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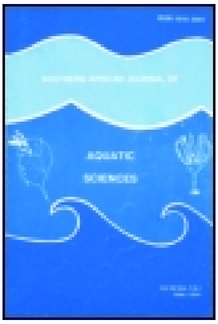

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MANAGEMENT OPTIONS FOR SHALLOW HYPERTROPHIC LAKES, WITH PARTICULAR REFERENCE TO ZEEKOEVLEI, CAPE TOWN

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MANAGEMENT OPTIONS FOR SHALLOW HYPERTROPHIC LAKES, WITH PARTICULAR REFERENCE TO ZEEKOEVLEI, CAPE TOWN

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Summary

Zeekoevlei, a freshwater coastal lake, is an important regional recreation area in the south-western Cape, South Africa. The lake is hypertrophic, experiences perenially dense populations of cyanobacteria (*Microcystis*), invasive bulrush and reed encroachment, and has a thick benthic layer of sediments rich in organic matter. User and scientific surveys have indicated that management problems centre around the dense phytoplankton population and the nutrient loading of the lake. Both in-lake and catchment-based management options for improving the water quality of the lake were evaluated. Given the present socio-economic constraints in South Africa, only catchment-based management can be recommended before any rehabilitation measures are undertaken in the lake itself. This would entail the investigation and implementation of measures to reduce levels of catchment-derived nutrient loading by managing the water quality of agricultural (predominantly horticulture) and urban catchment runoff.

Introduction

Zeekoevlei (34°04'S, 18°31'E), a freshwater coastal lake, is situated on the sandy Cape Flats of Metropolitan Cape Town (Figure 1). Because it is surrounded by urban development the lake has been subjected to massive anthropogenic perturbation, in terms of both nutrient loading and water level regulation. Zeekoevlei is also an important regional recreation area, forming part of a proposed Recreation Park for Metropolitan Cape Town (Quick and Thornton 1991). The main recreational uses include power boating, skiing, yachting, windsurfing, canoeing, fishing and picnicking (Quick and Johannson 1992).

To the detriment of its recreational function, the lake experiences dense algal blooms, encroachment of bulrushes and reeds along the shore and shallow areas, and has a thick benthic layer of sediments of algal origin (Harding 1991, Quick and Johannson 1992). Thornton *et al* (1989), Thornton and McMillan (1989) and Quick and Johannson (1992) have shown that the influence of water quality on user-avoidance is inversely correlated to the visual appearance of the waterbody. The presence of "pea-soup green" water, accumulations of malodorous decaying algal cells and the build-up of sediments rich in organic matter lead to user avoidance with the associated problems and implications for water quality managers (Bruwer 1979, Chutter 1989).

Using information from the Cape Town City Council (CCC) and the Western Cape Regional Services Council (RSC), from biological and physico-chemical research (Harding 1991, 1992a), and a user survey (Quick and Johannson 1992; Table 1), this paper identifies the priority management concerns in Zeekoevlei. A literature review of general management options for shallow eutrophic lakes follows, with particular reference to appropriate management recommendations for Zeekoevlei.

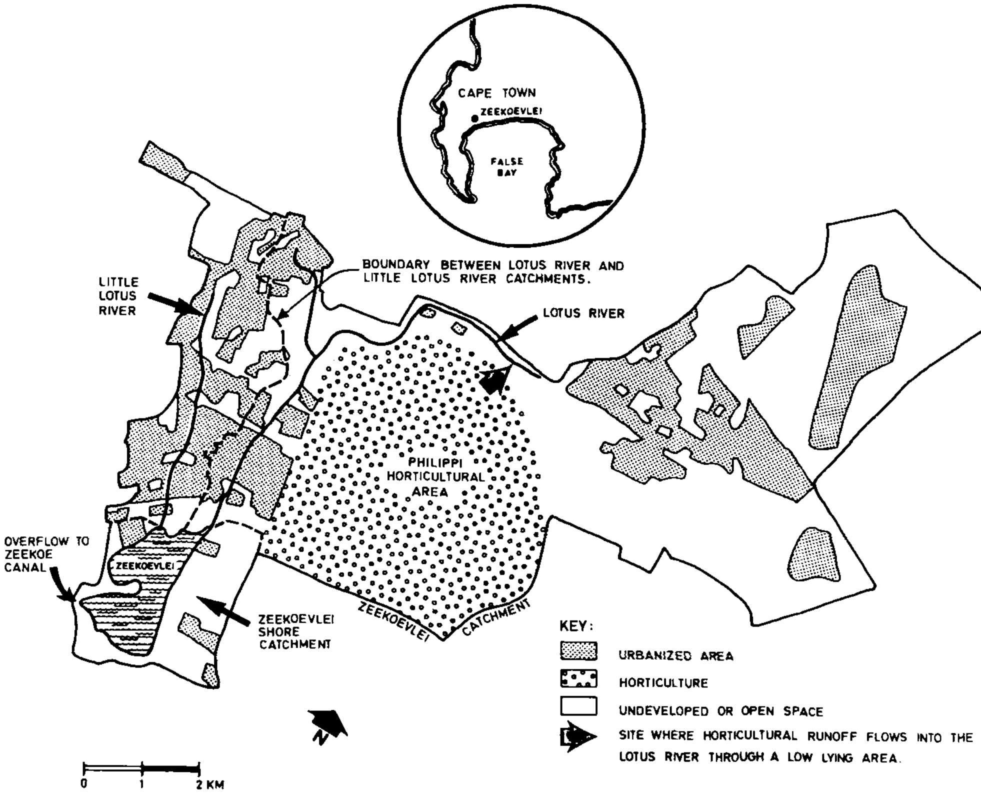

Figure 1. Zeekoevlei and catchment, showing influent rivers, urbanised area and the Philippi horticultural area.

Description of Zeekoevlei and historical review

Zeekoevlei is a shallow (mean depth 1.9 m) hypertrophic lake with a surface area of 256 ha (Figure 2). Water residence time has been estimated to be 0.25 y (I.Morrison, CCC, pers. comm.). Typical water quality conditions in Zeekoevlei and influent rivers are given in Table 2 and are summarised below.

Mean annual nitrogen and phosphorus concentrations in the lake are 3.60 mg l^{-1} and 0.55 mg l^{-1}, respectively, and open-water chlorophyll *a* concentrations reach 600 μg l^{-1} with a mean of 200 μg l^{-1}. The lake is fed by two nutrient-rich rivers, the Lotus and Little Lotus, which drain a combined catchment of approximately 8000 ha (Figure 1). Typical mean flows, and total nitrogen and total phosphorus concentrations in the Lotus and Little Lotus Rivers for 1986-1990 are: 14 600 Ml y^{-1}, 2.87 mg l^{-1}, 0.54 mg l^{-1}, and 2 600 Ml y^{-1}, 1.94 mg l^{-1}, 0.23 mg l^{-1}, respectively. Estimated riverine

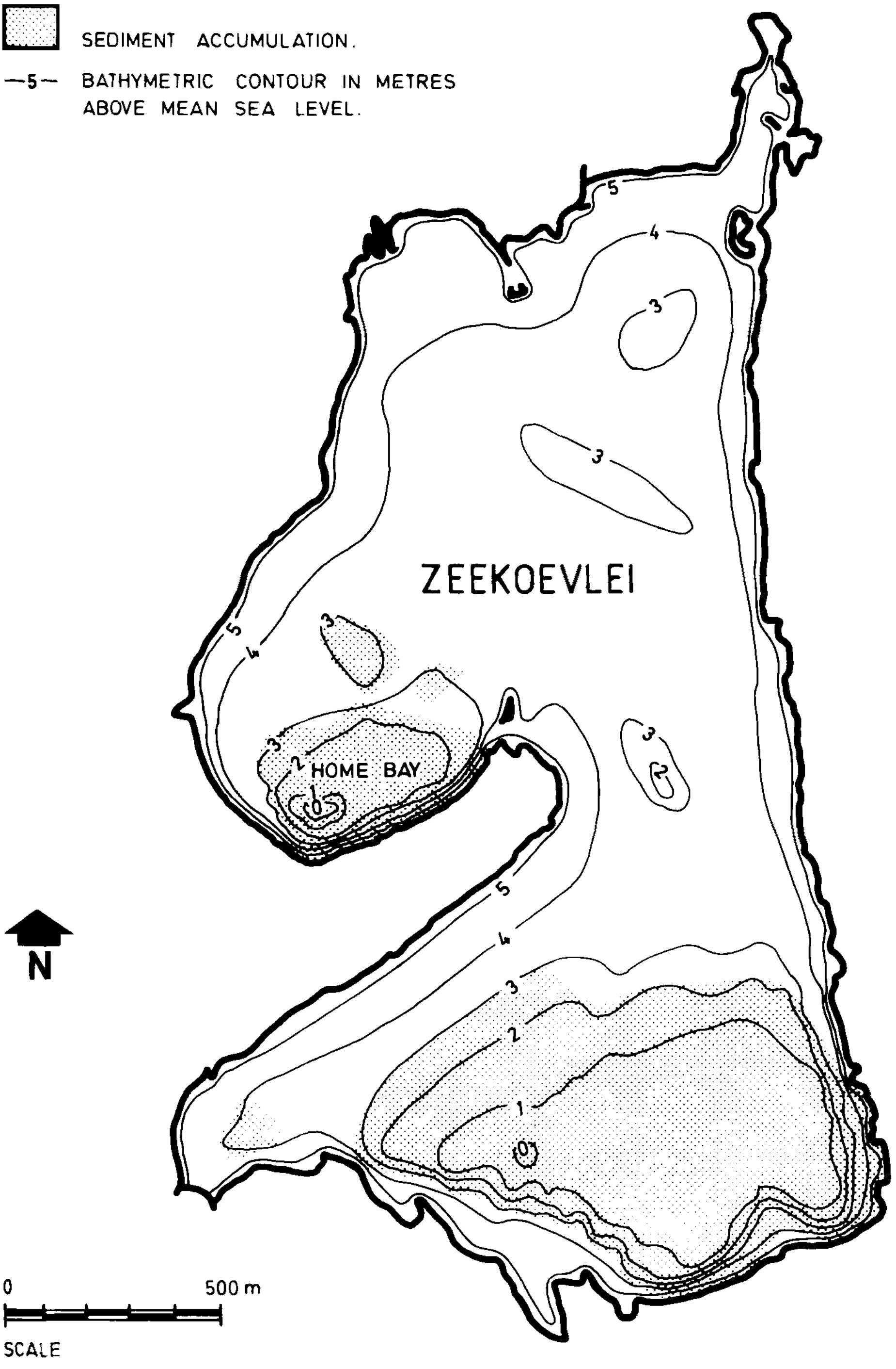

Figure 2. Bathymetry of Zeekoevlei and areas of sediment accumulation. (Approximately 120 000 m^3 of sediment have accumulated in the Home Bay area, and 883 000 m^3 in the south of the lake.)

Table 1. Water quality problems as identified by researchers (Harding 1991, 1992a) and a user survey (Quick and Johannson 1992).

Problem	% of users concerned*	Cause
Odour	60	decomposing cyanobacterial scums and accumulated sediments
Colour	50	dense phytoplankton populations
Appearance	49	phytoplankton growth and floating debris
Silt/mud	28	accumulated sediments primarily of cyanobacterial origin
Litter	26	wind blown debris, littering, and pollution of influent rivers
Invasive macrophytes	16	dense growth of reeds and bulrushes along the shore, and water hyacinth in sheltered areas of the lake
Obstacles in water	12	various
Taste	12	phytoplankton, and accumulated sediments
Other	5	various

* N = 1484

nutrient loads, based on mean, flow-weighted, concentrations of total nitrogen and phosphorus are 85 tonnes of nitrogen and 10 tonnes of phosphorus per annum.

The combination of high nutrient loading rates, high incident solar radiation (long mean day length of 8 h), and diurnal mixing of the water column has resulted in dense populations of cyanobacteria occurring in Zeekoevlei (Harding 1992a). The hypertrophic conditions, coupled with the consistently low N:P ratios (<10:1 by mass) are characteristic of systems where the phytoplankton is dominated by cyanobacteria (Walmsley and Butty 1980, Barica 1981, Thornton 1987).

In addition, encroaching stands of bulrushes and reeds occur along the entire shoreline, and substantial quantities of organic sediments have accumulated within the basin. Field studies by the CCC in 1989 showed that this sediment occupies approximately 20% (1.1 x 10^6 m^3) of the original lake volume of 5 x 10^6 m^3, and reaches depths of up to 3 m in certain places (Figure 2). Sediment is estimated by the CCC to be accumulating at a rate of 35 000 m^3 y^{-1}. Investigations into the nutrient dynamics of Zeekoevlei are still in their early stages. Initial estimates from unpublished CCC data give an internal loading rate of orthophosphate in Zeekoevlei of 8500 kg y^{-1} (R. Dick, CCC, pers. comm.). This is similar to conditions in the hypertrophic reservoir Hartbeespoort Dam (SA National Institute for Water Research 1985).

Harrison (1962) and Bickerton (1982) reported that cyanobacterial algal blooms did occur in Zeekoevlei from time to time in the past. However, hydraulic flushing and occasional drying out phases of the lake served as natural mechanisms to reduce the phytoplankton biomass and to allow sufficient light for the rooted hydrophyte *Potamogeton pectinatus* to become established (Harrison 1962). Thus, the lake cycled between periods of algal and macrophyte dominance.

The historical development of permanent cyanobacterial dominance in Zeekoevlei has been described in detail by Harding (1991). During the past half-century increased use of fertilizers to support intensive horticultural activities, and large-scale catchment urbanization including low income and sub-economic housing components, have contributed to nutrient loading to the lake (information from the Cape Town City Council; see Figure 1). The implementation of water level control, through the construction of a weir in 1948, combined with large-scale herbicide control of submerged hydrophytes, have reduced the effects of flushing, increased water retention time and effectively eliminated the natural periodic cycling of phytoplankton and macrophyte flora in Zeekoevlei (Bickerton 1982, Harding 1991).

Table 2. Water quality of Zeekoevlei and influent rivers during the period April 1989 to March 1991 (for methods see Harding, 1992a).

Parameter	Zeekoevlei Mean ± SD	n	Lotus River Mean ± SD	n	Little Lotus River Mean ± SD	n
Temperature (°C)	17.7 ± 3.7	202	18.6 ± 5.0	49	18.7 ± 4.9	35
Dissolved Oxygen (mg l^{-1})	9.6 ± 1.45	225	9.9 ± 3.0	46	9.6 ± 2.6	32
Oxygen saturation (%)	101 ± 17	219	106 ± 44	46	102.4 ± 34	32
Water transparency (m)	0.28 ± 0.09	206	-	-	-	-
Suspended solids (mg l^{-1})	59 ± 25	96	15 ± 23	22	17 ± 17	17
pH	9.5 ± 0.52	202	8.2 ± 0.4	48	8.1 ± 0.6	32
Conductivity (mS m^{-1})	131 ± 27	206	133 ± 26	49	78.5 ± 15	35
Kjeldahl-N (mg l^{-1})	3.6 ± 1.3	107	2.2 ± 1.5	24	2.6 ± 4.5	17
Ammonia-N (mg l^{-1})	0.10 ± 0.21	105	0.26 ± 0.43	24	0.52 ± 0.96	17
Nitrate-N (mg l^{-1}) *1	0.14 ± 0.59	105	2.80 ± 2.08	23	1.80 ± 1.06	17
Total-P (mg l^{-1})	0.55 ± 0.22	107	0.64 ± 0.40	24	0.53 ± 0.49	17
Soluble-P (mg l^{-1}) *2	0.16 ± 0.22	100	0.40 ± 0.35	24	0.31 ± 0.31	17
Ortho-P (mg l^{-1})	0.13 ± 0.21	109	0.34 ± 0.33	24	0.25 ± 0.26	17
Reactive silicon (mg l^{-1})	0.44 ± 41	80	2.50 ± 1.87	20	3.70 ± 2.67	13
Total alkalinity (mg l^{-1})	147 ± 30	92	221 ± 42	22	129 ± 16	15
Chlorophyll *a* (μg l^{-1})	217 ± 120	151	-	-	-	-

SD = standard deviation, n = number of samples/readings

*1 Nitrate-N expressed as sum of nitrite and nitrate-N

*2 Soluble-P = total filterable phosphorus

The Zeekoevlei phytoplankton is now dominated year-round by *Microcystis* spp., with genera of Chlorophyta and diatoms showing muted sub-dominant population maxima during the summer and winter, respectively, and Cyanophyte blooms occurring during the early spring (Harding 1992a; Figure 3).

The physical, chemical and biotic conditions which promote dense populations of cyanobacteria in freshwater lakes, with particular reference to Zeekoevlei, are summarized in Table 3. A study by Harding (1991) provided further insight into the mechanisms which may have been operating in Zeekoevlei during past years. Zeekoevlei experienced *Microcystis* maxima during the spring seasons of a two year (1989 to 1991) period. These maxima occurred at a time when incident solar radiation, water temperatures and concentrations of nitrogen and phosphorus in the lake were increasing, and wind speeds were low.

During winter and spring, most of the preconditions listed in Table 3 occurred in Zeekoevlei (Harding 1991). A large population of *Microcystis* cells was present in Zeekoevlei year-round. These formed thin surface layers and windrows, as well as dense scums in sheltered areas around the perimeter of the lake. The morphometry of Zeekoevlei provides natural, sheltered accumulation sites for *Microcystis* during windy conditions. These populations may seed the main lake body when conditions are more favorable (i.e. reduced turbulence). This occurs from mid-winter to mid-spring when relatively low wind speeds prevail (3 m s^{-1}), and by September mean hours of sunlight per day increase from a mid-winter minimum of 6.0 h per day.

The spring maxima of *Microcystis* populations in Zeekoevlei coincide with the seasonal peaks of soluble reactive phosphorus in the lake (Harding 1991, 1992a; Figure 3). Elevated algal crops have been related to phosphorus inputs in other waterbodies (e.g. Okada *et al* 1982, Garnier

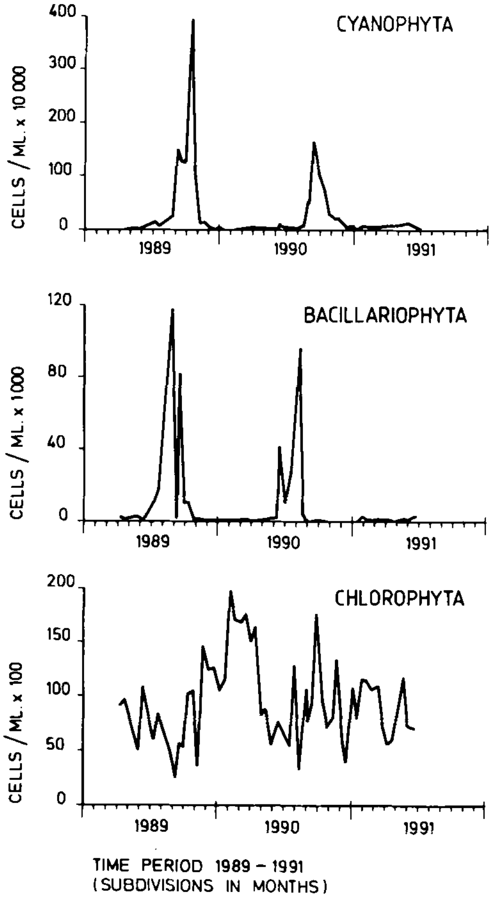

Figure 3. Population density of phytoplankton species in Zeekoevlei from January 1989 to December 1991 (note vertical axis scale difference). (From Harding 1992a.)

Table 3. Physical-chemical and biotic conditions that promote the development of dense cyanobacterial populations (after Paerl 1988, Zohary and Breen 1989), with particular reference to Zeekoevlei.

Physical-chemical or biotic condition	Occurrence in Zeekoevlei + = compliance - = non-compliance
1. Formation of nuisance "blooms"	
horizontally distinct water mass	+
vertically stratified water column	- (*1)
warm weather	+
high photosynthetically active radiation	+
enhanced allochthonous organic loading	+
enhanced allochthonous inorganic loading	+
biologically available metals	? (*2)
sui sediments for seed beds	+
algal - bacterial synergism	?
algal - micrograzer synergism	?
absence of macrograzer activity	+
2. Formation of scums	
large standing stock of cyanobacteria	+
buoyant species	+
low (relative) wind speeds	+
sheltered areas	+
high photosynthetically active radiation	+

(*1) Although Zeekoevlei is never vertically stratified, the combination of the shallow water column and regular mixing (diurnal) results in a reactor-type mixed situation where the cells of the *Microcystis* population do not become nutrient limited and spend long periods of time in the euphotic layer.

(*2) The year-round dense cyanobacterial population indicates that such metals are readily available in Zeekoevlei.

and Montesanto 1988), and sudden increases in cyanobacterial population have previously been significantly correlated with soluble reactive phosphorus concentrations (e.g. Chang and Rossman 1988).

Apart from nutrient inputs via the rivers, internal loading from the accumulated sediment in Zeekoevlei probably play a significant role in the supply of phosphorus (see internal loading rates earlier in this section, and also Cooke *et al* 1977, Turner *et al* 1983, and Otsuki *et al* 1981). Indeed, such a sediment-rich system has probably become self-sustaining (see Allanson *et al* 1990).

Management options for hypertrophic lakes and their applicability for Zeekoevlei

Several well documented options, and their advantages and disadvantages, exist for lake restoration (US Environmental Protection Agency 1980, 1990). However, the scale and adaptation, or combination, of methods necessary for a particular waterbody are usually site-specific and are dependent on the severity of the conditions. The EPA (1990) emphasise that the desired uses of a lake should be clearly defined early in the management process so that the appropriate restoration techniques are evaluated. In the case of Zeekoevlei, a user assessment study

Table 4. Potential sources of non-point nutrient loading to Zeekoevlei and control measures (modified after Novotny and Chesters, 1981).

	Potential source of nutrient loading						
Control measure	street surface/ parking areas/ pavements	undeveloped land/public open space	sewer malfunction	horticulture	informal housing	industry/ landfill runoff	construction sites
street sweeping	x						
litter collection	x	x			x		
dog litter control	x	x					
fertilizer control				x			
zoning controls		x				x	
control direct discharge of nutrients to storm drains				x		x	x
eliminate cross connections with wastewater sewers			x			x	
clean catch basins	x						x
clean stormwater sewers and drainage channels	x						x
direct runoff away from contaminated areas				x	x	x	x
store and treat nutrient-rich runoff *	x			x	x	x	x
grade parking areas and recreational lawns for temporary storage of runoff	x	x					
increase infiltration by using permeable surfaces and soakaways	x			x	x	x	x
effective sewer maintenance			x				
provide surfaced roads, sewage and stormwater systems					x		

*this can be achieved by diverting the first flush to the sewage system, using wet and dry ponding systems and using wetlands.

was conducted by Quick and Johansson (1992) before the present study was initiated.

Uttormark and Hutchins (1978) divided restoration techniques into three groups:

1. reduction of nutrient inflow;
2. disruption of internal nutrient cycles; and
3. acceleration of nutrient outflow.

These standard approaches, and their applicability in the Zeekoevlei context, are described below under the headings of "catchment" and "in-lake" options. Shallow lakes are generally more productive than deep lakes (US Environmental Protection Agency 1990), and shallow hypertrophic systems do not always respond to rehabilitation in the same way as deep stratified lakes. In particular, decreased nutrient loading has not always proved effective in decreasing phytoplankton populations as internal loading from the sediments may retard restoration (e.g. Ryding and Forsberg 1976, Willen 1987, Rossi and Premazzi 1991). Some deep lake options, such as hypolimnetic discharge or aeration, are not applicable to shallow systems such as Zeekoevlei and have been excluded from this discussion.

Mass-balance models have been used to improve the design procedures for lake management (see Welch 1984). Whilst such models have been proved capable of predicting general lake response to remedial treatment, they are less reliable in shallow lakes having large internal sources of phosphorus. Furthermore, the available loading and flushing data for Zeekoevlei are not accurate enough for models to be used with confidence.

Catchment options

1. Management of urban and agricultural runoff

Most of the water flowing into Zeekoevlei consists of agricultural and urban runoff (Figure 1), containing high concentrations of nutrients. The primary source of nutrient loading into Zeekoevlei has been identified as emanating from agricultural/horticultural activities in the Lotus catchment (Harding, unpubl. data; see Figure 1 for location). Chemical sampling of the Lotus catchment by the CCC in 1991/92 revealed that surface runoff from agricultural land is high in soluble reactive phosphorus (1.0 mg l^{-1}), and that at its point of entry to the Lotus River raises the mean soluble reactive phosphorus concentration by an average of 50% (from 0.512 to 0.775 mg l^{-1}).

Nonpoint nutrient pollution control measures can be divided into three broad groups: source control; collection control of runoff (e.g. temporary storage and infiltration) that reduces loading to receiving waters; and treatment of runoff. These are discussed in detail by Novotny and Chesters (1981), US Environmental Protection Agency (1987), Ellis (1989), and Smisson (1991). A summary of potential sources of nonpoint nutrient pollution in the Zeekoevlei catchment, and potential control measures is given in Table 4.

2. Biological treatment/wetlands and chemical treatment

The option of treating input water biologically in wetlands or treatment works (for the first flush only), or chemically (treatment works) before it enters the vlei are measures which have been used successfully on a man-made lake in Western Bohemia (Fiala and Vasata 1982). The required land space (for wetlands), and treatment plant costs (for chemical or biological treatment) limit the suitability of this type of option for the Lotus and Little Lotus Rivers directly upstream of Zeekoevlei.

However, there are areas of land adjacent to the Philippi agricultural area in the Lotus River catchment through which nutrient-rich runoff flows (see Figure 1). These low lying lands may be suitable for the construction of a wetland to "treat" or "polish" agricultural runoff prior to discharge into the Lotus River (see *Recommendations* below).

3. Nutrient diversion

The successful use of diversion techniques relies upon the availability of an alternative receiving water or treatment works into which the nutrient load can be diverted.

Lake Washington is regarded as a classic example of what can be achieved with nutrient diversion (Edmondson 1972, Edmondson and Lehman 1981). Loading of effluents reaching the lake were reduced to virtually zero over a five-year period by diversion to a treatment works. During the subsequent seven-year period, the water quality of this previously eutrophic system improved. In particular, nutrient levels were reduced, and phytoplankton biomass and the proportion of blue-green algae decreased.

In a second example, an 80% reduction in phosphorus loads to Shagawa Lake, Minnesota, resulted in 40-80% reductions in total and soluble reactive phosphorus concentrations; chlorophyll *a* concentrations decreased by over 50% (Larsen *et al* 1979). Similarly, diversion of sewage effluent from Lakes Waubesa and Kegonsa (Sonzogni and Lee 1974) resulted in considerable improvement in lake water quality.

No measurable reductions in total phosphorus, chlorophyll *a*, phytoplankton biomass or Secchi transparency were recorded in Lake Sammamish following the diversion of nutrients, though the blue-green algal component of the phytoplankton decreased by 50% (Welch 1977, Welch *et al* 1980). High, anaerobic release of phosphorus from the sediments was implicated in the maintenance of lake trophic stability.

In the case of Zeekoevlei, the Lotus River, which is responsible for most of the allochthonous nutrient loading of the lake, could be diverted, at great cost, to flow directly into the adjacent ocean. Apart from probable detrimental effects that these nutrients (and high faecal coliform counts (Harding 1992c)) would have on the water quality of the nearshore ocean environment, this option would have a marked effect on the hydraulics and water level of Zeekoevlei, and reduce its recreation function. "Topping up" of the lake from the adjacent wastewater treatment works would be counterproductive as nutrient levels in the effluent (flow 55 000 Ml y^{-1}, mean total total nitrogen 3.7 mg l^{-1}, and total phosphorus 3.9 mg l^{-1}) are higher than those in the Lotus River (Table 2).

4. Dilution and flushing

The option of dilution by introducing nutrient-poor water to a eutrophic lake requires the presence of a suitable source of water (Welch and Patmont 1980, Welch 1981). Flushing may be utilised to bring about "washout" of algal cells if sufficiently high flows can be achieved. Generally, flushing rates should exceed 10% of lake volume per day in order to be effective as a biomass control measure (Welch 1984). The mean annual flow from the wastewater treatment works adjacent to Zeekoevlei is only twice that of the annual riverine inflow, and peak flows on an annual basis only exceed 10% of the lake volume for 5% of the time. Therefore this is not a suitable management option for Zeekoevlei.

5. Education

Improved education of the catchment population regarding the causes of water quality problems is an essential part of any catchment management programme. Extensive on-going public education programmes are needed to emphasise the methodology and need for good catchment "house keeping". It should, however, be noted that education programmes are particularly difficult to effect in sub-economic and informal housing areas, such as those in the Zeekoevlei catchment.

6. Legislation

The application of wastewater phosphorus standards has been shown to be effective in reducing the nutrient loading flux into lakes (SA National Institute for Water Research 1985, Chutter 1989). However, a full discussion of the legislation affecting South Africa's waters is outside the scope of this paper. The status of South African water laws has been the subject of a recent symposium (see Southern African Society of Aquatic Scientists 1989). A recent positive move has been the decision to focus more attention on site-specific receiving-water standards for rivers, and translate these into limits for effluent disposal (SA Department of Water Affairs 1991). This policy will be implemented in South Africa in parallel with existing effluent discharge standards.

In-Lake Options

1. Dredging

The removal or inactivation of sediment nutrient sources from Zeekoevlei would be essential for reducing internal phosphorus loading and long-term improvement. This technique is regarded as most appropriate for lakes whose high phosphorus content and eutrophic state are sustained by an internal supply of phosphorus from bottom sediments, even after the inflow of phosphorus has been reduced (Welch 1984, US Environmental Protection Agency 1980).

Apart from its role as an internal nutrient source, the presence of the sediments in Zeekoevlei presents a physical hindrance to yachtsmen and waterskiers. In addition, odours (hydrogen sulphide) emanating from the sediments, especially on calm days, are objectionable, and low oxygen concentrations in sheltered areas result in occasional fish kills (Harding 1991).

A small scale dredging operation was conducted in Home Bay, Zeekoevlei during 1983 (Figure 2). An estimated 200 000 m^3 of material was removed, leaving a deep hole (depth 4m) in which future sediments could accumulate (W. Harding, unpubl. data). The dredging had no visible effect on water quality, and by 1989 the hole was once again full (Davies and Day 1986, Cape Town City Council bathymetric survey in 1989).

The cost of removing the sediment from Zeekoevlei was estimated during 1990 at R10 million and would necessitate a large-scale programme. With any dredging effort, the problems of transporting, storing, drying and disposal of the sludge have to be answered (Davies and Day 1986). The large amount of material in Zeekoevlei compounds the scale of this option. Complete removal of sludge should drastically reduce the internal nutrient loading and lead to a subsequent decrease in overall phytoplankton numbers and an increase in water clarity (US Environmental Protection Agency 1980). Improved water clarity would then promote the re-establishment of rooted macrophytes.

However, this would only be a relatively short-term measure if the influent rivers, in their present nutrient-enriched state, continue to load the lake with nutrients (Keize and Sinke 1992). Overall, in-lake phosphorus concentrations might be lower than at present but, with time, the system would return to the state that existed in the pre-dredging era. At the present rate of accumulation of 35 000 $m^3 y^{-1}$, it would take approximately 30 years. Therefore, the long-term success of any dredging option will be dependent on the parallel control of the external nutrient sources (Davies and Day 1986).

An alternative to large-scale "once-off" dredging would be a long term, small scale "continuous" programme. This would prolong the time required before any noticeable improvement would be apparent and would invite public criticism. In addition, the economies of scale gained with a large-scale programme would be lost in a small-scale long-term project (M. Lief, CCC, pers. comm.)

The disadvantages of large-scale dredging include cost, temporary phosphorus release from the sediment, increased phytoplankton productivity, noise, lake drawdown, temporary reduction in benthic fish food organisms, the potential for toxic material release to the overlying water and the potential for environmental degradation at the dredged material disposal site (Peterson 1982). With a small-scale dredging operation all these factors would be reduced in scale.

2. *Sediment treatment*

The bottom sealing/nutrient (phosphorus) inactivation of sediments, using low or non-toxic chemical or mineral additives such as lime, alum or ferric chloride, is a relatively inexpensive option, but would obviously not accommodate all the Zeekoevlei water-users because the sediment would still be present in the lake. Sanville *et al* (1976) suggested that this type of treatment may be required in shallow lakes, despite continued loading of the system with nutrients.

Cooke *et al* (1982) applied aluminium sulphate, following nutrient diversion, to two lakes, and recorded an increase in water transparency with a concomitant decrease in algal biomass. No deleterious side-effects were observed. Francko and Heath (1980) found that alum was unable to remove complex phosphorus compounds from the water column itself. Alum treatment of a shallow lake (mean depth 2 m), and approximately half the area of Zeekoevlei, curtailed phosphorus loading and blue-green algal dominance for a one-year period (Welch *et al* 1982). Return of macrophytes, and their subsequent decay, was attributed as being the reason for the recurrence of internal phophorus loading (Welch *et al* 1982).

In-lake nitrogen fertilization could be employed to increase the N:P ratio to one which would promote the growth of a different phytoplankton assemblage. This costly technique, requiring frequent re-dosing, has met with mixed success in other parts of the world (Lathrop 1988, Schindler 1975). Shapiro *et al* (1983) showed that in a total of 70 experiments, pH-lowering resulted in a shift from blue-green algae to green algae, principally *Scenedesmus* spp.

3. Biological treatment

Biological (biomanipulatory) controls, other than harvesting, are seldom used as restoration options (Shapiro *et al* 1983), although the impact of biotic interactions has been found to be significant in a number of cases (van Liere *et al* 1990, Leah *et al* 1980). Recent studies have shown that fish removal in shallow lakes frequently results in decreased turbidity, increased macrophyte populations and significant reductions in algal standing stocks (Gophen 1990a and 1990b, McQueen 1990).

Keating (1976) showed that extracellular products of bloom-forming algal species play a significant (allelopathic) role in the bloom sequences of eutrophic waters. Furthermore, the inhibition of diatom growth by blue-green algal metabolites may be a widespread freshwater phenomenon. Keating (1976) proposed a strategy for bloom control, incorporating the elimination of winter blue-green algal blooms using algicides such as copper-sulphate, and the enhancement of diatom growth by the addition of silica.

According to Hecky and Kilham (1988) some freshwater diatom species outcompete other algal groups for nitrogen and phosphorus when adequate silica is available. Zeekoevlei has a low (<1:1) silica to phosphorus ratio (Table 2), and therefore the manipulation of silica concentrations could promote a phytoplankton assemblage with a higher proportion of diatoms.

Fish may contribute markedly to the nutrient cycling of lakes (Bork *et al* 1979). For example, the elimination of bottom-feeding fish in Lake Marion (172 ha; mean depth 1.98 m) revealed that fish excretion provided approximately half the total phosphorus input (88 mg m^{-2} y^{-1} out of a total of 172 mg m^{-2} y^{-1}) to the lake (Shapiro *et al* 1983). Reduced densities of planktivorous fish, and the concomitant development of dense cladoceran populations were shown to prevent the appearance of blue-green algal blooms in experimental ponds (Spencer and King 1987).

Other factors may also be implicated in the sediment release of phosphorus from the upper 0.5 m of sediments. For example, physical mixing caused by turbulence and gas ebullition, and bottom-feeding fish, such as carp, which disturb the sediments. The recreational use of motorboats have also been shown to increase turbidity and phosphorus concentrations in shallow lakes (Yousef *et al* 1980).

Zeekoevlei has large populations of carp (*Cyprinus carpio*) and Mozambique bream (*Oreochromis mossambicus*), which were estimated in 1977 to be 683 and 91 kg ha^{-1}, respectively (Hamman *et al* 1977). The harvesting of fish from Zeekoevlei as a method of removing phosphorus from the system should be investigated. An additional benefit of carp harvesting would be an improvement in water clarity, as carp are bottom feeders and continually stir up the sediments.

A secondary effect of removing carp

would be a decrease in nutrients which are resuspended with the sediments disturbed during bottom-feeding. It is unlikely that fish removal will increase the level of planktivore grazing, as *Microcystis* is inedible to most zooplankton, including those in Zeekoevlei (Jarvis 1987, Reynolds 1987, S.Combrink, CCC, pers. comm.).

Examples of successful lake restoration programmes

Lake Trummen (Sweden) presents an interesting example of what might be achieved with Zeekoevlei (Cronberg 1982, International Lake Environment Committee 1988). Lake Trummen is smaller than Zeekoevlei, being 100 ha in area, with a mean depth of 1.6 m and a volume of 1.26 million m^3. Water residence time was equivalent to 0.4 y, and the catchment area encompassed 13 km^2. Lake utilization included fisheries, tourism and recreation. Since the turn of the century, increases in the nutrient loads to this lake changed the trophic state from oligotrophic to eutrophic.

Annual cyanobacterial blooms (*Anabaena* and *Microcystis* spp) occurred, causing unsightly conditions, offensive odours and fish-kills. Excessive reed growth further complicated the situation. During the 1950s, wastewater (municipal sewage and industrial wastewater) diversions had no visible effect on the trophic conditions. A restoration programme (1970-1971), comprising suction dredging, removed 600 000 m^3 (including 50 t of total phophorus and 450 t of total nitrogen) of sediments from the lake to specially prepared depositing ponds (18.5 ha in area). The bulk of the macrophyte growth was also removed.

The total cost (dredging and other aspects) of the Lake Trummen project (SA Rands, 1990 equivalent) was of the order of R6 million. The result was a massive (85-90%) decrease in phytoplankton biomass, with the dominant blue-green algal population being reduced to 5% of the pre-restoration value. The improved light conditions, resulting from the decrease in algae biomass, allowed the re-establishment of submerged plants such as *Potamogeton* and *Nitella*. Concentrations of total phophorus and total nitrogen were reduced by 90% and 70%, respectively (total nitrogen was reduced from 6 - 7 to 1 - 2 mg l^{-1}, and total phophorus from 0.7 to < 0.1 mg l^{-1}; Bork *et al* 1979).

Lake Trummen is regarded as the first successful example of whole-lake restoration on a large scale and has drawn world-wide attention. The need to divert the nutrient rich inputs to the lake, followed by in-lake treatments mirrors the Zeekoevlei situation closely and provides an excellent example of what might be achieved in the latter, given the requisite financial input. Restoration of eutrophic shallow water lakes in the Netherlands over the past decade is currently being evaluated (Biro and Talling 1990, Van Liere and Gulati 1992).

In 1983 Princess Vlei, a small coastal vlei situated to the north-west of Zeekoevlei, was dredged. This appears to have dramatically altered the density of phytoplankton (Harding 1992b). While no variation in external nutrient-loading of the system was apparent, either prior or subsequent to the dredging operation, algal biomass levels in Princess Vlei, as estimated by Secchi disk transparency and mean concentrations of chlorophyll *a*, were significantly altered. Transparency increased from a mean depth of 0.17 m to 0.50 m, and mean chlorophyll *a* decreased from 270 to 50 $\mu g\ l^{-1}$ (Harding 1991).

Conclusions and recommendations

The rehabilitation of Zeekoevlei poses a difficult problem for those tasked with the formulation of a restoration plan. The hypertrophic conditions, coupled with excessive nutrient inputs from the catchment and the large volume of accumulated sediments, pose an enormous management problem. This is especially acute under the present socio-economic conditions in South Africa.

Both catchment- and lake-based management strategies are needed for Zeekoevlei. These should focus on removal of the accumulated sediments in the lake and a reduction in inflowing nutrient levels.

Funds are not currently available for a dredging programme. At this stage in South Africa's politico-economicdevelopment there are more pressing priorities such as job creation, housing and the provision of basic services. However, in the interim, a storage site, or use for the dredged sediments needs to be identified. Because of the large volume of nutrient-rich sediment in the lake, and heavy nutrient loading from influent rivers, Zeekoevlei is endowed with a resilience to any minor attempts to alter the phosphorus balance in the vlei such as phosphorus inactivation and bottom-sealing of the sediments, and biological harvesting. Such measures would only be practicable in conjunction with a dredging operation to remove the bulk of the accumulated sediments and management of the catchment to reduce nutrient loading from influent rivers. Hence lake-based options, on their own, are not considered feasible at the present time.

Catchment-based water quality management can and should be implemented. The most obvious first steps in this regard are:

1. Although a major point source input from agricultural runoff has been identified, further investigations are needed to determine if there are other point source inputs into the Lotus and Little Lotus River catchments.
2. A management plan is needed for the agricultural area which aims at both farmer education and the utilization of the wetland area through which the agricultural runoff discharges.
3. A management plan is needed for the present and future urbanized area of the Lotus and Little Lotus catchments. This should consider the measures described in this paper for managing urban runoff. In addition, a public education component which points out the sources of nutrient pollution, implications, and good house keeping measures which should be taken to minimise nutrient pollution should also be included.

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