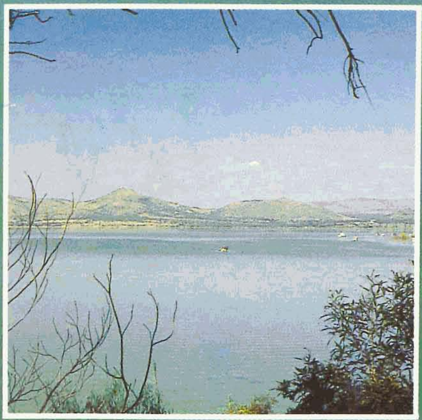
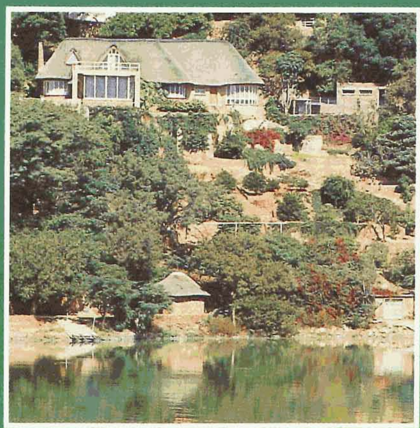
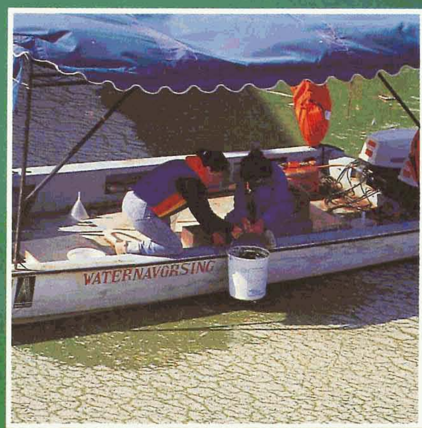


THE HARTBEESPOORT DAM ECOSYSTEM PROGRAMME





1980 - 1988

Acknowledgements

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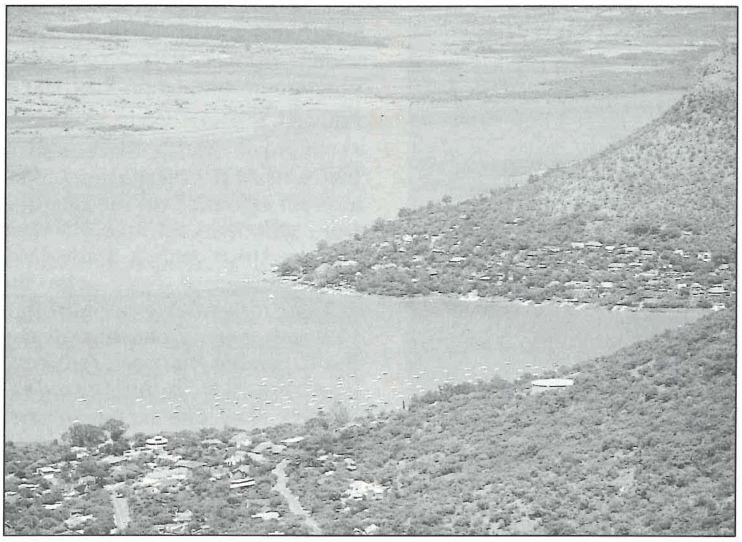
THE metropolis of Johannesburg and its satellite towns along the Witwatersrand, lie on the watershed between the Limpopo and the Vaal/Orange river systems. Sources of freshwater for the Witwatersrand area are mainly impoundments on rivers which are located topographically below the urbanized and industrialized regions, so that water has to be pumped up for use. Because of the scarcity of water, current legislation requires that wastewater be treated to an acceptable standard and then returned to the stream of origin. After use and treatment, water from the Witwatersrand flows from the elevated regions back into the rivers and impoundments. The rate at which water is used and the quantity which is treated and discharged into local rivers is increasing with the growth of this commercial, industrial and mining metropolis. It is therefore hardly surprising that impoundments supplying water to the Witwatersrand are becoming over-enriched with nitrogen and phosphorus from local effluents. This enrichment process is called eutrophication.



Hartbeespoort Dam from Cableway

Eutrophication causes many changes in the biology and chemistry of lakes and reservoirs. Several of these changes are generally detrimental and can be expensive to rectify. The water becomes green as a result of excessive growth of microscopic floating algae. In severely eutrophic or hypertrophic (over-enriched) water bodies, smelly, green scums of buoyant algae accumulate on the surface, while the waters below become devoid of oxygen. Other hypertrophic water bodies become covered with floating aquatic plants. In both situations the fish population increases and angling is usually good. However, there is an obvious deterioration in the aesthetic appearance and recreational value of such reservoirs. At the same time, it becomes difficult to produce drinkable water with an acceptable taste.

Hartbeespoort Dam is strikingly scenic and is set in a broad valley with steep mountain ridges as a backdrop. Its main feeder river, the Crocodile, drains the northern slopes of the Witwatersrand and consequently receives substantial flows of treated wastewater effluents. Over the years the reservoir has become hypertrophic.

In an attempt to curb the deterioration, and improve the water quality in South African reservoirs, an effluent standard limiting the phosphorus concentration of wastewater to 1 mg/litre (1 part per million), was proclaimed in 1980. This standard was intended to be implemented in certain sensitive catchments, including that of Hartbeespoort Dam, by 1985. The levels of enrichment with nitrogen and phosphorus in this reservoir, are excessive even by international standards. However, they represent the potential future conditions of several other reservoirs in the Republic of South Africa Estimation of the effect of the phosphate standard on Hartbeespoort Dam's trophic status (using contemporary eutrophication models) has indicated that the lake would remain eutrophic even after implementation of the phosphate standard. Studies of lakes carried out in South Africa and other parts of the world in the 1970s, highlighted a need to understand how low hypertrophic ecosystems function. In 1979 Hartbeespoort Dam was chosen by the National Institute for Water Research (now the Division of Water Technology), CSIR, as a site for an intensive ecosystem study. It was intended that understanding gained from this study would facilitate decisions on management measures required for improving water quality in the reservoir, as well as in other over-enriched lakes.

It has been established in many earlier studies that the key to rehabilitating nutrient-enriched lakes is phosphorus. Therefore the approach adopted in this Hartbeespoort Dam study was that the research should be based on a quantitative understanding of how the ecosystem functions, and particularly on the cycling of phosphorus. It was considered essential that studies of the major components of the lake's ecosystem, such as sediments, algae, zooplankton, fish, and phosphorus dissolved in the water, should be inter-related. A simulation modelling approach was followed, which required research emphasis on processes and their rates and driving forces. It became apparent that the algological expression of extreme enrichment, or hypertrophy, in Hartbeespoort Dam, was due as much to the physical conditions of wind, temperature and water currents, as to the nutrient status of the lake.

This report reviews the studies made of Hartbeespoort Dam from 1980 to 1988. It records the scientific achievements, and highlights the implications of the study for reservoir management.

Major research findings

Physical features

Hartbeespoort Dam is shallow and irregular in shape, with a long shoreline in relation to its surface area. The water evaporation rate is high because of the sunny climate, and wind speeds in the area tend to be low. In spring, the lake becomes stratified, which means that as it heats up the surface waters become warm while the deep water remains cold. No mixing occurs between these two layers of different temperature. The boundary between them is called the thermocline, in which a steep temperature and density gradient is present. This layered or stratified condition persists throughout the summer. The warmer top layer supports the growth of algae (phytoplankton), water fleas (zooplankton) and fish. The deep water stays relatively cool and is able to support the growth of bacteria only. In autumn the top and bottom layers of the water mix, and the lake remains destratified throughout the winter.

Chemical features

After the lake stratifies in summer, the oxygen in the bottom layer is rapidly consumed by bacteria and chemical processes, causing the bottom layer to become devoid of oxygen (anaerobic). The bottom anaerobic layer may extend upwards to within eight to ten metres of the lake surface. In this region hydrogen sulphide, which has a 'rotten egg' smell, is formed when micro-organisms die and settle to the bottom where they decompose.

Collection of fish samples for population estimates.

Hydrogen sulphide is highly toxic to most animals, and fish populations are highly sensitive to oxygen depletion. There is no evidence of fish deaths due to lack of oxygen in Hartbeespoort Dam, but further deterioration in the water quality could lead to a significant decline in the reservoir's fish population. The hydrogen sulphide is released from water which is drawn off into the lake's two outlet canals, and this produces the noticeably unpleasant pervasive odour near the dam wall.

The Crocodile River contributes over 95 per cent of the phosphorus which enters the lake (the phosphorus load). Sixty per cent of the phosphorus present is in a form which can be taken up by algae (soluble reactive phosphorus). Calculations show that 62-77 per cent of the annual total phosphorus inflow remains within the system and is therefore accumulating. The phosphorus loading rate varies between 15 and 26 grammes per metre squared, per annum, and is one of the highest recorded in Southern Africa.

Phosphorus is released from the sediments and accumulates deep in the lowest water layer of the lake (the hypolimnion), in which there is no dissolved oxygen in summer. However, some of this phosphorus is carried from the lowest levels during winter, when the deep water is mixed into the upper water during the annual mixing cycle. This annual process of phosphorus release is therefore likely to inhibit the lake's rapid response to rehabilitation by phosphorus load reduction, as indicated below.

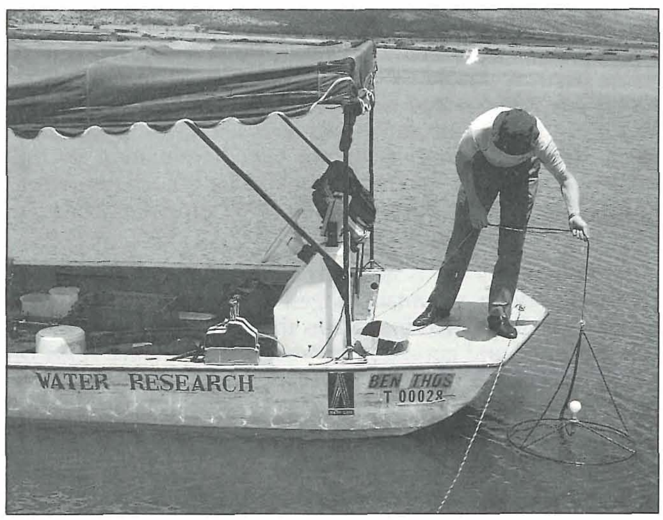
The Crocodile River also contributes over 97 per cent of the total amount of nitrogen entering the lake (the nitrogen load), and more than 80 per cent of this nitrogen load is composed of nitrates. Rates of nitrification and denitrification (the biochemical binding and liberation of nitrogen) measured in Hartbeespoort Dam, are among the highest in the world. Between 35 per cent and 45 per cent of the total annual nitrogen load is lost by denitrification, and a further 30 per cent is lost via the outflow of lake water. In 1986 Rand values, the nitrogen which was lost from Hartbeespoort Dam by denitrification was estimated to be worth R600 000, in the form of fertilizer for farmers using lake water for crop irrigation during the 1985-86 hydrological year.

The ratio of nitrogen to phosphorus (N:P ratio), in Hartbeespoort Dam water is generally between 7 and 1, which is low. Low N:P ratios promote the growth of undesirable blue-green algae, which float and form scums.

Approximately 700 tonnes of phosphorus are being deposited on the lake's sediments each year. This amount is nearly three times in excess of the annual external phosphorus load, which shows that re-suspension of phosphorus occurs within the lake (internal cycling), and accounts for most of the sedimenting material. Calculations suggest that approximately 1 700 tonnes of phosphorus have accumulated in the sediments of Hartbeespoort Dam during the last ten years. The greatest accumulation has taken place near the Crocodile River inflow.

Sediment studies have also shown that the phosphate concentration in water immediately above the sediment has a direct influence on the rate of phosphate uptake or release from sediments throughout most of the lake. Therefore it is expected that with a gradual reduction in the phosphorus concentration of water entering the reservoir, its sediments will begin to release some of their accumulated phosphorus. However, even if phosphorus concentrations which enter via the Crocodile River are reduced (a reduction in phosphorus load), the lake's response to this reduction may nevertheless be very slow due to the release of some of the previously accumulated sedimental phosphorus. For these reasons Hartbeespoort Dam is likely to remain over-enriched for a long period.

Studies of the Hartbeespoort Dam carbon budget have shown that the major source of organic carbon comes from phytoplankton production rather than from carbon which enters via the Crocodile River. Although respiration in the sediments was shown to have caused major organic carbon loss, the lake accumulated carbon at a mean rate of 20 grammes per square metre per year between 1982 and 1986.



Measurements of light penetration

Biological features

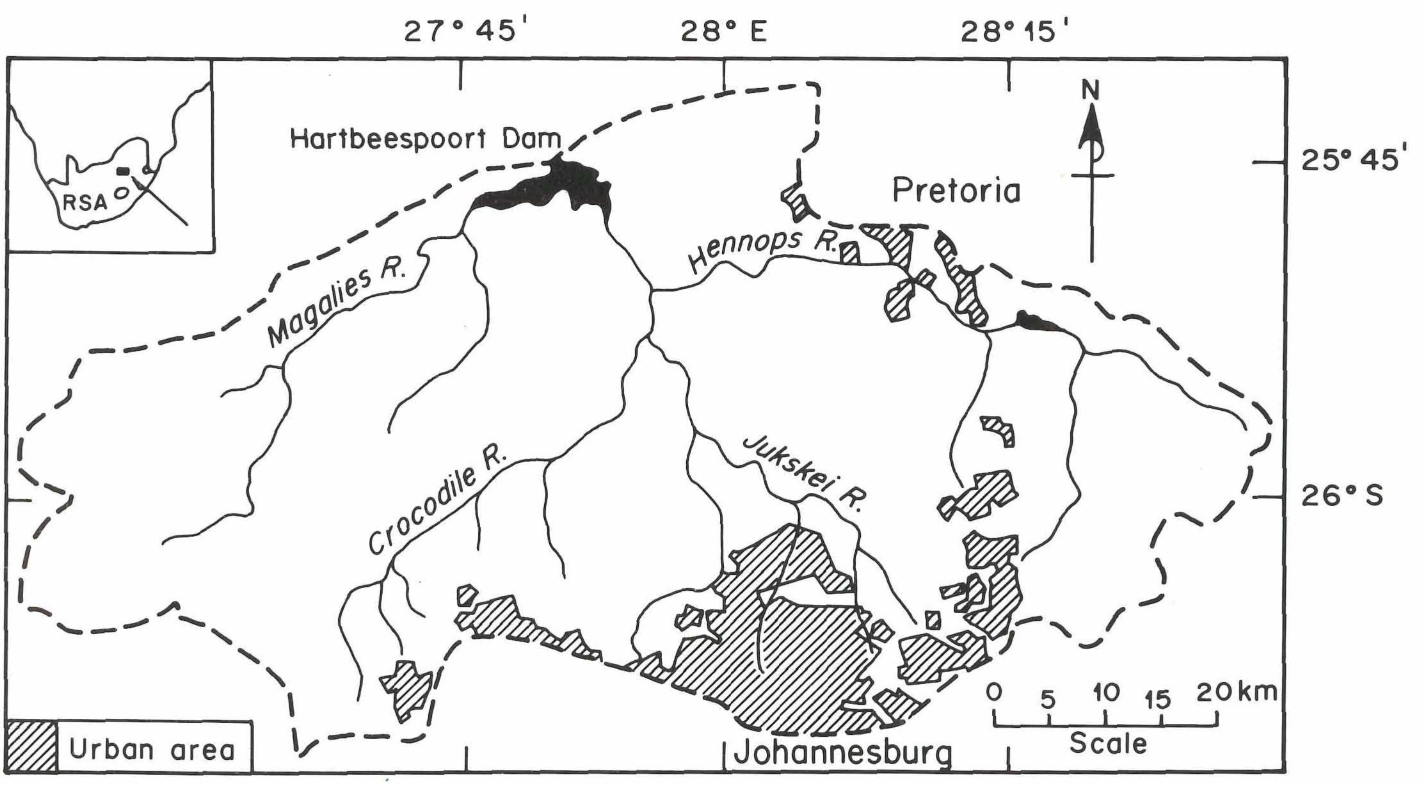
Bacteria are abundant in Hartbeespoort Dam, and at times total up to 44 million per millilitre of water. They are very small in comparison with bacteria in other lakes, and as such are not a major food resource for filter-feeding zooplankton. However, they are the main decomposers of dissolved and particulate organic matter originating from algae, zooplankton and fish. This process of decomposition releases phosphorus and nitrogen into the water.

There is a prolific growth of algae during much of each year because of the over-abundance of plant nutrients in Hartbeespoort Dam water. Large quantities of the blue-green alga *Microcystis aeruginosa* are usually present in the lake for a period of six to ten months of the year. This *Microcystis* forms large masses or 'scums', which are transported around the lake according to changes in the wind. Huge accumulations, called 'hyperscums', occasionally form in the Crocodile River arm of the lake, or at the dam wall. These hyperscums can be as much as a metre thick, and may cover several hundred square metres. They gradually decompose and produce strong, unpleasant odours which are carried over a wide area.

The *Eichhornia crassipes* plants, or water hyacinths as they are commonly known, which once covered much of Hartbeespoort Dam, were removed by herbicides in 1977/1978 and are now kept under control by local authorities. Without this control they would soon reclaim the lake's surface.

Hartbeespoort Dam's zooplankton population is large in comparison with that of other lakes, but small in relation to the amount of algae which are their primary food resource. *Microcystis* colonies are too large to be consumed by zooplankton. The small size of the bacteria and the low concentrations of detritus (dead organisms and particulate organic matter) make these poor alternative food sources. In fact, when *Microcystis* colonies are abundant, they actually lower zooplankton feeding rates by interfering with efficient filter-feeding processes. The zooplankton population reaches its highest levels in the two months of the year when *Microcystis* does not dominate the algal population, and when there are larger quantities of smaller algae on which they can feed. Therefore the zooplankton do very little to assist in the control of *Microcystis* and scum accumulation in Hartbeespoort Dam.

There are large quantities of fish in Hartbeespoort Dam. Ninety per cent consist of blue kurper, catfish and carp, which survive because of their ability to live in hypertrophic waters. These fish tend to feed on the lower sediments and on animals living in these sediments. The predatory black bass and yellow fish, which are important angling species, cannot live in the lake. Estimates of total fish stocks present in the reservoir have approached 1 400 tonnes. Carp account for 65 per cent of the angler's entire catch. Fish-kills, which are due to water temperatures falling below 12° Celsius, can have a major effect on the blue kurper young-of-the-year. Using a mathematical model, predicted fish yields (maximum harvests) are 170 tonnes per year for blue kurper, 375 tonnes per year for carp, and 25 tonnes per year for catfish.



The catchment of Hartbeespoort Dam. Inset shows position in southern Africa.

The Hartbeespoort Dam ecosystem model

During the course of this study of phosphorus cycling in Hartbeespoort Dam, a mathematical model of the lake ecosystem was developed. This ecosystem model, which is called TROFIC, was designed to:

(i) promote integration of the multi-disciplinary research programme;

(ii) summarize our knowledge of ecosystem processes and nutrient pathways;

(iii) quantify phosphorus cycling in the lake; and

(iv) permit the evaluation of various management options aimed at alleviating problems associated with the over-enriched condition of the reservoir.

To run, the model requires input data on the phosphorus load entering the lake, and information on the volumes of water entering and leaving the reservoir, in addition to data concerning the climate. The basic components of the model are shown in the diagram. TROFIC simulates the flow, or cycling, of phosphorus between the water, sediments, and organisms of the lake. It can be used to make various predictions, including the amount of phosphorus in the water, and the abundance of algae. The model is structured so that it can simulate different environmental conditions, and it can therefore be used to test various lake management strategies aimed at improving conditions in Hartbeespoort Dam. TROFIC can also make predictions regarding the likelihood of success for proposed rehabilitation strategies.

Lake management

It has been estimated by using TROFIC, that Hartbeespoort Dam will take approximately seven years of normal inflow to respond fully to a reduction in the phosphorus load of 75 per cent (equivalent to full implementation of the 1 mg/litre phosphate standard). But phosphorus and chlorophyll concentrations will remain at levels typical of enriched or eutrophic lakes.

Studies of phytoplankton population dynamics in the reservoir have demonstrated that the calm climate and stable water column enhance the proliferation of blue-geen algae. Hypothetical rehabilitation of the lake by mixing the surface and deep waters artificially (aeration and destratification) has been examined, using the ecosystem model. TROFIC indicates that the amount of algae in the lake will decline in proportion to the amount of vertical mixing introduced. If buoyant blue-green algae no longer remain the most abundant form under the new conditions, then zooplankton grazing on more edible algal forms can further reduce the amount of algae present. TROFIC has also indicated that direct manipulation of the various fish populations (biomanipulation), is unlikely to be successful in reducing the amount of algae in such an enriched, or hypertrophic lake.

Another management option which was brought to light by the study, was the flushing downstream of scums which form at the lake wall late in autumn. In this way the winter *Microcystis* population would be drastically reduced, and hyperscum formation would be prevented. However, the consequences of such treatment on downstream water quality would need investigation.

Products and achievements

Publications

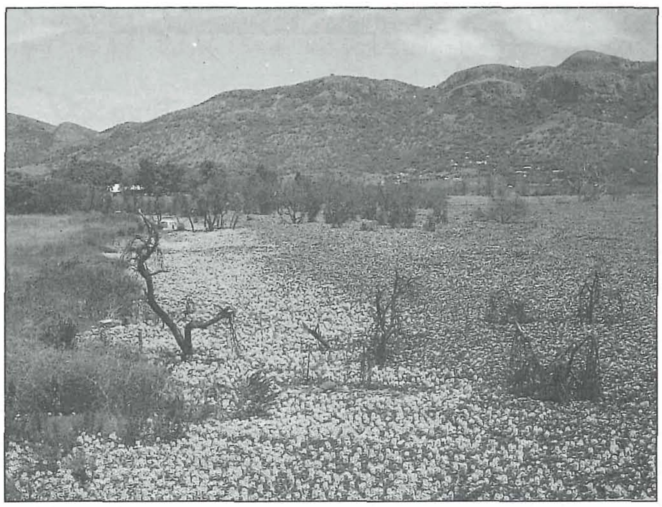
To date, 97 articles, which were fully or partially based on work originating from the Hartbeespoort Dam Ecosystem Programme, have been published in international journals. Three Ph.D. theses have originated from this programme and a fourth one is almost complete. Twenty-six additional articles have appeared in popular magazines, as reports, or as chapters in the proceedings of scientific symposia (see Appendix).

Programme spin-offs

The Hartbeespoort Dam programme is a model study of hypertrophy and its effects on lake biology and chemistry. Nutrients are so abundant in the reservoir that algal growth rates are not restricted at any time of the year, and the lake has therefore served as a natural laboratory in which the effects of physical factors on the biota could be investigated. The studies of Hartbeespoort Dam have demonstrated the upper limits of algal biomass; the rates of photosynthesis which can be attained in freshwater lakes, and the way in which light availability and temperature regulate these upper values.

The programme introduced an ecosystem modelling approach to South African limnology. This emphasized the importance of quantifying direct and indirect interrelationships between different organisms, and between the organisms and their environment.

The Hartbeespoort Dam Programme was the largest lake ecosystem research programme to have been carried out in Southern Africa. It has produced one of the longest and largest data bases for freshwater ecosystems. The data have been used extensively to test eutrophication models which were developed both locally and overseas, and to evaluate theories and hypotheses on the response of organisms to excessive nutrient enrichment. The data are stored on computer files and are available for use in a wide range of future applications.



Marginal flowering zone of water hyacinth (December 1977).

An important consequence of the Hartbeespoort Dam study is a change in the scientific concept of hypertrophy. Previously, Dr J Barcia of Canada had described characteristic hypertrophic systems as shallow, small water bodies which alternate between phases of extremely high algal biomass and productivity, and stages of massive die-offs in these populations, followed by oxygen depletion and, frequently, severe loss of fish life. However, the Hartbeespoort Dam study has demonstrated, among other things, that hypertrophic systems are not necessarily small and shallow, and that they may be much more stable than was previously imagined.

Subtropical Hartbeespoort Dam is subject to semi-arid climatic conditions with summer rainfall, high solar radiation, and low-speed winds. These conditions make it different from the more commonly studied temperate lakes, and for this reason the eight-year data base is unique and of value to the international scientific community. Results obtained from Hartbeespoort Dam demonstrate that principles developed in temperate lakes must often be carefully modified before they can be applied to subtropical lakes.

The Hartbeespoort Dam Ecosystem Programme members have participated in many conferences and workshops overseas, and the programme itself has contributed to an improved international image of the study of inland waters, or limnology, in South Africa.

New methodologies developed

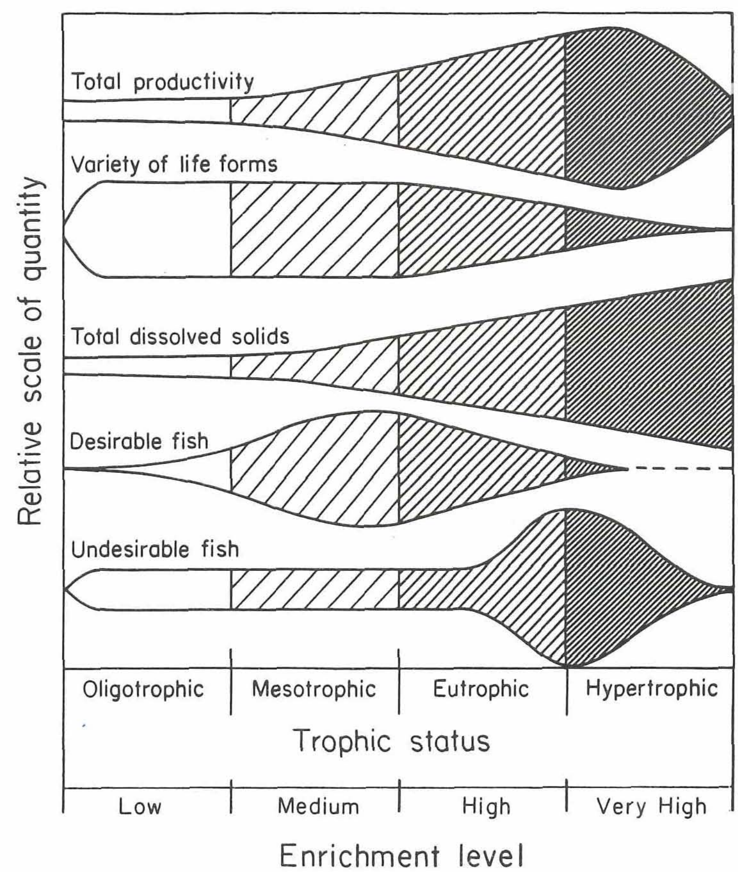
- A method for extraction and purification of radioactive-labelled DNA from aquatic bacteria.
- A method for measuring zooplankton feeding rates on size-fractionated radioactive-labelled algal colonies and on natural, free-living bacteria cells under hypertrophic conditions.
- The design of hose-pipe samplers for the accurate sampling of buoyant algal populations.
- The design of a gravity sediment corer with a continuous-flow adaptor, for studies of chemical exchanges between the sediment and the water above.
- Methods for sampling algae and interstitial water taken from hyperscums.

The Hartbeespoort Dam video programme

Hartbeespoort Dam – A Story of a Hypertrophic Lake, is the title of a 14-minute video programme produced by the Hartbeespoort Dam team. The video illustrates the worst aspects of hypertrophy: uncontrollable growth of aquatic weeds, and massive blooms and hyperscums of blue-green algae. This video has been shown at many local and international scientific meetings, and at various universities and research organizations throughout the world.

Prospects for the future

Many of Southern Africa's water supply reservoirs are becoming more and more enriched as a result of man's population growth and his varied activities. The detailed ecosystem study of hypertrophic Hartbeespoort Dam has elucidated many of the important processes and consequences of excessive enrichment. This timeous gathering of data and information can be of increasing value for the successful future management of our environment and our water supplies. Indeed, the Hartbeespoort Dam study showed that an improvement in water quality and a reduction in algal problems could be expected if the water column were to be mixed artificially by aeration. At the same time it indicated that other in-lake management options, such as the introduction of algal-eating fish in order to reduce algal abundance, would be unlikely to have the desired effect. Similar studies are likely to be required in the future as our environment is challenged by new and greater stresses.



Likely changes in a selection of lake characteristics with increasing enrichment.

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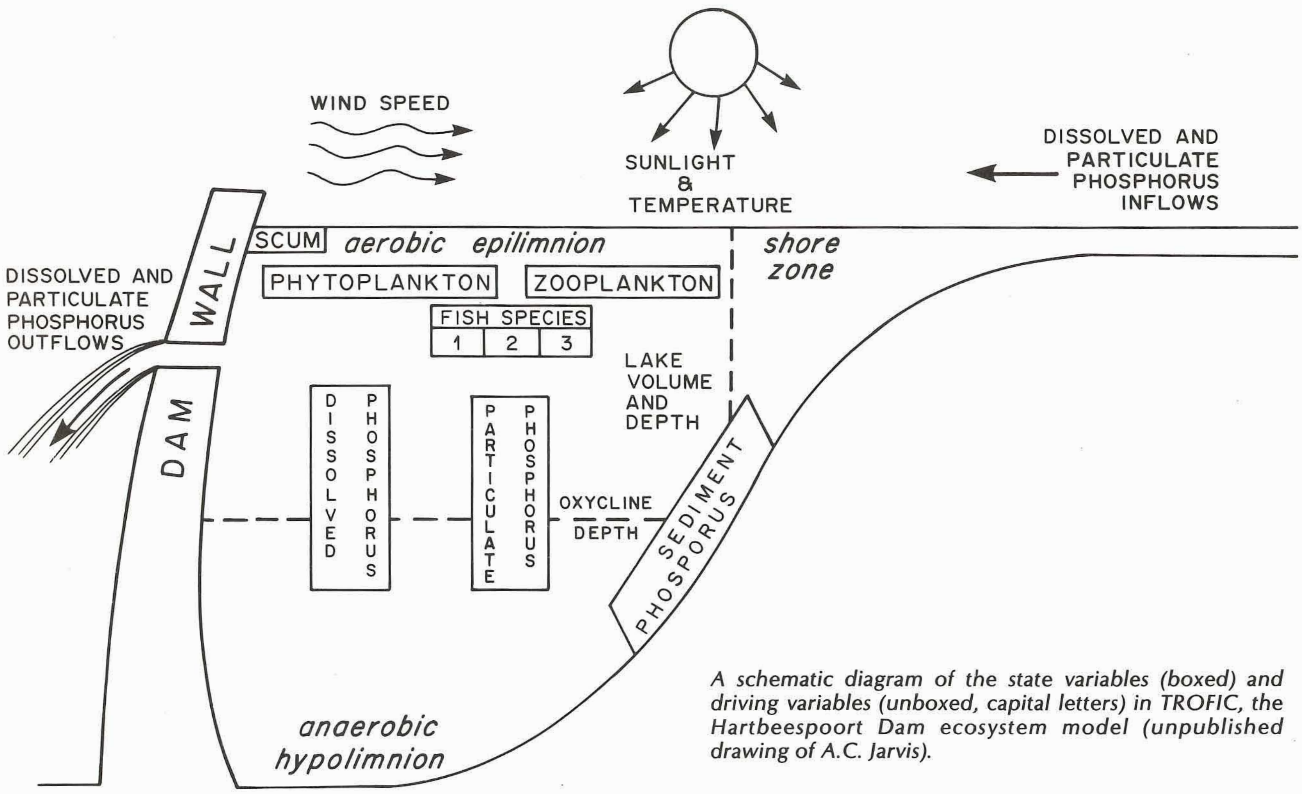

A schematic diagram of the state variables (boxed) and driving variables (unboxed, capital letters) in TROFIC, the Hartbeespoort Dam ecosystem model (unpublished drawing of A.C. Jarvis).

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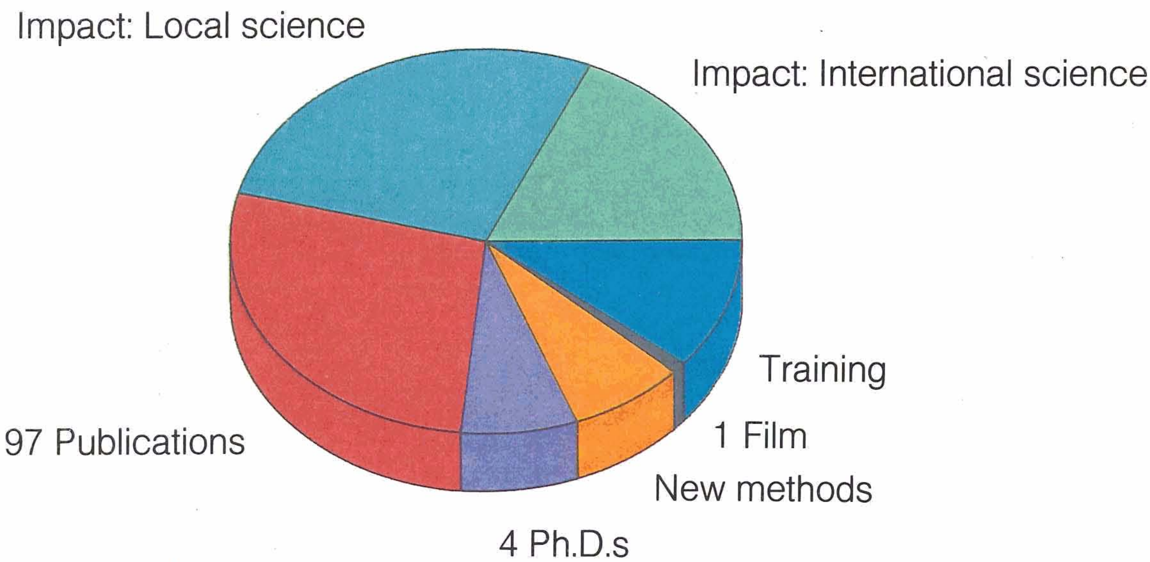
Microcystis hyperscum at the dam wall.

Microcystis hyperscum.

PRODUCTS OF HARTBEESPOORT DAM ECOSYSTEM PROGRAMME



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