Dam, before and after impoundment, and found that the range was reduced from 19.6 °C (pre-impoundment) to 12.8 °C (post-impoundment), and that seasonal effects are delayed by the thermal inertia of the reservoir water mass.

The seasonal average water temperatures at the different sampling points during the present study period are illustrated in Figure 7. Summer temperatures reach up to 27.6 °C in the Vaal River and during winter as low as 10.3 °C in the Orange River at Aliwal North. At Norvalspont, approximately four kilometers downstream of the Gariep Dam, the water temperature is constantly lower than the surface water temperature in the dam. During the study period the water temperature at Norvalspont was on average 2.7 °C lower than those of measurements taken in the Gariep Dam. This could also be seen to a lesser extent in the Orange River at Havenga Bridge, situated below the Vanderkloof Dam. The reason for this is probably because Havenga Bridge is further downstream of the Vanderkloof Dam than Norvalspont is from the Gariep Dam.

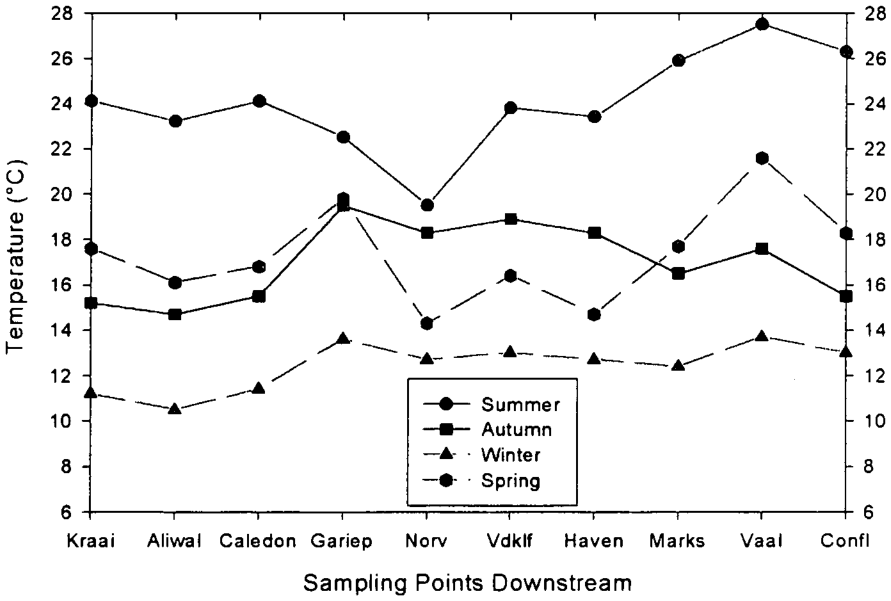


Figure 7. Seasonal average water temperatures at the different sampling points in the Orange River system, during the study period

As discussed earlier, the water that is being released from the dams came from the hypolimnion, which contains colder water and thus reduce the temperature downstream of the dams. The effects of these reduced temperatures in the Upper Orange River should be investigated further. However, Dallas and Day (1993) reported that changes in water temperature that are unrelated to natural variation in temperature may have an effect at the organism, species and/or community level. Howells (1983, cited in Dallas & Day, 1993) concluded that lower temperature ranges may influence movement, behaviour, the onset or maintenance of sexual maturity, life stage development and growth and size.

Pitchford and Visser (1975) also noted that the persistent increase in winter and decrease in summer temperatures downstream of the Gariep Dam might encourage the perennial development of *Schistosomiasis* host snails and the possibility of summer transition of bilharzia (in some water systems). Palmer (1995a) found that water temperature also dictates the rate of blackfly (*Simulium chutteri*) larval development.

The diel temperatures in the Orange River at Marksdrift and in the Vaal River, for 17 and 18 September 1998 are illustrated in Figure 8. Fluctuations in atmospheric temperatures are significantly greater than those in water, which is more thermally stable. In the Vaal River the maximum water temperature was 21.2 °C at 15:00 and the minimum water temperature was 16.1 °C at 21:00. In the Orange River at Marksdrift, the maximum water temperature was 16.8 °C at 15:00 and the minimum water temperature was 14.8 °C at 09:00.

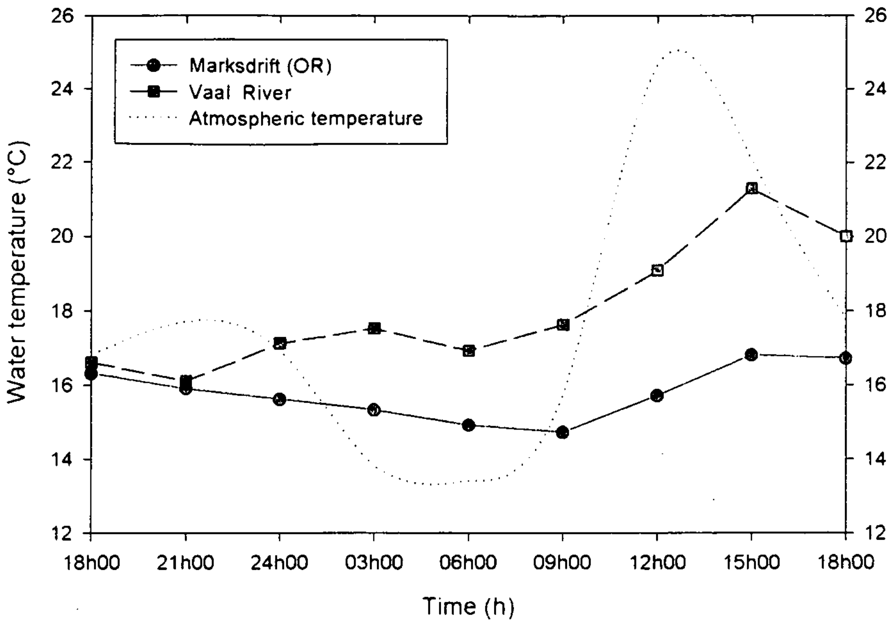


Figure 8. Diel Temperatures (°C) in the Orange River at Marksdrift and in the Vaal River at the Confluence, for 17 & 18 September 1998

The diel temperatures in the Orange River at Marksdrift and in the Vaal River for 22 and 23 April 1999 are illustrated in Figure 9. In the Vaal River the maximum water temperature was 19.3 °C at 16:00 and the minimum temperature was 16.7 °C at 08:00. In the Orange River at Marksdrift the maximum water temperature was 17.3 °C at 16:00 and the minimum water temperature was 15.4 °C at 02:00. During the studies in both September 1998 and April 1999, the water temperatures of the Orange River at Marksdrift were constantly lower than the water temperatures of the Vaal River. This could be ascribed to the cold hypolimnetic water that is being released from the Vanderkloof Dam. Another reason might be that the water in the Orange River at Marksdrift flows much faster than the water in the Vaal River and, thus, has less time to be heated by sunlight.

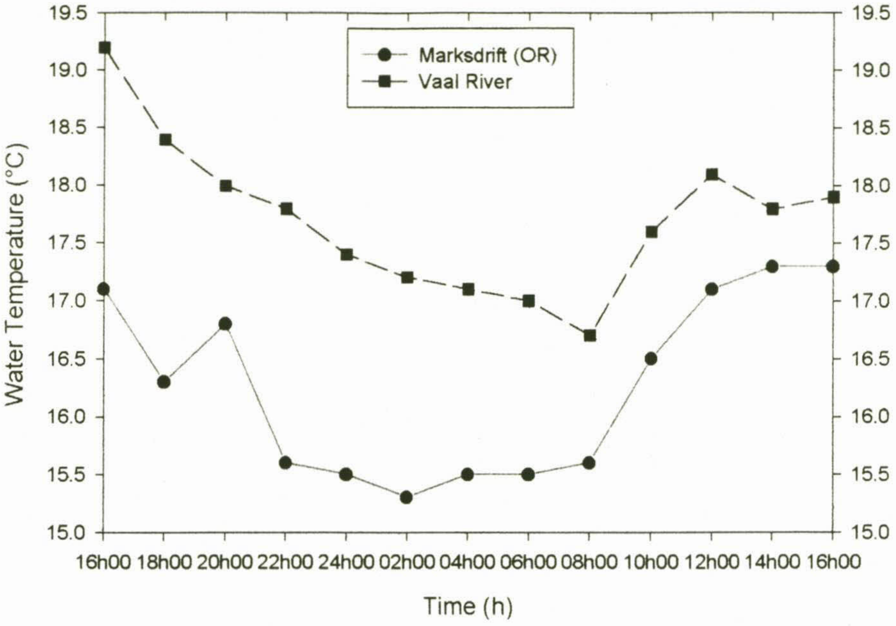


Figure 9. Diel Temperatures (°C) in the Orange River at Marksdrift and in the Vaal River at the Confluence, for 22 & 23 April 1999

4.3.2 Turbidity and Total Suspended Solids

The total suspended solids (TSS) concentration gives an indication of the amount of suspended materials in water. As the discharge of sediment washed into rivers increases, the concentration of suspended solids also increases, due to rainfall and resuspension of deposited sediment. As the flow decreases the suspended solids settle out at a rate which is dependant on particle size and the hydrodynamics of the water body (DWAF, 1996).

Turbidity gives an indication of the optical property that causes light to be scattered and adsorbed rather than transmitted in straight lines through a water sample. Suspended matter causes light scattering, while inorganic matter causes the adsorption of light (DWAF, 1996).

The major part of suspended material found in most natural waters is made up of soil particles, which is derived from land surfaces. Land-use practices such as overgrazing, non-contour ploughing and removal of riparian vegetation accelerate erosion and result in increased quantities of suspended solids in associated rivers (DWAF, 1996). It was estimated that South African rivers carry between 100 and 150 million ton sediment annually, and from this, 40 million tons can be ascribed to the Orange River (DWAF, 1986).

Continuous high-level sediment inputs may have very serious consequences for the riverine biota. As light penetration is reduced, primary production decreases and food availability to organisms higher in the food chain is diminished. Community composition may change depending on which organisms are best able to cope with this alteration in habitat. Suspended inorganic material carries an electrical charge (e.g. PO_4^{3-}). This causes a variety of dissolved substances, including nutrients, trace metal ions, and organic biocides to adsorb onto the surfaces of these particles (DWAF, 1996). These substances are often not readily available and this may be advantageous in the case of toxic trace metal ions, but disadvantageous in the case of nutrients.

The turbidity at the different sampling points for 1998 and 1999 is illustrated in Figure 10. The average turbidity in the Kraai River was 38 NTU. This relatively low turbidity is ascribed to the mechanically stable rocks of the Drakensberg, Cave sandstone and Red Beds Etages over which it initially flows. The high turbidity of the Caledon River (550 NTU on average) may be ascribed to the relatively soft sandstone and mudstone of the Beaufort Series over which it flows. The Orange River mainly flows over the unstable mudstone of the Molteno Etage and Beaufort Series (Keulder, 1974) which might give rise to the relatively high turbidity of the

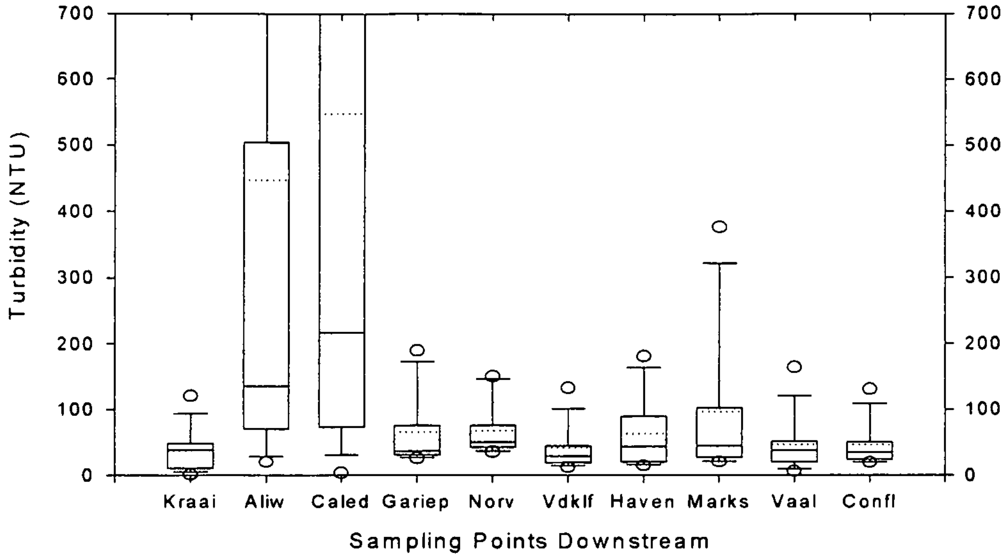


Figure 10. Box plots of turbidity at the different sampling points in the Orange River system during the study period

(The 5th and the 95th percentiles are shown as symbols (o) below and above the 10% and 90% caps respectively. The lower and upper horizontal lines of the box plot indicate the 25 and 75 percentiles respectively, while the median is indicated by a solid horizontal line inside the box plot. The dotted line represents the mean value)

Orange River at Aliwal North. The average turbidity at Aliwal North was 450 NTU. However, the turbidity values in the Gariep Dam and downstream were much lower, with an average of 73 NTU, which suggested that the dam acted as a sediment trap. The relatively low turbidity in the Vaal River, which was 47 NTU on average, corresponds with the average turbidity of 62 NTU that Roos (1991) found for the Vaal River during his study period from 1985 to 1989, which included the floods of 1988.

Vaithiganathan *et al.* (1992), among others, also found that the two dams in the Cauvery River in India act as sediment traps. They also found that the removal of coarser sediments at dam sites had a significant influence on the elemental chemistry, and in turn adverse effects on water quality. Grobler and Davies (1981) demonstrated conclusively that bottom sediments could act as an important source of phosphate to algae. Rooseboom (1972) did some research on the sediment transport within the Gariep Dam. Rooseboom reported that sedimentation occurred primarily at the beginning of the dam and ascribed it to the decrease in flow of the sediment-transporting incoming water. Hart (1990) found the same trend in the Vanderkloof Dam, where the Secchi depth transparency doubled from approximately 18 cm at the turbid inflow, to 33 cm near the dam wall. The low turbidity in the dams, together with low turbulence, has a stimulating influence on algal growth.

The seasonal variation in turbidity at the different sampling points is illustrated in Figure 11, showing the drastic decrease in turbidity in and below the dams. Above the dams the highest turbidity was found during February and the lowest during July. In and downstream of the Gariep Dam the seasonal patterns were almost completely diminished. This indicates that turbidity above the dams are closely linked to flow and rainfall, with the highest turbidity occurring during summer rainfall, coupled with high flow and *vice versa*. Several authors also noted the positive correlation between rainfall, flow and turbidity (Grobbelaar *et al.*, 1980; Vaithiganathan *et al.*, 1992).

Water turbidity is generally considered to be equivalent to some measure of the concentration of suspended solids. An increasing trend, but no statistically significant correlation, was found for the Orange River and tributaries. This was probably because the river system includes both lenthic and lotic systems.

Grobbelaar and Stegmann (1976) found that coloured inorganic turbidity is common in South Africa. They also found that the turbidity in the Gariep Dam was caused by colloidal inorganic material, while Hart (1990) found that the Vanderkloof Dam was characterized by mineral turbidity. In the Orange River at Aliwal North 42 %

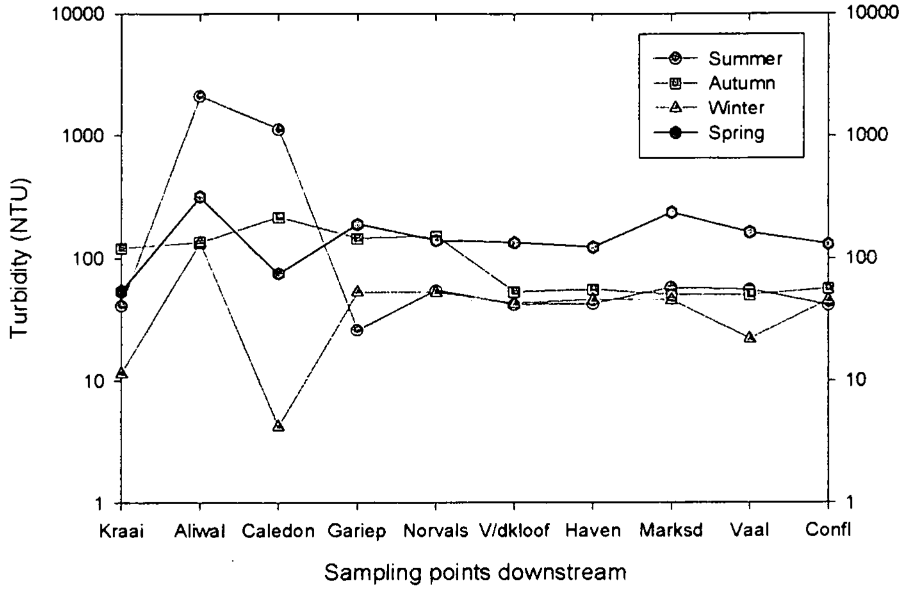


Figure 11. Average seasonal turbidity (NTU) at the different sampling points in the Orange River system during the study period

of the variation in turbidity was associated with variation in TSS during this study. However, in the Orange River at Marksdrift (downstream of the dams) only 0.9 % of the variation in turbidity was associated with variation in TSS and consequently was statistically insignificant. Thus, it is clear that the turbidity in the Orange River is influenced by factors like the dissolved organic colour of the water and should be investigated further.

Significant correlations between turbidity and TSS were illustrated in other systems. Roos (1991) found a statistically significant correlation between turbidity and TSS (r^2 = 0.92 on a log scale), for the Vaal River. A statistically significant correlation (r^2 = 0.83 on a log scale) between turbidity and TSS was also found in 34 Alaskan rivers (cited in Roos, 1991).

4.3.3 Rainfall and Flow

Rivers differ from lenthic systems, such as lakes and wetlands, in that unidirectional movement of the water has an effect on plant and animal life. Flow and rainfall influence the input of allogenic substances and the breakdown of organic matter.

The allocation of compensation flows, which not only satisfy the water demands of downstream users, but also maintain the river as a viable and healthy ecosystem, is one of the major challenges that river management faces worldwide. Conflict around the Orange River arises between:

1) the demands of agriculture,
2) the generation of hydro-electricity, and
3) the preceived environmental requirements.

Agriculture requires the flow to be stable, so as neither to flood nor to strand pumps. Peak agricultural demand is in summer. The generation of hydro-electricity, on the other hand, releases short term (bi-daily) pulses of water during peak electricity demands, mainly in winter. Both of these requirements are in conflict with the preceived environmental requirement, which is to simulate natural summer floods and winter droughts (Balance & King, 1999).

The total annual rainfall at Aliwal North for 1980 to 1999 is shown in Figure 12. Significant fluctuations in yearly rainfall are evident over this period. The lowest rainfall since 1980 until 1999 occurred during 1999 (259 mm) and the highest rainfall occurred during 1988 (963 mm).

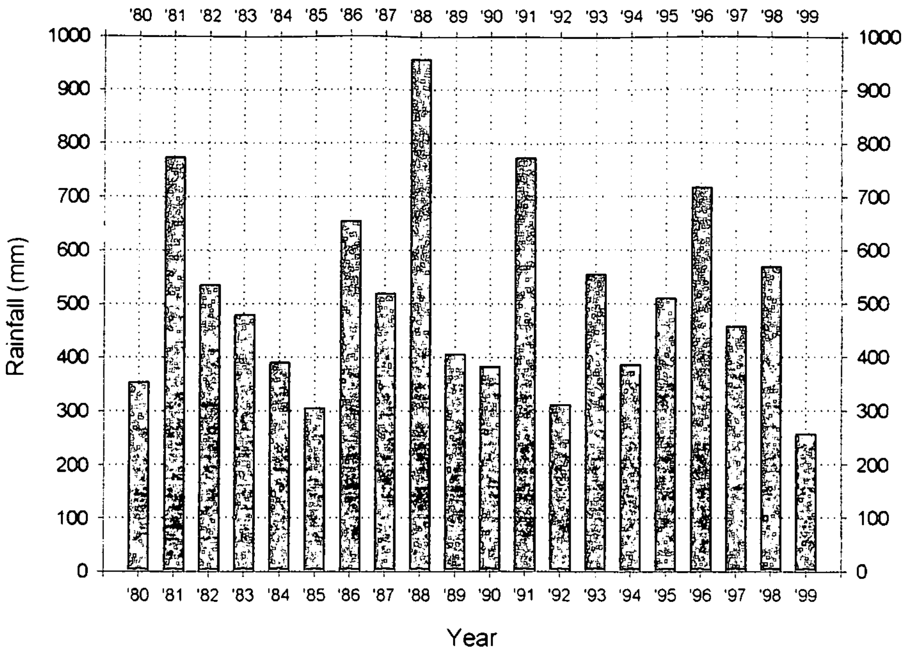


Figure 12. Total annual rainfall (mm) at Aliwal North since 1980 until 1999

The daily release of water from the turbines in the Gariep Dam for 1999 is illustrated in Figure 13. An average of 84 $m^3.s^{-1}$ water was released daily. During the cold months (May to August) more water was released from the turbines than in some of the warmer months, with the exception of September, thus reducing winter droughts. Despite this evidence that seasonal flow patterns are diminished below the dams, no attempt is made to simulate natural flow conditions by varying it seasonally (Balance & King, 1999).

Although the water requirements of agriculture and the generation of hydro-electricity can be accurately quantified, the amount of water required to simulate natural conditions is difficult to quantify. Heritage *et al.* (1997) also emphasized that it is essential to quantify the water requirements of the environment reliably, if the country's water resources are to be optimized for all demand sectors. They made this statement in the light of the current view of the new Water Act (1998), that the riverine environment is considered a resource in South Africa, and thus have a legitimate demand in the competition for the nation's limited water resources.

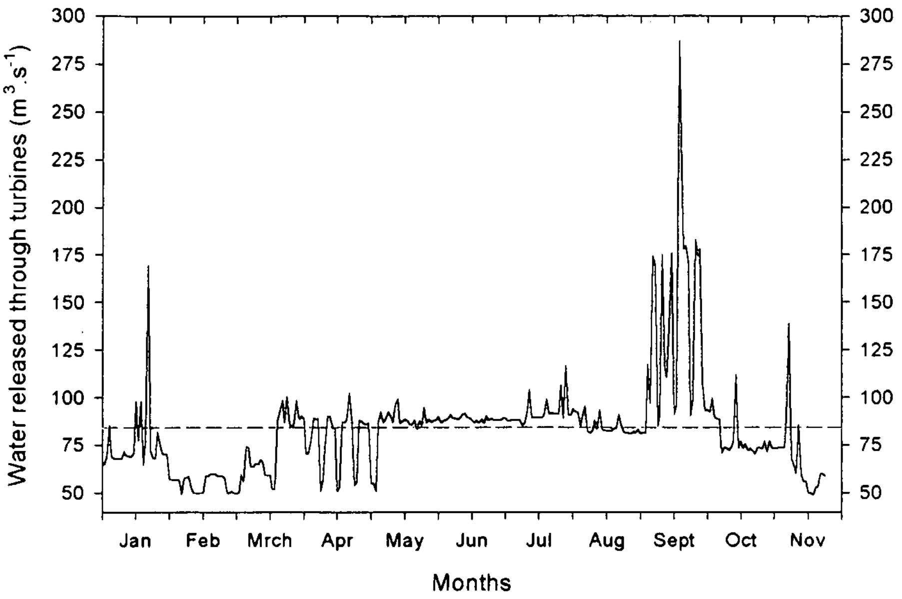


Figure 13. The daily discharge ($m^3.s^{-1}$) from the turbines in the Gariep Dam, from January to November 1999. Dashed line indicates the average discharge

One of the main effects of impoundments in the Orange River has been to convert the river from seasonal to perennial by reducing downstream seasonal flow-fluctuations (Palmer, 1995a). Monthly flow from 1960 - 1970 in the Orange River at Marksdrift, before the building of the dams, is illustrated in Figure 14. Distinct seasonal flow patterns were evident, with high flow (average 180 $m^3.s^{-1}$) during the summer months (high rainfall) and low flow (average 35 $m^3.s^{-1}$) during the winter months. Fluctuation in monthly flow from 1977 – 1987 in the Orange River at Marksdrift, after the building of the dams, is illustrated in Figure 15. Seasonal flow patterns are now much less conspicuous. The average flow during the summer was approximately 150 $m^3.s^{-1}$, and during the winter it was approximately 100 $m^3.s^{-1}$.

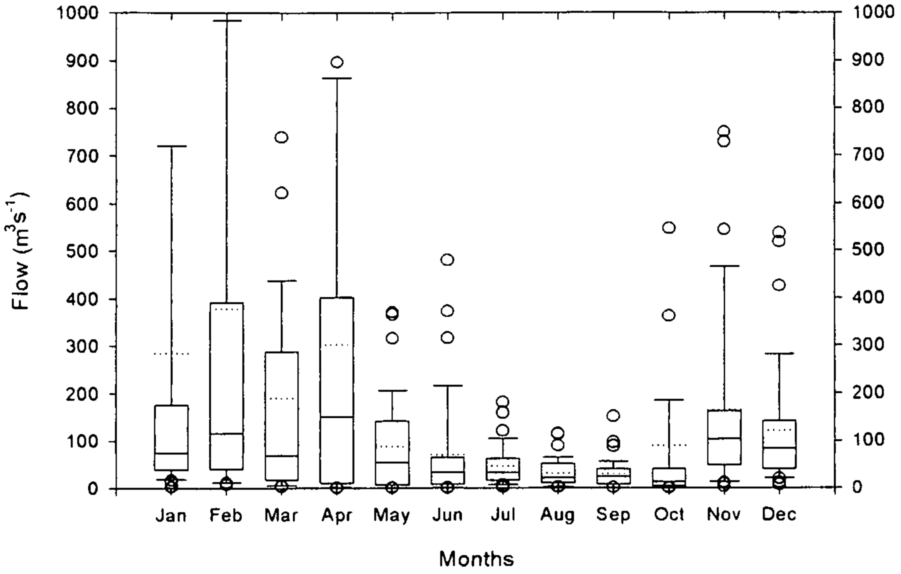


Figure 14. Fluctuations in monthly flow at Marksdrift before the building of the dams (1960 - 1970)

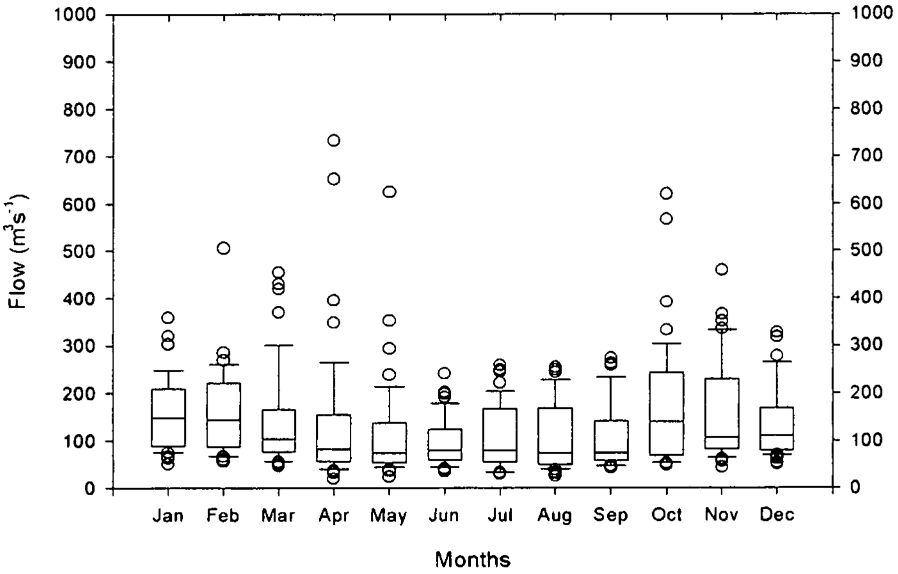


Figure 15. Fluctuations in monthly flow at Marksdrift after the building of the dams (1977 - 1987)

The monthly flow and rainfall averages, for 1998 and 1999, in the Orange River at Aliwal North and at the turbines in the Gariep Dam, are illustrated in Figure 16. As the Orange River are mainly situated in the summer-rainfall area, the highest rainfall (131 mm) occurred between October and March whereas from May to September very low rainfall (sometimes less than 5 mm) were experienced. The flow was at its highest in March 1998, at 661 $m^3.s^{-1}$ at Aliwal North, in the Orange River, and 622 $m^3.s^{-1}$, in the Gariep Dam, at the turbines. A decrease in flow could be observed from April 1998, which coincide with a decrease in rainfall, until the summer rain in November 1998, when the flow also increased again.

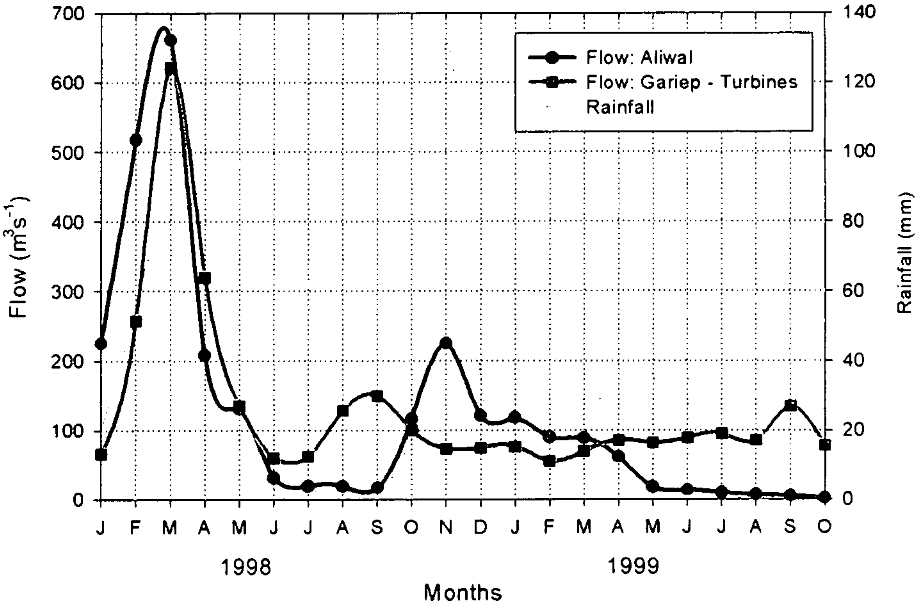


Figure 16. Monthly flow and rainfall averages in the Orange River at Aliwal North and through the turbines in the Gariep Dam, during the study period

Natural flow, as could be found at Aliwal North, showed low flow values during winter periods. On the other hand, regulated flow, as could be found at the Gariep Dam turbines, showed an increase in water releases during winter. The water released through the turbines is used for hydroelectric power generation and for irrigation purposes downstream. This very limited period of low flow downstream of the dams is probably the main cause of the problems with the blackflies, which is experienced downstream (Palmer, 1995a). However, the problems with the blackflies are only experienced in the Orange River after its confluence with the Vaal River. The main reason for this is the relatively constant low flow in the Orange River.

4.4 CONCLUSIONS

The hypolimnetic water releases from the Gariep and Vanderkloof Dams cause a significant decrease in temperature (2.7 °C on average) downstream of the dams. The Upper Orange River is a turbid system with an average turbidity of 232 NTU. The dams cause the total suspended solids and turbidity in the river system to decrease, as they act as sediment traps. A decrease in turbidity cause the light penetration to increase and results in more favourable conditions for photosynthesis which may stimulates primary productivity and can lead to algal blooms (Roos & Pieterse, 1995a). Selkirk (1982) concluded that light must be regarded as the primary limiting factor in both the Gariep and Vanderkloof Dams and that nutrients would only be limiting should there be an increase in water transparency.

Rainfall, and thus corresponding flow, also influences turbidity. The dams, which are being used for hydro-electric power generation, almost completely diminished seasonal flow patterns and changed the Orange River into a highly regulated system. This interference with the seasonal flow patterns in the river is probably one of the main reasons for outbreaks of *Simulium chutteri* (blackflies). In 1990 blackflies accounted for up to R 33 million per annum in lost of animal production in the Northern Cape (Palmer, 1995a). The expansion of swamps and marches in the regulated parts of the river function as breeding places for mosquitoes and snail-intermediates for human- and animal parasites. The disturbance in the seasonal flow patterns also interferes with the so-called ‘flushing flows’ that act as environmental cues for various aquatic organisms, as well as maintain the river form (Jørgensen & Padisak, 1996).

CHAPTER 5

CHEMICAL PARAMETERS

5.1 INTRODUCTION

A large number of different properties and parameters are available to describe the chemical characteristics of rivers (Dallas & Day, 1993). These range from general descriptors, such as measures of salinity and acidity, to composition in terms of major cation and anion content, and to the concentrations of organic and inorganic micro-pollutants (Webb & Walling, 1992)

The transfer of chemical elements through the hydrological cycle involves a complex interaction of chemical, biological and hydrological systems and processes. The nature of dissolved chemical element (solute) behaviour in river systems ultimately reflects the various sources and stores of dissolved material that are present in the drainage area and the different processes that mobilize and modify chemical constituents found in draining waters (Webb & Walling, 1992). Although in-stream transformations of solutes through physical, chemical and biological processes can exert a considerable influence on water chemistry, solute behaviour is determined largely by the interaction of hydrological and biogeochemical processes at a basin-wide scale (Walling, 1980).

5.2 MATERIALS AND METHODS

In the laboratory 500 ml of each water sample was filtered through 47 mm glass fibre filters (Whattman GFC, particle retention: 0.7 µm). The remaining portions of each sample were analysed immediately for total phosphorus (TP).

Background readings had been taken spectrophotometrically for all the chemical analyses on unfiltered samples. Specific wavelengths of certain chemical analysis were used for measurement. The Hitachi spectrophotometer was zeroed with the control of each chemical analysis. Calibration standards were prepared in order to plot a standard curve from which the concentrations could be determined by means of regression analysis on a computer program.

5.2.1 Dissolved oxygen concentration and percentage saturation

The short- and long-term variations in dissolved oxygen of lakes and rivers are good measures of their trophic states. For example, oligotrophic water shows little variation from saturation, while eutrophic water may range from virtual anoxia in the hypolimnion to supersaturation in the epilimnion (Wetzel, 1983).

At each sampling site the dissolved oxygen concentration ($mg.l^{-1}$) and the percentage saturation (%) were measured *in situ*, using a YSI Model 50 B dissolved oxygen meter equipped with a 5739 probe. The altitude of the sampling area was taken into consideration for calibration.

5.2.2 pH and Alkalinity

The pH of natural water is a measure of the acid-base equilibrium of various dissolved compounds and is a result of the carbon dioxide-bicarbonate-carbonate equilibrium that involves various constituent equilibria, all of which are affected by temperature. Conditions that favour production of hydrogen ions result in a lowering of pH, referred to as an acidification process. Alternatively, conditions that favour nautralisation of hydrogen ions result in an increase in pH, referred to as an alkalinisation process. The pH of water does not indicate the ability to neutralise additions of acids or bases without appreciable change. This characteristic, termed buffering capacity, is controlled by the range of acidity or alkalinity (Dallas & Day, 1993).

The pH was determined *in situ* with a HANNA HI 9073 C Microcomputer pH meter. The pH meter was calibrated using standard buffer solutions at pH values of 7.0 and 10.0. Alkalinity is numerically the equivalent concentration of a titratable base. Therefore, alkalinity was determined by titration with a standard solution of a strong acid to equivalency points dictated by pH values at which the alkaline contributions of hydroxide, carbonate and bicarbonate were neutralised (Wetzel & Likens, 1979).

5.2.3 Conductivity

Electrical conductivity is often used as a measure of dissolved material. Since the electrical conductivity of water is a function of the number of charged particles (ions) in solution, it is also a measure of total quantity of salts and, therefore, of total dissolved solids in a sample of water.

Conductivity serves as an indication of the total dissolved salts in the water. It was determined with a HANNA (HI933000) conductivity meter *in situ* and expressed as $mS.m^{-1}$.

5.2.4 Phosphorus

Phosphorus is a common growth-limiting factor for phytoplankton in lakes because it is often present in low concentrations. Most phosphorus is held in a biologically unavailable form by particles in lake water. Domestic, agricultural and some industrial wastes are sources of soluble phosphate and may cause cultural eutrophication (Horne & Goldman, 1994).

The dissolved phosphorus, reactive phosphate–phosphorus (PO_4-P) and total phosphorus (TP) were determined.

a) Dissolved reactive orthophosphate-phosphorus (PO_4-P)

Dissolved reactive orthophosphate-phosphorus (PO_4-P) concentration ($\mu g.l^{-1}$) was determined spectrophotometrically on filtered (0.45 µm) samples at 690 nm, using the Stannous Chloride method as described in Standard Methods for the Examination of Water and Wastewater (APHA, 1995). The method is based upon molybdophosphoric acid that has been formed and reduced by stannous chloride to intensely coloured molybdenum blue.

During the 24-hour study a HANNA Microprocessor Phosphate meter (HI 93713) was used to determine the concentration. The water samples were mixed with a standard phosphate powder, for colour development, before they were measured.

b) Total phosphorus (TP)

As phosphorus may occur in combination with organic matter, a digestion method to determine total phosphorus must be able to oxidize organic matter effectively to release phosphorus as orthophosphate (APHA, 1995). For this purpose an ultra violet photo-oxidation unit was used to digest unfiltered samples after which the Stannous Chloride method was again used to determine the concentration ($\mu g.l^{-1}$) of phosphate-phosphorus (PO_4-P) (APHA, 1995).

5.2.5 Nitrate nitrogen (NO_3-N)

Nitrogen forms part of many essential cell constituents, such as chlorophyll, enzymes, storage compounds, etc. (Dallas & Day, 1993). During the fall and winter, releases from sediments, tributary inflows, precipitation and replenishment from the hypolimnion increase the nitrate and sometimes the ammonia concentrations. However, nitrate and ammonia are not always present in adequate amounts in natural waters and may limit plant growth (Horne & Goldman, 1994).

The concentration of nitrate nitrogen (NO_3-N) ($\mu g.l^{-1}$) in the filtered samples was determined spectrophotometrically by the Nitrate Brucine-sulphate method described by Jenkins and Medsker (1963). The concentration was determined by the reaction of nitrate with brucine sulphate. The resulting colored complex was measured at 410 nm.

During the 24-hour study a HANNA Microprocessor Nitrate meter (HI 93728) was used to determine the concentration. The samples were mixed with a standard nitrate powder before they were measured.

5.2.6 Silica-silicon (SiO_2-Si)

Silica plays an intriguing role in aquatic systems, since it apparently accounts for the success of diatoms, which dominate most aquatic systems.

Silica-silicon (SiO_2-Si) concentration ($\mu g.l^{-1}$) was determined spectrophotometrically on filtered samples at 410 nm, using the molybdosilicate method as described in Standard methods for the examination of water and wastewater (APHA, 1995). The principle of this method is based upon Ammonium molybdate at pH approximately 1.2, which reacts with silica and any phosphate present to produce heteropoly acids. The intensity of the yellow color is proportional to the concentration of 'molybdate-reactive' silica.

5.2.7 Other chemical parameters

Additional chemical data (1980 – 1999) were requested from the Department of Water Affairs and Forestry in Pretoria for Aliwal North, Gariep Dam, Vanderkloof Dam and Marksdrift. The data included conductivity, TDS, pH, sodium, magnesium, calcium, fluoride, chloride, nitrate, sulphate, phosphate, calcium carbonate, silica and potassium.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Dissolved oxygen concentration and percentage saturation

Oxygen is continually consumed in respiration by both plants and animals but is produced by plant photosynthesis only when sufficient light and nutrients are available. Cold, well-oxygenated water (0 °C to 5 °C) contains less than 5 percent of oxygen contained in a similar volume of air, and this amount rapidly decreases as water temperature increases (Horne & Goldman, 1994). The lack of oxygen in water relative to air means that respiration and decomposition easily deplete oxygen unless continually replenished by the air.

The dissolved oxygen concentration (surface water) in the Upper Orange River system varied between 4.7 and 11.6 mg.l^{-1} (Figure 17). This presented percentage oxygen saturation between 47 and 135 %. The highest average dissolved oxygen concentration (9.1 mg.l^{-1}) was at Norvalspont, below the Gariep Dam, during summer. This can be ascribed to the relatively cold water that flowed relatively fast over the stones in the stream and thus, aerated the water. Allan (1995) hypothesized that dissolved oxygen is not a limiting factor for biota in running water.

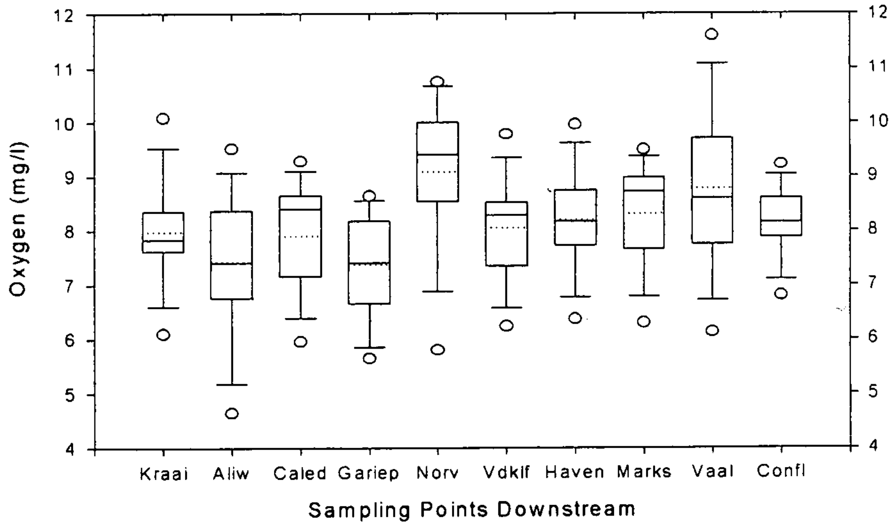


Figure 17. Box plots of the oxygen concentrations (mg/l) at the different sampling points in the Orange River system, during the study period

The single most important environmental factor regulating the concentration of oxygen is temperature (Horne & Goldman, 1994). The average seasonal oxygen concentrations at the different sampling points for the study period are illustrated in Figure 18. At low water temperatures (winter average temperature) high oxygen concentrations were found (average 9.2mg.l^{-1}). The oxygen concentration decreased (summer average of 7.1 mg.l^{-1}) with an increase in the water temperature (summer average of 24 °C).

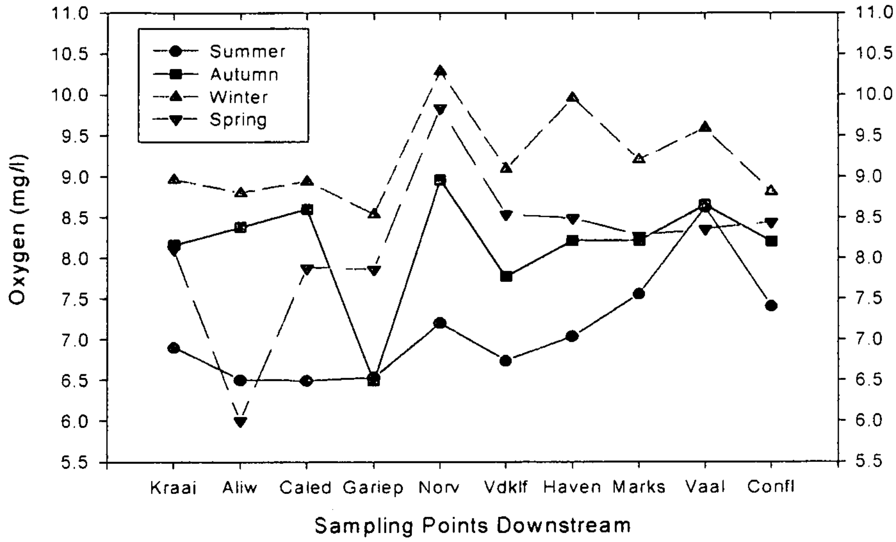


Figure 18. Seasonal variation in oxygen concentrations (mg/l) at the different sampling points in the Orange Rvier system, during the study period

The oxygen-depth profile in the Gariep Dam, near the dam wall, on 19 February 1999 (Figure 19) followed the same pattern as the temperature-depth profile (Figure 5) that was done simultaneously. Dissolved oxygen concentrations were relatively high in the epilimnion (8.2 mg.l^{-1}) and very low (anoxic) in the hypolimnion (0.1 mg.l^{-1}). These measurements were done at the dam wall during a bloom of *Microcystis* sp. The oxygen decline in the hypolimnion was indirectly due to the high algal productivity in the epilimnion, since the more organisms in the epilimnion, the more dead and decomposing material sunk through the hypolimnion to the dam bottom and used up oxygen.

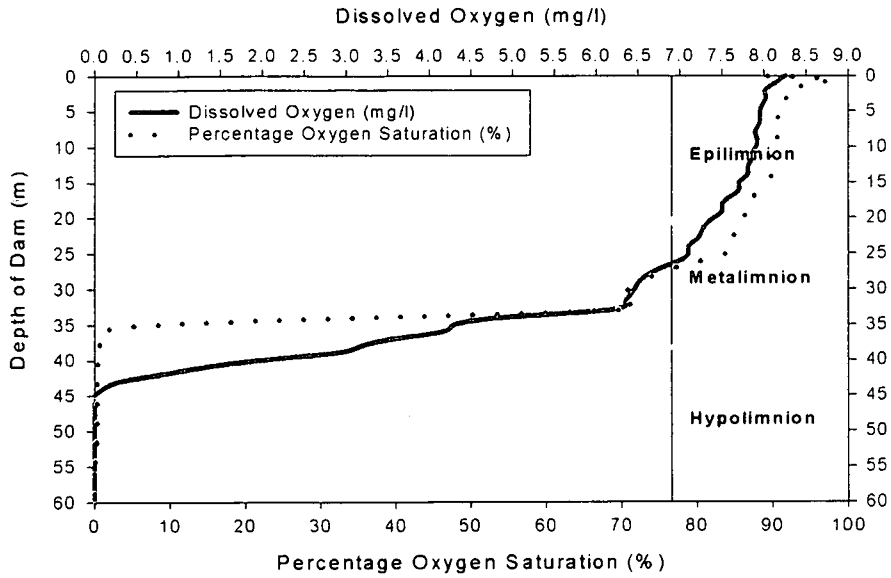


Figure 19. An oxygen-depth profile in the Gariep Dam on 19 February 1999

5.3.2 pH and Alkalinity

pH is defined as the negative $\log_{10}$ of the hydrogen ion activity:

$$pH = -\log_{10} [H^+]$$

pH is determined by the concentration of hydrogen ions (H^+). Since pH is a log scale, a change of one unit means a ten-fold change in $[H^+]$ (DWAF, 1996).

The pH of natural water is influenced by geological and atmospheric influences. pH determines the chemical form, and thus potential toxicity, in which numerous elements and molecules are found in water (Horne & Goldman, 1994). Changing the pH of water changes the concentration of both H^+ and OH^- ions, which affects the ionic and osmotic balance of aquatic organisms. Relatively small changes in pH are not normally lethal, although sublethal effects such as slow growth and reduced fecundity may occur due to increased physiological stress placed on the organism by increased energy requirements (DWAF, 1996).

The average pH values since 1980 until 1999 are shown in Figure 20. The coloured solid lines indicate the regression over time in the Orange River at Aliwal North, the Gariep and Vanderkloof Dams and in the Orange River at Marksdrift. All four sampling points showed a progressive increase in pH over time. The average pH during the 1980's was 7.3 and increased to an average of 8.2 during the 1990's. As pH is closely linked to carbonate (Dallas & Day, 1993; Roos & Pieterse, 1995a and DWAF, 1996) the increase in calcium carbonate concentrations since 1980 until 1999 (Figure 21) might be responsible for the increase in pH values over the same period. The source of the calcium carbonate is unknown at present.

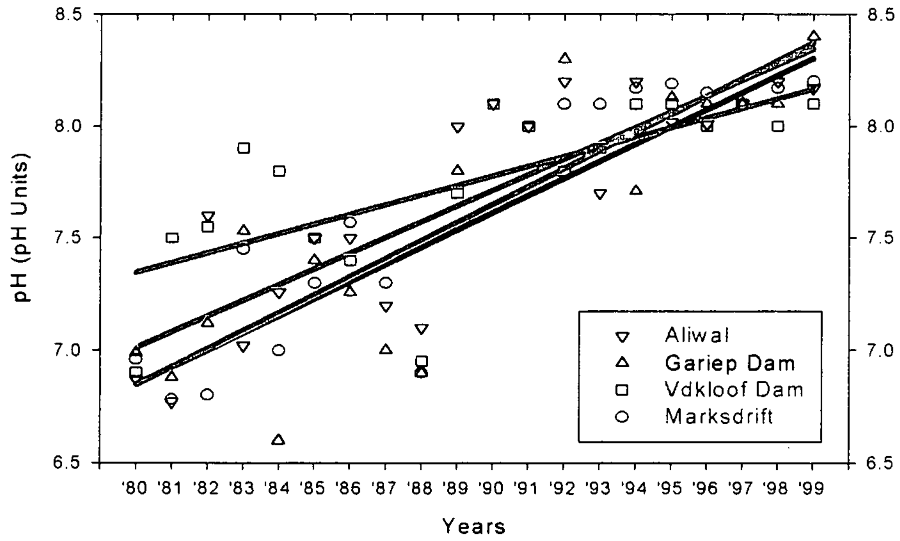


Figure 20. The annual average pH from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

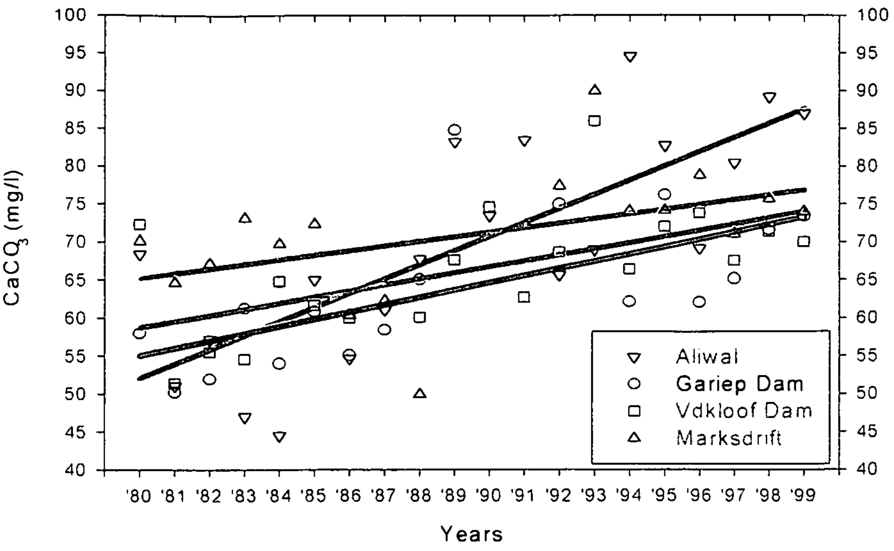


Figure 21. The annual average calcium carbonate concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

The average pH of the Upper Orange River was 8.1 indicating mainly alkaline conditions. The average pH for the tributaries was relatively high at 8.3 for both the Kraai and Caledon Rivers and 8.7 for the Vaal River (Figure 22). The small variation in pH values (Figure 22) and the high alkalinity (Figure 27) during the study period in the Kraai River indicated a well-buffered system. The high pH

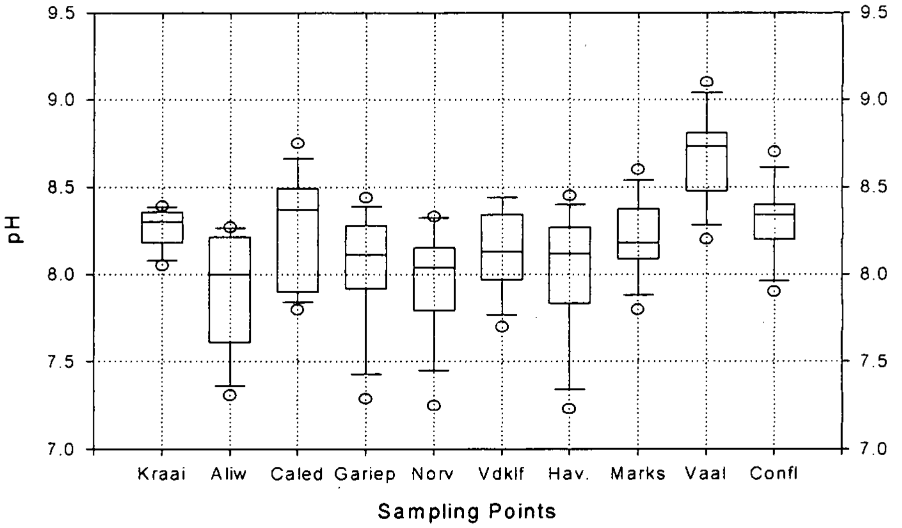


Figure 22. Box plots of pH at the different sampling points in the Orange River system during the study period

values in the Vaal River can be ascribed to the high primary production in the Vaal River, which lowers the CO_2 concentration and thus increases the pH.

The pH target water quality range for irrigation purposes varies between 6.5 and 8.4 (DWAF, 1996). The pH values for the Upper Orange River were well within this range. However, the pH in the Vaal River was above this target range (with a maximum of 9.1 pH units) and has a detrimental effect on the water quality of the Orange River below the confluence.

The Upper Orange River system displayed seasonal variation in pH values over the study period, with spring pH values significantly lower than winter pH values (Figure 23). At the sampling points upstream of the dams, as well as in the Gariep Dam and at Norvalspont, relatively low pH values were encountered during periods of high flow and *vice versa*. This is probably because water that has percolated through the soil is rich in carbon dioxide and similarly tends to be rich in hydrogen ions (Hynes, 1970). However, seasonal pH patterns further downstream were

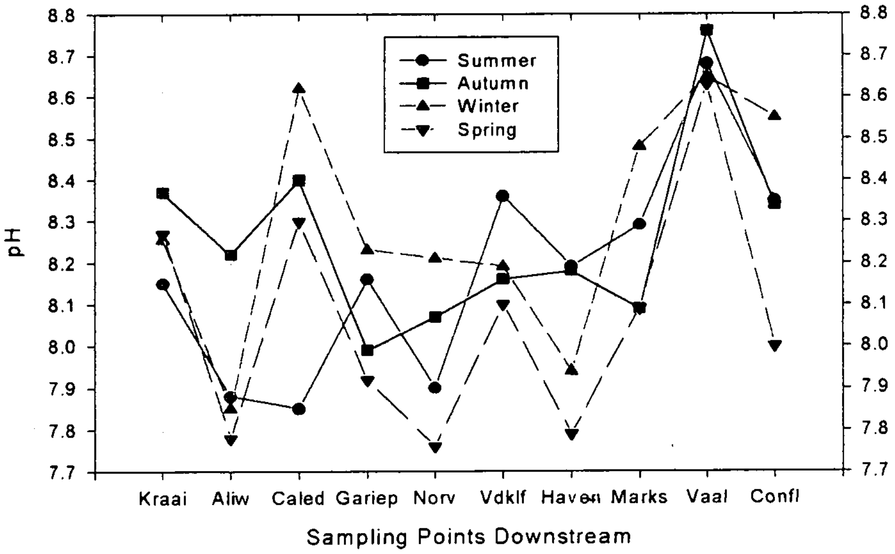


Figure 23. Seasonal average pH at the different sampling points in the Orange River system, during the study period

diminished. The Vaal River also displayed no seasonal variation in pH values over the study period. Roos & Pieterse (1995a) reported low pH values during periods of high flow in the Vaal River. Egborge (1971) also observed that pH is generally lower during the flood season in the Oshun River (Nigeria).

The diel variation in pH and dissolved oxygen in the Orange River at Marksdrift and the Vaal River, for 17 and 18 September 1998 is illustrated in Figures 24 and 25. The pH in the Orange River showed very little fluctuation over the 24-hour study period, with a slight increase (about 0.05 pH units) during the day. On the other hand, the pH at the Vaal River showed much more fluctuation, as well as a much steeper increase in pH during the day, which could be ascribed to photosynthetic activity. During the night the average pH was 8.15 and during the day it was 8.58 pH units.

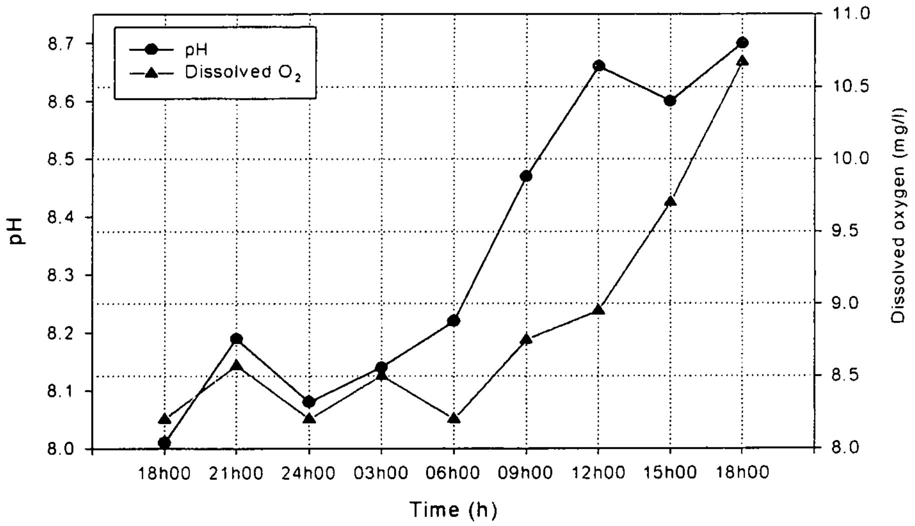


Figure 24. Diel variation in pH and dissolved oxygen in the Vaal River for 17 & 18 September 1998

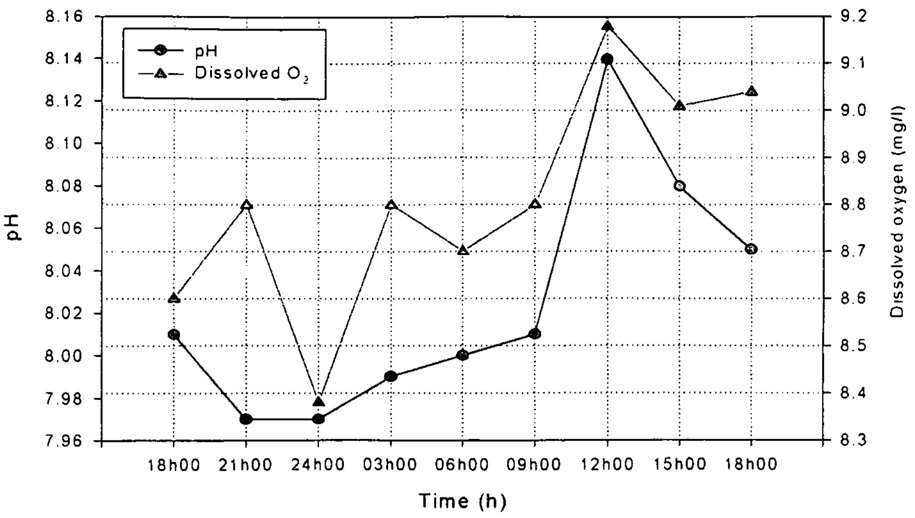


Figure 25. Diel variation in pH and dissolved oxygen in the Orange River at Marksdrift for 17 & 18 September 1998

The average oxygen concentration at night in the Orange River was 8.81 $mg.l^{-1}$, whereas it was 8.86 $mg.l^{-1}$ in the Vaal River. On average the oxygen levels in the Orange River reached 9.2 $mg.l^{-1}$, and those in the Vaal River reached 10.7 $mg.l^{-1}$ during the day. Photosynthesis does not take place during the night and, as a result, excessive CO_2 is formed by respiration. When CO_2 dissolves in water, carbonic

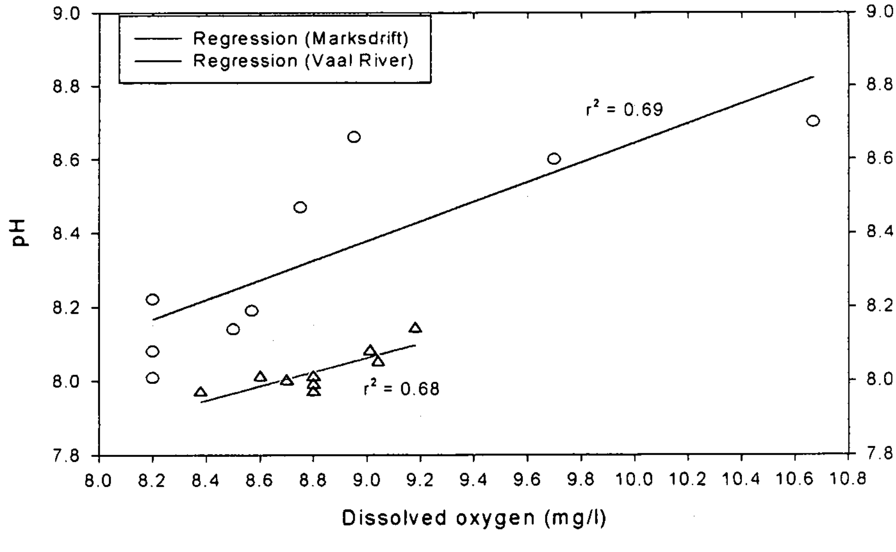


Figure 26. Relationship between pH and dissolved oxygen in the Orange River at Marksdrift and in the Vaal River for 17 & 18 September 1998

acid is formed and the pH is reduced. During the day most or all of the CO_2 is utilised and this leads to an increase in the dissolved oxygen concentration, as well as the pH. A statistically significant correlation between pH and dissolved oxygen was found in both the Orange and Vaal Rivers (Figure 26). In the Orange River, 68 % of the variation in pH was associated with the variation in dissolved oxygen concentration. In the Vaal River, 69 % of the variation in pH was associated with the variation in dissolved oxygen concentration.

The total alkalinity in the Upper Orange River system ranged between 69.4 and 157.5 mg $CaCO_3.l^{-1}$ for 1999 (Figure 27). The high average alkalinity of 95.2 mg $CaCO_3.l^{-1}$ suggests that the Upper Orange River system is well buffered. However, the average alkalinity in and directly downstream of the dams was significantly lower at 72.7 mg $CaCO_3.l^{-1}$ and thus, would have lower buffering capacities than the river.

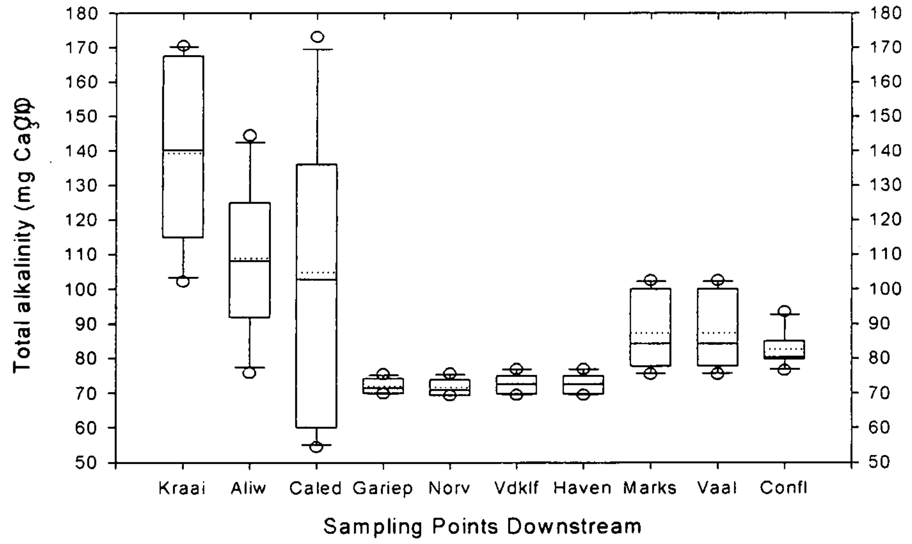


Figure 27. Box plots of the total alkalinity (mg/l) at the different sampling points in the Orange River system during 1999

The seasonal average total alkalinity is shown in Figure 28. Seasonal patterns in alkalinity could only be seen upstream of the dams. Upstream of the dams (and in the Vaal River) alkalinity was relatively high in winter (low discharge) and relatively low in summer (high discharge), but the dams diminished this pattern. Roos (1991) reported reduced alkalinity with increased discharge in the Vaal River and ascribed it to dilution of calcium bicarbonate. This compound is a major component in the regulation of the alkalinity and pH values of natural water.

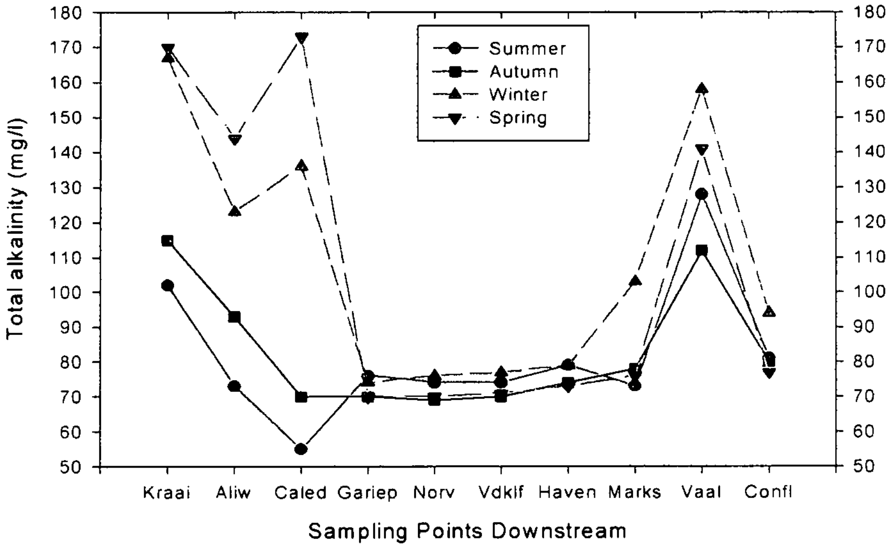


Figure 28. Seasonal average total alkalinity (mg/l) at the different sampling points in the Orange River system for 1999

5.3.3 Conductivity, Total Dissolved Solids (TDS) and Major ions.

One of the major descriptors of the "quality" of a water sample is the total amount of dissolved material. "Conductivity" is a measure of the ability of a sample of water to conduct an electrical current: the higher the conductivity, the greater the number of ions in solution (DWAF, 1996).

The conductivity in the Upper Orange River system varied greatly (Figure 29). The average conductivity in the Upper Orange River during the study period was 19.6 mS.m^{-1}. The average conductivity in the tributaries was higher at 27.3 mS.m^{-1} in the Kraai River, 23.9 mS.m^{-1} in the Caledon River and 65.2 mS.m^{-1} in the Vaal River. The average conductivity for unpolluted rivers in general is 35 mS.m^{-1} (Webb & Walling, 1992). The target water quality range for irrigation purposes is <40 mS.m^{-1} (DWAF, 1996).

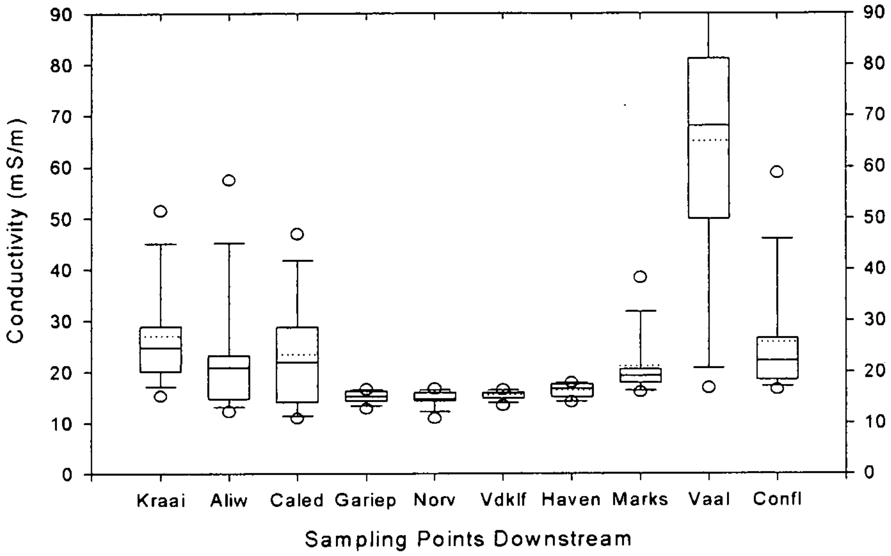


Figure 29. Box plots of the conductivity (mS/m) at the different sampling points in the Orange River system during the study period

Hart (1990) reported very high average conductivity values of 150 mS.m^{-1} for the Vanderkloof Dam. However, this is not confirmed in any other literature (to the best of my knowledge) or seen in my data or data requested from DWAF and thus, was ascribed to a convergion mistake with the conductivity units. Grobbelaar (1998) reported average conductivity values at Aliwal North over the period 1977 until 1997 to be 20 mS.m^{-1}. Roos (1991) reported a high average conductance of 76 mS.m^{-1} for the Vaal River. This high conductivity for the Vaal River was also found by Grobler *et al.* (1986). They predicted that the Vaal River water would probably clarify due to salinisation. This, as well as the high nutrient supply, might result in more intensive algal blooms.

The average seasonal conductivity for the study period is shown in Figure 30. The lowest conductivity occurred during summer upstream of the dams and indicated that conductivity decrease during periods of high discharge due to dilution. The conductivity in and downstream of the dams (up to the Vaal River confluence) was relatively low and the seasonal patterns were diminished. Palmer and O'Keeffe (1990a) also reported that conductivity values in the Great Fish River dropped from 210 mS.m^{-1} upstream of a dam to 130 mS.m^{-1} downstream of a dam.

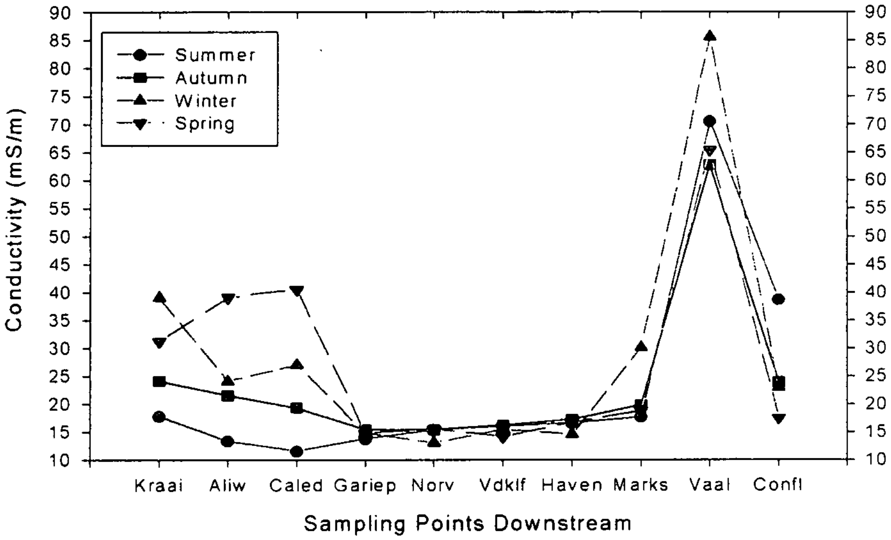


Figure 30. Seasonal average conductivity (mS/m) at the different sampling points in the Orange River system during the study period

In the Upper Orange River system a statistically significant inverse correlation (r = 0.5) was found between the conductivity and turbidity (Figure 31). Roos and Pieterse (1995b) reported that salinity in the Vaal River displayed seasonal changes that were strongly influenced by the turbid conditions that followed high discharge periods. Egborge (1971) also noted a correlation between transparency and conductivity in the Oshun River, Nigeria.

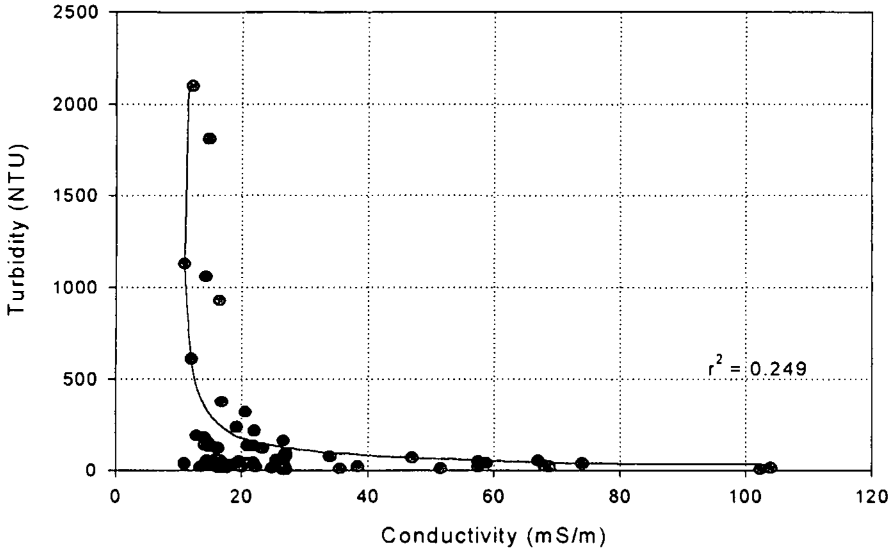


Figure 31. Correlation between conductivity (mS/m) and turbidity (NTU) in the Orange River system during the study period

Conductivity and total dissolved solids (TDS) correlate closely (Dallas & Day, 1993). The average conversion factor for most water is 6.5. The conversion equation is as follows (DWAF, 1996):

$$\text{Conductivity (mS.m}^{-1}\text{ at 25 °C)} \times 6.5 = \text{TDS (mg.l}^{-1}\text{)}$$

However, the conversion factor for the Upper Orange River was found to be 7.1 during this study. The average annual TDS concentration since 1980 until 1999 is illustrated in Figure 32. The average TDS concentration increased from 121 mg.l^{-1} in the 1980's to 144 mg.l^{-1} in the 1990's at all four sampling points. This increase in TDS concentrations was probably caused by the intensive irrigation in the Upper Orange River system. Du Plessis and Van Veelen (1991) stated that irrigation, as well as industrial and mining development, promotes salinisation. This situation could worsen in future with the expected decrease in flow in the Orange River due to increased water demands.

TDS represents the total quantity of dissolved material, both organic and inorganic, both ionized and un-ionized, in a sample of water. The greatest mass of this material in natural waters comprises inorganic ions. The commonest of these are usually the cations Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} and the anions CO_3^{2-}, SO_4^{2-} and Cl^{-1}.

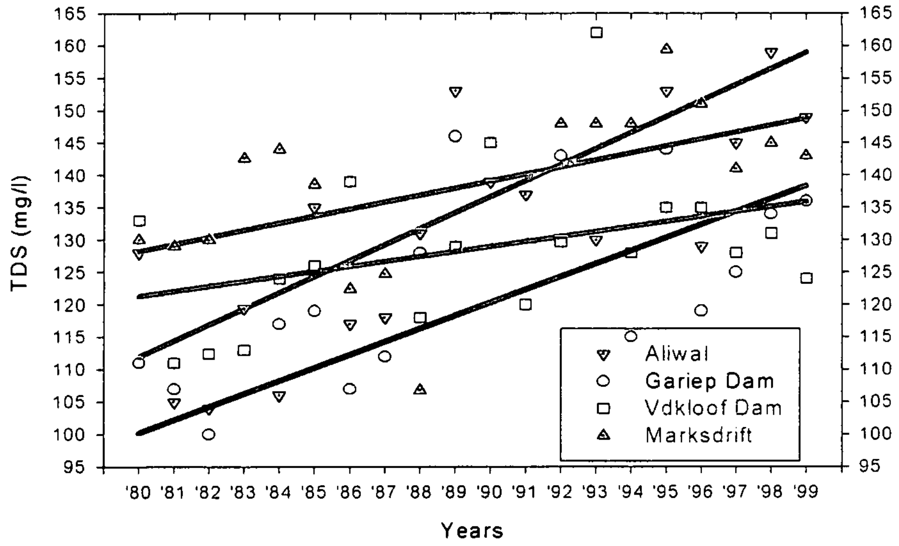


Figure 32. The annual average total dissolved solids (TDS) concentration (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

Together, these are often referred to as the major ions. Other inorganic ions include nutrients such as NO_3^- and PO_4^{3-} and various trace metals such as iron, copper, aluminium and zinc (Wetzel, 1975).

Milli-equivalents were estimated for TDS, by dividing the concentration of each ion by its molecular mass and dividing the result by the charge. The milli-equivalents per liter and percentage of the elements in the Orange River at Aliwal North, in the Gariep Dam and in the Orange River at Marksdrift are shown in Table 4.

Over large regions of the temperate zone, dominance by calcium and bicarbonate ions prevails in open systems (Wetzel, 1983):

Cations: Ca > Mg > Na > K

Anions: $CO_3 > SO_4 > Cl$

Table 4. Composition of TDS (in $meq.l^{-1}$ and percentage) in the Orange River at Aliwal North, in the Gariep Dam and in the Orange River at Marksdrift.

Ion	**Aliwal**	**Aliwal**	**Gariep**	**Gariep**	**Marksd.**	**Marksd.**
	($meq.l^{-1}$)	(%)	($meq.l^{-1}$)	(%)	($meq.l^{-1}$)	(%)
Ca^{2+}	0.2670	15.4	0.2206	14.6	0.2329	13.7
K^{+1}	0.0205	1.2	0.0298	2	0.0312	1.8
Na^{+1}	0.2305	13.3	0.2240	14.8	0.3286	19.2
Mg^{+2}	0.1605	9.2	0.1251	8.3	0.1335	7.9
$CaCO_3$	0.8912	51.2	0.7505	49.5	0.7614	44.5
Cl^{-1}	0.1072	6.2	0.0942	6.2	0.1444	8.4
SO_4^{-2}	0.0526	3	0.0597	3.9	0.0642	3.7
PO_4^{-3}	0.0001	0.005	0.00006	0.004	0.00008	0.005
NO_3^{-1}	0.0028	0.2	0.0064	0.4	0.0078	0.5
NH_4^{+1}	0.0016	0.1	0.0011	0.1	0.0017	0.1

The TDS composition influence the distribution and dynamics of algae and larger aquatic plants in freshwater (Wetzel, 1975). The TDS composition differed between the three sampling points in 1998 and is shown in Figures 33, 34 and 35.

In the Orange River at Aliwal North calcium ions dominated sodium ions and bicarbonate ions dominated chloride ions:

Cations: Ca > Na > Mg > K

Anions: $CO_3 > Cl > SO_4$

However, in the Gariep Dam and in the Orange River at Marksdrift, sodium ions dominated calcium ions and bicarbonate ions dominated chloride ions:

Cations: Na > Ca > Mg > K

Anions: $CO_3 > Cl > SO_4$

According to Wetzel (1983) dominance of sodium is an indication of high-salinity water. Gibbs (1970) developed mechanisms for explaining world water chemistry. He distinguished between three mechanisms, namely atmospheric precipitation, rock dominance and evaporation. A boomerang-shaped envelope of data is produced if all three mechanisms are of more or less equal importance.

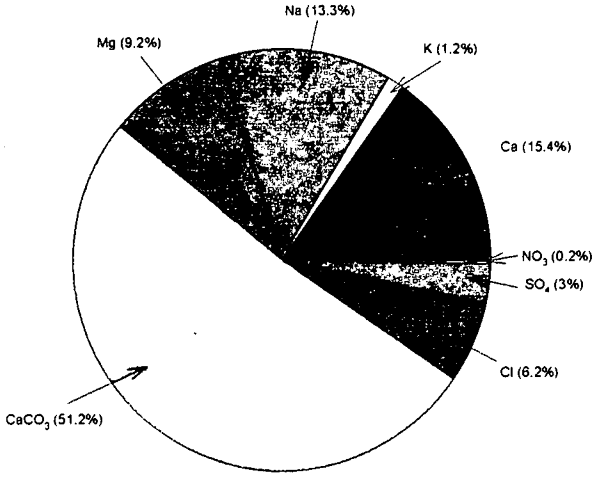


Figure 33. The TDS composition in the Orange River at Aliwal North for 1998

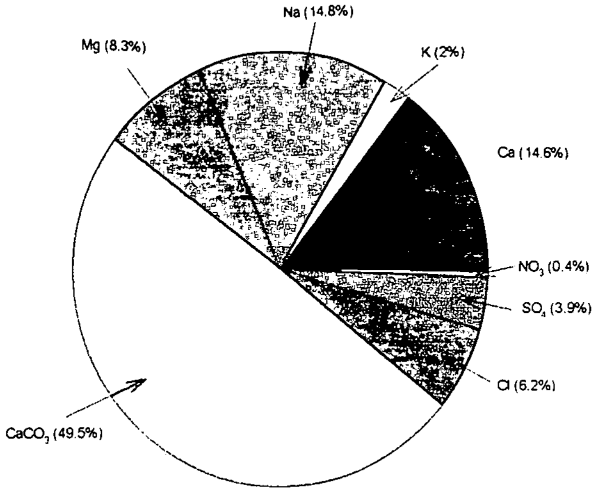


Figure 34. The TDS composition in the Gariep Dam for 1998

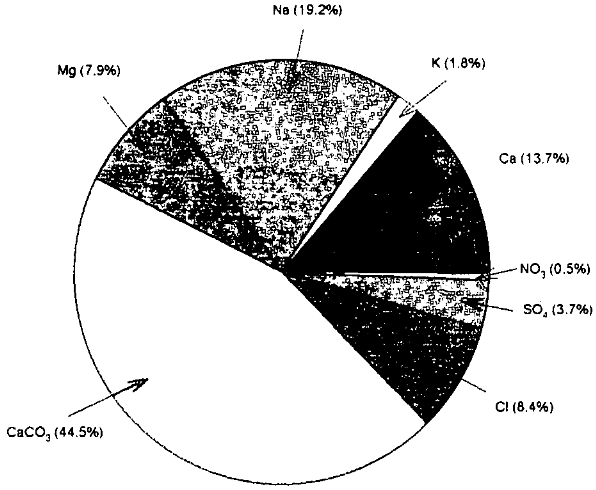


Figure 35. The TDS composition in the Orange River at Marksdrift for 1998

According to Gibbs (1970) Na-dominance usually indicates rivers and lakes located in hot, arid regions, where evaporation is the most important mechanism, which is a possible explanation for the high Na concentration in the Upper Orange River, especially downstream of the dams. Everson (1999) found that the Orange River evaporation losses vary between 516 and 841 million m^3 per annum for the low and high flows respectively. McKenzie and Roth (1994) reported that the nett evaporation losses occurring from the Orange River are likely to be higher than the 800 million m^3 per annum initially estimated. The estimated total nett evaporation loss occurring along the full length of the Orange River is in the order of 960 million m^3 per annum (i.e. approximately 30.4 $m^3.s^{-1}$) (McKenzie & Roth, 1994).

Kilham (1990) differs from Gibbs (1970) in that he found that data for African water are shaped like an alchemist's retort rather than a boomerang. According to Kilham (1990) the explanation for this discrepancy for the upper arm (high salinities) is simple. The major mechanism controlling the evolution of African waters during evaporative concentration is precipitation of $CaCO_3$.

Grobbelaar (1998) reported the ionic dominance of the Orange River at Aliwal North for the period 1977 until 1997 to be Ca > Mg > Na > K : HCO_3 > Cl > SO_4. The ionic dominance differs from the dominance found during this study for 1998 and 1999. The Great Fish River in the vicinity of the Elandsdrift Dam is dominated by Na > Ca > Mg > K (Palmer & O'Keeffe, 1990a).

The mean cation and anion composition of river water of the world and for the Upper Orange River are shown in Table 5 and 6 (modified from Wetzel, 1983; Webb & Walling, 1992 and Horne & Goldman, 1994). The mean cation and anion composition of the Upper Orange River were relatively proportional to the composition of river water of the world.

Table 5. Mean cation composition of river water of the world and Orange River (mg.l^{-1}).

Cations	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}
North America	21	5	9	1.4
South America	7.2	1.5	4	2
Europe	31.1	5.6	5.4	1.7
Asia	18.4	5.6	5.5	3.8
Africa	12.5	3.8	11	-
Orange River	19.1	6.6	6.2	1.2
Australia	3.9	2.7	2.9	1.4
World	15	4.1	6.3	2.3

Table 6. Mean anion composition of river water of the world and Orange River (mg.l^{-1}).

Anions	CO_3^{2-}	SO_4^{2-}	Cl^{-}	NO_3^{-}
North America	68	20	8	1
South America	31	4.8	4.9	0.7
Europe	95	24	6.9	3.7
Asia	79	8.4	8.7	0.7
Africa	43	13.5	12.1	0.8
Orange River	65.1	11.1	4.7	0.3
Australia	31.6	2.6	10	0.05
World	58.4	11.2	7.8	1

Calcium

Calcium is one of the major elements essential for living organisms. Although it is a vital element, very little is known about the actual effects of changes in its concentration on aquatic biotas (Horne & Goldman, 1994). The average calcium concentration in the Upper Orange River (19.1 mg.l^{-1}) during the study period was higher than the average calcium concentration for African rivers (12.5 mg.l^{-1}). The calcium concentration was also higher than the average concentration for world rivers (15 mg.l^{-1}) (Wetzel, 1983).

The calcium concentration in the Upper Orange River showed a slight increase since 1980 until 1999, especially in the Orange River at Aliwal North (Figure 36). The concentration increased from 17.4 mg.l^{-1} during the 1980's to 18.8 mg.l^{-1} during the 1990's.

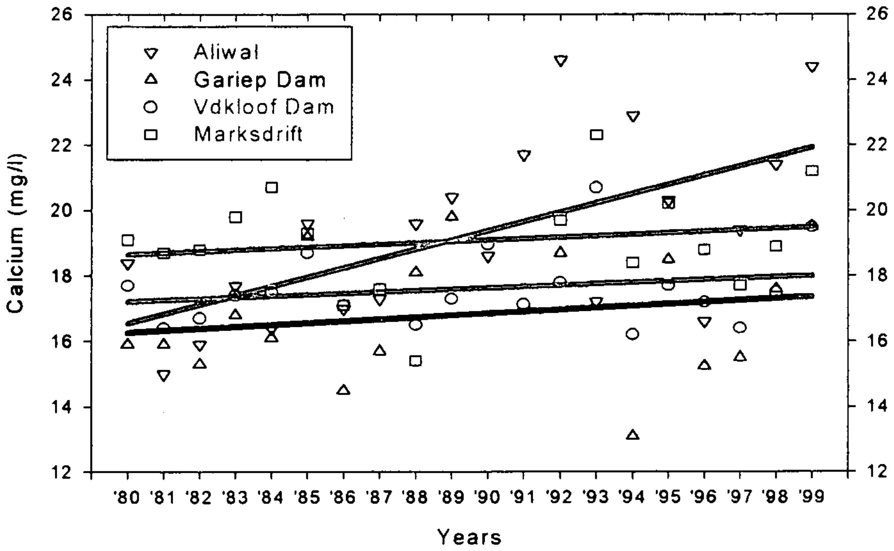


Figure 36. The annual average calcium concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

Magnesium

Magnesium is an essential element that is found in chlorophyll and in a variety of enzymes and it is also involved in the processes of muscle contraction and the transmission of nervous impulses (Dallas & Day, 1993). The average concentration in the Upper Orange River during the study period, was relatively high (6.6 mg.l^{-1}). The magnesium concentration in African rivers (3.8 mg.l^{-1}) (Wetzel, 1983) in general, is only slightly lower than the world average (4.1 mg.l^{-1}) (Webb & Walling, 1992). The magnesium concentration in the Upper Orange River increased slightly over time (1980 until 1999) from 6.3 to 7 mg.l^{-1} (Figure 37).

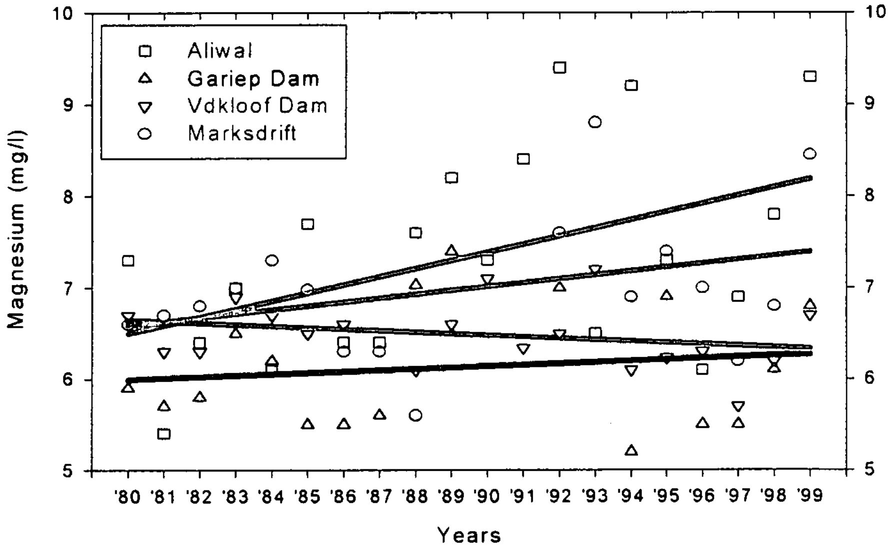


Figure 37. The annual average magnesium concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

Sodium

Sodium is ubiquitous in natural water and is the major cation in seawater and in many South African inland waters. It is the major cation involved in ionic, osmotic and water balance in all organisms and is also involved in the transmission of nervous impulses and in muscle contraction. Sodium is probably the least toxic metal cation (Dallas & Day, 1993) and its effects on aquatic systems are almost entirely as a major contributor to TDS. During the study period the average sodium concentration in the Upper Orange River was 6.2 $mg.l^{-1}$. The sodium concentration in African rivers is almost twice as high (11 $mg.l^{-1}$) than those of the rest of the world (average 6.3 $mg.l^{-1}$) (Wetzel, 1983). The target water quality range for irrigation purposes are < 70 mg $Na.l^{-1}$ and the Upper Orange River is well within the range of good quality (Class I) irrigation water (DWAF, 1996).

The average annual sodium concentrations since 1980 until 1999 are illustrated in Figure 38. A decrease in the sodium concentrations could be seen upstream and in the dams (6 $mg.l^{-1}$ to 5.1 $mg.l^{-1}$). However, at Marksdrift below the dams, increased sodium concentrations could be seen (7.2 $mg.l^{-1}$ to 7.9 $mg.l^{-1}$). Increased salt concentrations could be ascribed to various factors, e.g. back-flow water from irrigation or high evaporation.

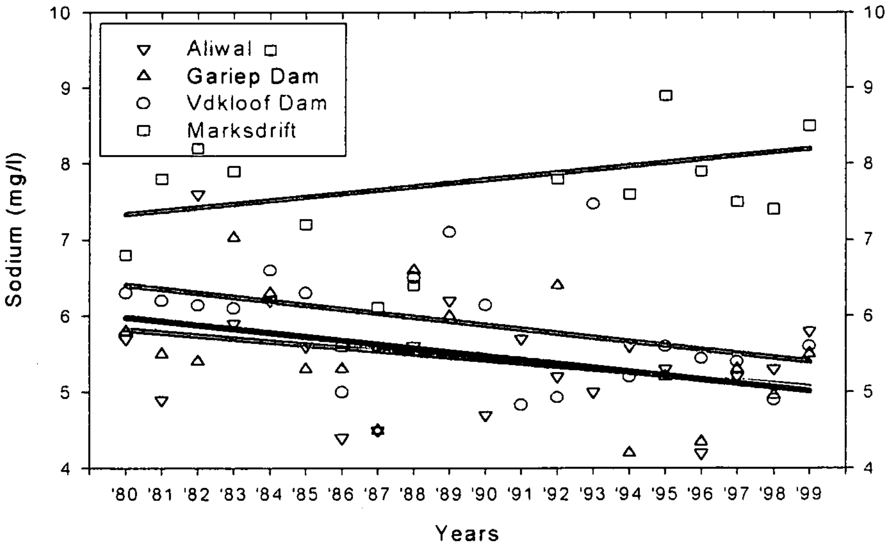


Figure 38. The annual average sodium concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

Potassium

Potassium, like sodium, is involved in ionic balance in all organisms and is involved in the transmission of nervous impulses and in muscle contraction in animals. Potassium can sometimes act as a nutrient, the lack of which limits plant growth (Dallas & Day, 1993). The average potassium concentration in the Upper Orange River (1.2 mg.l^{-1}) was slightly lower (2.3 mg.l^{-1}) than the average concentration for world rivers (Wetzel, 1983).

The annual average potassium concentrations since 1980 until 1999 (Figure 39) showed the same trend as the sodium concentrations over the same period (Figure 38). Marksdrift is the only sample point that showed an increase in the potassium concentrations (1.5 mg.l^{-1} to 1.7 mg.l^{-1}) over time, while all the other points showed decreased concentrations.

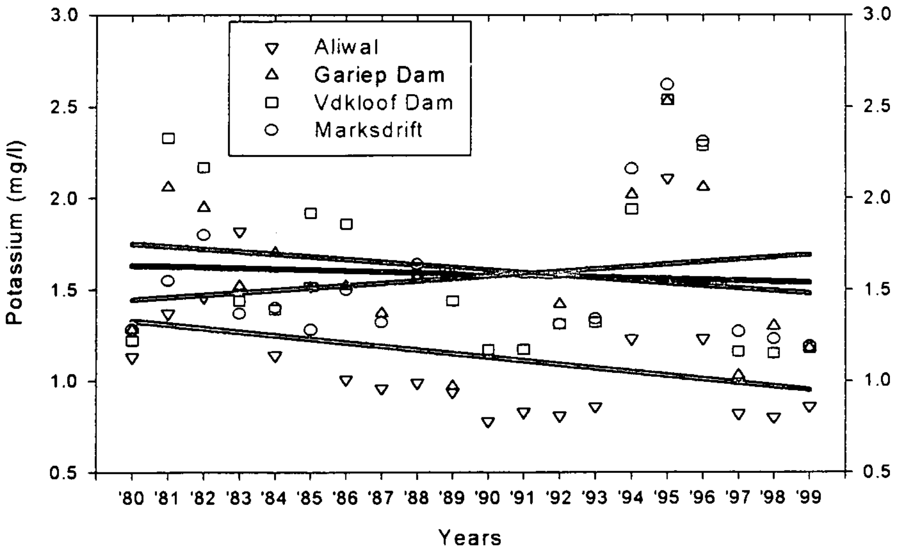


Figure 39. The annual average potassium concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

Carbonate

Carbonate ions, together with free CO_2, are the equilibrium products of CO_2 dissolved in water. They are usually expressed as alkalinity (DWAF, 1996). Since plants require carbon dioxide for photosynthesis, CO_2 and its equilibrium products can sometimes act as limiting nutrients. The carbonate concentration in the Upper Orange River was high with an average of 65.1 $mg.l^{-1}$. The average carbonate concentration for African rivers is 43 $mg.l^{-1}$ (Wetzel, 1983).

Sulphate

Sulphur in water occurs largely as the sulphate ion. In living systems, sulphur is an essential component of proteins and is thus an essential element. Sulphates themselves are not toxic (Dallas & Day, 1993). The average sulphate concentration in the Upper Orange River was 11.1 $mg.l^{-1}$. The sulphate concentrations for African

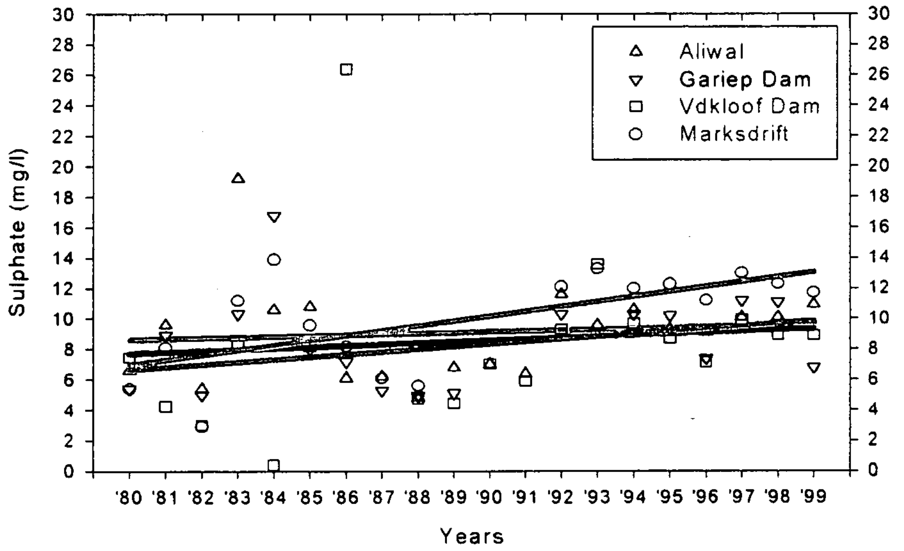


Figure 40. The annual average sulphate concentration (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

rivers (13.5 mg.l^{-1}) (Wetzel, 1983) are well within the range for world rivers (11.2 mg.l^{-1}) (Webb & Walling, 1992).

The annual average sulphate concentrations since 1980 until 1999 are shown in Figure 40. The average sulphate concentration at all four sampling points increased from 8.1 to 10.3 mg.l^{-1} over the study period.

Chloride

Chloride is the major anion in seawater and in many inland waters, particularly in South Africa. Chloride ions are essential components of living systems, being involved in the ionic, osmotic and water balance of body fluids (Dallas & Day, 1993). Except where they have an effect by increasing the total dissolved solids, they exhibit no toxic effects on living systems (Horne & Goldman, 1994). The average chloride concentrations in the Upper Orange River were relatively low (4.7 mg.l^{-1}) during the study period. African rivers have on average the highest chloride concentrations (12.1 mg.l^{-1}) in the world (Wetzel, 1983).

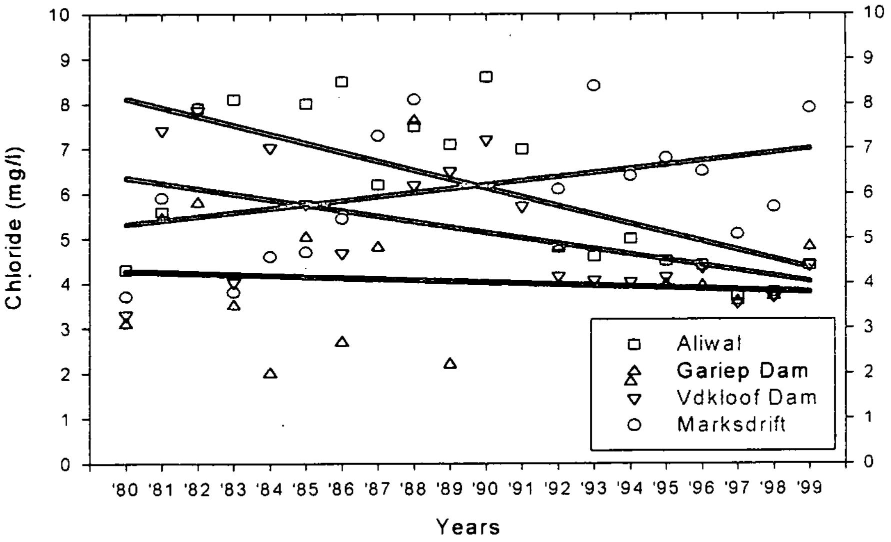


Figure 41. The annual average chloride concentrations (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

The annual average chloride concentrations since 1980 until 1999 are illustrated in Figure 41. The chloride concentration followed the same trend as the sodium and potassium concentrations. Chloride concentrations at Marksdrift increased from an average of 5.2 to 6.3 $mg.l^{-1}$ over the study period. At the other three sampling points the concentration decreased from an average of 6.5 $mg.l^{-1}$ during the 1980's to 4.4 $mg.l^{-1}$ during the 1990's.

Chloride is an essential plant micro-nutrient. Chlorides are very soluble and are not adsorbed to any significant degree by soil. They are readily transported with the soil water, are taken up by roots and conveyed in the transpiration stream to accumulate in the leaves. When the accumulated concentration in leaves exceeds the crop's tolerance, injury symptoms develop in the form of leaf burn, starting at the tips of leaves, which in extreme cases result in leaf drop. Crops vary in their sensitivity to chloride, and suffer yield reduction once the threshold concentration (100 $mg.l^{-1}$) in the soil solution is exceeded (DWAF, 1996). However, the low chloride concentration in the Upper Orange River held no threat to crops.

5.3.4 Phosphorus

Phosphorus occurs most commonly in dissolved form as the inorganic PO_4^{3-} ion. Much phosphorus may be unavailable for plant growth because it is adsorbed onto suspensoids or bonded to particles such as iron, calcium, etc. During low flow periods, streambed sediments act as a sink for phosphorus entering the stream at high concentrations from point sources. Under highflow and/or anoxic conditions adsorbed phosphorus may be released from the sediments. Higher concentrations of phosphorus are likely to occur in waters that receive sewage and leaching or runoff from cultivated lands (Dallas & Day, 1993) and may result in eutrophication (Horne & Goldman, 1994).

a) Phosphate phosphorus (PO_4-P)

The average annual PO_4-P concentrations since 1980 until 1999 are illustrated in Figure 42. The PO_4-P concentration decreased slightly from an average of 0.038 mg.l^{-1} during the 1980's to 0.025 mg.l^{-1} during the 1990's at all four sampling points. The reason for this progressive decrease in PO_4-P concentrations might be increased consumption of PO_4-P by algae. In relation to other macro-nutrients required by biota, phosphorus is least abundant and commonly the first element to limit biological productivity (Harris, 1986).

The average PO_4-P concentration in the Upper Orange River system during this study was 28.3 μg.l^{-1} and ranged between 1 and 112.6 μg.l^{-1} (Figure 43). The world

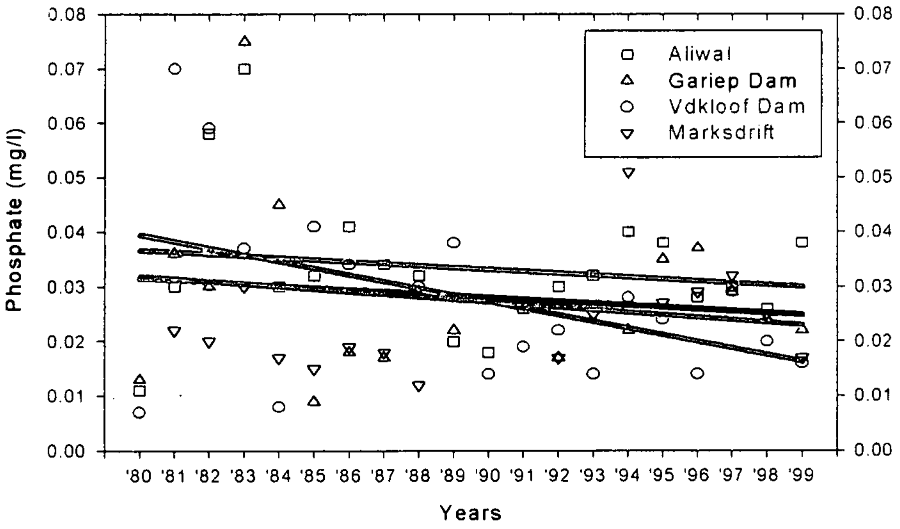


Figure 42. The annual average phosphate phosphorus concentrations (PO_4-P) (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

average PO_4-P concentration in rivers is 100 µg.l^{-1} (Horne & Goldman, 1994). Grobbelaar (1998) reported PO_4-P concentrations of approximately 30 µg.l^{-1} since 1977 until 1997 at Aliwal North. The average PO_4-P concentration in the eutrofied Vaal River was 16 µg.l^{-1} (Roos, 1991).

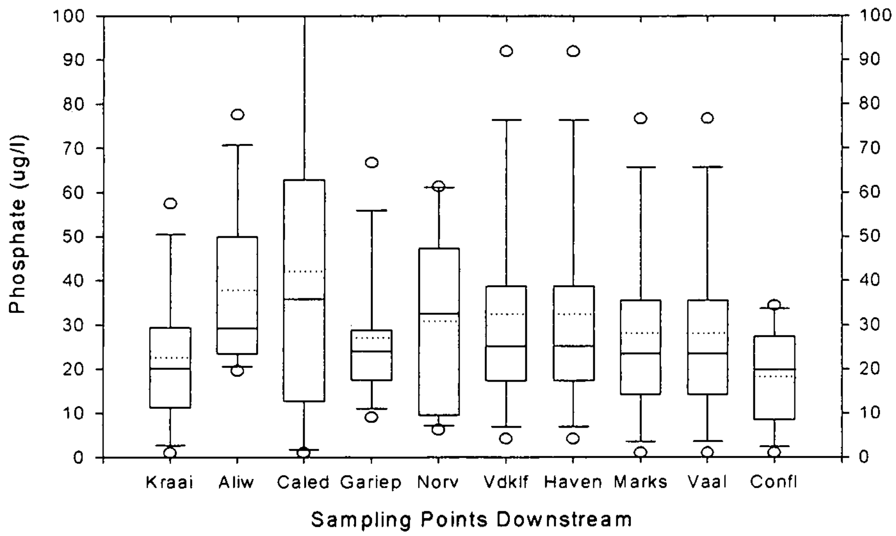


Figure 43. Box plots of the phosphate phosphorus (PO_4-P) (µg/l) at the different sampling points in the Orange River system during the study period

The PO_4-P concentrations in the Upper Orange River system were slightly affected by discharge, with the highest PO_4-P concentrations usually occurring during summer (Figure 44). Roos and Pieterse (1995a) reported that PO_4-P concentrations in the Vaal River were higher during periods of high discharge, especially during flood periods.

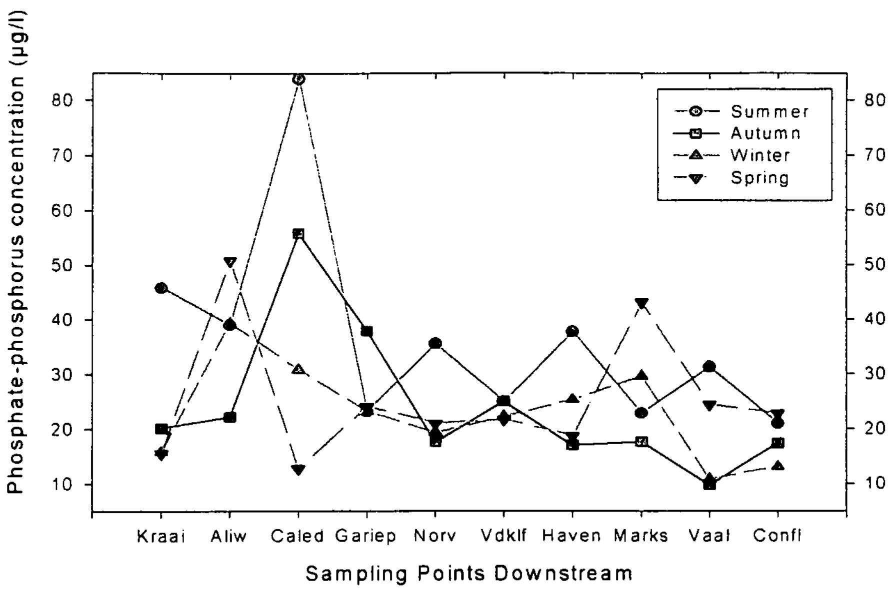


Figure 44. Seasonal average phosphate-phosphorus (PO_4-P) (µg/l) concentrations at the different sampling points in the Orange River system during the study period

An inverse trend was found between the PO_4-P and calcium (Ca) concentrations in the Upper Orange River (Figure 45). The solubility of phosphate in natural water is limited by Ca, Fe or Al ions (Cloot & Roos, 1996 and House, 1999). However, Golterman (1988) predicted that only Ca would reach concentrations sufficiently high to interfere with, and thus control, the solubility of phosphate. Lund (1965) stated that because inorganic phosphorus is utilised rapidly and can be stored in excess of immediate needs, the total amount of phosphorus present might be a better indication of the fertility of the water.

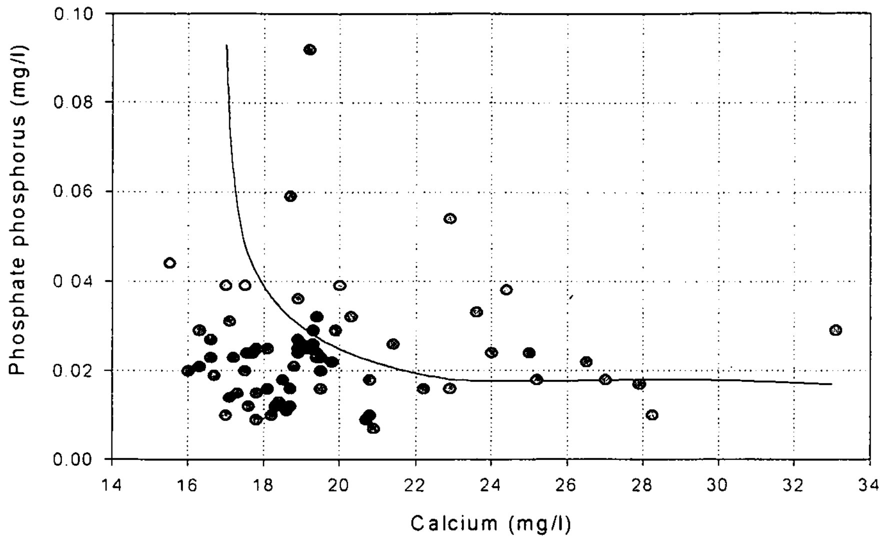


Figure 45. Correlation between phosphate phosphorus and calcium concentrations (mg/l) in the Orange River system during the study period

b) Total phosphorus (TP)

The TP concentrations in the Upper Orange River system during the study period ranged between 1 and 757 $\mu g.l^{-1}$, with an average concentration of 107 $\mu g.l^{-1}$ (Figure 46). This concentration compared well with the TP concentration in flowing

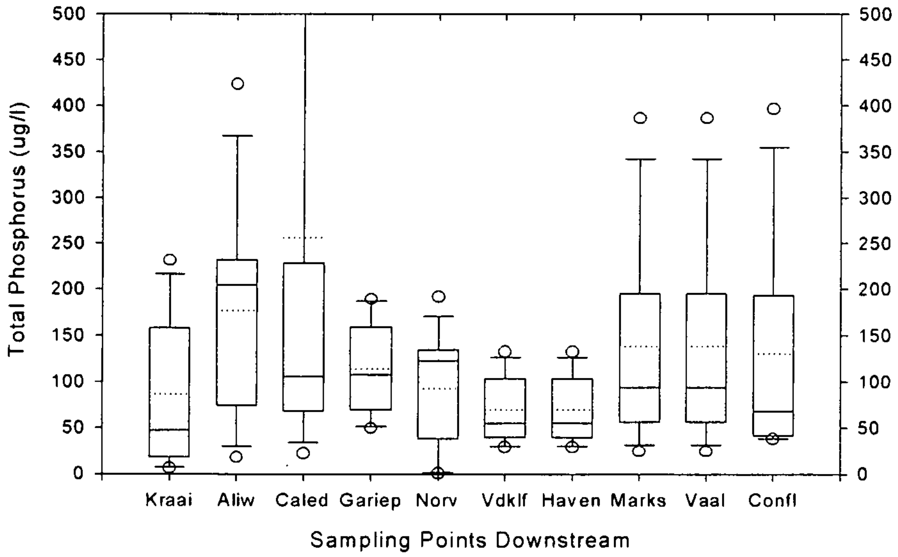


Figure 46. Box plots of the total phosphorus (TP) (µg/l) at the different sampling points in the Orange River system during the study period

water which is generally less than 100 µg.l^{-1} (Wetzel, 1983). However, the TP concentration in unpolluted water should be between 10 and 50 µg.l^{-1} (Wetzel, 1983). Roos and Pieterse (1995a) reported high average TP concentrations of 202 µg.l^{-1} for the eutrified Vaal River.

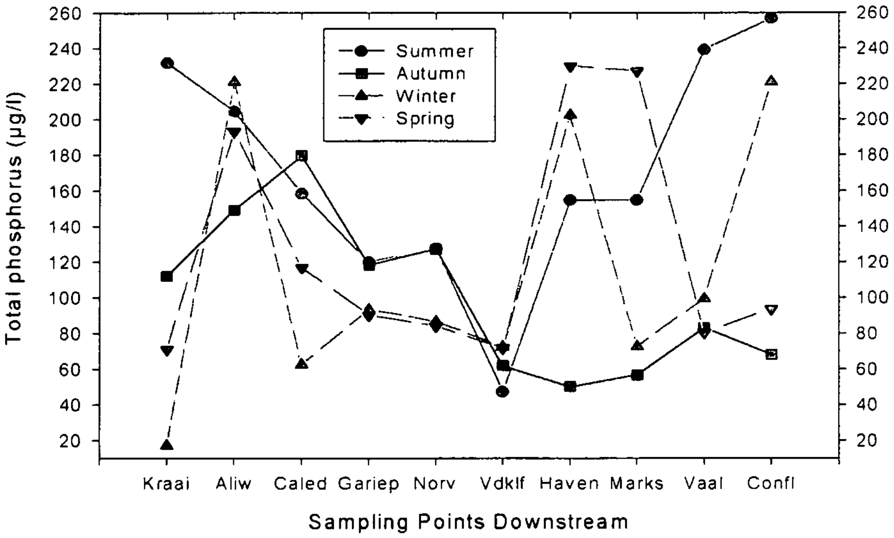


Figure 47. Seasonal average total phosphorus concentrations (TP) (µg/l) at the different sampling points in the Orange River system during the study period

The Upper Orange River system did not display distinctive seasonal patterns in TP concentrations although high concentration did occur during periods of high discharge in the Kraai and Vaal Rivers, as well as in the Orange River after the Orange-Vaal confluence (Figure 47). Golterman (1975) hypothesized that 2 mechanisms are involved in the high phosphate concentrations after rain, namely percolation and erosion.

Firstly, substantial amounts of phosphorus are probably due to wash-out from fertilised agricultural soil by run-off, which suggests that fertilised soil is an important diffuse source of nutrients. Secondly, erosion occurs where the soil is geologically unstable, or where plant cover is scarce or absent. Since erosion represents the removal of solid materials, much of which are in the form of clay particles, the phosphate adsorbed to the particles is carried of as silt (Horne & Goldman, 1994).

5.3.5 Nitrate-nitrogen (NO_3-N)

Nitrogen forms part of many essential cell constituents, such as chlorophyll, enzymes, storage compounds, etc. In both natural and polluted waters, nitrogen may be present in many forms, but the ones that are measured by the common water quality tests include ammonia, organic nitrogen, nitrites and nitrates (Dallas & Day, 1993). The nitrogen cycle differs from the phosphate cycle in that nitrogen may enter and leave the cycle as gaseous N_2 by nitrogen fixation (e.g. blue-green algae such as *Anabaena* sp. has the ability to metabolise nitrogen directly from the air by fixation mechanisms and incorporate it into tissue). Bacterial and chemical denitrification, which occurs in oxygen-poor conditions, may also influence the nitrogen concentrations (Wetzel, 1983).

Nitrates are the end products of the aerobic stabilization of organic nitrogen and may enter water via fertilizers, agricultural runoff, etc. In spite of their many sources, nitrates are seldom abundant in natural surface waters, because photosynthesis constantly converts nitrates to organic nitrogen in plant cells (Dallas & Day, 1993).

The average annual NO_3-N concentrations since 1980 until 1999 are illustrated in Figure 48. The NO_3-N concentrations in the Orange River at Aliwal North decreased from 0.33 $mg.l^{-1}$ during the 1980's to 0.23 $mg.l^{-1}$ during the 1990's. The NO_3-N concentrations in the dams and downstream increased from 0.45 $mg.l^{-1}$ during the 1980's to 0.58 $mg.l^{-1}$ during the 1990's. Palmer and O'Keeffe (1990b)

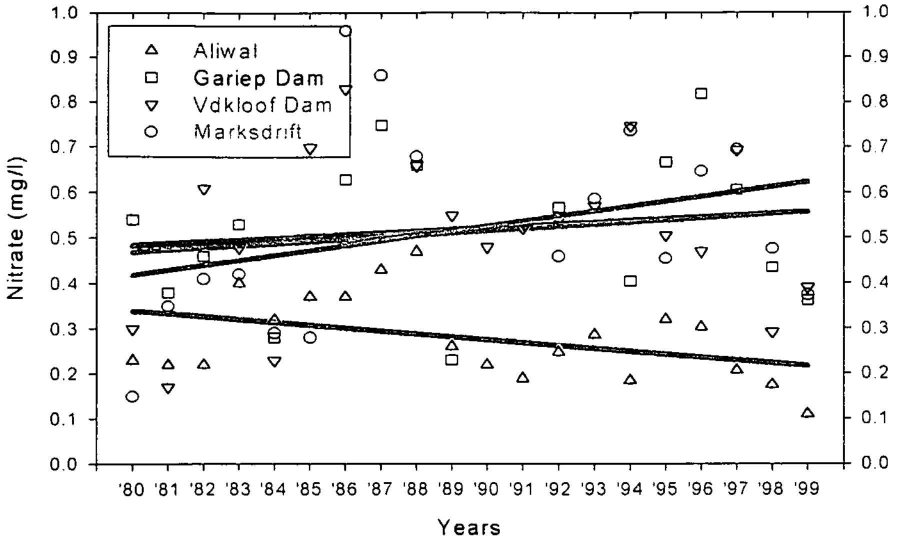


Figure 48. The annual average nitrate concentrations (NO_3-P) (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

reported increased NO_3-N concentrations downstream of reservoirs in the Buffalo River. They ascribed this increase in NO_3-N concentrations to fixation of atmospheric nitrogen by algae, as was shown in studies by Horne and Goldman (1994). This could also be the reason for the increased NO_3-N concentrations in the dams, as nitrogen fixers like *Anabaena* was found in high concentrations during favourable conditions in the dams.

This increases in the NO_3-N concentrations in the dams and downstream could also be seen in Figure 49. The NO_3-N concentration ranged between 1 $\mu g.l^{-1}$ and 670 $\mu g.l^{-1}$, with an average of 312 $\mu g.l^{-1}$. This concentration is lower than the world average for rivers, i.e. 1 000 $\mu g.l^{-1}$ (Goldman & Horne, 1983), but higher than the concentration for unpolluted world rivers, i.e. 100 $\mu g.l^{-1}$ (Webb & Walling, 1992).

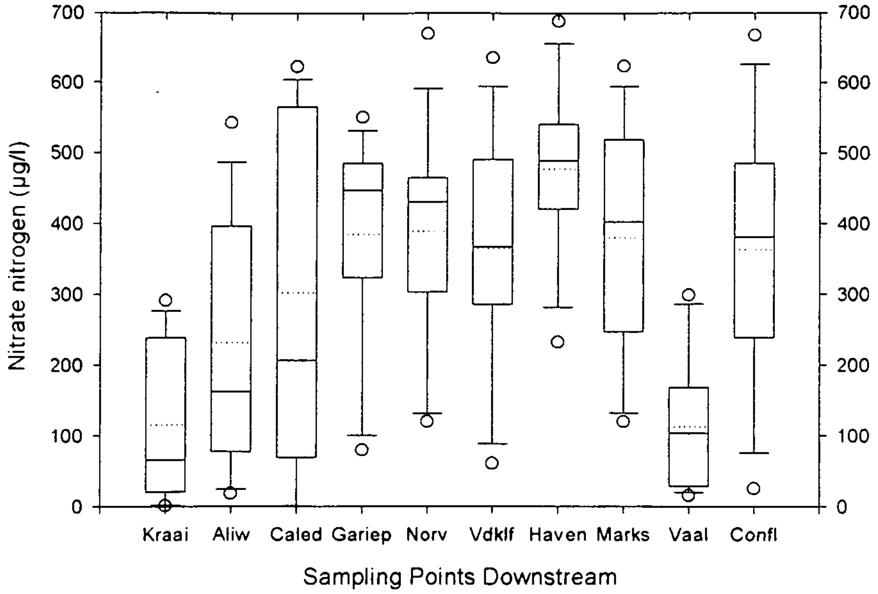


Figure 49. Box plots of the nitrate nitrogen concentrations (NO3-N) (µg/l) at the different sampling points in the Orange River system during the study period

The Upper Orange River system displayed only slight seasonal patterns in NO_3-N concentrations. The highest concentration occurred in the dams during summer (Figure 50), ascribed to nitrogen fixation as previously discussed. Discharge did not

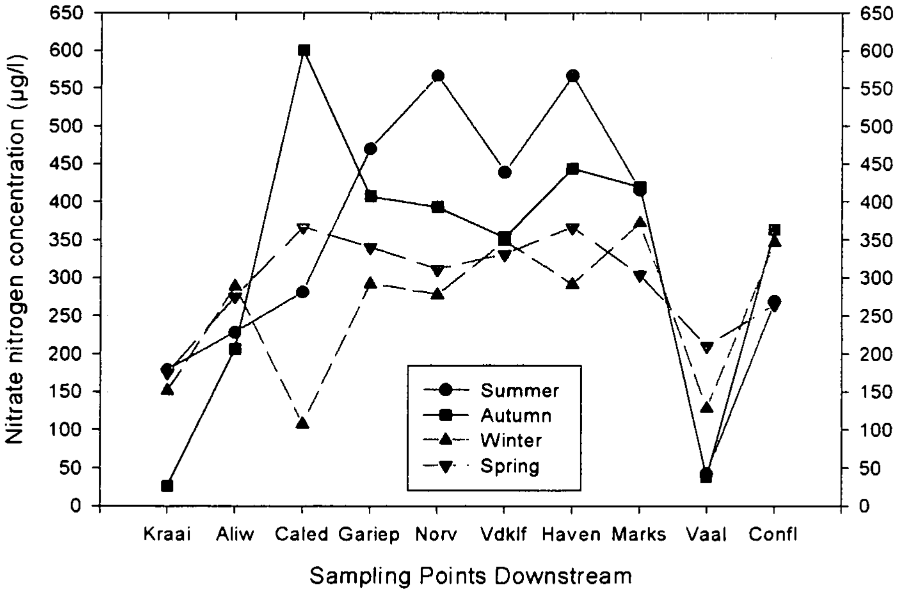


Figure 50. Seasonal average nitrate nitrogen concentrations (NO_3-N) (µg/l) at the different sampling points in the Orange River system during the study period

seem to significantly affect the NO_3-N concentrations in the Upper Orange River system.

5.3.6 N:P ratios

The average $NO_3:PO_4$ ratios in the Upper Orange River was 13.8 and ranged between 5.1 in the Kraai River and 19.8 in the Orange River below the confluence. Harris (1986) showed that the average TN:TP ratio is a function of the trophic status of lakes, primarily influenced by TP in the following relationship:

$$TN:TP = 12.1 \div TP^{0.118}$$

This relationship predicted the following TN:TP ratios for the Upper Orange River system (Table 7) (the relevance of this relationship by Harris (1986) on the Orange River was not tested).

Table 7. The $NO_3:PO_4$ ratios and predicted TN:TP ratios for the Upper Orange River system (Harris, 1986)

Sampling point	**$NO_3:PO_4$ ratio**	**Predicted TN:TP ratio**
Kraai River	5.1	16.2
Aliwal (OR)	6.1	14.8
Caledon River	7.2	14.4
Gariep Dam	14.2	15.6
Norvalspont (OR)	12.7	16
Vanderkloof Dam	11.3	16.6
Havenga (OR)	18.9	14.5
Marksdrift (OR)	13.5	15.3
Vaal River	6	15.6
Confluence (OR)	19.8	15.4

Sakamoto (1966) reported that the chlorophyll yield in Japanese lakes was a logarithmic function of both total phosphorus (TP) and total nitrogen (TN). The author concluded that over the range 10 < TN:TP <17 by weight, chlorophyll yield was very nearly balanced with respect to both TP and TN, but that chlorophyll was dependent only on TP when the TN:TP ratio was >17.

The relatively high TN:TP ratios in the Upper Orange River system reflected high nitrogen concentration and low phosphorus concentrations, thus indicated PO_4-P limitation. However, Toerien *et al.* (1975) suggested that the Orange River and the Gariep Dam are NO_3-N limited.

Silicon-silica (SiO_2-Si)

Silica plays an intriguing role in aquatic systems, since it apparently accounts for the success of diatoms, which dominate most aquatic systems. Most algae and animals have at best only a minor need for silicon, but in the diatoms, silica (SiO_2) forms the rigid algal cell wall or frustule, which may account for half the cell's dry weight. The form of silicon when used as a structural component in algae is hydrated to form amorphous silica ($SiO_2 \, . \, nH_2O$) (Horne & Goldman, 1994). According to Cloot *et al.* (1995) the viability of Si as an indicator of the presence of diatoms is higher than any other nutrient.

The annual average silica concentration since 1980 until 1999 is shown in Figure 51. A decrease in the silicon-silica concentration could be seen over the study period at all four sampling points. The silica concentration decreased from an average of 8.5 $mg.l^{-1}$ during the 1980's to an average of 7.8 $mg.l^{-1}$ during the 1990's. This decrease in silica concentration could be ascribed to increased algal concentration

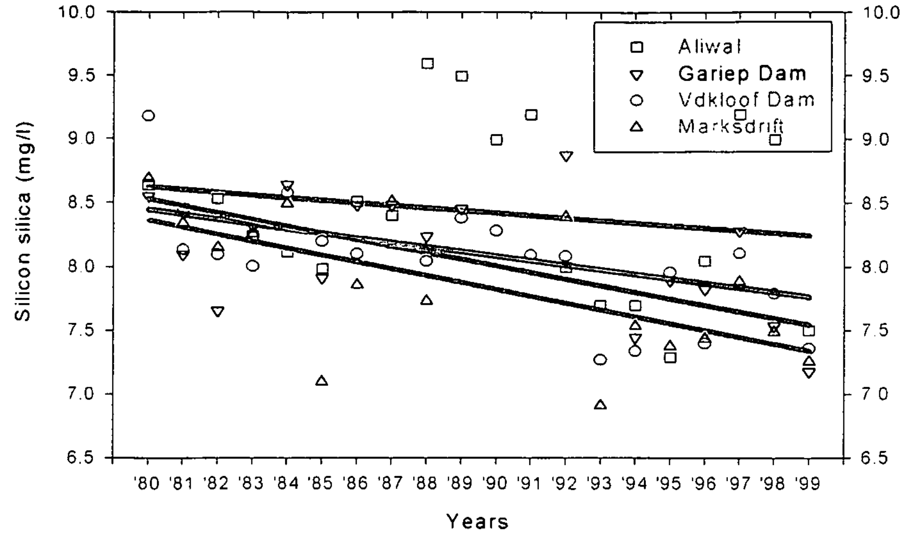


Figure 51. The annual average silicon silica concentrations (SiO_2-Si) (mg/l) from 1980 to 1999, with the solid lines indicating the regression over time at that specific sampling point

(especially diatoms). It is a well-known fact that silica (SiO_2) is incorporated into diatom cell walls and that increased diatom productivity will significantly decrease the silica content of the water (Wang & Evans, 1970; Kilham, 1971; Edwards, 1974; Wetzel, 1983; Horne & Goldman, 1994; Carter-Lund & Lund, 1995 and Cloot *et al.*, 1995). The rate of silica uptake by a diatom cell depends on the species involved as well as on the orthosilicic acid concentration in the immediate vicinity of the cell (Cloot *et al.*, 1995).

The silica concentrations at the different sampling points downstream during the study period are illustrated in Figure 52. The silica concentrations in the Upper Orange River system ranged between 0.5 $mg.l^{-1}$ in the Caledon River and 48.8 $mg.l^{-1}$ in the Kraai River. The average concentration in the Orange River was 15.2 $mg.l^{-1}$, while the average concentration in the Kraai River was 17.7 $mg.l^{-1}$ and for the Vaal River the average was 11.2 $mg.l^{-1}$. The silica concentrations in the Upper Orange River system, with the exception of the Vaal River, was higher than the world average concentration for silica in large rivers (13 $mg.l^{-1}$), while the silica concentration in world lakes showed values from 0.5 to 60 $mg.l^{-1}$ (Horne &

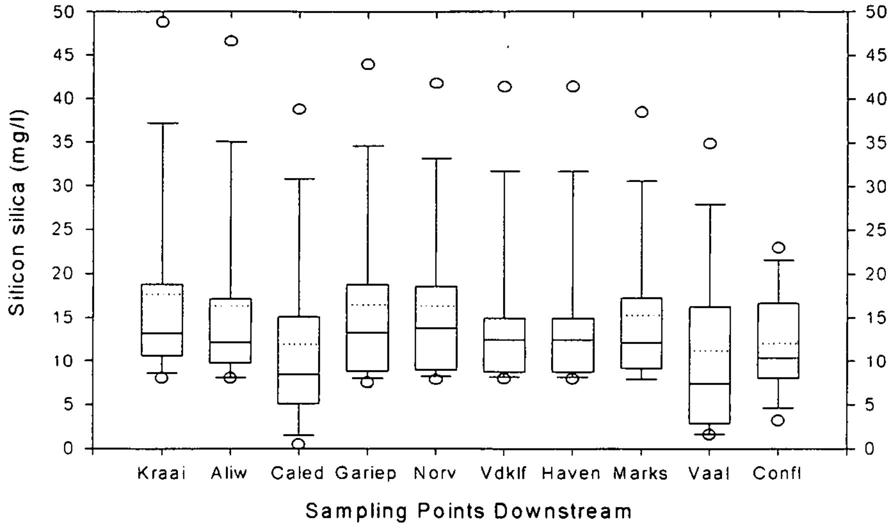


Figure 52. Box plots of the silicon silica concentrations (SiO_2-Si) (mg/l) at the different sampling points in the Orange River system during the study period

Goldman, 1994). The concentrations are also much higher than the average silica concentrations of 7.5 mg.l^{-1} for European rivers (Wetzel, 1983).

The silica concentrations in the Upper Orange River system displayed distinctive seasonal patterns (Figure 53). The highest silica concentrations occurred during spring. Upstream of the dams the lowest silica concentrations occurred during winter. In summer the lowest silica concentrations were observed in the dams and downstream. The silica concentrations in the Upper Orange River system showed little response to change in discharge.

Edwards (1974) also noted this insensitivity of silica concentrations to changes in discharge for some Norfolk rivers. Since diatoms occurred in the system throughout the year, the high silica concentration during spring might be ascribed to silica recycling. Cole (1983) reported that about 30 % of the silica that reached the sediment via diatom frustules in Lake Ontario were retained there permanently and the remaining 70 % is regenerated slowly from the sediment and incorporated in subsequent diatom blooms. However, silica recycling in the Upper Orange River system needs to be investigated further.

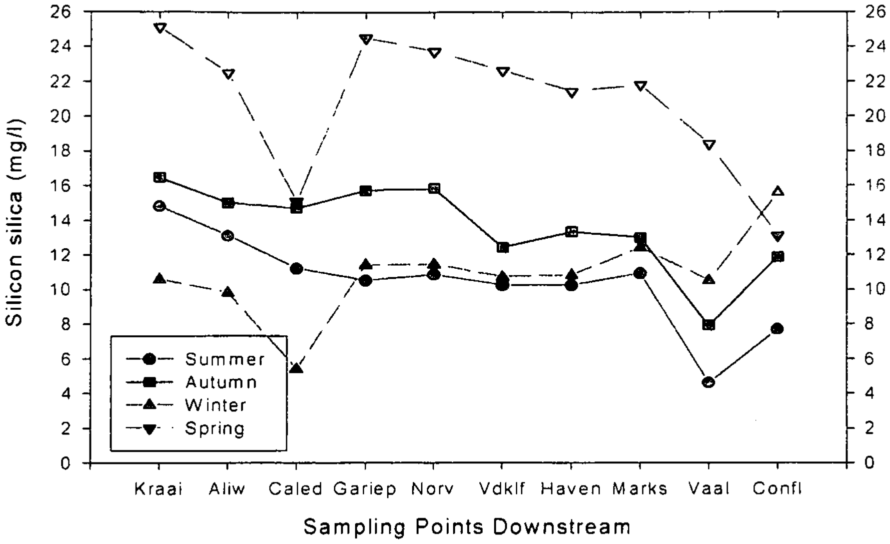


Figure 53. Seasonal average silicon silica concentrations (SiO_2-Si) (mg/l) at the different sampling points in the Orange River system during the study period

5.4 CONCLUSION

The dissolved oxygen concentration in the Upper Orange River system was fairly high and ranged between 4.7 and 11.6 $mg.l^{-1}$ (47 and 135 % oxygen saturation) in the epilimnion during the study period. An oxygen-depth profile in the Gariep Dam on 19 February 1999 showed relatively high dissolved oxygen concentrations in the epilimnion (8.2 $mg.l^{-1}$) and nearly anoxic conditions (0.1 $mg.l^{-1}$) in the hypolimnion. The oxygen decline in the hypolimnion was indirectly due to high algal production in the epilimnion during an algal bloom.

The pH increased from an average of 7.3 to 8.2 since 1980 until 1999. The average pH of the Upper Orange River during 1998 and 1999 was 8.1 and indicated mainly alkaline conditions. Statistically significant correlations were found between the pH and the dissolved oxygen concentration in both the Orange and Vaal Rivers. The average total alkalinity in the Upper Orange River system of 95.2 mg $CaCO_3.l^{-1}$

suggested that the Orange River is well buffered, although the buffering capacity is lower in the dams and downstream.

The average conductivity in the Upper Orange River was relatively low at 19.6 $mS.m^{-1}$ during the study period. The average conductivity in the tributaries was higher, with the highest average values (65.2 $mS.m^{-1}$) occurring in the Vaal River. The high average conductivity of the Vaal River had a detrimental influence on the conductivity in the Orange River after the Orange-Vaal confluence. An inverse trend was found between the conductivity and turbidity in the Upper Orange River system during the study period.

The average TDS concentration increased from 121 $mg.l^{-1}$ to 144 $mg.l^{-1}$ since 1980 until 1999. This increase in TDS was probably due to reduced flow caused by the dams, as well as more intensive irrigation practices along the river. In the Orange River at Aliwal North, Ca dominated the cations and the anions were dominated by CO_3^-. In the Gariep Dam and in the Orange River at Marksdrift Na dominated the cations and the anions were also dominated by CO_3^-. According to Wetzel (1983) Ca dominance prevails in open systems, situated in temperate zones. Gibbs (1970) reported that Na dominance usually indicates rivers and lakes located in hot, arid regions where evaporation plays an important role. High evaporation rates (30.4 $m^3.s^{-1}$) occurred along the full length of the Orange River (McKenzie & Roth, 1994) and that could partially explain the Na dominance in the system in and downstream of the dams.

The average PO_4-P concentration decreased slightly since 1980 until 1999. This decrease might be ascribed to the assimilation by algae, as phosphorus is usually the first element to limit biological productivity. The average PO_4-P concentration in the Upper Orange River system (28.3 $\mu g.l^{-1}$) was much lower than the world average for rivers (100 $\mu g.l^{-1}$) (Horne & Goldman, 1994). A statistically significant inverse correlation was found between the PO_4-P and Ca concentrations in the Upper Orange River for 1998 and 1999. High Ca concentrations reduce the solubility of phosphorus (Cloot & Roos, 1996, House, 1999). The average TP concentration in the Upper Orange River system was 107 $\mu g.l^{-1}$ and compared well with TP concentrations in flowing water (100 $\mu g.l^{-1}$) (Wetzel, 1983).

The average NO_3-N concentrations in and downstream of the dams increased from 0.45 $mg.l^{-1}$ to 0.58 $mg.l^{-1}$ from 1980 to 1999. These increases in NO_3-N concentrations are probably due to excessive fertilisers and nitrogen fixation by algae. The average NO_3-N concentration in the Upper Orange River system for 1998 and 1999 was 312 $\mu g.l^{-1}$ and thus three times higher than the concentration for unpolluted world rivers (100 $\mu g.l^{-1}$) (Webb & Walling, 1992). The average TN:TP ratio for the Upper Orange River system was 15.4 during 1998 and 1999.

Seasonal patterns for nearly all parameters were diminished by the dams. At best only slight seasonal patterns were observed in the Upper Orange River system and the correlation between elements and discharge was relatively small and limited to sampling points upstream of the dams.

CHAPTER 6

BIOLOGICAL PARAMETERS

6.1 PHYTOPLANKTON

6.1.1 Introduction

The term algae collectively refers to a wide range of pigmented, oxygen-producing, photosynthetic organisms usually present in surface waters. Virtually all aquatic organisms without roots, stems and leaves are regarded as algae (DWAF, 1996). Algae range from microscopically small unicellular forms, the size of bacteria, to larger filamentous forms which can be meters in length.

The algae of the open water of streams and lakes, namely phytoplankton, consist of a diverse assemblage of algal families. Despite differing physiological requirements and variations in tolerance to physical and chemical environmental parameters, a number of phytoplankton species coexist in phytoplankton populations (Wetzel, 1983).

Several major environmental factors interact to regulate spatial and temporal growth of phytoplankton. A number of inorganic and organic nutrient factors play critical roles in succession of algal populations. The population development and duration of the population can also be influenced, to a lesser extent, by herbivorous predation and parasitism (Steinberg & Hartmann, 1988).

Rates of algal production increase as nutrient limitations of phytoplankton are increasingly met by nutrient inputs to water ecosystems today. The density of phytoplankton populations progressively reduce the light available and the depth of the photic zone (Grobbelaar, 1989). A point is rapidly reached at which self-shading inhibits further increases in productivity, regardless of nutrient loading and availability.

6.1.2 Composition and classification of algae

Phytoplankton consists of the assemblage of small organisms that have no or very limited powers of locomotion and are more or less subject to distribution by water movements (Carter-Lund & Lund, 1995). Certain planktonic algae have limited powers of locomotion; they move largely by means of flagella or various mechanisms that alter their distribution by changes in buoyancy (Steinberg & Hartmann, 1988). Most algae, however, are free floating. Phytoplankton is largely restricted to lenthic waters and larger rivers of reduced current velocity.

6.1.2.1 Pigments

Photosynthetic pigments, namely the chlorophylls, carotenoids and biliproteins, are primary characteristics among algal groups. Chlorophyll *a* is the primary photosynthetic pigment of all oxygen-evolving photosynthetic organisms and is present in all algae and photosynthetic organisms, other than the photosynthetic bacteria. Chlorophyll *b*, although common in higher plants, is found only in the green algae and the euglenophytes. This pigment functions as a light-gathering pigment in which absorbed light energy is transferred to chlorophyll *a* for primary photochemistry. Chlorophyll *c* most likely functions as an accessory pigment to photosystem II. Chlorophyll *d*, of no known function, is a minor pigment component found only in certain red algae (Wetzel, 1983).

6.1.2.2 Cyanophyceae (Blue-green algae)

The Cyanophyceae family is the only group of primitive algae with prokaryotic cell structure such as the bacteria and is also referred to as cyanobacteria. Prokaryotic cells are undifferentiated and exhibit a lack of mitochondria, chloroplasts, and internal membranes, except the photosynthetic thylakoidal membranes. A cell wall of mucopeptides is present. Reproduction is usually by binary fission, and nuclear division does not occur by mitosis, as in eukaryotic cells of other algae and higher organisms.

The blue-green algae are mostly filamentous, but a number of important planktonic members are unicellular and usually occur in large colonies. Blue-green algae are also known for their mucilaginous sheaths in both individual cells and in colonies (Steinberg & Hartmann, 1988) often of irregular and variable size and form.

The differentiation of certain vegetative cells into heterocysts is unique to all filamentous blue-green algae except the Oscillatoriaceae. These vegetative cells develop a thick envelope over the cell wall, except at the polar regions, in which the heterocyst is connected to adjacent vegetative cells by a pore channel, through which exchange of metabolic products occurs. In contrast to vegetative cells, heterocysts lack phycobilins, which are the primary light absorbers in blue-green algae. Carbon assimilated by vegetative cells in the light passes into the heterocysts in the dark and provides energy for their metabolism in nitrogen fixation. While nitrogen fixation is not limited solely to heterocysts, it is certainly the major sites of nitrogen fixation under aerobic conditions (Wetzel, 1975).

In freshwater, the blue-green algae are often responsible for the occurrence of toxic algal blooms. In South Africa the most common bloom-forming toxic species are

Microcystis spp., *Anabaena* spp. and *Oscillatoria* spp. although a number of other species may also produce toxins on occasion (DWAF, 1996). Blue-green algae produce a variety of neurotoxins, saxitoxins, hepatotoxins (microcystins) and lipopolysaccaride endotoxins. These toxins have been associated with a number of livestock and game deaths, as well as widespread gastroenteritis in human populations. The toxins are predominantly intracellular in healthy blooms. The toxins are released once the cells mature, senesce and die. Toxicity can unfortunately not be predicted, as there is no correlation between the density of the bloom and toxic production. The toxin production is also highly variable (Van Halderen *et al.*, 1995).

6.1.2.3 Chlorophyceae (Green algae)

Chlorophyceae is an extremely large and morphologically diverse group of algae, the majority belonging to the orders Volvocales (e.g., *Chlamydomonas*, *Sphaerocystis*, *Eudorina* and *Volvox*) and Chlorococcales (e.g., *Scenedesmus*, *Ankistrodesmus*, *Selenastrum* and *Pediastrum* spp.). Many species are flagellated in some stage of their life cycle.

Asexual reproduction through vegetative division is common to most of the green algae. Cell division in colonial species results in enlargement of the colony. New colonies are, however, only formed by fragmentation of the colony. Sexual reproduction in green algae is diverse and varies between isogamy, anisogamy and oogamy.

Most planktonic green algae are rather ubiquitous in distribution among waters of differing salinity within the normal limnological range, however, as a whole they are less cosmopolitan than most unicellular algae (Carter-Lund & Lund, 1995).

6.1.2.4 Bacillariophyceae (Diatoms)

A considerable majority of the Bacillariophyceae species is sessile and associated with littoral substrata. Their silicified cell walls are a primary characteristic (Horne & Goldman, 1994). Both unicellular and colonial forms are common among the diatoms. The group is commonly divided into the Centrales; centric diatoms, which have radial symmetry and the Pennales; pennate diatoms, which exhibit essentially bilateral morphology.

The cell wall or frustule of diatoms, which is often used as taxonomic characteristics (Jüttner *et al.*, 1996), consists of two lid-like valves, one of which fits within the other and is connected by bands that constitute the girdle. Vegetative reproduction by cell division, is the most common mode of multiplication. Sexual reproduction occurs periodically when the size of the cells becomes reduced from asexual reproduction (Wetzel, 1975).

6.1.2.5 Euglenophyceae (Euglenoids)

Euglenophyceae is a relatively large and diverse group of algae, but few are truly planktonic. Almost all euglenoids are unicellular, lack a distinct cell wall and possess flagella. Reproduction occurs by longitudinal division of the motile cell and sexual reproduction has not yet been substantiated.

Some euglenoids are unpigmented and phagotrophic, thus able to ingest solid particles. They are probably best considered as Protozoa. However, most are photosynthetic and facultatively heterotrophic (Wetzel, 1983). Euglenophyceae is mainly associated with organic polluted water.

6.2 MATERIALS AND METHODS

6.2.1 Chlorophyll *a* concentration

Chlorophyll *a* is the primary photosynthetic pigment of all oxygen-evolving photosynthetic organisms. It is thus used as an index of the trophic status of a water body. Measuring the chlorophyll *a* concentration can provide a convenient estimation of the algal biomass (Walmsley, 1984). The chlorophyll *a* concentration in the Orange River system was estimated by using a modified ethanol extraction method, similar to that of Sartory and Grobbelaar (1984). A known volume (usually between 50 and 100 ml) of water (depending on the amount of suspended solids) was filtered through 47 mm glass fibre filters (Whattman GFC, particle retention: 0.7 μm). After filtration the filter paper was put in 10 ml 95% ethanol and boiled for precisely 5 minutes at 78 °C. Then cooled in the dark, the absorbency was measured at 665 nm and 750 nm. Followed by adding 100 μl of 0.3 N HCl and waiting 2 minutes, the absorbency was measured again at 665 nm, with a Philips UV/Visible Spectrophotometer PU 8700 Series. The chlorophyll *a* concentrations were estimated by the following equations:

Chlorophyll *a* concentration in extract (mg/l) = $(A_{665} - A_{665a}) \times 28.66$

where:

A_{665} = absorbance of ethanol extract at 665 nm before acidification minus absorbance at 750 nm.

A_{665a} = Absorbance of ethanol extract at 665 nm after acidification minus the absorbance at 750 nm.

Chlorophyll *a* concentration in original sample:

$$\text{Concentration } (\mu g.l^{-1}) = \frac{\text{concentration of extract x extract volume}}{\text{Volume of filtered sample in liter}}$$

6.2.2 Algal identification

Dominant algal species was collected *in situ* and fixed by 2 % formaldehyde in a 100 ml sampling container. Applying pressure to cells can damage the gasvacuoles of the cyanobacteria. Damage to the gasvacuoles causes the cyanobacteria to settle out at the bottom of the container for countings. Hitting a rubber stopper on a container, filled with sampled water, with a rubber hammer generated this pressure. After this, 2 or 5 ml (depending on the suspended solids and detritus in the water) of the sampled water was extracted and put into Utermöhl counting chambers. The rest of the volume was filled by distilled water and sealed with a cover-glass slip.

A Zeiss inverted light microscope was used to identify the dominant species and 20 blocks of known dimensions was counted. These results were then multiplied by a convergent factor to obtain the total counts. Algal species was determined as a percentage of the total community.

6.2.3 Primary Productivity

Water sampling for *in situ* primary production determination by natural phytoplankton assemblages was done three times during the study period (September 1998, February 1999 and April 1999) in the Orange River, Vaal River and the Gariep Dam.

It was assumed that the water in the rivers are well mixed and that the residence time of any given algal cell at any one depth is insufficient for adaptation to occur. Thus, samples taken at different depths would then show the same photosynthetic properties as those from the well-mixed depth. Therefore, only one sub-surface water sample was collected in the middle of the rivers, with a 2*l* Van Dorn sampler. However, water mixing in the dam with high residence time is not sufficient and a modified hosepipe was used to get an integrated sample that represented various vertical depths.

The ^{14}C used was packed in a glass ampoule containing 20 µCi in 1ml distilled sterile aqueous solution. The content of this ampoule was put into a plastic container. In both the rivers and the dam, 100 ml round bottom flasks (DURAN – Schott), with a standard ground socket and plastic stoppers were used as incubation flasks and 100 ml was measured out from the plastic container and put into each of the incubation flasks.

One darkened and two translucent (light) bottles (in a horizontal position) were suspended on an aluminium rod in the middle of the rivers and in the dam, near the damwall. The dark bottles were prepared by painting the bottles black and then covering it with aluminium foil. Click-on metal clamps on an aluminium disk were used with each bottle attached to it and hanging in a almost perpendicular position. The aluminium disks were placed at different depths i.e. at the surface (0 cm) 12,5 cm, 25 cm, 50 cm, 75 cm, 100 cm, and 150 cm.

Incubation times of 4 hours were used, between 10:00 and 14:00. After incubation the bottles were stored in a darkened wooden box (to prevent exposure to light) and taken for immediate processing, using the acidification and bubbling method (Schindler *et al.*, 1972).

After the incubation period, 10 ml was extracted from each incubation bottle and put into a scintillation vial. Then, 0.5 ml of a 0.1 N HCl solution was added and the scintillation vials were put into a bubbling apparatus for 5 minutes to strip the inorganic $^{14}CO_2$ from the water samples. After bubbling, 10 ml of a liquid scintillation counting solution, Insta Gel (a xylene-based cocktail manufactured by Packard), was added to each sample as well as 0.5 ml of a carbon dioxide absorber, Carbo-sorb II. The samples were then stored in the dark and further processed in the laboratory.

The total cumulative uptake of ^{14}C during incubation was determined and normalized to incubation time to give an hourly rate, by using the equation according to Vollenweider (1969):

$$P_z = \frac{{}^{14}C \text{ ass} \times {}^{12}C \text{ avail}}{{}^{14}C \text{ added}} \times K1 \times K2 \times K3 \times K4$$

where:

P_z = hourly rate (time-integrated average) of total carbon assimilated (photosynthesis) at depth z (mg $C.m^{-3}.h^{-1}$)

^{14}C ass = average disintegrations per minute (DPM) of aliquots from 2 light bottles minus DPM in dark bottle

^{14}C added = total ^{14}C (DPM) available for assimilation

^{12}C avail = total DIC available for photosynthesis ($mg.l^{-1}$). Calculated from total alkalinity, pH and temperature values

K_1 = a conversion factor for the aliquots

K_2 = isotopic factor (=1.06); the isotope discrimination factor corrects for the fact that ^{14}C, being heavier than ^{12}C, is taken up more slowly

K_3 = a dimension factor to convert $mg.l^{-1}$ to $mg.m^{-3}$ (x 1000)

K_4 = a time factor. If K_4 is not used in the formula, then Pz will be equal to $mg.m^{-3}.xh^{-1}$ (where x = incubation time)

The maximum light saturated chlorophyll-specific photosynthetic rate (or assimilation number) (P^Bm, mg C. mg $Chla^{-1}$. h^{-1}), was determined by dividing the *maximum rate of photosynthesis in the depth profile* (Pm, mg $C.m^{-3}.h^{-1}$) by the *average chlorophyll a concentration in the euphotic zone* (Harris, 1980).

6.3 RESULTS AND DISCUSSIONS

6.3.1 Algal identification

The algal species that were found in the Orange River and tributaries during the study period are listed in alphabetical order below the family to which it belongs.

1. CYANOPHYCEAE
Anabaena circinalis
Apatococcus vulgaris
Chroococcus dispersus
Merismopedia minima
Microcystis aeruginosa
Oscillatoria simplicissima
Raphidiopsis sp.

2. BACILLARIOPHYCEAE
Cyclotella spp.
Melosira (*Aulocoseira*) *granulata*
Navicula sp.
Nitzschia sp.
Pennate diatoms (other)
Centric diatoms (other)

3. CHLOROPHYCEAE
Actinastrum hantzchii
Ankistrodesmus sp.
Carteria sp.
Chlamydomonas spp.

Chlorella sp.
Closterium sp.
Coelastrum sp.
Cosmarium sp.
Crucigenia tetrapedia
Eudorina sp.
Monoraphidium arcuatum
M. circinale
Oocystis sp.
O. solitaria
Pandorina morum
Pediastrum sp.
Scenedesmus spp.
Selenastrum sp.
Tetrastrum sp.
Tetraedron regulare

4. EUGLENOPHYCEAE
Euglena pusilla
Lepocinclis sp.
Strombomonas sp.
Trachelomonas sp.

6.3.2 Spatial variation in phytoplankton

The chlorophyll *a* concentration in the study area ranged between 0.4 and 114.6 µg.l^{-1} (Figure 54). However, the chlorophyll *a* concentration in the Gariep Dam during February 1999, taken at the surface directly in the bloom, was 1 084 µg.l^{-1} (note that this value was not taken into account in the calculations). The average chlorophyll *a* concentration in the Orange River (including the dams) was 10.8 µg.l^{-1} and indicated mesotrophic conditions.

According to the South African Water Quality Guidelines for recreational use (DWAF, 1996), chlorophyll *a* concentration above 30 µg.l^{-1} for free-floating algae, can cause severe nuisance algal blooms. Walmsley (1984) also found that at

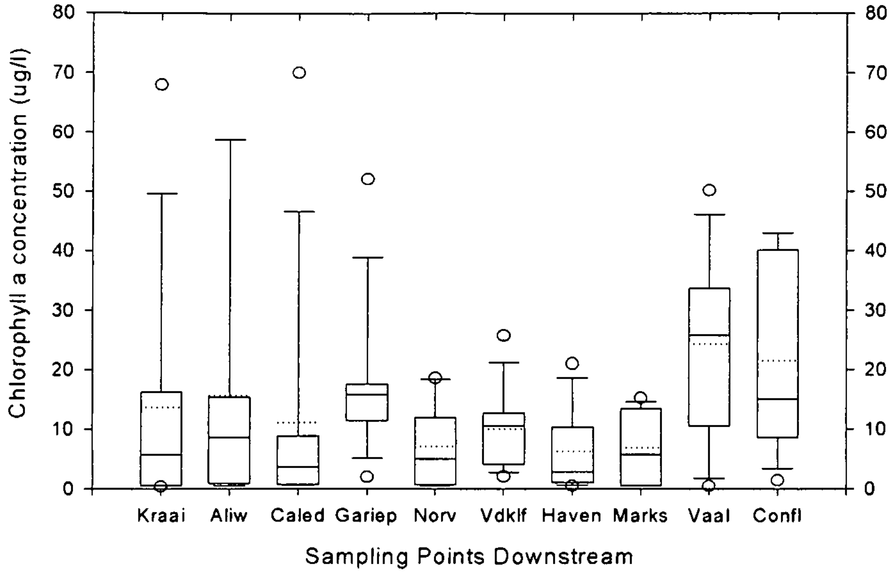


Figure 54. Box plots of the chlorophyll *a* concentrations (µg/l) at the different sampling points in the Orange River system during the study period

chlorophyll *a* concentrations of higher than 30 µg.l^{-1} severe nuisance conditions could be encountered. Thus, for this study, chlorophyll *a* concentrations higher than 30 µg.l^{-1} were considered as algal blooms.

A positive trend could be observed between the chlorophyll *a* concentrations and the algal cell counts at the different sampling points (with the exception of the dams). The average chlorophyll *a* concentrations and the cell counts for the Orange River and tributaries during the study period are illustrated in Figure 55.

Relatively low chlorophyll *a* concentrations (13.7 µg.l^{-1}) and low cell counts (5 004) were found in the Kraai River. This might be ascribed to the relatively low nutrient concentration of this nearly pristine mountain stream. At Aliwal North the relatively high turbidity (Figure 10), and thus light, was probably the main factor limiting the chlorophyll *a* concentrations (15.7 µg.l^{-1}) and the cell counts (3 288). Grobbelaar (1992) concluded that mainly turbidity influences overall productivity in the Modder

River (South Africa). The very turbid Caledon River had a chlorophyll *a* concentration of 16 $\mu g.l^{-1}$ and cell counts of 9 312 algal cells.

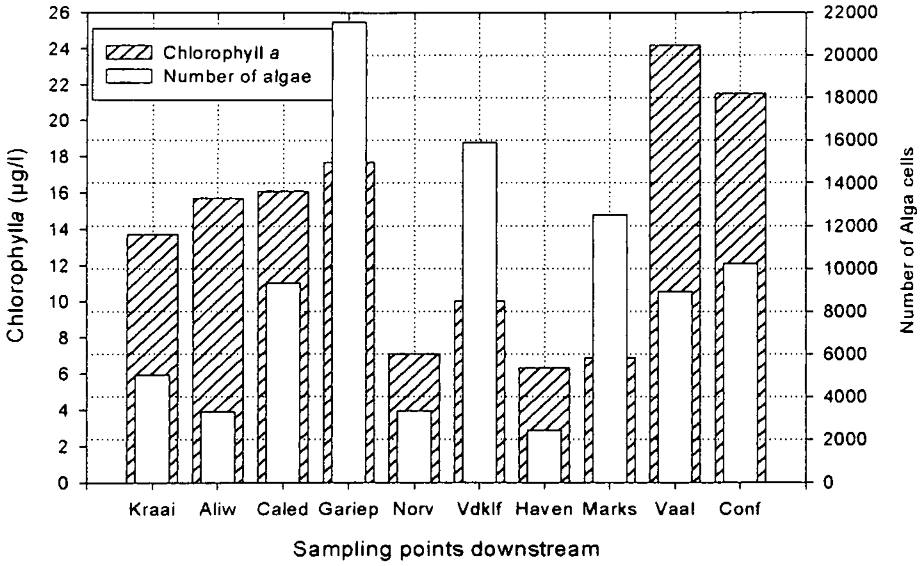


Figure 55. The relationship between the chlorophyll *a* concentrations and the cell counts at the different sampling points in the Orange River system during the study period

In the Gariep Dam the average chlorophyll *a* concentration was 17.7 $\mu g.l^{-1}$, with high cell counts (21 564). The average chlorophyll *a* concentration in the Vanderkloof Dam was 10 $\mu g.l^{-1}$, but the cell counts (15 894 algal cells) were lower than those found in the Gariep Dam. It is well documented that increased water residence time leads generally to higher algal abundance (Carter-Lund & Lund, 1995 and Søballe & Kimmel, 1987). Reid (1997) concluded that high flow events on rivers regulated for hydroelectric power generation might trigger algal blooms that are not linked to eutrophication. However, this did not seem to be true for the Orange River system during the study period.

At Norvalspont and Havenga Bridge, sampling points in the Orange River below the Gariep and Vanderkloof Dams, the cell counts were only 3 328

(7 μg chlorophyll *a* .l^{-1} on average) and 2 430 (6.3 μg chlorophyll *a*.l^{-1} on average) respectively. Both these dams are used for hydroelectric power generation as previously discussed. Blinn *et al.* (1998) found that water discharges from hydropower dams exert major influences on downstream algal communities. Dams typically reset physiochemical conditions in downstream tailwaters to those of lower order streams, which results in critical changes throughout the food web (Ward & Stanford, 1979).

In the Orange River at Marksdrift average chlorophyll *a* concentrations of 7 μg.l^{-1} and cell counts of 12 513 cells were found. In the Vaal River and the Orange River below the confluence, respectively 24.2 μg.l^{-1} and 21.5 μg.l^{-1} on average were found. However, the cell counts were relatively low in relation to the chlorophyll *a* concentration, at 8 928 and 10 234 cell counts respectively.

A statistically significant correlation could not be found between the chlorophyll *a* concentrations and the cell counts. This can be ascribed to the variation in the algal composition, e.g. diatoms contain less chlorophyll than green and blue-green algae. Another reason for this lack of correlation might be the cell countings where the sizes of the colonies of algae (e.g. *Microcystis*) are not taken into account.

Søballe and Kimmel (1987) found that rapid water renewal had significant and similar negative impacts on both the abundance and predictability of suspended algae in systems. Phytoplankton has different physiological requirements and vary in terms of limits of tolerance to physical and chemical environmental parameters (Wetzel, 1983) and therefore vary spatially and seasonally in an aquatic system.

The algal species composition is illustrated in Figure 56. In the Kraai River diatoms (Bacillariophyceae) constituted 71 % of the algal population. In the Orange River at

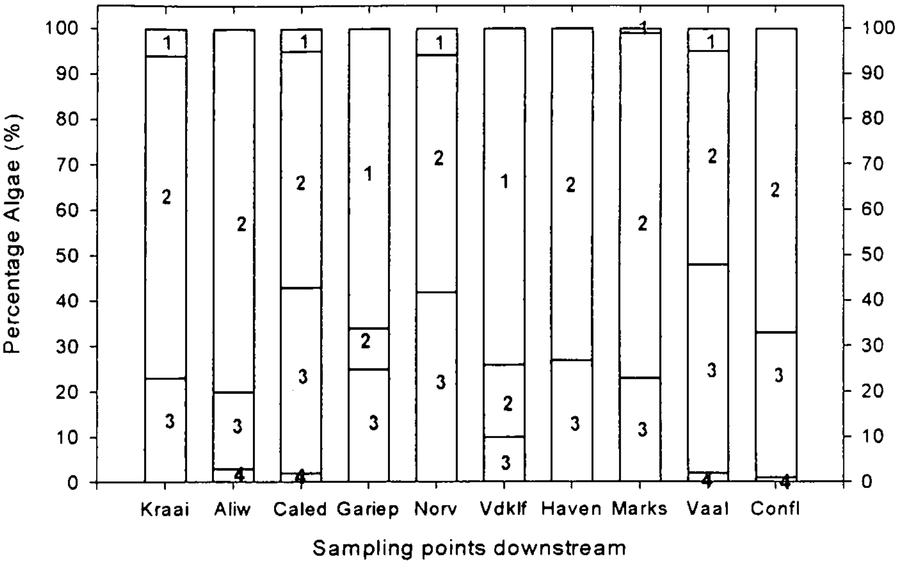


Figure 56. The algal species composition at the different sampling points in the Orange River system during the study period. (1 = Cyanobacteria; 2 = Bacillariophyceae; 3 = Chlorophyceae; 4 = Euglenophyceae)

Aliwal North 80 % of the algal population consisted of diatoms. In the Caledon River only 52 % consisted of diatoms and 41 % of green algae (Chlorophyceae). In the Gariep Dam cyanobacteria dominated the algal population (66 %). In the Orange River at Norvalspont, directly below the Gariep Dam, diatoms dominated at 52 % and green algae with 42 %. The species composition in the Vanderkloof Dam was, like the Gariep Dam, dominated by cyanobacteria (74 %). In the Orange River at Havenga Bridge diatoms constituted 73 % of the algal populations. Diatoms (76 %) dominated in the Orange River at Marksdrift. In the Vaal River the species composition consisted of 47 % diatoms and 46 % green algae. In the Orange River below the confluence with the Vaal River, diatoms constituted of 67 % and green algae of only 32 % of the algal populations.

According to Reynolds (1992) diatoms (Bacillariophyceae) and green algae (Chlorophyceae) tend to be the common organisms in rivers. Egborge (1974) found that Bacillariophyceae generally dominate the phytoplankton in African rivers in open water. Jüttner *et al.* (1996) also found that in rivers, diatoms are the most abundant and specie-rich primary producers. Roos and Pieterse (1996) noted that diatoms usually dominate in the Vaal River system. This seems also to be true for the Orange River and tributaries. However, when the turbulence of the water column is rather low, as it is in sheltered lakes, cyanobacteria can build up dense populations (Steinberg & Hartmann, 1988). This cyanobacteria build up could be seen in both the Gariep and Vanderkloof Dams. Cyanobacteria are able to maintain their position in the waterbody by their ability to regulate buoyancy (either by gas vesicles mediated by cell turgor pressure or by an increase in heavy substances, for example polysaccharides). The growth in the metalimnion of stable stratified lakes is favoured by the extremely effective light-capturing mechanisms, especially of species containing phycoerythrin.

Bahnwart *et al.* (1999) found that longitudinal change in diversity and biomass reflected downstream variations in flow velocity and river morphology. Cyanobacteria and diatom species were subjected to large biomass losses along fast flowing, shallow river sections, whereas Chlorophyceae were favoured. Diatoms benefited from low flow velocity and increased water depth in the downstream river. They concluded that changes in water depth and flow velocity have been found as key factors that cause the longitudinal differences in phytoplankton composition and biomass.

6.3.3 Seasonal variation in phytoplankton

Phytoplankton is subjected to strong seasonal influences (Horne & Goldman, 1994). The seasonal (summer and winter) composition of algae in the Orange River (including the dams), is given in Figure 57. In summer Bacillariophyceae constituted 60 % and Cyanophyceae 33 %, while during winter Bacillariophyceae constituted 50 % and Chlorophyceae 48 % of the total algal population.

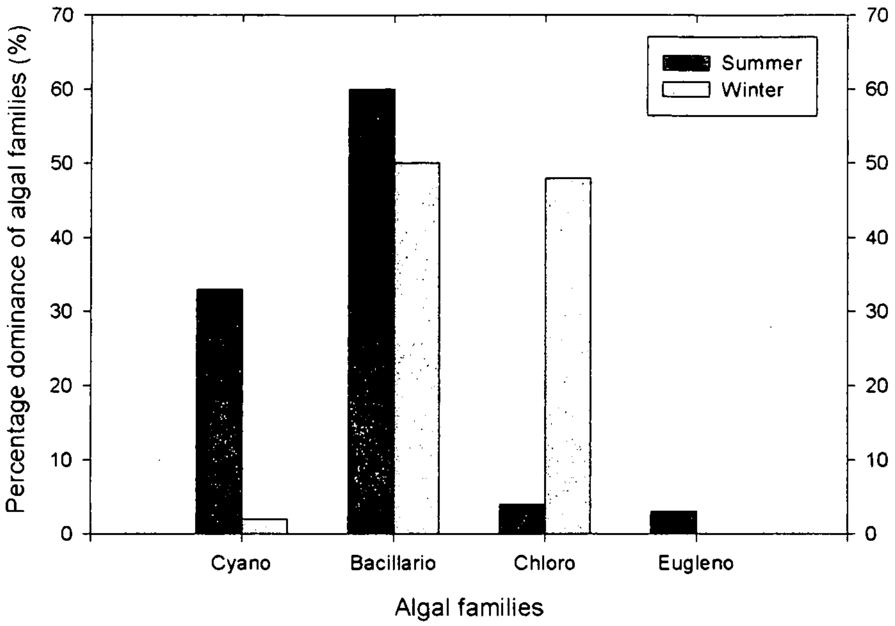


Figure 57. Seasonal algal family dominance (%) in the Orange River system during the study period

As discussed in the spatial variation in phytoplankton (6.3.2), various authors found that diatoms are the most abundant in rivers. Pritchard and Bradt (1984) reported that Bacillariophyceae increases when amounts of sunlight and nutrients are high (usually in spring and autumn). As Bacillariophyceae numbers increase, algae utilize the nutrients and concentrations decrease. In the Orange River system Bacillariophyceae occurred throughout the year. Jüttner *et al.* (1996) noted that diatom species richness and diversity were significantly higher in agricultural streams than in organically polluted streams. This coincides with the Orange River that is used intensively for irrigation purposes.

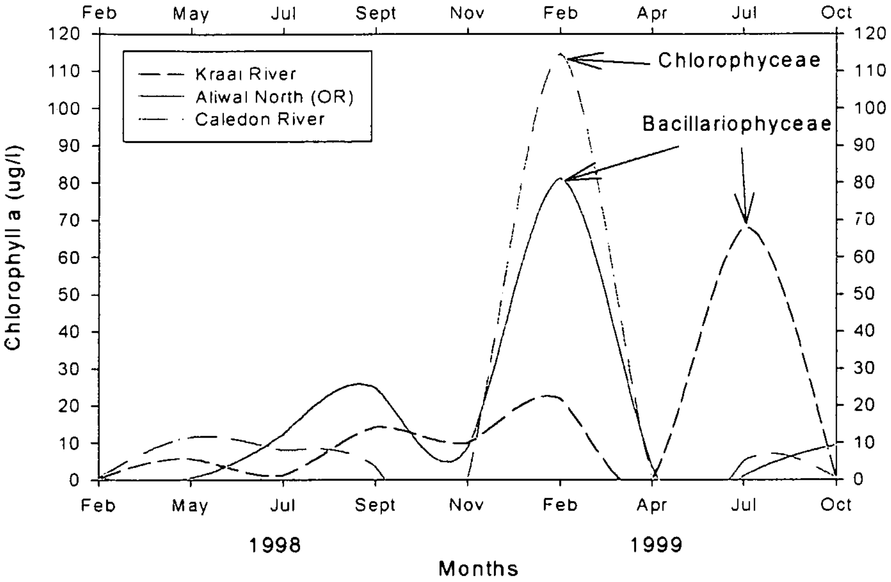


Figure 58. Seasonal variation in the chlorophyll *a* concentration in the Kraai River, the Orange River at Aliwal North and in the Caledon River during the study period

Cyanobacteria dominates when turbulence in the water column is rather low, also at low N:P ratios, at high water temperatures, at pH > 9 or at low light intensity (Steinberg & Hartmann, 1988). Cyanobacteria blooms were found in the Orange River in both the Gariep and Vanderkloof Dams, when turbulence in the water columns were low, water temperatures were relatively high (ranged between 22 and 24 °C) and the pH ranged between 8.1 and 8.3. Chlorophyceae dominates in relatively high N:P ratios, lower water temperatures and intermediate pH (Watson *et al.*, 1997). Chlorophyceae dominated in the Orange River when water temperatures ranged between 12 and 18 °C and at an average pH of 8.1 pH units.

The seasonal variation in chlorophyll *a* concentration in the Kraai River, the Orange River at Aliwal North and the Caledon River is shown in Figure 58. One notable Bacillariophyceae (diatom) bloom of 68 $\mu g.l^{-1}$ chlorophyll *a* was found in the Kraai River during July 1999. In the Orange River at Aliwal North two peak chlorophyll *a* concentrations were observed, one in September 1998 (24 $\mu g.l^{-1}$) and the other in February 1999 (81.2 $\mu g.l^{-1}$). Bacillariophyceae dominated in the Orange River at Aliwal North on both occasions. The chlorophyll *a* in the Caledon River showed a very prominent increase of 114.6 $\mu g.l^{-1}$ during February 1999. The bloom was caused by Chlorophyceae and, to a lesser extent, by Euglenophyceae.

The seasonal variation in chlorophyll *a* in the Gariep Dam and at Norvalspont showed two increases in chlorophyll *a* concentrations in the Gariep Dam, with low chlorophyll *a* concentrations at Norvalspont (Figure 59). The first increase in chlorophyll concentration in the Gariep Dam was in September 1998 (52 $\mu g.l^{-1}$), the second in February 1999 (1084 $\mu g.l^{-1}$). Both increases were caused by cyanobacteria. The chlorophyll *a* concentration within the February 1999 bloom was 40 times larger than the concentration in the non-bloom patches (26.8 $\mu g.l^{-1}$). At Norvalspont two increases in Bacillariophyceae concentrations could be

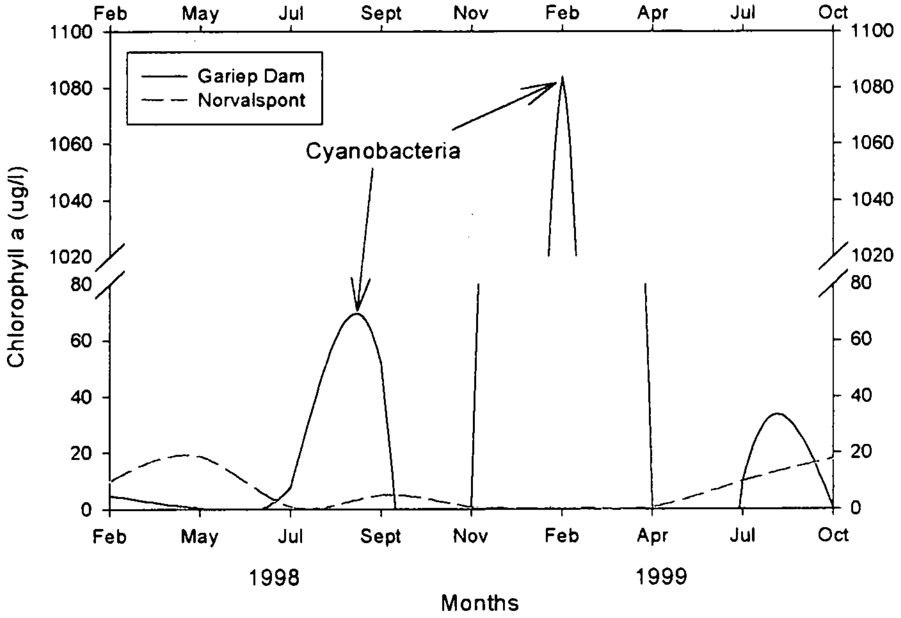


Figure 59. Seasonal variation in the chlorophyll a concentration in the Gariep Dam and at Norvalspont during the study period

distinguished. The first chlorophyll increase that occurred in May 1998 was 18.6 $\mu g.l^{-1}$ and the second increase in October 1999 was 17.9 $\mu g.l^{-1}$.

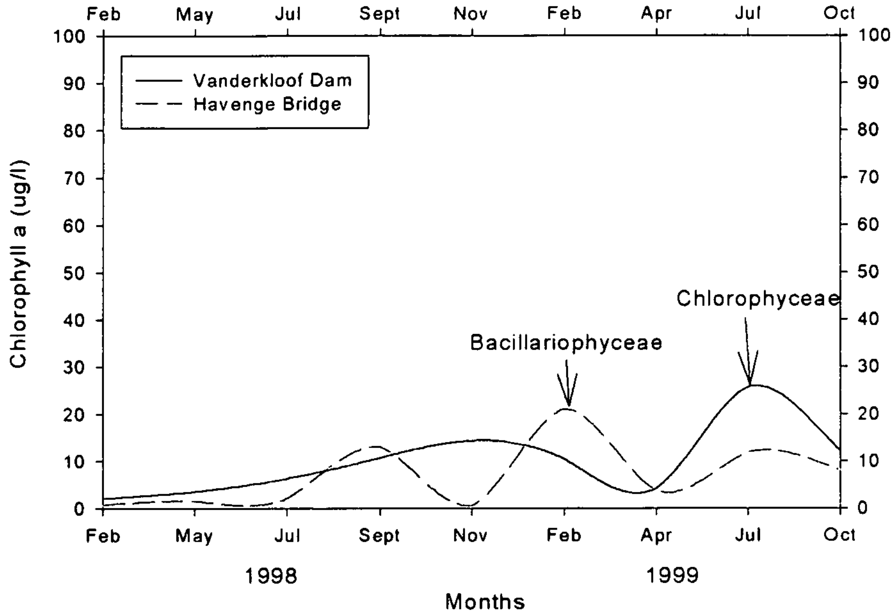


Figure 60. Seasonal variation in the chlorophyll a concentration in the Vanderkloof Dam and at Havenge Bridge during the study period

The variation in chlorophyll *a* concentration in the Vanderkloof Dam and Havenga Bridge is shown in Figure 60. In the Vanderkloof Dam two increases in concentration could be observed. The first increase in November 1998 (14.3 $\mu g.l^{-1}$) showed a long, gradual build-up period. The second increase in July 1999 was 25.8 $\mu g.l^{-1}$. Chlorophyceae in the Vanderkloof Dam succeeded cyanobacteria. The variation in chlorophyll *a* concentration in the Orange River at Havenga Bridge also showed two increases in concentration. The first increase was in September 1998 (12.9 $\mu g.l^{-1}$) (Chlorophyceae) and the second increase was in February 1999 (21 $\mu g.l^{-1}$) (Bacillariophyceae).

The Orange River at Marksdrift showed various small seasonal fluctuations in chlorophyll *a* concentrations (Figure 61). These small fluctuations were probably

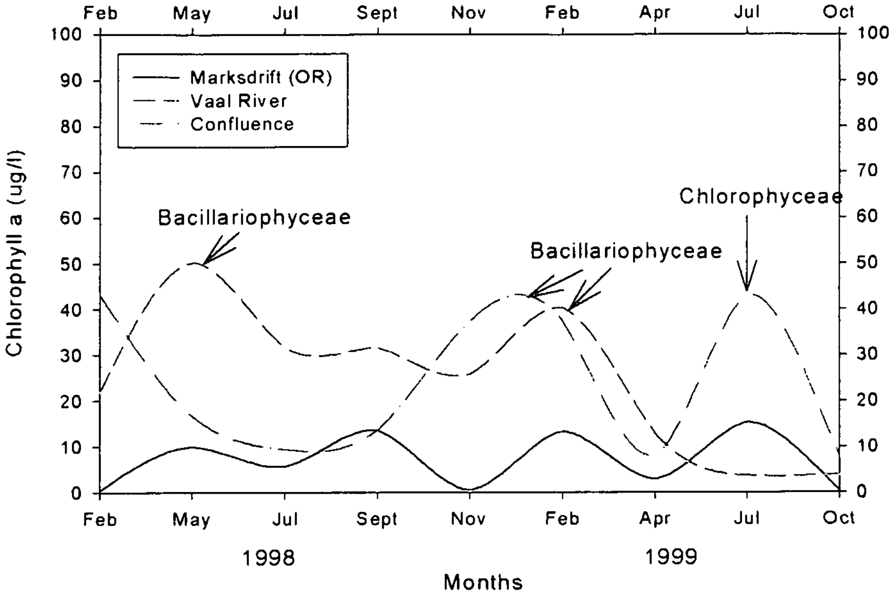


Figure 61. Seasonal variation in the chlorophyll a concentration in the Orange River at Marksdrift, in the Vaal River and in the Orange River below the confluence, during the study period

caused by the pulsating effect of the water released from the Vanderkloof Dam. Slightly higher chlorophyll *a* concentrations were observed during May 1998, September 1998, February 1999 and July 1999. Bacillariophyceae dominated the system. The Vaal River displayed relatively high chlorophyll *a* concentrations throughout the study period (average of 24.2 $\mu g.l^{-1}$) (Figure 61). Two distinctive blooms could be observed; the first in May 1998 (50.2 $\mu g.l^{-1}$) and the second in February 1999 (40.1 $\mu g.l^{-1}$). Bacillariophyceae caused the bloom in May 1998. Chlorophyceae gradually increased in concentrations until they reached a co-existence with the Bacillariophyceae in February 1999 and after that both concentrations decreased. In the Orange River below the confluence three distinctive blooms could be observed (Figure 61). The first bloom was in February 1998 and reached 43 $\mu g.l^{-1}$ (Bacillariophyceae), the second bloom was in February 1999 (37.3 $\mu g.l^{-1}$) (Bacillariophyceae) and the third bloom was in July 1999 (43 $\mu g.l^{-1}$) (Chlorophyceae).

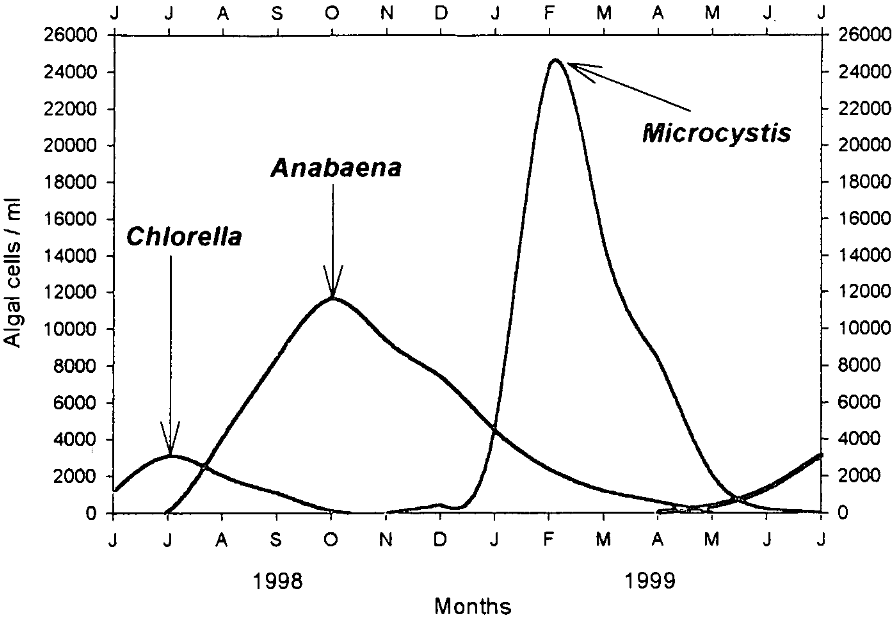


Figure 62. A representation of the algal succession in the Gariep Dam during the study period

A representation of the algal succession in the Gariep Dam is given in Figure 62. It should be noted, however, that it gives only an indication of the succession and that it was necessary to make some suppositions because the sampling frequency was low and it is possible that some of the chlorophyll *a* concentration and cell count peaks could have been missed. *Chlorella* (Chlorophyceae) dominated during the winter and reached maximum concentrations in June. It was succeeded by *Anabaena* (Cyanophyceae) in spring and dominated in October. The *Anabaena* was succeeded by *Microcystis*, which dominated in February. Palmer (1995a) found that algal blooms in the Vanderkloof Dam were restricted to summer months, and changed from high densities of *Anabaena* in December, to high densities of *Microcystis* in February to March. Talling (1986) noted that *Anabaena* dominated in September and October in Lake Tanganyika.

6.3.4 Relationship between phytoplankton (expressed as chlorophyll *a* concentration) and other variables

Rivers and impoundments are mosaics of micro-environments that differ in chemical nature and are potentially limited by different nutrients. Nutrient spatial heterogeneity includes spatial and seasonal variation in concentrations of: 1) the same nutrient, 2) different nutrients and/or 3) different forms of the same nutrient (e.g. organic versus inorganic) (Pringle, 1990). Therefore it is important to investigate the nutrients available for algal growth in the Orange River and tributaries.

6.3.4.1 Turbidity

An inverse trend between the chlorophyll *a* concentration and the turbidity could be seen in the dams and downstream (Figure 63). As the dams act as sediment traps (Figure 10), light penetration into the water column increases and this generally leads to increased chlorophyll *a* concentrations. The average turbidity above the dams is 344.4 NTU and the average turbidity in and downstream of the dams is 63.2 NTU. Grobler and Davies (1981) concluded that sediments might act as direct sources of phosphate to algae. This might explain the high chlorophyll *a* concentrations and the high turbidity upstream of the dams. However, in the dams where sedimentation occurred, light availability might be sufficient to support algal growth, but phosphate concentrations could become limiting.

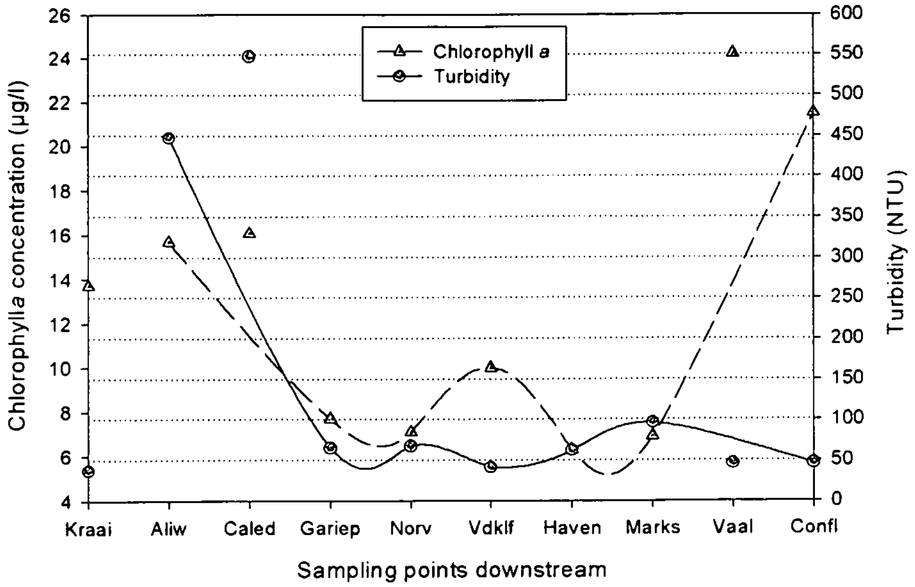


Figure 63. The average chlorophyll *a* concentration (µg/l) and turbidity (NTU) at the different sampling points in the Orange River system during the study period

6.3.4.2 Total phosphorus (TP)

A statistically significant correlation could not be found between the chlorophyll *a* concentration and the TP concentration (Figure 64). This could be ascribed to the predictions by Grobler and Davies (1981) that phosphorus bind to sediments, thus as the dams act as sediment traps, so they also act as nutrient traps. Therefore, a measurement of the concentration of a nutrient is not sufficient indication of whether or not it is limiting. What needs to be known, is the pool size and the rate of turnover (Harris, 1986). The pool size and rate of turnover for TP should be investigated further, in and downstream of the dams. The average TP concentration for the Orange River system was 143 µg.l^{-1}.

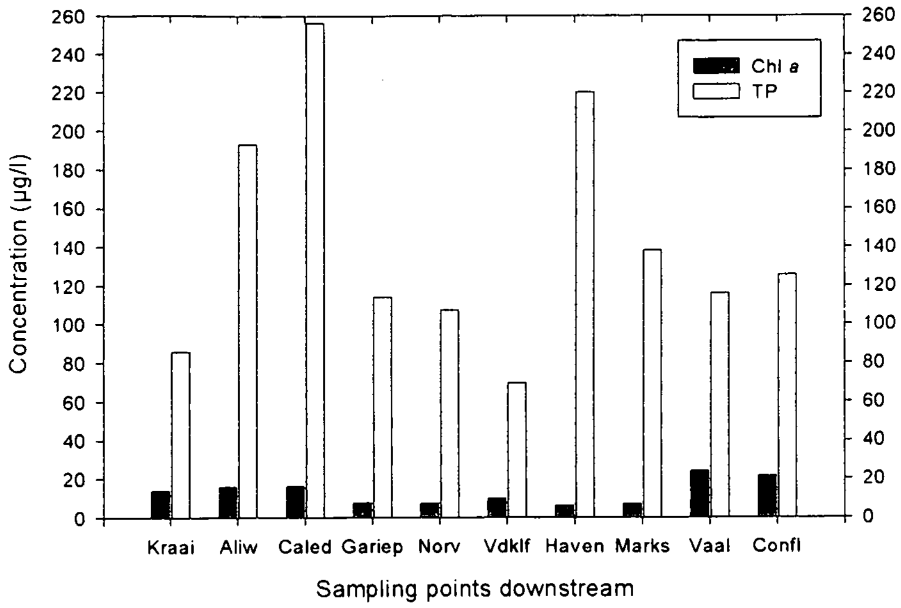


Figure 64. Average chlorophyll a and total phosphorus concentrations at the different sampling points in the Orange River system during the study period

6.3.4.3 Silicon-silica (SiO_2-Si)

The average silica concentration was 14.7 mg.l^{-1}. A significant inverse trend was found between the chlorophyll *a* and the silica concentrations (Figure 65).

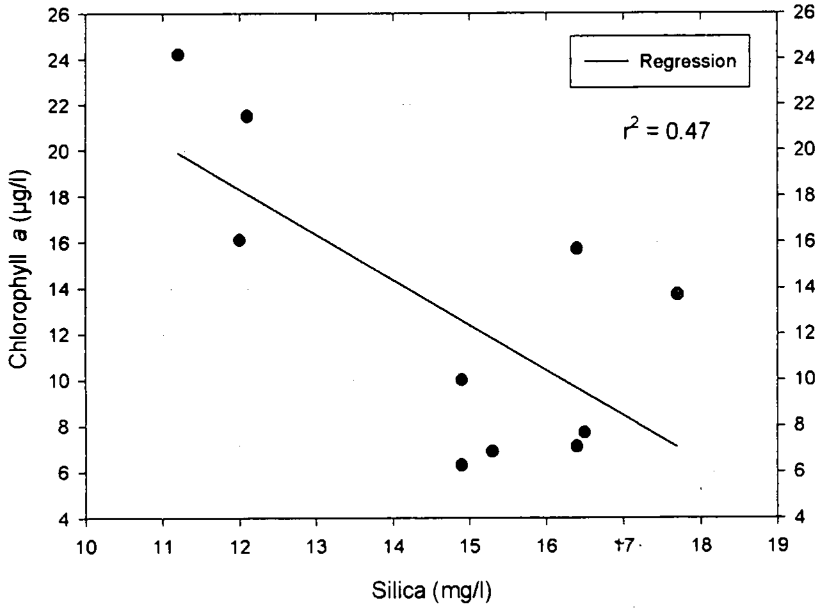


Figure 65. The relationship between chlorophyll *a* and silica based on the average concentrations for each sampling point

However, a statistically significant correlation was not found between the chlorophyll *a* concentration, the silica concentration and the occurrence of diatom blooms (Figure 66) in the greater part of the Upper Orange River. This suggests that other factors (e.g. nitrogen and phosphorus) might influence the algal composition in the Upper Orange River. In the Vaal River and the Orange River below the confluence, a correlation was found between high chlorophyll *a* concentrations, low silica concentrations and high diatom assemblages. This corresponds with observations for the Vaal River and other systems (Kilham, 1971; Descy *et al.*, 1987 and Roos & Pieterse, 1996).

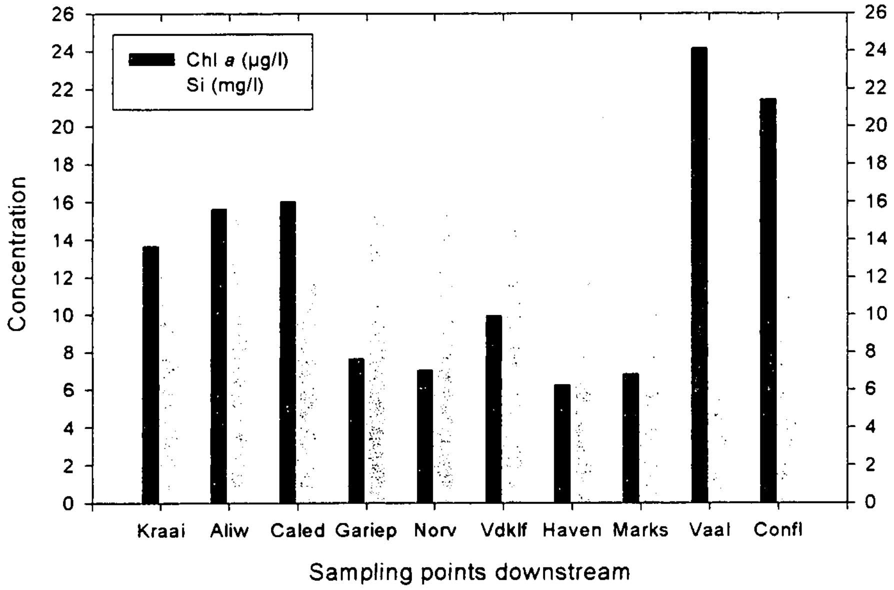


Figure 66. The average chlorophyll *a* (µg/l) and silica (mg/l) concentrations at the different sampling points in the Orange River during the study period

6.4 PRIMARY PRODUCTION

Tilzer (1986) described primary production as the production by autotrophic organisms that transform inorganic carbon and nutrient salts into living matter. The primary production process by photo-autotrophic organisms is a two step chain of reactions. The first step is photosynthesis that can be defined as the formation of carbon skeletons for the body substance (essentially carbohydrates) from inorganic precursors by utilizing radiant energy:

$$n\ CO_2 + 2n\ H_2O \longrightarrow n\ (CH_2O) + n\ O_2 + n\ H_2O$$

The process of photosynthesis can be subdivided into two sets of reactions. The light reactions provide the cells with energy (as energy-rich ATP) and reductant ($NADPH_2$). The electrons originate from the cleavage of water molecules and oxygen is released. In the dark reaction CO_2 is bound to an organic acceptor molecule (ribulose diphosphate). In a complex set of cyclic reactions (Calvin Cycle) carbohydrates are synthesized and ribulose diphosphate is regenerated. The dark reactions utilize both energy (ATP) and reductant ($NADPH_2$) which were formed by the light reactions (Tilzer, 1986).

The second step of the primary production process is biosynthesis: The carbon skeletons originating from photosynthesis serve as building-blocks for the formation of all the cellular components, which include proteins, nucleotides and lipids, beside carbohydrates. The required energy is drawn either from ATP originating from photosynthesis (photophosphorylation) or from the combustion (respiration) of some of the carbohydrates originally formed by photosynthesis (oxidative phosphorylation).

Lamberti and Steinman (1997) defined primary production as the conversion of solar energy to reduced chemical energy, or specifically as the amount of organic matter formed from inorganic carbon by photosynthetic organisms during a specified time interval. The total amount of carbon fixed during the interval is the gross primary production (GPP). Because plants also respire to drive their cellular metabolism, some of this fixed energy is lost as CO_2; this process is termed autotrophic respiration (R_A). The remaining fixed carbon allocated to biomass represents the net primary production (NPP). Therefore,

$$\mathrm{GPP} = \mathrm{NPP} + R_A$$

However, various authors were critical of the use of the term "primary production" in aquatic ecology. Flynn (1988) stressed that the term "CO_2-fixation" is more accurate, concise and descriptive. Talling (1984) also suggested that $^{14}CO_2$-fixation rates give an estimate of photosynthesis, not production. For the purpose of this study the term "primary production" will be used due to the abundant use thereof in literature.

6.4.1 RESULTS AND DISCUSSIONS

Plots of photosynthetic rates versus depth revealed the responses of phytoplankton to various light intensities. The variation in chlorophyll-specific photosynthetic rate with depth, in the Gariep Dam (19/02/99) is illustrated in Figure 67. The measurements were done during a bloom of *Microcystis*, but primary production studies were done at the damwall and not in the bloom patches.

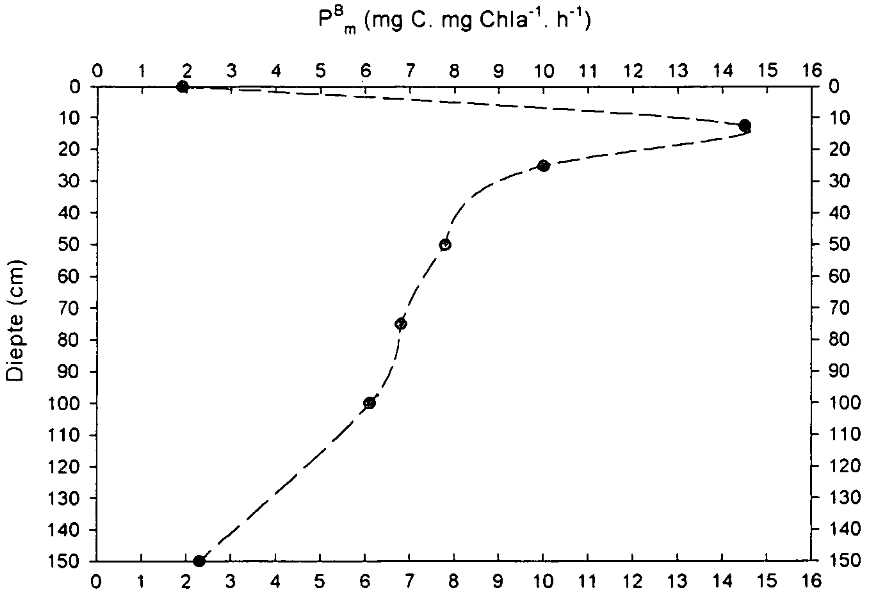


Figure 67. Variation in chlorophyll-specific photosynthetic rate (mg C. mg Chla^{-1}. h^{-1}) with depth (m), in the Gariep Dam (19/02/99)

Photoinhibition occurred at the surface. A noticeable increase in production could be seen at a depth of 12.5 cm (14.6 mg C. mg Chla^{-1}. h^{-1}), whereafter the production slowly decreased. Algal production at 150 cm was only 2.2 mg C. mg Chla^{-1}. h^{-1}.

The relationship between depth and underwater light intensity in the Gariep Dam is shown in Figure 68. The reduction of light in the water-column can be expressed in terms of the (vertical) extinction coefficient k (also called attenuation coefficient):

$$I_Z = I_O e^{-kZ}$$

or $$k = (\ln I_O - \ln I_Z) \div z$$

where:

k = extinction coefficient (m^{-1})

I_O = subsurface (or incoming) light intensity (μE.m^{-2}.s^{-1})

I_Z = light intensity at depth z (μE.m^{-2}.s^{-1})

z = depth (m)

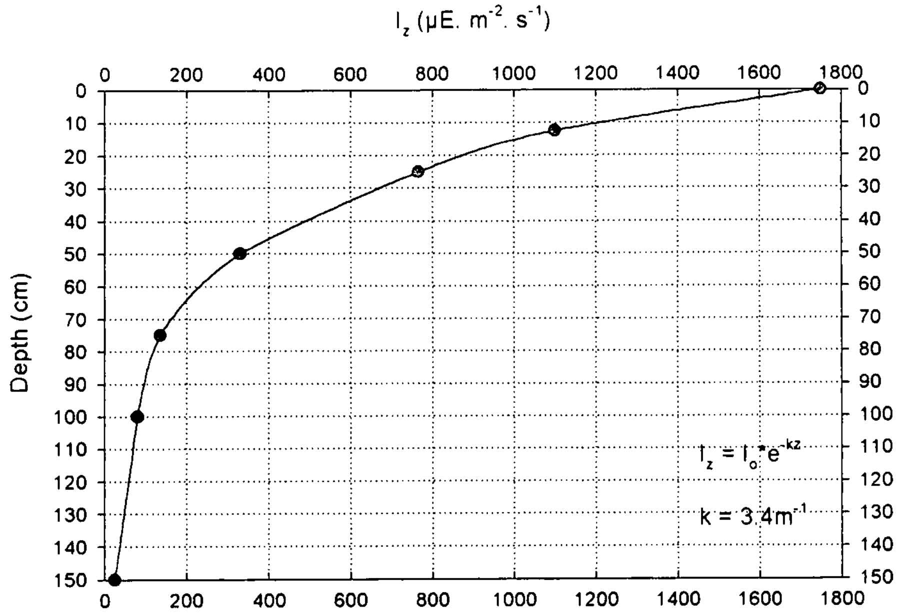


Figure 68. The relationship between depth and underwater light intensity (I_z) in the Gariep Dam (19/02/99)

Stegmann (1975) conducted his primary production studies shortly after the completion of the Gariep Dam and he hypothesized that the nutrient status of the Gariep Dam does not appear to be the limiting factor as far as phytoplanktonic growth is concerned. The limited euphotic zone, which is caused by the turbid water, would rather limit large algal populations. Thus, Stegmann (1975) found low primary production values (average 2 mg C. mg $Chla^{-1}$. h^{-1}) for the Gariep Dam during his study. However, over the years light penetration in the water column improved and the euphotic zone in the Gariep Dam during this study was at a depth of 160 cm and the attenuation coefficient for the Gariep Dam was 3.4 m^{-1}. Thus, light appeared to have a major influence on the algal production in the Gariep Dam during the study.

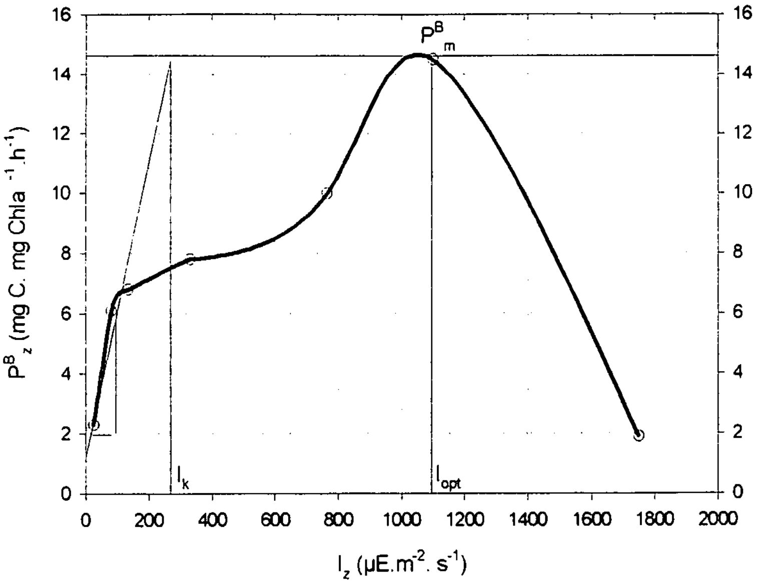


Figure 69. Relationship between photosynthesis per unit chlorophyll *a* (P^B_z) and underwater light intensity (I_z), in the Gariep Dam for 19/02/99.

The relationship between chlorophyll-specific photosynthetic rate (P^B) and underwater light intensity (I), i.e. the P *vs.* I curve, in the Gariep Dam for 19 February 1999 is illustrated in Figure 69. The maximum specific photosynthetic rate (P^B_m) was 14.5 mg C. mg Chla^{-1}.h^{-1}. The light intensity at maximum photosynthesis (I_{opt}) was 1 100 µE.m^{-2}.s^{-1} and the irradiance at onset of light saturation (I_k) was at a light intensity of 279 µE.m^{-2}.s^{-1}. The photosynthetic efficiency (slope of P *vs* I curve) was relatively high at 5 units.

In the Vaal River (28/04/99) the variation in chlorophyll-specific photosynthetic rate with depth is illustrated in Figure 70. The Vaal River followed the expected primary production curve for slow flowing water bodies. This coincides with the production that was found for the Vaal River during 1987 to 1989 (Roos, 1991). The low production values at the surface (23 mg C. mg Chla^{-1}. h^{-1}) were probably due to photo-inhibition. At 50 cm an increase in production was observed (76 mg C. mg Chla^{-1}. h^{-1}). At 75 cm the production began to decrease due to light

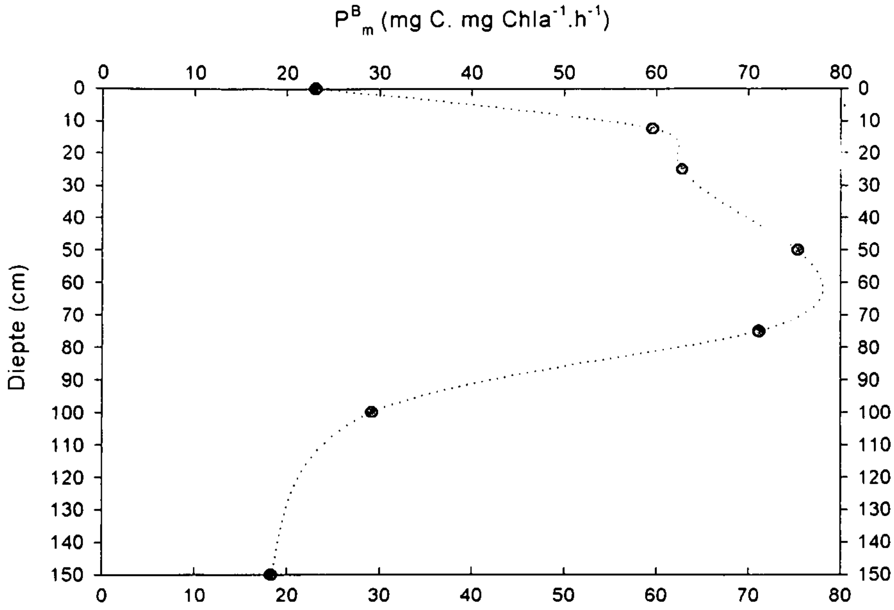


Figure 70. Variation in chlorophyll-specific photosynthetic rate (mg C. mg Chla^{-1}. h^{-1}) with depth (m), in the Vaal River (28/04/99)

limitation, as can be seen in Figure 71. Algal production at 150 cm was 18 mg C. mg Chla^{-1}. h^{-1}. The Vaal River has an attenuation coefficient of 2.6 m^{-1} and the depth of the euphotic zone was 170 cm during the study period.

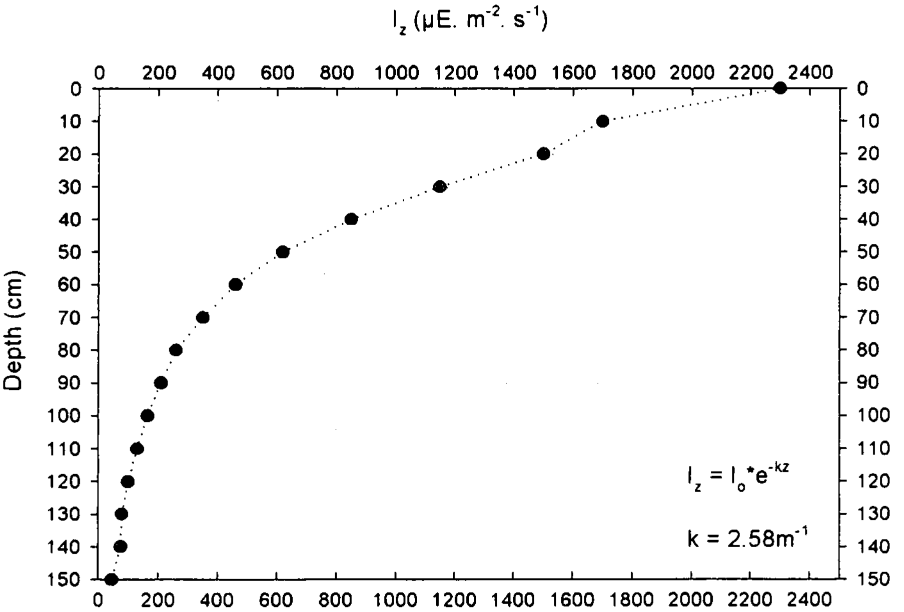


Figure 71. The relationship between depth and underwater light intensity (I_z) in the Vaal River (28/04/99)

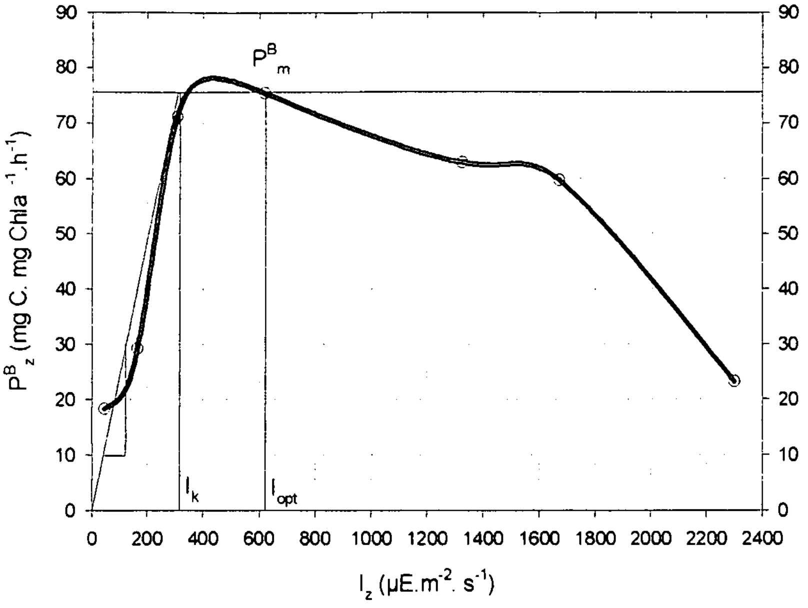


Figure 72. Relationship between photosynthesis per unit chlorophyll *a*(P^B_z) and underwater light intensity (I_z), in the Vaal River for 28/04/99

The relationship between chlorophyll-specific photosynthetic rate (P^B) and underwater light intensity (I), i.e. the P *vs.* I curve, in the Vaal River for 28 April 1999 is illustrated in Figure 72. The maximum specific photosynthetic rate ($P^B{}_m$) was 75.4 mg C. mg Chla^{-1}.h^{-1}. The light intensity at maximum photosynthesis (I_{opt}) was 620 µE.m^{-2}.s^{-1} and the irradiance at onset of light saturation (I_k) was at a light intensity of 324 µE.m^{-2}.s^{-1}. The photosynthetic efficiency (slope of P *vs* I curve) was 4.3 units.

6.5 GROWTH CHARACTERISTICS OF PHYTOPLANKTON IN THE UPPER ORANGE RIVER

According to Thompson & Hosja (1996) a number of factors influence phytoplankton growth rate, biomass and species composition. The most important factors will be briefly discussed in this section.

6.5.1 Light

Solar radiation is of fundamental importance to the entire dynamics of freshwater ecosystems (Wetzel, 1975). Growth of algae and photosynthetic rates are directly related to quantitative light intensity. Response to light intensity, however, is variable among species and in many a considerable degree of adaptation to changing light intensities occurs (Walsby, 1992). Adaptation to higher or lower light intensity occurs mainly by changing the amount of pigment per cell. Cells adapted to high light intensity have a lower chlorophyll *a* content per cell than those adapted to low light intensities (Wetzel, 1983).

According to Imboden (1992) some of his colleagues pioneered the analysis of how growth rate responds to irradiance. Their results showed that the greatest increases in growth rate for a given increase in light uptake rate, was achieved by the green algae *Scenedesmus*. At relatively high irradiance this organism would grow faster than the cyanobacteria *Oscillatoria* and *Aphanizomenon*. At low irradiance, however, the cyanobacteria grew faster. The reason for this seems to be that they have a lower maintenance energy requirement.

Underwater light attenuation in turbid systems is largely a function of suspended particle concentration and size (Dokulil, 1994). The Orange River is a relatively turbid system and, thus, has restricted light penetration and availability. Selkirk (1982) did a study in the Vanderkloof Dam and the factors that limit algal growth. The turbid Vanderkloof Dam receives most of its inflow from the Gariep Dam. At least part of the year this water is probably hypolimnetic and rich in both nutrients and silt (Selkirk, 1982). In the Vanderkloof Dam, with an epilimnetic depth of 25 m and a euphotic depth of about 1 m, the relative proportion of euphotic (Z_{eu}) to mixed depth (Z_{mix}) is 1/25 or 0.04. Roos (1991) found that at a Z_{eu}:Z_{mix} of less than 0,02 very little primary production can take place because the rate of carbon assimilation is lower than the rate of carbon used. Assuming full circulation within the mixed depth of the epilimnion, the effect of this low value causes algal cells to receive only comparatively short periods of exposure to photosynthetically active radiation before passing below the compensation depth. Selkirk (1982) concluded that rapid attenuation in light was due to suspended solids, the primary cause of algal growth limitation in the Vanderkloof Dam. Probably the same attenuation effect of light might also be true for the Gariep Dam. However, there are certain cyanobacteria that can overcome this light limitation. The success of these organisms is ascribed to their gas vacuoles, which enable them to perform vertical migration or to maintain themselves in the euphotic zone in calm periods (Walsby, 1992).

6.5.2 Temperature

The ecological effects of light and temperature on the photosynthesis and growth of algae are inseparable because most light entering water is converted to heat. As water reaches its maximum density at 4 °C, temperature is the key factor in thermal stratification. Greater algal respiration often occurs in shallow water due to higher water temperatures compared to deeper and cooler water systems (Dokulil, 1994). Hynes (1970) noted that many stream algae have been driven by evolutionary circumstances to operate at temperatures well below their optimum, because of the effect of shading in running waters.

In the Upper Orange River system the temperature regime is greatly influenced by the dams. Pitchford and Visser (1975) found an increase in the winter temperature (±2 °C) and a decrease in the summer temperatures (±3 °C) below the Gariep Dam. The same temperature fluctuations seem to be true for the Vanderkloof Dam. This could also be seen at Norvalspont below the Gariep Dam during this study, where the average temperature was 2.7 °C cooler than in the dam.

6.5.3 Flow

The fundamental physical and biotic processes of rivers, river impoundments, and lakes are the same. These processes may differ in magnitude and relative importance among system types as a result of dissimilarities in horizontal water movements (Søballe & Kimmel, 1987). A major factor that influences algal growth in rivers, is the persistent and unidirectional passage of water (Hynes, 1970). Water movement is important in the physical movement of algae into or out of the photic zone. Water movement is also critical in the vertical transport of nutrients from lower depths and littoral regions to open water.

Søballe and Kimmel (1987) found that rapid water renewal had significant and similar negative impacts on both the abundance and predictability of suspended algae in all system types. Water residence time should be a useful predictor of similarities and differences among aquatic ecosystems. Horizontal water movement controls the time available for attached or suspended biota to interact with transported materials, and in addition, a number of factors important to aquatic ecosystem function are related to water movement (e.g., abrasion, resuspension, turbulence, diffusion, dilution, spatial and temporal variability, turbidity and nutrient supply) (Søballe & Kimmel, 1987).

The nett negative influence of rapid water renewal on algal abundance can be attributed to several major factors. It is well documented that increased water residence time leads generally to higher algal abundance in systems constrained by temporal, rather than nutrient limitations on algal colonization, growth and reproduction (Søballe & Kimmel, 1987).

Steinberg and Hartmann (1988) found the following: a) when the turbulence of the water column is rather low, as it is in sheltered or meromictic lakes, cyanobacteria can build up dense populations, b) if the turbulence of the water column is high (mixing depth much greater than the euphotic depth) or the mixing pattern is irregular, as in slow flowing or regulated rivers (e.g., the Orange River) cyanobacteria are out-competed, c) in the presence of frequent or permanent turbulence, but with mixing depths lower or not much greater than the euphotic zone (as it is the case in shallow unstratified lakes) cyanobacteria can outgrow normally dominant algal species under conditions of low N:P ratios, high water temperatures, pH > 9 or low light availability.

Roos and Pieterse (1996) observed that the numerous weirs in the middle Vaal River decrease the flow velocity and increase the residence time, which counteracts the dilution of phytoplankton and permits the building up of high phytoplankton concentrations. The same is true for the Upper Orange River, where the Gariep and Vanderkloof Dams decrease the flow velocity. The water that is released on a daily basis via the turbines for hydro-electric power generation, as well as to meet irrigation demands, changed the Orange River into a highly regulated system. Seasonal flow patterns below the dams are almost completely diminished (Figures 14 and 15) and the dams also interfere with the so called "flushing-flows" which act as environmental cues for various aquatic organisms, as well as maintaining river form and sediment sorting.

6.5.4 Nutrients

Rhee & Gotham, (1980) reported that there is no multiple nutrient limitation for phytoplankton growth. Growth is regulated by the single nutrient in shortest supply (Droop, 1974 and Smith, 1982), confirming Liebig's "law of the minimum". A simple paraphrase by Hutchinson (1973) stated that yield of any organism will be determined by the abundance of the substance that is the least abundant in the environment in relation to the needs of the organism. These findings suggest that species-specific optimum nutrient ratios may be a basis for exclusion or coexistence of competing species.

The optimum nutrient ratio is the ratio at which a transition from one nutrient limitation to another takes place. Interspecies differences in this ratio may determine the degree, as well as the kind of nutrient limitation (Rhee & Gotham, 1980). In principle, the concentration of a limiting nutrient can be estimated from the Redfield ratio (106C : 16N : 1P) for the key nutrients. For example, if the optimum N:P ratios for species A and B are 20 and 30 respectively, both species will be phosphorus (P) limited when the ratio is greater than 30 and nitrogen (N) limited when the ratio is less than 20. However, species A are more P limited than species B and species B is more N limited than species A. This means that when N:P > 30, species B will competitively eliminates species A. At N:P ratios between 20 and 30 both species will coexist. Rhee and Gotham (1980) found that the N:P ratios are species specific and ranged from 7 in *Melosira binderana* to 30 in *Scenedesmus obliquus*. The ratio appears to be generally high in green algae and low in diatoms. A low N:P ratio can be expected for blue-green algae, since they are associated with enriched waters (Steinberg & Hartmann, 1988 and Watson *et al.*, 1997). Heterocystous N_2-fixing species are favoured (e.g., *Aphanizomenon* and *Anabaena*), when the inorganic nitrogen content is almost completely exhausted, whereas only poor nitrogen-fixing cyanobacteria (*Microcystis*) or non-nitrogen-fixing cyanobacteria (e.g., *Oscillatoria*) thrive in lakes with high allochtonous loadings of nitrogen (Steinberg & Hartmann , 1988).

The average TN:TP ratio for the Upper Orange River system was 15.4. Downing and McCauley (1992) reported that TN:TP is high in oligotrophic lakes and very low in eutrophic lakes. Toerien and Steyn (1975) suggested that the Orange River and the Vanderkloof Dam are N limited on the basis of bioassays and it is therefore not unreasonable to extent this hypothesis to the Gariep Dam. However, Selkirk (1982) regarded light as the limiting factor in the Vanderkloof Dam, and only should there be an increase in water transparency, could nutrients be possibly limiting.

In contrast, Hecky and Kilham (1988) stated that a current dogma of aquatic science is that marine and estuarine plankton tends to be nitrogen limited, while freshwater phytoplankton tends to be phosphorus limited. Findings by Thompson and Hosja (1996) support this theory in that low nitrogen concentrations limited phytoplankton biomass in the Upper Swan River Estuary (Western Australia). Pieterse and Toerien (1978), demonstrated a positive correlation between chlorophyll *a* and PO_4-P concentrations in the Roodeplaat Dam, further supporting this theory. In the late seventies, phosphorus control was recommended as the legislated basis for controlling eutrophication in North American and European inland waters (Hecky & Kilham, 1988). In South Africa, the universal 1 mg P l^{-1} standard for effluents in sensitive catchments was legislated in 1985 (Grobbelaar, 1992).

Although N and P are the key nutrients for most algae, the availability of a third nutrient may limit the growth of particular species e.g. the availability of silica to diatoms can be their primary limiting factor. Kilham (1971) observed that when silica become depleted, diatoms become scarce and are ultimately replaced by algae not requiring silica. However, silica does not seem to be the limiting factor controlling diatom assemblages in the Upper Orange River. In running water the change in silica concentration is also due to diatom activity. Wang and Evans (1970) found that, in the Illinois River, the dissolved silica concentration was lower downstream than upstream. They ascribed it to absorbtion by diatoms and diatom settling to the river bottom. However, Hynes (1970) predicted that it is unlikely that silica (SiO_2-Si) will ever be a limiting factor in running waters, as most rocks and soils contain silicates. It was noted by Kilham (1971) that attempts to correlate water chemistry (more specific SiO_2-Si) with particular diatom species in eutrophic lacustrine environments have produces puzzling and often contradictory conclusions. However, the residence time of an impoundment should be taken into consideration here: the longer the residence time, the more silica and diatoms will settle out to the bottom.

Except for the above-mentioned nutrients, there are still numerous other nutrients, trace metals and vitamins that interact with the algae (see Wetzel, 1975) and that all should be taken into account. It is clear that algal growth is a function of a combination of different, interacting factors. In this study, the seasonal as well as spatial variations in algal growth were determined, taking the numerous factors that could possibly influenced it, into account.

6.6 TROPHIC STATUS OF THE UPPER ORANGE RIVER AND TRIBUTARIES

The limitations and shortcomings of the classical trophic classification along the oligotrophic – eutrophic series is well known and not yet solved. The terms oligotrophic, mesotrophic and eutrophic are still used without a definite and universally acceptable scale of references (Vollenweider *et al.*, 1974). The terms oligotrophy and eutrophy were introduced in limnology's founding years to distinguish the classical differences between deep, clear, Caledonian types of mountain lakes and the shallow, productive Baltic type of lowland lakes (Thienemann, 1918 and Reynolds, 1998). Guidelines for judging the trophic status of inland water are given in Table 8.

Table 8. Guidelines for judging the trophic status of inland water. (Modified from: Chapman (1996); DWAF (1996); National Eutrophication Survey*^{2} (1974); Walmsley*^{1} (1984) and Wetzel*^{3} (1983).

	Ultra-oligotr.	**Oligotrophic**	**Mesotrophic**	**Eutrophic**	**Hypertrophic**
Annual mean chl a (µg/l) *^{1}		< 3.5	3.5 – 14	> 14	
Annual mean chl a (µg/l) *^{2}		< 7	7 – 12	> 12	
Annual mean chl *a* (µg/l) *^{3}	<1	1 – 5	5 – 15	15 – 75	>75
Prim.Prod. (mg C/m^2/d)	<30	30 – 100	100 – 300	300 – 3000	>3000
Mean TP (µg/l)	<5	5 – 20	20 – 100	100 – 500	>500

The values used, to determine the trophic status, imply that oligotrophic impoundments should experience no algal problems, mesotrophic impoundments should experience a certain degree of algal problems, while eutrophic impoundments should experience extreme algal problems.

Rodhe (1969) has related his terminology to different ranges of annual production. Rodhe restricted his usage of the term "oligotroph" to lakes having an annual production up to 25 gC.m^{-2} per year. Lakes having an annual production of more than 300 gC.m^{-2} per year was considered polluted, with a considerable range of values depicting the mesotrophic state.

Reynolds (1998) investigated concepts relating to the selection of phytoplankton along trophic gradients. After an international workshop, Reynolds found that phycologists have little difficulty in distinguishing what they classify intuitively as "oligotrophic species", "eutrophic indicators" or "mesotrophic assemblages". The data used by Reynolds (1998) is summarised in Table 9.

6.6.1 RESULTS AND DISCUSSIONS

The classification of the Orange River and tributaries on the average chlorophyll *a* concentrations, primary production and mean TP concentrations during the study period are given in Table 10.

According to the chlorophyll *a* concentrations in the guidelines for judging the trophic status of inland water (Table 8) the Orange River, with the exception of the Gariep Dam during bloom periods and the Orange River below the confluence with the eutrified Vaal River, can be classified as mainly mesotrophic. The primary production in the Gariep Dam indicated mesotrophic conditions, while those of the Vaal River indicated eutrophic conditions. The TP concentrations in the Orange River system were relatively high, with the exception of the Kraai River and the Vanderkloof Dam, and indicated eutrophic conditions.

Table 9. A trophic spectrum of major genera of phytoplankton (modified from Reynolds, 1998)

TROPHIC STATUS	ULTRAOLIGOTROPHIC ……………………MESOTROPHIC…………………………………HYPER-EUTROPHIC
Nutrient supply	Strongly deficient ………………………………………………adequate………………………………………saturating
Alkalinity	Acid………………………………………………………………………………………alkaline……………calcareous
Clarity	Clear………turbid
Diatoms	*C. glomerata / C. comensis* ......*C. meneghiniana*......*S. minutulus*...*S. neoastraea*....*S. rotula*...*S. hantzschii* .....*Urosolenia*...... .....*Tabellaria* ....*Asterionella* ....*Fragilaria* ....*Diatoma* ....*Aulacoseira distans* ......*A. subartica* .... *A.ambigua* ...... *A. granulata* ....*Melosira varians* ....
Chlorophytes	..................................*Chlorella spp*... ....*Chlamydomonas*... ....*Scenedesmus*............................. *Gonium*.....*Eudorina*.....*Pandorina* ....*Coelastrum. Pediastrum* .....*Sphaerocystis, Gemellicystis*.......... ..*Staurodesmus*.........*Cosmarium*........*Staurastrum*...........*Closterium*......
Cyanobacteria	..*Merismopedia*.......*Gloeotrichia*.....*Coelosphaerium*.........*Planktothrix*......*Limnothrix/Pseudanabaena*. ..*A.solitaria*.................*Gomphosphaeria*.........................*Microcystis*....... ...*A. lemmermanni*.................*A.flos-aquae/A.circinalis*.......... .....*Aphanizomenon*......
Dinoflagellates	..............................*Peridinium, Ceratium*.................
Cryptophytes	..............................*Rhodomonas*...............*Cryptomonas*......................................
Chrysophyceae	*Dinobryon*... *Uroglena*........ *Mallomonas*............... *Synura*...... *Chrysosphaerella*...
Euglenoids	... *Euglena* ... ... *Phacus* ... ... *Lepocinclis* ...

Table 10. Classification of the Orange River and tributaries based on average annual chlorophyll *a* concentrations ($\mu g.l^{-1}$), primary production ($mg\ C.m^{-2}.d^{-1}$) and the mean TP concentrations ($\mu g.l^{-1}$).

Sampling point	**Chl *a***	**Prim.Prod**	**TP**
Kraai River	15.7		85.8
Aliwal North(OR)	13.7		193.3
Caledon River	16.1		256.4
Gariep Dam	125*	169	114
Norvalspont (OR)	7.1		107.5
Vanderkloof Dam	10		69.8
Havenga Bridge (OR)	6.3		220.2
Marksdrift (OR)	6.9		138
Vaal River	24.2	1164.3	116
After Confluence	21.5		125.5

* high average chlorophyll *a* concentration due to the February 1999 algal bloom.

The trophic spectrum of Reynolds (1998) was used to determine the selection of phytoplankton along the trophic gradients in the Orange River and tributaries. The genera of phytoplankton that was found is given in Table 11 a, b and c.

Table 11 a. The genera of phytoplankton that were found in the Kraai River, the Orange River at Aliwal North and in the Caledon River.

Kraai	**Aliwal (OR)**	**Caledon**
Anabaena	*Cyclotella*	*Anabaena*
Chlorella	*Chlorella*	*Cyclotella*
Coelastrum	*Scenedesmus*	*Melosira*
Scenedesmus	*Euglena*	*Chlamydomonas*
		Chlorella
		Closterium
		Lepocinclis

Table 11 b. The genera of phytoplankton that were found in the Gariep Dam, in the Orange River at Norvalspont, in the Vanderkloof Dam and in the Orange River at Havenga Bridge.

Gariep	**Norvals**	**Vanderkloof**	**Havenga**
Anabaena	*Anabaena*	*Anabaena*	*Cyclotella*
Microcystis	*Cyclotella*	*Merismopedia*	*Melosira*
Cyclotella	*Melosira*	*Microcystis*	*Chlamydomonas*
Melosira	*Chlamydomonas*	*Cyclotella*	*Chlorella*
Chlamydomonas	*Chlorella*	*Melosira*	
Chlorella	*Coelastrum*	*Chlamydomonas*	
Coelastrum	*Scenedesmus*	*Chlorella*	
Eudorina			

Table 11 c. The genera of phytoplankton that were found in the Orange River at Marksdrift, in the Vaal River and in the Orange River after the Orange-Vaal confluence.

Marksdrift	**Vaal**	**Confluence**
Anabaena	*Anabaena*	*Cyclotella*
Cyclotella	*Merismopedia*	*Melosira*
Melosira	*Cyclotella*	*Chlamydomonas*
Chlamydomonas	*Melosira*	*Chlorella*
Chlorella	*Chlamydomonas*	*Closterium*
Pediastrum	*Chlorella*	*Scenedesmus*
Scenedesmus	*Coelastrum*	*Lepocinclis*
	Pandorina	
	Pediastrum	
	Scenedesmus	
	Lepocinclis	

Coelastrum, *Eudorina* and *Merismopedia* indicate oligotrophic water conditions. *Chlamydomonas*, *Melosira* and *Scenedesmus* indicate oligotrophic to mesotrophic water conditions. *Pandorina* and *Pediastrum* indicate mesotrophic conditions, while *Closterium* and *Microcystis* indicate mesotrophic to eutrophic conditions. *Euglena* and *Lepocinclis* indicate hyper-eutrophic conditions. *Anabaena*, *Chlorella* and *Cyclotella* are found throughout the trophic spectrum (oligotrophic to eutrophic).

Although the trophic status for the Orange River and tributaries differ with the different classification methods that were used, there are some similarities. The Orange River can broadly be classified as a mesotrophic system. However, the Vaal River is classified as eutrophic and that has a negative influence on the trophic status of the Orange River below the confluence.

6.7 CONCLUSION

The average chlorophyll *a* concentration for the Upper Orange River was 10.8 $\mu g.l^{-1}$, while the average concentrations for the tributaries ranged between 13.7 and 24.2 $\mu g.l^{-1}$. Algal blooms were occasionally experienced in the dams and the chlorophyll *a* concentration during one such bloom in the Gariep Dam reached up to 1 084 $\mu g.l^{-1}$. This high chlorophyll *a* concentrations gave an indication that eutrophic- to hypertrophic conditions sometimes prevailed in the Gariep Dam.

Four algal families were represented in the Upper Orange River and tributaries during the study period, namely cyanobacteria, Bacillariophyceae, Chlorophyceae and Euglenophyceae. Cyanobacteria and Bacillariophyceae dominated in the system during warmer months and Chlorophyceae replaced the cyanobacteria during cooler months. The algal species composition at each sampling site also varied greatly, with the greatest diversity and richness of species occurring in the Vaal River, indicating eutrophication.

Light penetration in the Gariep Dam and the Vaal River had a major effect on the primary production of algae during this study. High flow resulted in high turbidity, which limited the light penetration in the water column. The attenuation coefficient for the Gariep Dam was 3.4 m^{-1}, while those for the Vaal River was 2.6 m^{-1}. The maximum primary production in the Gariep Dam was 14.6 mg C. mg $Chla^{-1}$. h^{-1} at a depth of 12.5 cm. In the Vaal River the maximum primary production was 76 mg C. mg $Chla^{-1}$. h^{-1} at a depth of 50 cm. According to the primary production in the Gariep Dam it can be classified as mesotrophic, while the high primary production in the Vaal River indicated eutrophic conditions.

Algal growth in the Upper Orange River is strongly influence by turbidity on occasions of high flow. The relatively high total phosphorus (TP) concentrations in the Upper-Orange River indicated mainly eutrophic conditions. During periods of sufficient light penetration, relatively stable water columns and warm temperatures nutrients became the limiting factor in the Orange River, especially in the dams. The N:P ratios and the silica concentrations strongly influenced the algal species composition. According to the algal composition the Upper Orange River could broadly be classified as a mesotrophic water ecosystem, which is influenced negatively by the confluence with the eutrophied Vaal River.

6.8 BIOMONITORING

6.8.1 Introduction

It has long been known that some components of the aquatic flora and fauna of streams and rivers respond in a predictable fashion to changes in the physical and chemical nature of water (Chutter, 1998a). Biological monitoring or biomonitoring techniques can be used to assess the overall soundness of, and quantify the impacts on, aquatic ecosystems.

Two premises underpin SASS (Davies & Day, 1998). The first is that some invertebrate taxa are much more sensitive to chemical pollutants than others. The assemblage of families of invertebrates present at a site in a natural river, at any particular time, may include some families that are fairly sensitive to, and some that are fairly tolerant of, pollution. The second premise is that the invertebrate faunal assemblage at any site, at any time, is dependent not only on the water quality at the time of sampling, but also on the conditions that have pertained at that site over the entire life span of the assemblage. This is particularly true for the more sedentary forms, since mobile ones are able to move away and then later to recolonise a site from further upstream as soon as conditions are suitable (Chutter, 1998b).

The SASS score sheet has a long list of invertebrate families, with a number between 1 and 15 opposite each name. These numbers have been allocated to each family according to its perceived sensitivity to water quality change, the most tolerant families being scored 1 and the most sensitive 15. The SASS score is the sum of the numbers against each taxon present and the Average Score Per Taxon (ASPT) is the SASS score divided by the number of taxa found. The less altered the water quality, the higher the SASS score and the ASPT.

Various factors play major roles in the scores recorded (Chutter, 1998b). Available habitats at the sampling points are an example of one such factor. Aquatic invertebrates are specialised in their habitat requirements, so that some families are present only on stones in the current, others only on stones out of the current, others only in marginal vegetation and so forth. The absence of certain biotopes (habitats) can have a major impact on the SASS4 score measured, but has a much lesser impact on the ASPT.

6.8.2 MATERIALS AND METHODS

The field procedures of the SASS4 method mimic the BMWP (Biological Monitoring Working Party) method on which it is based. Invertebrates were collected using a standardised sampling net, following methods as defined on the SASS4 field record sheet under procedure protocols (see Appendix 2). The content of this sampling net was then poured over into another net of a 1000 micron mesh, while twigs and leaves were removed. The contents were placed finally in a large tray with clean water. The invertebrates were identified and the data was recorded on a score sheet.

The score sheet consists of space to record when and where the sample was collected, a long list of invertebrate groups, mainly at the family level, and a number between 1 and 15 opposite each name, as previously explained. These score sheets were completed for each biomonitoring site. The categories used to classify habitats, SASS4 and ASPT values are given in Table 12.

Table 12. Categories used to classify habitat, SASS4 and ASPT values (Taken from Thirion *et al.*, 1995)

HABITAT	SASS4	ASPT	CONDITION
> 100	>140	>7	Excellent
80-100	100-140	5-7	Good
60-80	60-100	3-5	Fair
40-60	30-60	2-3	Poor
<40	< 30	< 2	Very Poor

6.8.3 Sampling Sites

6.8.3.1 Kraai River (Near Aliwal North)

The water was not flowing at the time of sampling and only isolated pools were present. A list was made of the invertebrates present at the site, but SASS4 could not be conducted due to the flow cessation. The site has the potential for SASS4 sampling when the river is flowing.

6.8.3.2 The Orange River at Havenga Bridge

The water at this site was medium to fast flowing. White water cascades were sampled for the SIC (Stones in current) biotope. The stones were large and mostly unmovable which is not ideal for the SIC biotope. No marginal vegetation (MV) was present. Lots of algae were observed on the stones.

6.8.3.3 The Orange River at Norvalspont

SIC and MV were sampled. The flow in the river was slow and no white water was present.

6.8.3.4 The Orange River at Marksdrift

Only MV was sampled. SIC biotope was present but the river was to deep and fast flowing to sample the SIC biotope

6.8.3.5 Vaal River (Near Douglas)

The water at this site was flowing very slowly at the time of sampling and it was very polluted. Lots of bottles, plastic and other refuse occurred, scattered along the banks. The "stones out of current" (SOOÇ) biotope was sampled but the level of the water was very low.

6.8.4 RESULTS AND DISCUSSIONS

The state of the invertebrate community at specific sites in the Orange and Vaal River was determined using the SASS4 methodology. The scoring system usually depends on sampling all biotopes present. The scores obtained during this study were, however, only from SIC (stones in current) and MV (marginal vegetation) biotope at Norvalspont, SIC at Havenga Bridge and MV at Marksdrift. The SOOC (stones out of current) biotope was sampled at the Vaal River site, as the water was not flowing over the stones. As only some of the biotopes were sampled a very low SASS score might be expected according to Chutter (1995, 1998b). A summary of the SASS, ASPT, Habitat, Adjusted SASS and Integrated habitat assessment scores are shown it Table 13.

Table 13: Summary of SASS, Average score per taxa (ASPT), Adjusted SASS score and Integrated Habitat Assessment System (IHAS) collected at sites in Orange River and Vaal River.

Sites	**SASS**	**ASPT**	**No. of Taxa**	**Hab. Score**	**Adj. SASS**	**IHAS score**
Havenga	24	4.8	5	69	65	42
Norvals	35	3.5	10	86	70	53
Marksdrift	25	6.2	4	88	58	51
Vaal	14	4.6	3	61	64	26

It can be seen that the Vaal River site had the lowest SASS score and the site at Norvalspont had the highest SASS score (Figure 73). The comparison of the Habitat scores between sites indicates that Marksdrift has a slightly higher habitat score than Norvalspont (Figure 74).

A summary of the families found at the sites sampled is shown in Table 14. The most families present at a site were found at Norvalspont. Baetidae was present at all the sites sampled. The SASS scores obtained at the sites indicate a poor river condition. However, the ASPT and Habitat scores place the sites into a fair to good river condition (Table 12). This could be ascribed to the absence of biotopes during sampling and the low flow conditions at some of the sites.

Table 14: Summary of families found at sampling sites on Kraai River, Orange River and Vaal River. A= 1-10; B=10-100

Families	**Kraai**	**Norvals**	**Havenga**	**Marksdrift**	**Vaal**
Aeshnidae	**A**				
Ancylidae		**A**	**A**		
Baetidae	**A**	**A**	**A**	**B**	**A**
Chironomidae	**A**	**A**			**A**
Coenagriidae		**A**			
Dytiscidae	**A**				
Hirudinea		**A**			
Hydropsychidae		**A**	**B**		
Lymnaeidae		**B**			
Muscidae		**A**			
Planarians		**A**	**A**		
Planorbidae		**A**			
Polymitarcyidae	**A**				
Shrimps				**A**	**A**
Simuliidae			**B**		
Trichoptera case larvae				**A**	
Veliidae				**A**	

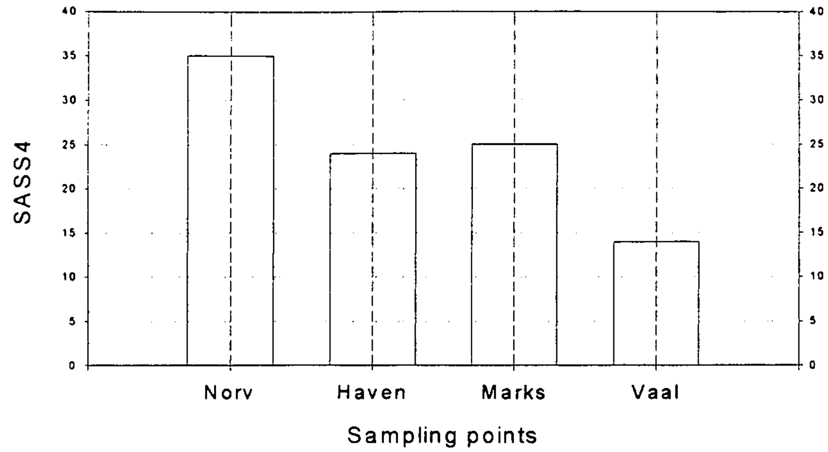


Figure 73. SASS4 scores for sites in the Orange River system on 21 - 22 October 1999

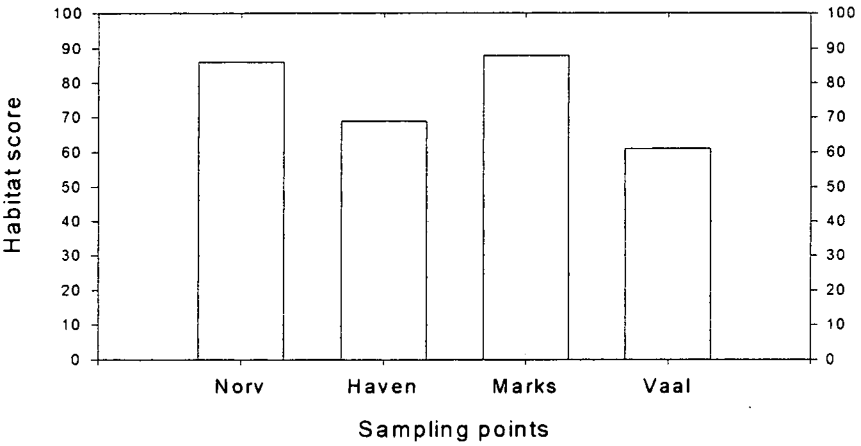


Figure 74. Habitat scores for sites in the Orange River system on 21 - 22 October 1999

The results (Table 13) show that the sample score (SASS) and number of taxa were the highest at Norvalspont. The Adjusted SASS score and IHAS (Integrated Habitat Assessment System) scores are both the highest at Norvalspont. The Adjusted SASS score, which is the original SASS score plus the adjustment made due to the lack of biotopes (habitats) present, is being tested at present (McMillan, 1998). The score indicates that if an ideal situation should occur where all the biotopes might be present, then the SASS score obtained would be equal to the

Adjusted SASS score. This would make it possible to compare various sites even though all biotopes were not present at all sites. The Adjusted SASS score indicates that Norvalspont has the highest score and this coincides with the original SASS score obtained (Table 13). The higher SASS score obtained at Norvalspont is because two biotopes were sampled where only one biotope was sampled at each of the other sites.

The high ASPT score calculated for Marksdrift indicates that more sensitive families such as shrimps and Trichoptera case larvae were present at Marksdrift than at the other sites (Table 13). The number of families present at this site is, however, lower than at the other sites in the Orange River.

The IHAS score is a habitat score, which is determined by the stream condition as well as the biotopes sampled, the sampling time and the presence or absence of algae. The IHAS score indicates that Norvalspont has a higher score than Marksdrift, which is in contrast with the habitat score obtained. This might also be ascribed in that two biotopes were sampled at Norvalspont and only one biotope was sampled at Marksdrift, which would produce a lower IHAS score, as the biotopes sampled have an influence on the IHAS score.

The low SASS score found during this study coincides to some degree with the SASS scores Chutter (1995) found during his sampling of the Orange and Vaal River. He attributed the low scores to the building of dams, which cause the trapping of silt and sand in the river channel.

In studies done by Wright *et al.* (1995) and Nalepa (1978), it was found that chironomids occurred at sites where organic pollution was present and that a decrease in the number of Trichoptera and Ephemeroptera families occurred at these sites. Large numbers of obese Hydropsychidae were found at Havenga Bridge. Chutter (1995) states that the abundance of species from this family found below dam outlets indicates that they have benefited from the impoundments. The Simuliidae family is also found in larger numbers in rivers where the flow is regulated (Palmer & O'Keeffe, 1990c and Chutter, 1995).

Chutter (1995 & 1998b) stated that the invertebrate fauna directly downstream of impoundments was noticeably depauperate, consisting of only a few species. Palmer and O'Keeffe (1990a,c) also found that the number of invertebrates immediately downstream of impoundments was generally less than upstream. They also found that conditions took between 25 to 86 km to recover to above-impoundment levels. The same trend was found during this study, but this could also be ascribed to the low flow conditions as well as the absence of biotopes sampled. Chutter (1998b) sampled the Orange River and Vaal River on other occasions and found that most of the worms, snails and crabs could survive the cessation of flow in a river providing there was standing water present in the river channel. However, the more specialised and mainly insect families could not survive these conditions.

6.8.5 CONCLUSION

Low SASS4 scores were obtained during sampling in the Upper-Orange River. It is, however, important to note that few conclusions can be drawn from a once-off sampling effort. The low scores indicate poor water quality in the Upper Orange River system. Chutter (1998a) also reported that the invertebrate community of the Orange River is poor in taxa. The author ascribed the poor water quality to excessive amounts of silt and sand in the river channel. Studies have shown that low

SASS4 scores could also be a result of absence of biotopes (habitats), low-flow conditions due to impoundments, seasonality, etc. The presence of hydropsychids as well as chironomids and simulids indicates that the sites are impaired, either due to organic pollution or regulation of flow. Trichoptera and Ephemeroptera families are, however, also present at some of the sites and this indicates that the water quality can be considered fair to good.

CHAPTER 7

RIVER ECOSYSTEMS

7.1 HYPOTHESIS CONCERNING RIVER ECOSYSTEMS

7.1.1 The River Continuum Concept

The river continuum concept (RCC) was formulated by Vannote *et al.* (1980) in an attempt to synthesize information, gathered over many years for North American rivers, into a set of general hypotheses concerning river ecosystems. The RCC logically regards the entire lotic system as a continuous drainage basin gradient and states that, from the headwaters to the mouth of any river, there is a gradation of physical-chemical conditions that triggers a series of responses within the riverine populations (Cummins, 1977). This in turn results in a continuum of biotic adjustments and consistent patterns of loading, transport, utilization and storage of water and matter along its length. A pictorial representation of the RCC is illustrated in Figure 75 (adapted from Cummins, 1979), showing the downstream gradient of physical factors and the corresponding biological adjustments.

Headwaters tend towards detritus-based heterotrophy ($P/R < 1$, where P represents the productivity and R the respiration component), relying on allochtonous inputs of organic material for their energy. The effects of riparian vegetation is insignificant, but primary production may often be limited by depth and turbidity (Cummins, 1979). Phyto- and zooplanktonic organisms are rare because of low nutrients and they are swept away by the current, while fish is highly adapted to maintaining position in the fast-flowing water. General invertebrate functional groups like shredders, collectors, grazers and predators dominate these reaches (Vannote *et al.*, 1980).

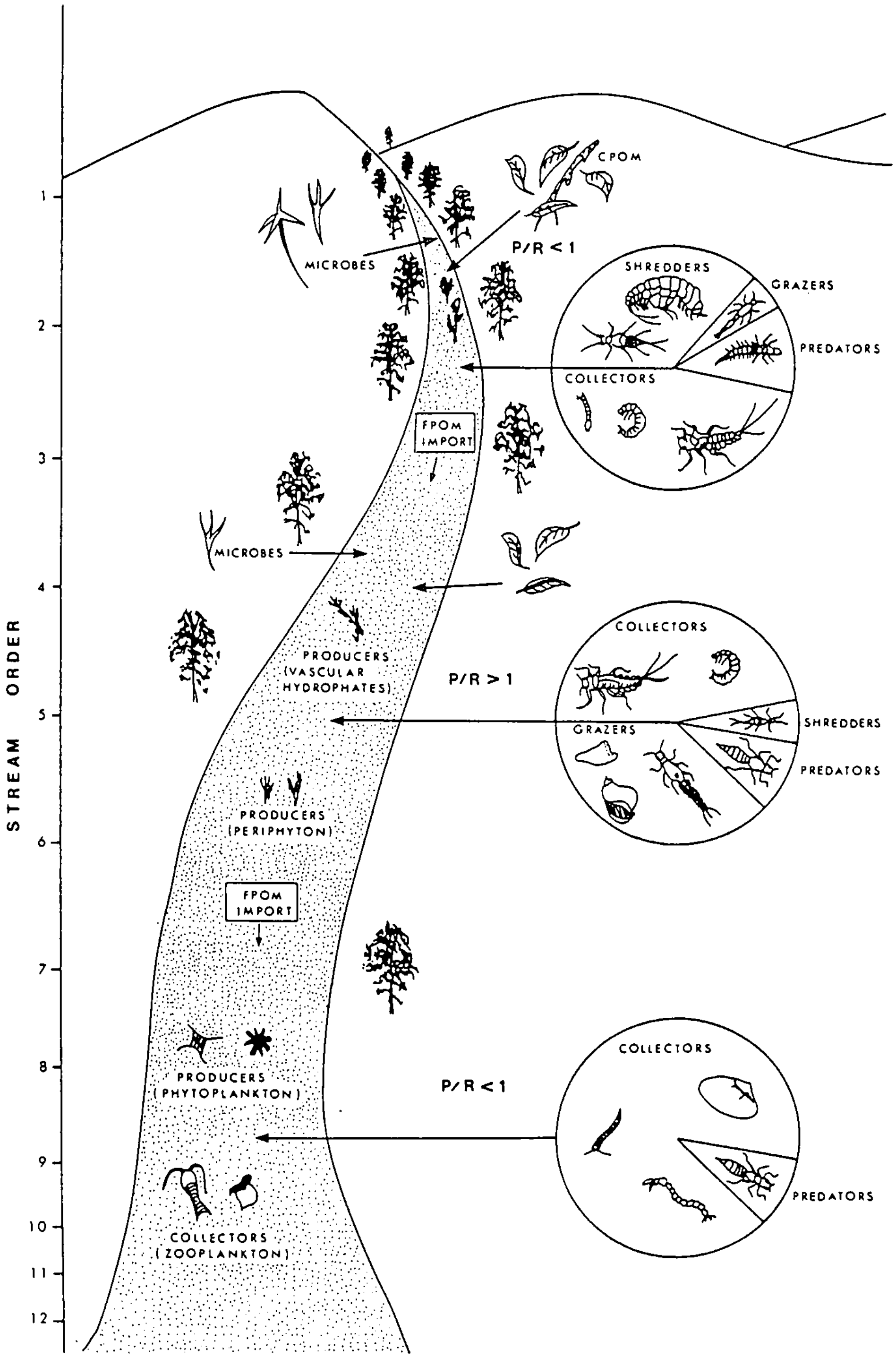


Figure 75. A pictorial representation of the river continuum concept.

Downstream, in the middle reaches, the system becomes more autotrophic (P/R > 1), with an increased production of autochthonous organic material, because of reduced riparian vegetation and relatively shallow clear water. With a general reduction in detritus particle size, collectors and grazers dominate the macroinvertebrate assemblages (Vannote *et al.*, 1980). Water temperature increase encourages the growth of mosses and algae and some plankton occurs in sheltered backwaters (Day *et al.*, 1986).

Further downstream, in the mature lower reaches, the system becomes heterotrophic again, due to attenuation from depth and turbidity in the large rivers (Cummins, 1979). Increasing levels of nutrients allow a more abundant and luxuriant growth of plants such as reeds and bulrushes. Increased sunlight and the slow flow encourage the growth of phytoplankton. Collectors dominate the macroinvertebrate assemblages (Cummins, 1977).

The downstream communities in the continuum depend on the inefficient use of nutrients from the upstream communities. Thus, lotic systems receive a continual supply of nutrients from upstream so that one would not expect nutrients to exert a primary limitation on algal and microbial biomass (Elwood *et al.*, 1981).

Cushing *et al.* (1983) reported that it is unsatisfactory to classify streams into subjectively defined isolated reaches, thus losing sight of interactions between reaches and obscuring important ecological similarities. They concluded that streams exhibit more continuity along their length and among themselves and that the differences are simply local expressions of general geomorphic processes. The most common criticisms of the RCC are that stream physical parameters are often interrupted by the legacy of events and lithological changes. The RCC notion of absence of succession is also rejected (Allanson *et al.*, 1990).

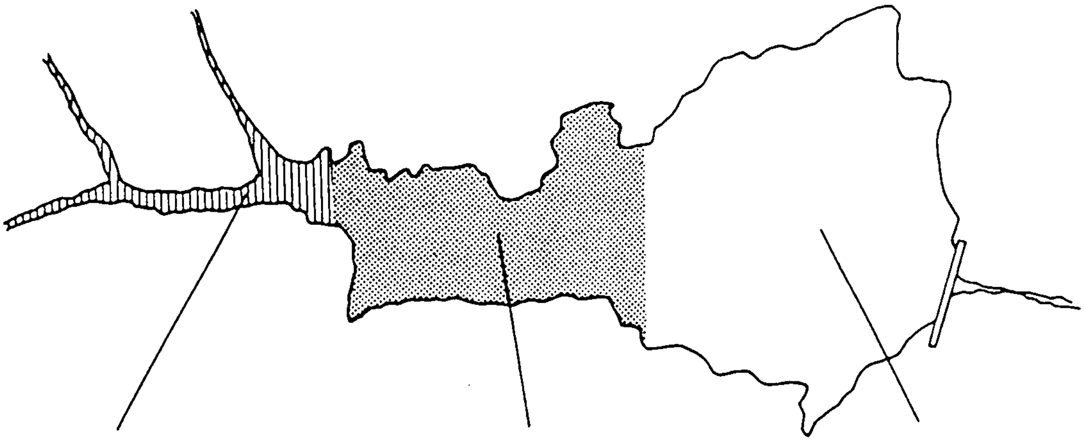
7.1.2 The Serial Discontinuity Concept

The Serial Discontinuity Concept (SDC) (Stanford & Ward, 1979 and Ward & Stanford, 1983) builds directly upon the RCC. Given that river communities represent a continuum, the construction of an impoundment creates a discontinuity of hydrological, physico-chemical and biotic factors.

In the case of the dam, the pre-impoundment conditions are not restored for some distance downstream. The 'reset distance' is the distance downstream a dam needed for the river to recover from the effects of impoundment. The effect an impoundment has on lotic reaches is a function of the position of the dam along the longitudinal stream profile. For example, whereas a headwater dam will greatly alter the CPOM/FPOM ratio, with attendant biotic response, a dam on the lower reaches of a river system may not significantly change the size composition of transport detritus. In contrast, the clarifying effect of an impoundment will have a major influence on the light penetration in a turbid river, but will have little effect on the transparency of headwater (Ward & Stanford, 1982).

Kimmel and Groeger (1984) investigated numerous physical, chemical and biological factors that change during the transition from a lotic to a lentic system. They distinguished between three zones, namely the riverine zone, transitional zone and lacustrine zone (Figure 76).

Reservoirs, unlike many natural lakes, have a distinct riverine zone dominated by flow and mixing. A transition zone where inflow velocity slows, follows the riverine zone, rapid sedimentation begins and water clarity increases. It often happens that the inflowing river water is colder than surface waters of the reservoir, and then a "plunge point" is found where these heavier waters lose velocity and descend to a depth that is equal to their density, creating a distinct underflow. Nutrient loading to a reservoir may not mix with upper waters at all but instead be carried along the reservoir's bottom. The lacustrine zone near the dam wall is the most lake-like, with a higher probability of a classic nutrient limitation of algal growth and sometimes thermal stratification.



RIVERINE ZONE	TRANSITIONAL ZONE	LACUSTRINE ZONE
• NARROW BASIN	• BROADER, DEEPER BASIN	• BROAD, DEEP, LAKE-LIKE
• HIGH FLOW	• REDUCED FLOW	• LITTLE FLOW
• HIGH SUSP. SOLIDS, LOW LIGHT	• LOWER SUSP. SOLIDS, MORE LIGHT	• CLEARER
• HIGH NUTRIENTS, ADVECTIVE SUPPLY	• ADVECTIVE NUTRIENT SUPPLY REDUCED	• INTERNAL NUTRIENT RECYCLING, LOW NUTRIENTS
• LIGHT LIMITED PHOTOSYNTHESIS	• HIGH PHOTOSYNTHESIS	• NUTRIENT LIMITED PHOTOSYNTHESIS
• ALGAL CELL LOSS BY SEDIMENTATION	• ALGAL CELL LOSS BY SEDIMENTATION, GRAZING	• ALGAL CELL LOSS BY GRAZING
• ORGANIC MATTER SUPPLY ALLOCHTHONOUS	• INTERMEDIATE	• ORGANIC MATTER SUPPLY AUTOCHTHONOUS
• MORE "EUTROPHIC"	• INTERMEDIATE	• MORE "OLIGOTROPHIC"

Figure 76. Longitudinal zonation in environmental factors which control primary productivity, phytoplankton biomass and trophic state within reservoir basins (according to Kimmel & Groeger, 1984).

7.1.3 The Nutrient Spiraling Hypothesis

This hypothesis refers to one of the salient differences between lentic and lotic systems. In a lentic system, nutrients are cycled, being taken up by living organisms and returned to the environment in the process of decomposition (Day *et al.*, 1986). In a lotic system nutrients exhibit a storage-cycle-release phenomenon which, when combined with downstream displacement, results in "nutrient spiralling". The "tightness" of the nutrient spirals has been proposed as an index of efficiency of nutrient utilization and may also be indicative of the ability of an ecosystem to resist and recover from perturbation (Newbold *et al.*, 1981).

Riffle-pool sequencing, debris dams, and even leaf packs function as retention devices, which increase spiraling efficiencies (Wallace *et al.*, 1977). It is not known how stream regulation influences spiraling efficiency, but such data are important in substantiating the dependence of downstream communities on upstream processes (Ward & Stanford, 1982).

7.1.4 The Intermediate Disturbance Hypothesis

The hypothesis suggests that the level of natural 'disturbance' or variability in an ecosystem determine the diversity of plant and animal species in a particular environment (Connel, 1978). It assumes that high diversity is a result of intermediate frequency of disturbance, while either "too low" or "too high" frequencies of disturbance will result in a low biotic diversity (Jørgensen & Padisák, 1996).

7.1.5 Resilience of rivers

A further consideration of river functioning has not been formally stated as a concept but is nonetheless of great practical importance. Given time and space, rivers are capable of returning to their equilibrium state if perturbed as long as the majority of their abiotic and biotic characteristics are not damaged (Day *et al.*, 1986 and Davies *et al.*, 1995).

7.2 APPLICATION OF SOME OF THE RIVER CONCEPTS TO THE UPPER ORANGE RIVER

Most rivers in Southern Africa that have been over-exploited, degraded, polluted or regulated by impoundments (Davies *et al.*, 1993) and the Upper Orange River is no exception. Both the Gariep and Vanderkloof Dams are situated in the Upper Orange River.

The Serial Discontinuity Concept assumes the validity of the River Continuum Concept and proposes that dams act as disruptions to the natural continuum of hydrological, physico-chemical and biotic changes down an impounded river (Stanford & Ward, 1979 and Palmer & O'Keeffe, 1990b). Kimmel and Groeger (1984) as discussed in 7.1.2 also described these changes. However, the conditions in the Upper Orange River differed slightly from what they found. High flow did occur in the riverine zone, with low flow in the lacustrine zone in the Gariep Dam. The turbidity in the riverine zone was high and was reduced by the dams. However, the nitrate concentrations were higher in the dams and downstream than it was upstream. The phosphate concentrations did decrease slightly in the dams and downstream. Thus, if nutrients did limit photosynthesis in the dams, it would be limited by phosphorus. Based on the chemical and biological data during this study, the riverine zone in the Upper Orange River appeared to be more oligotrophic, while the lacustrine zone appeared to be more meso- to eutrophic.

One of the main effects of impoundments on the Upper Orange River has been to convert the river from seasonal to perennial by reducing downstream seasonal flow fluctuations (Figures 14 & 15). This stable flow and reduction of winter droughts is one of the main reasons for outbreaks of the pest blackfly, *Simulium chutteri* (Chutter, 1998b).

Both the Gariep and Vanderkloof Dams are used for hydroelectric power generation. Depending on the depth below surface level from which the water is released, temperatures of the out-flowing water might be very different from the normal water temperatures in non-impounded rivers. Pitchford and Visser (1975) reported that the average water temperature downstream of the Gariep Dam was reduced by 2 °C after impoundment. During this study the water temperature at Norvalspont was on average 2.7 °C lower than those of measurements taken in the Gariep Dam (Figure 7). Blinn *et al.* (1998) hypothesized that reduced chemical conditions that occur in the lower anoxic regions of reservoirs during summer may periodically result in the release of harmful compounds. As an example, Hannan and Young (1974) reported elevated concentrations of H_2S in the tailwater of a regulated stream in Texas.

The high residence time in the dams studied, together with the decreased flow downstream of the dams, resulted in high chlorophyll *a* concentrations in and downstream of the dams (Figure 54). Blooms of *Anabaena* sp. occurred in the dams during September 1998 and *Microcystis aeruginosa* blooms occurred during February 1999. However, the blooms in the Vanderkloof Dam were less conspicuous than the blooms in the Gariep Dam.

The average conductivity in the Orange River at Aliwal North was 23.2 $mS.m^{-1}$, while the average conductivity in and downstream of the dams (with the exception of the tributaries) was 19.6 $mS.m^{-1}$ (Figure 29). Calcium (15.4 %) and carbonate (51.2 %) dominated the TDS composition at Aliwal North, while sodium (14.8 % and 19.2 %) and carbonate (49.5 % and 44.5 %) dominated in the Gariep Dam and in the Orange River at Marksdrift. Wetzel (1983) hypothesized that calcium dominates in open systems situated in temperate regions, while Gibbs (1970) reported sodium dominance in rivers and lakes situated in hot, arid regions with high evaporation.

The average turbidity at Aliwal North was 450 NTU, while the average turbidity in and downstream of the dams was 73 NTU (Figure 10). This suggested that the dams might act as sediment traps and thus increase water clarity downstream. This could also favours excessive algal growth.

The average nitrate concentrations increased from 230 $\mu g.l^{-1}$ at Aliwal North to an average concentration of 380 $\mu g.l^{-1}$ in and below the dams (Figure 49). This increase in nitrate concentration could be ascribed to nitrogen fixation by algae and to agricultural runoff. However, the average phosphate concentrations decreased from 38 $\mu g.l^{-1}$ at Aliwal North to 27 $\mu g.l^{-1}$ in and downstream of the dams (Figure 43). This could be ascribed to consumption by algae, adsorption to clay particles or to dilution.

Impoundments also exert major influences on the biota. The algal species composition at Aliwal North consisted mainly of Bacillariophyceae and to a lesser extent Chlorophyceae (Figure 56). Cyanobacteria requires a stable water column and thus thrived in dams. Downstream of the dams the species composition consisted of cyanobacteria, Bacillariophyceae and Chlorophyceae. Low SASS4 scores were also obtained. Chutter (1995 & 1998b) stated that the invertebrate fauna directly downstream of impoundments was noticeably depauperate, consisting of only a few species. Palmer and O'Keeffe (1990a) also found that the number of invertebrates in the Great Fish River was generally fewer immediately downstream of the dam than upstream. In the Fish River conditions took between 25 and 86 km to recover to above-impoundment levels. Palmer and O'Keeffe (1990b) hypothesized that the larger the river, the longer the recovery distance because the larger the dam, the larger the disturbance.

The recovery distance (also called the "discontinuity distance" by Ward and Stanford (1983)) can be defined as that length of stream which is required for any parameter to return to values close to those measured at the inflow to an impoundment, or to achieve a new equilibrium (Palmer & O'Keeffe, 1990b).

The Upper Orange River catchment is moderately developed and it is likely that the downstream recovery would be masked by agricultural runoff, as well as by urban and industrial pollution from the Vaal River catchment, after the Orange-Vaal confluence.

7.3 MODELLING

Eutrophication modelling is a rapidly developing field of water-resources research. Models have proved to be invaluable for improving our understanding of the processes operating in the water environment. They can also be used to assist with management and planning decisions. It is foreseen that water quality models will in future become increasingly refined and integrated with the increasingly complex water quality problems we can expect to face in the future (Du Plessis &

Van Veelen, 1991). Modelling forms an integral part of present-day research and plays an important role to predict and forecast situations that can arise in dynamic ecosystems. The choice of a model for impact assessment on aquatic ecosystems should be based on the hydrological or water resources problems to be studied (Arnell, 1992).

7.3.1 Simplification, idealization and realism in mathematical models

A mathematical water quality model is defined as a method that integrates fundamental principles from many scientific fields for assessment of the state of water ecosystems (Chen, 1970). It can also be defined as a symbolic and simplified representation of a complex system in which the behaviour of the system is represented by a set of equations, together with logical statements expressing the relationships between variables and parameters (Goodall, 1972 and Gold, 1977).

Complete ecosystem models that account for all the input-output behaviour of the ecosystem are impossible to construct (Levins, 1966 and Jørgensen, 1976). Models must therefore be both idealizations and simplifications of real systems. Idealization may be achieved, for example, by replacing complex mathematical expressions for certain processes with simplified mathematical equations describing those processes under ideal conditions such as steady state or complete mixing. Simplification can be achieved by limiting the number of system components in the model by including only those of particular interest, or by simplifying assumptions about the interaction between the system and its environment (Jørgensen, 1976 and Gold, 1977).

Mathematical models of ecosystems should be as realistic, as general and as precise as possible. Realism means that the model parameters and processes are realistic representation of the actual system parameters and processes. It is essential that the purpose of the model be stated explicitly before applying it (Jørgensen, 1976). The art of modelling has been expressed as the ability to make the correct assumptions and to simplify (but without over-simplification) as much as possible (Levins, 1966 and Jørgensen, 1976).

7.3.2 Classification of mathematical models

7.3.2.1 Stochastic and deterministic models

In stochastic models one of the model variables may be regarded as a random variable having a probability distribution (Gold, 1977) therefore the output is uncertain, as the model does not yield a unique output for a specific input. In deterministic models all the variables are free from random variation so that the model does have a unique output for a specific input data and parameter set (Zeigler, 1976 and Gold, 1977).

7.3.2.2 Conceptual and empirical models

Fleming (1975) described empirical models as "the direct approach involving some mathematical equation which, given a certain input, yields an output. Minimal consideration is given to the relationship of the parameters in the equation to the processes being considered." Gold (1977) uses the terms correlative (for empirical) and explanatory (for conceptual) and defined these as: "A correlative model is one that is required only to reflect an observed relation between two (or more) variables. An example of one such an empirical model is EUTROMOD.

7.3.3 EUTROMOD

EUTROMOD is a spreadsheet-based watershed and lake modelling procedure developed for eutrophication management, with an emphasis on uncertainty analysis. The model estimates nutrient loading, various trophic state parameters, and trihalomethane concentrations using data on land use, pollutant concentrations and lake characteristics. The model was developed using empirical data from the USEPA'' national eutrophication survey, with trophic state models utilized to relate phosphorus and nitrogen loading to in-lake nutrient concentrations. The phosphorus and nitrogen concentrations were then related to maximum chlorophyll level, secchi depth, dominant algal species, hypolimnetic dissolved oxygen status and trihalomethane concentrations. EUTROMOD utilizes annual mean precipitation and coefficient of variation to account for hydrologic variability.

With sufficient information on the catchment EUTROMOD could be applied to the Upper Orange River system. The next step in the investigation of the Upper Orange River would be the application of a model.

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APPENDIX 1

Figure a. A bloom patch of *Microcystis aeruginosa* (The oxygen was 111.7 % saturated at that specific moment).

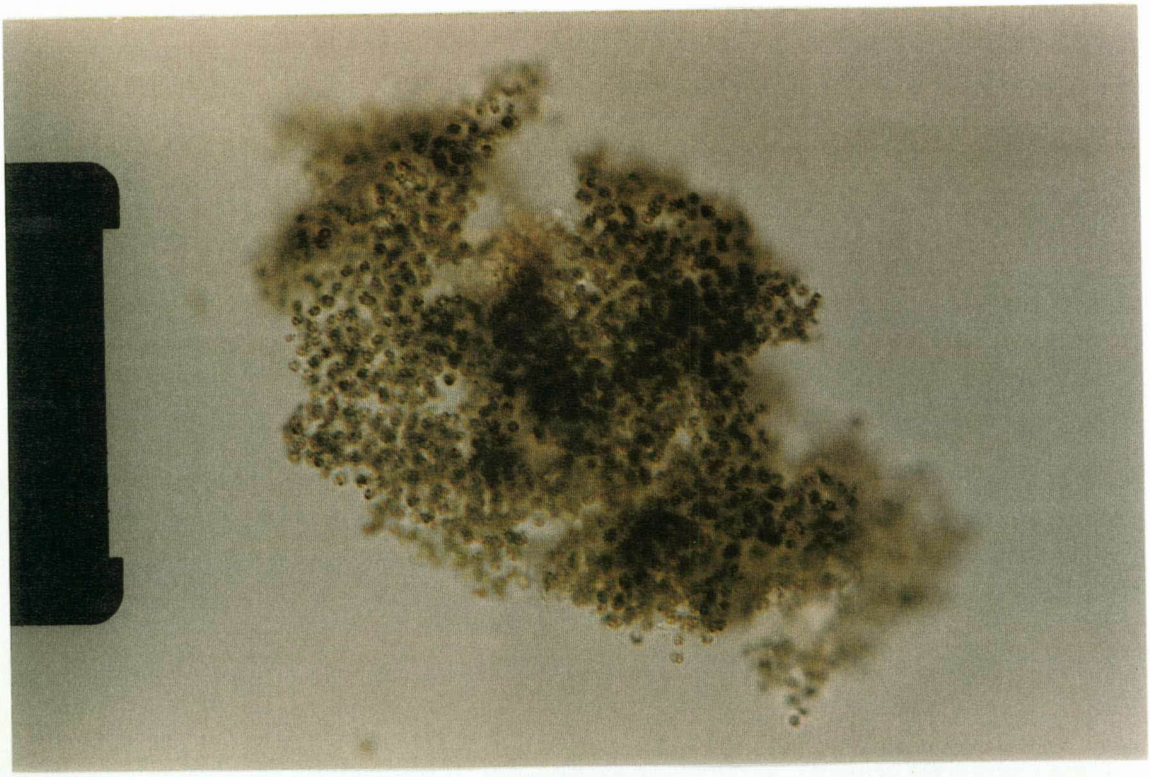

Figure b. Colony of *Microcystis aeruginosa* (Colony size: 133μm on scale)

APPENDIX 2

SASS4 score sheet

SASS4

River..........................Date..................Time.................

Sampling point..

Temp..................pH..................EC(mS/m).....................

DO(mg/l).................% sat.................Turb....................

Biotopes sampled

(1)SIC............(Type./time...)

(2)Marg veg............Dom.sp..

(2)Aq veg............Species...

(1)SOOC...........(3)Sand...........(3)Mud..........(3)Gravel..........

Other.......................................HABS1......................

Procedure Protocols

If SIC all kickable, sample for 2 min., otherwise for maximum of 5 min.
Gravel 1/2 min.
Marg/Aq veg. back & forward sweep 2 m.
SOOC kick +- 1m
Sand/mud stir with feet & sweep net over disturbed area for 1/2 min.
Any other biotopes - 1/2 min.
Complete top of form.
Tip net contents into tray. Remove leaves, twigs & trash.
Check taxa present FOR THE LESSER of 15 minutes or 5 minutes since the last taxon was found.
Estimate abundance on scale: A 1-10; B 11-100
C 100 - 1000; D >1000
BEFORE LEAVING THE SAMPLING POINT CHECK THAT THIS FORM HAS BEEN FULLY COMPLETED!!!

* Air breather

TAXON	SCOR	ABUN		
BIOTOPES		1	2	3
Porifera	5			
Coelenterata				
Hydra sp.	1			
Turbellaria				
Planarians	5			
Annelida				
Oligochaeta	1			
Hirudinea	3			
Crustacea				
Amphipoda	15			
Crabs*	3			
Shrimps	8			
Hydracarina				
Hydrachnellae	8			
Plecoptera				
Notonemouridae	12			
Perlidae	12			
Ephemeroptera				
Polymitarcyidae	10			
Ephemeridae	15			
Baetidae 1 sp	4			
2 spp	6			
> 2 spp	12			
Oligoneuridae	15			
Heptageniidae	10			
Leptophlebiidae	13			
Ephemerellidae	15			
Tricorythidae	9			
Prosopistomatidae	15			
Caenidae	6			
Odonata				
Chlorolestidae	8			
Lestidae	8			
Protoneuridae	8			
Platycnemidae	10			
Coenagriidae	4			
Calopterygidae	10			
Chlorocyphidae	10			
Zygoptera juvs	6			
Gomphidae	6			
Aeshnidae	8			
Corduliidae	8			
Libellulidae	4			

Hemiptera	SCOR	ABUN		
		1	2	3
Notonectidae*	3			
Pleidae*	4			
Naucoridae*	7			
Nepidae*	3			
Belostomatidae*	3			
Corixidae*	3			
Gerridae*	5			
Veliidae*	5			
Megaloptera				
Corydalidae	8			
Trichoptera				
Hydropsychidae 1 spp	4			
2 spp	6			
> 2 spp	12			
Philopotamidae	10			
Polycentropodidae	12			
Psychomyiidae	8			
Ecnomidae	8			
Hydroptilidae	6			
Other movable case larvae:				
case types score fam				
1 8 1	8			
2 15 1	15			
3 20 1	20			
4 30 2	30			
5 40 2	40			
>5 50 3	50			
Lepidoptera				
Nymphulidae	15			
Coleoptera				
Dytiscidae (adults*)	5			
Elmidae/Dryopidae	8			
Gyrinidae (adults*)	5			
Haliplidae (adults*)	5			
Helodidae	12			
Hydraenidae (adults*)	8			
Hydrophilidae (adults*)	5			
Limnichidae	8			
Psephenidae	10			

Observations:

Diptera	SCOR	ABUN		
		1	2	3
Blepharoceridae	15			
Tipulidae	5			
Psychodidae	1			
Culicidae*	1			
Dixidae*	13			
Simuliidae	5			
Chironomidae	2			
Ceratopogonidae	5			
Tabanidae	5			
Syrphidae*	1			
Athericidae	13			
Empididae	6			
Ephydridae	3			
Muscidae	1			
Gastropoda				
Lymnaeidae*	3			
Melaniidae*	3			
Planorbidae*	3			
Physidae*	3			
Ancylidae	6			
Hydrobidae*	3			
Pelecypoda				
Sphaeridae	3			
Unionidae	6			
Sample score				
No. of families				
Score/taxon (ASPT)				
Air breathers fam.				
Air breathers score				

Other families present

The authors Habitat Quality Index (HQI) scoresheet

HABITAT Q.I. River ____________ Ref Point ____________ Date: ____________

V 2

1: RIVER BED COMPONENTS

0 2 4 6 8 10 12 14 16 18 20

d | b + c + >50% d | >90% b | <10% a >50% b + c / d | 10% a >50% b + c / d | 30% a 30% b + c / d | 50% a 30% b + c / d | a d | 75% a + c / a | 75% a + b + c / d | >80% a the rest c | >80% a the rest b

a = rocks : b = sand : c = mud : d = boulders or bedrock

☐

2: EMBEDDEDNESS

0 2 4 6 8 10 12 14 16 18 20

bedrock | most rubble mostly covered by fines | most rubble covered with green or brown algae | >50% of rubble covered with green or brown algae | most rubble unmoveable due to cementation | most rubble is covered with fines OR river mostly sand | 25% of rubble covered in green or brown algae | up to 50% of rubble unmoveable due to cementation | some sand or mud around rubble | rubble totally clear

☐

3: HABITAT SAMPLED

0 2 4 6 8 10 12 14 16 18 20

d, e, or f | b or c | a | 1 of a - c + 1 of d - f | b + c | a + c | a + b | b + c + 1 of d - f | a + b or c + 1 of d - f | a - c | a - c + e or f | a - d | a - d + e or f | a - f

a = stones in current : b = vegetation : c = sand : d = stones out of current : e = gravel : f = mud

☐

4: TYPES OF VELOCITY FEATURES

1 3 5 7 9 11 13 15

e | 1 of a - d + e or f | 2 of a - d | 2 of a - d + e or f | 3 of a - d | 3 of a - d + e or f | a - d | a - e

a = fast riffles : b = slow riffles : c = deep water or riffles : d = shallow water or riffles : e = pool : f = running water

☐

5: RIVER ENVIRONMENT

1 3 5 7 9 11 13 15

litter - dumping site | smelly water | rural settlement runoff | evidence of close farming/ agriculture | greenish water OR very silty from rain | within 20m of weir OR brown silty water | within 50m of weir OR water slightly discoloured | clear fresh flowing water

☐

6: HABITAT POTENTIAL

1 3 5 7 9 11 13 15

c or e | b or c + e | b or c + d | b, c | b, c, e | b, c, d | a | a, e | a, d | a, c, d OR a, b, e | a, b, d | a - c | a - c + e | a - d

a = riffles : b = hanging vegetation (leaves) : c = growing vegetation (stems) : d = pools : e = running water

☐

7: BANK EROSION

0 2 4 6 8 10

both banks near vertical | 1 bank near vertical | both banks steep and raw areas | 1 bank <30° other bank steep | all banks <45° | all banks <30°

☐

8: BANK COVER

0 2 4 6 8 10

little or no rocks/ vegetation | 80% banks is sand or soil | only one bank covered | 60% banks covered by rocks/ vegetation | 80% banks covered by rocks/ vegetation | all banks covered by vegetation

☐

9: BANK VEGETATION

0 2 4 6 8 10

no cover at all | little cover bridge etc. | c | b + c | a - c | a + c | b | a + b | a

a = shrubs : b = trees : c = grass and reeds

☐

INSTRUCTIONS:

Take each category and move up from the zero until you reach a number that best describes the sampling area. Circle the number and repeat for all nine categories. Add the total score, which is out of a possible maximum of 135.

EXAMPLES:

In category 1, the river bed consists of >80% rocks with sand and mud. You would give a score of 19. In category 5, a river with slightly discoloured water would score 13; and in category 8, a river consisting of one bank totally covered, and the other just sand would score 4.

TOTAL SCORE ☐

INTEGRATED HABITAT ASSESSMENT SYSTEM (IHAS)

version 2.0d
peter mac 12/98

River Name:

Site Name:

Date:

SAMPLING HABITAT

Stones In Current (SIC)

	0	1	2	3	4	5
Total length of white water rapids (ie: bubbling water) (in metres)	none	0-1	>1-2	>2-3	*>3-5*	>5
Total length of submerged stones in current (run) (in metres)	none	0-2	>2-5	*>5-10*	>10	▨
Number of separate SIC area's kicked (not individual stones)	0	1	2-3	*4-5*	6+	▨
Average stone sizes kicked (in cm's) (*<2 or >20* = <2 >20) (gravel <2: bedrock >20)	none	<2>20	2-10	11-20	*2-20*	▨
Amount of stone surface clear (of algae, sediment etc.) (in percent) *	n/a	0-25	26-50	*51-75*	>75	▨
PROTOCOL: time spent actually kicking SICs (in minutes) (gravel/bedrock=0min)	0	<1	>1-2	*2*	>2-3	>3

(* *NOTE:* up to 25% of stone is usually embedded in the stream bottom)

(E=SIC boxes total; F.=adjustment to equal 20; G=final total) SIC Scores: *actual* E *adj.* ± F *max. 20* G

Vegetation

	0	1	2	3	4	5
Length of fringing vegetation sampled (banks) (in metres)	none	0-½	>½-1	>1-2	*2*	>2
Amount of aquatic vegetation/algae sampled (underwater) (in square metres)	none	0-½	*>½-1*	>1	▨	▨
Fringing vegetation sampled in: (none, pool or still only, run only, mixture of both)	none	▨	run	pool	▨	*mix*
Type of veg. (percent leafy veg. as opposed to stems/shoots) (aq. veg. only=49)	none	0	1-25	26-50	*51-75*	>75

(H=Veg. boxes total; I=adjustment to equal 15; J=final total) Veg. Scores: *actual* H *adj.* ± I *max. 15* J

Other Habitat / General

	0	1	2	3	4	5
Stones Out Of Current (SOOC) sampled: (PROTOCOL - in square metres)	none	0-½	>½-1	*1*	>1	▨
Sand sampled: (PROTOCOL - in minutes) (present, but only below stones)	none	under	0-½	>½-1	*1*	>1
Mud sampled: (PROTOCOL - in minutes) (present, but only below stones)	none	under	0-½	*½*	>½	▨
Gravel sampled: (PROTOCOL - in minutes) *(if all, SIC stone size=<2)* **	none	0-½	*½*	>½**	▨	▨
Bedrock sampled: (*all*=no SIC, sand, gravel) *(if all, SIC stone size=>20)* **	none	*some*	▨	▨	all**	▨
Algal presence: (1-2m²=algal bed, rocks=on rocks, isol.=isolated clumps)	>2m²	rocks	1-2m²	<1m²	*isol.*	none
Tray identification: (PROTOCOL - using time: *corr*=correct times)	▨	under	▨	*corr*	▨	over

(** *NOTE:* you must still fill in SIC section)

(K=O.H./G boxes total; L=adjustment to equal 20; M=final total) O.H. Scores: *actual* K *adj.* ± L *max. 20* M

(S=total adjustment [F+I+L]; N= total habitat [G+J+M]) Habitat Totals: *adj.* ± S *max. 55* N

STREAM CONDITION

Physical

	0	1	2	3	4	5
River make-up: (*pool*=pool/still/dam only: run only: rapid only: *2 mix*=2 types etc.)	pool	▨	run	rapid	2 mix	3 mix
Average width of stream: (metres)	▨	>10	>5-10	<1	1-2	>2-5
Average depth of stream: (metres)	>2	>1-2	1	>½-1	½	<½
Approximate velocity of stream: (slow=<½m/s, fast=>1m/s)	still	slow	fast	med.	▨	mix
Water colour: (disc.=discoloured with visible colour but still clearish)	silty	opaque	▨	discol	▨	clear
Recent disturbances due to: (constr.=construction) ***	flood	fire	constr	other	▨	none
Bank / riparian vegetation is: (grass=includes reeds, shrubs=includes trees)	none	▨	grass	shrubs	mix	▨
Surrounding impacts: (erosn=erosion/shear banks, farm=farmland/settlements) ***	erosn.	farm	trees	other	▨	open
Left bank cover (rocks and vegetation): (in percent)	0-50	51-80	81-95	>95	▨	▨
Right bank cover (rocks and vegetation): (in percent)	0-50	51-80	81-95	>95	▨	▨

(*** *NOTE:* if more than one option, choose lowest)

(P=Physical boxes final total) Stream Conditions Total: *max. 45* P

Total IHAS Score: % T
(N+P)

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SUMMARY

The Upper Orange River is defined as the region between the source in the Drakensberg (Lesotho) and the Orange-Vaal confluence. Information on the water quality, phytoplankton composition and the influence of the dams on the Upper Orange River is limited. This study was conducted in order to determine seasonal and spatial patterns in the river system, as well as to determine the influence of the tributaries and the two major dams on the river system. Physical, chemical and biological factors were taken into account.

Hypolimnetic water released from the Gariep and Vanderkloof Dams caused a significant decrease in the temperature downstream of the dams. The dams acted as sediment traps and caused the TSS and turbidity in the river system to decrease. A decrease in turbidity resulted in an increase in the light penetration. This created more favourable conditions for primary production and led to algal blooms in the dams.

The dams are used for hydro-electric power generation and almost completely diminished seasonal flow patterns. This changed the Upper Orange River into a highly regulated system. The interference with seasonal flow patterns in the river is probably one of the main reasons for outbreaks of the pest blackfly, *Simulium chutteri* downstream of the dams.

The oxygen-depth profile in the Gariep Dam during summer stratification indicated relatively high dissolved oxygen concentrations in the epilimnion (8.2 $mg.l^{-1}$) and anoxic, near anaerobic, conditions (0.1 $mg.l^{-1}$) in the hypolimnion. The oxygen decline in the hypolimnion was indirectly the cause of high algal production in the epilimnion during algal blooms.

The average pH of the Upper Orange River system was mainly alkaline at 8.1, with an average total alkalinity of 95.2 mg $CaCO_3.l^{-1}$. This suggested that the Upper Orange River is a well-buffered system.

The average conductivity in the Upper Orange River was relatively low at 19.6 $mS.m^{-1}$, but increased significantly since 1980. Major ions at Aliwal North occurred in the following proportions, i.e. $Ca > Na > Mg > K$ for cations and $CO_3 > Cl > SO_4$ for anions. In the Gariep Dam and at Marksdrift the proportions were: Na > Ca > Mg > K for cations and CO_3 > Cl > SO_4 for anions.

The average PO_4-P concentration was relatively low at 28.3 $\mu g.l^{-1}$ and the average TP concentration was 107 $\mu g.l^{-1}$. The average NO_3-N concentration was high at 312 $\mu g.l^{-1}$ and increased in the dams and downstream probably due to agricultural fertilizers and nitrogen fixation by algae.

The average chlorophyll *a* concentration ranged between 0.4 and 1084 $\mu g.l^{-1}$, with and average concentration of 10.8 $\mu g.l^{-1}$. The very high chlorophyll *a* concentration was due to a bloom of *Microcystis* sp. during February in the Gariep Dam. Phytoplankton dynamics manifested themselves in seasonal cycles. Cyanobacteria and Bacillariophyceae dominated during warmer months. The Chlorophyceae replaced cyanobacteria during cooler months.

Light penetration in the Gariep Dam and the Vaal River had a major effect on the primary production. The maximum primary production in the Gariep Dam was 14.6 mg C. mg $Chla^{-1}$. h^{-1} and in the Vaal River the maximum primary production was 76 mg C. mg $Chla^{-1}$. h^{-1}. According to the primary production in the Gariep Dam it can be classified as mesotrophic, while the high primary production in the Vaal River indicated eutrophic conditions.

The dams exert major influences on the physical, chemical and biological parameters in the river. Low SASS4 scores were obtained and are an indication of poor water quality. This could be ascribed to disturbances by the dams. The serial discontinuity concept (SDC) is applicable in the Upper Orange River. It is likely that agricultural runoff, as well as urban and industrial pollution from the Vaal River catchment would mask the downstream recovery after the Orange-Vaal confluence.

Key words: Upper Orange River, water quality, phytoplankton, trophic status, chlorophyll *a*, nitrate, phosphate, primary productivity, SASS4.

OPSOMMING

Die Bo-Oranjerivier kan gedefinieer word as die gebied tussen die oorsprong in the Drakensberge (Lesotho) en die Oranje-Vaal samevloei. Beperkte inligting is beskikbaar oor die waterkwaliteit en die invloed van die damme op die Bo-Oranjerivier. Die doel van die studie was om seisoenale and ruimtelike veranderinge in die rivierstelstel te bepaal, sowel as om te kyk na die invloed van die sytakke en die twee groot damme op die rivierstelstel. Fisiese, chemiese en biologiese faktore is ondersoek.

Water wat vrygestel is vanuit die hipolimnion in die Gariep en Vanderkloof damme het gelei tot betekenisvolle verlaging in die watertemperatuur in die rivierstelsel onder die damme. Die damme het sediment teruggehou en dit het gelei tot verlaagde totale gesuspendeerde materiaal (TSS) en dus ook verlaagde troebelheid. Verlaagde troebelheid het verbeterde ligindringing tot gevolg gehad, wat gunstige toestande geskep het vir algopbloeie.

Die damme, wat gebruik word vir hidro-elektriese kragopwekking, het seisoenale vloeipatrone feitlik heeltemal uitgewis en dus die Bo-Oranjerivier verander in 'n hoogs gereguleerde stelsel. Die verandering in seisoenale vloei patrone is moontlik een van die hoof oorsake van die probleme wat onder die damme ondervind word met die swartvliegie, *Simulium chutteri*.

Die suurstof-diepte profiel in die Gariep dam gedurende somer stratifikasie het relatief hoë konsentrasies opgeloste suurstof getoon in die epilimnion (8.2 mg.l^{-1}) en feitlik anoksiese toestande in die hipolimnion (0.1 mg.l^{-1}). Die lae suurstof konsentrasies in die hipolimnion was die indirekte gevolg van die hoë alg produksie in die epilimnion gedurende 'n opbloei.

Die gemiddelde pH (8.1) was hoofsaaklik alkalies, met 'n gemiddelde totale alkaliniteit van 95.2 mg $CaCO_3$.l^{-1}. Dit dui daarop dat die Bo-Oranjerivier stelstel goed gebuffer is.

Die geleiding in die BO-Oranjerivier was relatief laag met 'n gemiddeld van 19.6 mS.m^{-1}. Die samestelling van makro ione by Aliwal Noord was soos volg: . Ca > Na > Mg > K vir katione en CO_3 > Cl > SO_4 vir anione. Die samestelling in die Gariep dam en by Marksdrift was soos volg: Na > Ca > Mg > K vir katione en CO_3 > Cl > SO_4 vir anione.

Die gemiddelde konsentrasie PO_4-P was relatief laag teen 28.3 $\mu g.l^{-1}$ en die gemiddelde konsentrasie TP was 107 $\mu g.l^{-1}$. The gemiddelde konsentrasie NO_3-N was hoog teen 312 $\mu g.l^{-1}$ en het vermeerder stroom-af moontlik a.g.v. bemestingstowwe en stikstof-vaslegging deur alge.

Die chlorofil *a* konsentrasie het gewissel tussen 0.4 en 1 084 $\mu g.l^{-1}$ met gemiddeld 10.8 $\mu g.l^{-1}$. Die hoë konsentratsie was as gevolg van 'n *Microcystis* opbloei in die Gariep dam gedurende Februarie. Fitoplankton dinamika het seisoenale patrone gevolg. Cyanobakterieë en Bacillariophyceae het gedomineer gedurende die warmer maande en Chlorophyceae het cyanobakterieë vervang gedurende die koeler maande.

Primêre produksie in die Gariep dam en in die Vaalrivier is hoofsaaklik bepaal deur ligindringing. Maksimum produktiwiteit in die Gariep dam was 14.6 mg C. mg $Chla^{-1}$. h^{-1} en in die Vaalrivier was dit 76 mg C. mg $Chla^{-1}$. h^{-1}. Na aanleiding van die primêre produksie kan die Gariep dam geklassifiseer word as mesotrofies, terwyl die hoë produksie in die Vaalrivier dui op eutrofiese toestande.

Die damme beïnvloed die fisiese, chemiese en biologiese toestande in die rivier. Lae SASS4 waardes is gevind, wat op swak waterkwaliteit dui. Die lae waardes kan toegeskryf word aan die versteuring van die rivierstelsel deur die damme. Die SDC (serial discontinuity concept) is van toepassing op die Bo-Oranjerivier. Dit is moontlik dat die herstel van die rivier stroomaf verskans kan word deur afloop vanaf landbou bemestingstowwe, sowel as deur stedelike en industriële besoedeling vanaf die Vaalrivier opvangsgebied, na die Oranje-Vaal samevloei.