Sources of phosphorus which give rise to eutrophication in South African waters*

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Abstract

Current knowledge on sources of phosphorus which give rise to eutrophication in South African waters is reviewed, as well as the factors controlling the relative contributions from different sources. Attention is focused on detergent phosphates as a controllable source. Initial cost-benefit estimates indicate that the costs associated with banning detergent phosphates will not be off-set by the benefits. Information needs and limitations in basic knowledge, particularly from the point of view of water resources management, are highlighted.

Introduction

Phosphorus is an essential element for all life. In aquatic ecosystems it is often the growth or yield limiting nutrient. For this reason control over phosphorus containing compounds*** in such systems presents a means of controlling the deleterious effects of eutrophication, viz. excessive and unwanted algal and plant growth (Toerien, 1977 and Walker, 1983). Phosphorus load control has been demonstrated internationally as one of the most effective ways of dealing with cultural (man-made) eutrophication, and is being successfully applied in the USA, Europe, Scandinavia and Japan (EWPCA, 1985). In South Africa the authorities legislated (Government Gazette, 1984a) phosphorus control by way of an effluent phosphate standard of 1 mg/ℓ dissolved ortho-phosphate (as P) for seven sensitive catchments.

In order to plan and implement a rational phosphorus load control programme, it is necessary to know the sources of phosphorus as well as their relative contributions. Sources of phosphorus may be divided into two categories i.e. point and nonpoint sources.

Point sources

Sewage and industrial effluents have been identified as the major point source contributors to the phosphorus load on the water environment in South Africa (Taylor *et al.*, 1984). The major sources of phosphorus in domestic wastewater are human excreta and synthetic laundry detergents. In a survey conducted by the authors, it was found that in South Africa human excreta accounts for about 50 to 65 per cent of the phosphorus load on wastewater treatment works and synthetic laundry detergents for the balance. (A report (Heynike and Wiechers, 1986) entitled *Detergent phosphates and their impact on eutrophication in South Africa*, which will give the details relating to the above reported findings, is currently being finalized). Other sources of phosphorus, such as industrial effluents discharging to municipal sewers, may cause deviations from these percentages.

Typical phosphorus concentrations for municipal wastewaters are listed in Table 1. Both the total phosphorus concentration as well as the distribution of the phosphorus forms vary significantly from location to location. These discrepancies are a result of the nature of the communities being served by these sewage works, as well as the different relative contributions of wastewaters from industry. The phosphorus content of human excreta is a function of dietary habits which in turn is a function of age, sex and race group. The average daily quantity of phosphorus derived from human excreta in South Africa is estimated at 1,3 g P per capita (Walker, 1985). The average daily quantity of phosphorus derived from household synthetic detergents is estimated to be about 1,0 g P per capita (Heynike and Wiechers, 1986). Industry can either add, or in the case of phosphorus deficient discharges, dilute the phosphorus concentration in municipal wastewaters (WPCF, 1983). Industrial wastewaters typically high in phosphorus include those generated from fertilizer production, feedlots, meat processing and packaging, milk processing and commercial laundries. Certain pulp and paper manufacturing processes discharge phosphorus deficient wastewaters.

Raw sewage contains a number of different phosphorus forms, *inter alia* organically bound and inorganic phosphorus, the latter includes simple ortho-phosphates and polyphosphates. The phosphorus containing compounds may be in a particulate, colloidal or dissolved form. The concentrations and loads of these various phosphorus forms arriving at a municipal works may vary diurnally, daily and seasonally. Typically, ortho-phosphate comprises 50 per cent or more of the total phosphorus in raw sewage (Table 1). Conventional activated sludge and biological filter wastewater treatment processes do not remove phosphorus to any significant extent, but increase the soluble ortho-phosphate content from 50 to about 90 per cent by transforming the organic and polyphosphates to ortho-phosphate (WPCF, 1983). This form is the easiest to remove by both chemical and biological means and is also the most readily available form for assimilation by algae and aquatic plants.

A wide range of processes exist for the removal of phosphorus from wastewater (WRC, 1984; 1985). Those most commonly in use are chemical removal (with ferric and alum salts) at biological filtration and conventional activated sludge plants, and biological removal where the Bardenpho, AO and Phostrip type activated sludge processes are used.

Total phosphorus loads from sewage works in the sensitive catchments have been estimated by the Department of Water Affairs (Grobler and Silberbauer, 1984). They reported measured loads for 1981, i.e. the period before the introduction of the effluent phosphate standard, as well as predicted loads, assuming the standard is enforced, at various times in the future, i.e. 1985, 1995 and 2000 (Table 2). Considerable reductions in the phosphorus load from sewage works (estimated for 1981) were

*Revised paper, originally presented at National Institute for Water Research/Institute of Water Pollution Control/Water Research Commission Symposium – "Impact of Phosphate on South African Waters" held at the CSIR Conference Centre, Pretoria, RSA on 22 November 1985.

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***"Phosphorus containing compounds" are referred to in an abbreviated form as "phosphorus" in this paper.

Received 2 December 1985.

TABLE 1
TYPICAL PHOSPHORUS CONCENTRATIONS IN MUNICIPAL SEWAGE (mg/ℓ as P)

City/Town and Works	Ortho-Phosphate	Total Phosphorus
Johannesburg*		
- Goudkoppies	3,6	8,0
- Olifantsvlei	4,5	8,1
- Northern Works	5,5	11,0
- Klipspruit	16,0	34,0
Pretoria, Daspoort**	7,5	10,5
Boksburg, Vlakplaats**	6,5	15,3
Cape Town, Cape Flats***	—	14,2
Pinetown, Umlaas****	7,0	12,2

*Johannesburg (1982)
**Wiechers *et al.* (1984)
***Ekama and Marais (1984)
****Kerdachi and Roberts (1985)

TABLE 2
ANNUAL TONNAGE OF TOTAL PHOSPHORUS DISCHARGED FROM WASTEWATER TREATMENT PLANTS TO RIVERS AND STREAMS IN SENSITIVE CATCHMENTS (AFTER DAVIDSON AND HOWARTH, SEE GROBLER AND SILBERBAUER, 1984)

Catchment	1981	1985	1995	2000
	Total Phosphorus (t P a^{-1})			
Lower Vaal River	1 093	331	504	634
Crocodile River	929	165	254	322
Umgeni River	330	49	73	108
Berg River	48	9	13	17
Buffalo River	29	6	9	11
Olifants River	20	22	18	22

anticipated as a result of the introduction of the effluent standard, e.g. 70 and 82 per cent reductions respectively for the Lower Vaal and Crocodile Rivers (Table 2). However, the impact of the standard will decrease in the long term due to the expected increases in population and development in these catchments and the concomitant increase in effluent volumes. By the year 2000 the phosphorus load reductions compared to loads estimated for 1981 were predicted to be 42 and 65 per cent for the Lower Vaal and Crocodile Rivers, respectively.

Sewage works usually discharge their treated effluents to rivers and streams, rather than directly to impoundments. Currently, however, problems experienced with eutrophication are mainly confined to impoundments, although there are exceptions such as the Vaal River (Wiechers and Best, 1985). For impoundments the major source of phosphorus is usually a river or tributary containing treated sewage effluent. There can be significant losses of phosphorus in river systems between the works discharge point and the point where the river flows into the impoundment. For example, a phosphorus mass balance for point sources discharging in the catchment of the Crocodile River System, flowing into the Hartbeespoort Dam, indicated that for the period March 1980 to April 1983 the total phosphorus input to this river system was 1 804 t of which only 863 t entered Hartbeespoort Dam (SSO, 1985). This reduction may be due to a number of factors such as losses through irrigation, chemical precipitation of phosphorus compounds in the river, adsorption onto sediments and assimilation by biota, as well as errors in load estimation (Simmons and Cheng, 1985).

Rivers receiving highly eutrophied effluents over long periods will probably have sediments which are highly enriched with phosphorus. With the introduction of the phosphate effluent standard the phosphorus load on the rivers will be significantly reduced. This may result in phosphorus release from the river sediments. Current knowledge in this regard, particularly for South African rivers, is very limited and does not allow satisfactory prediction of phosphorus losses or gains for management purposes.

Detergent phosphate

Synthetic laundry detergents in South Africa contain on average about 70 g P per kg detergent and hence comprise a primary source of phosphorus to the water environment. Since detergents are man-made products their manufacture and composition can be controlled. A number of overseas countries, for example the USA, Canada, the Netherlands, Switzerland and Japan have implemented detergent phosphate bans or reductions as part of their overall strategy to control phosphate discharge to the water environment (Heynike and Wiechers, 1986). Therefore, in South Africa where the authorities have already adopted a policy of controlling phosphorus by way of a special effluent phosphate standard, consideration of additional or alternative strategies such as detergent phosphate control appears to have merit.

The contribution of detergent phosphate to the total phosphorus load on sewage works in South Africa varies between 35 to 50 per cent, i.e. for a typical raw sewage total phosphorus of 10 mg/ℓ (as P), therefore, 3,5 to 5,0 mg/ℓ can be attributed to detergent phosphate. It is clear from these figures that a detergent phosphate ban could significantly reduce the phosphorus load on sewage works, but not to the level required to protect the aquatic environment from eutrophication-related water quality problems. Experience in the USA supports these findings, e.g. Maki *et al.* (1984) reported that detergent phosphate bans in various states in the USA did not reduce phosphorus to a level where it substantially improved the trophic status of lakes. Grobler and Silberbauer (1984) have come to a similar conclusion for South African impoundments. Consequently, the introduction of a detergent phosphate ban by itself will probably be of little value, but application of such a ban (or reduction) in combination with the effluent phosphate standard may hold potential for eutrophication control.

Since the 1 mg/ℓ effluent phosphate standard has already been promulgated and local authorities, industries and other effluent dischargers have already made very considerable investments in equipment and plant to remove phosphorus at sewage works, the question arises whether there is still a need to reduce the phosphorus load originating from detergents. Various factors are important in considering this question, i.e.:

- reduced phosphorus loads will be beneficial for biological phosphorus removal plants, since this technique has limitations as to the maximum amount of phosphorus it can remove. Many of the plants currently operating are able to remove significant quantities of phosphorus, up to 60 to 80 per cent of the total phosphorus load but still do not comply with the 1 mg/ℓ ortho-phosphate (as P) standard due to high total phosphorus concentrations in the incoming raw sewage;
- reduced phosphorus loads on chemical phosphorus removal plants will result in lower chemical requirements and less sludge, which in turn will reduce the cost of treatment;
- an argument used by the detergent manufacturers since the

start of the detergent phosphate debate in 1972, is that they cannot produce a phosphate-free product with a washing efficiency equivalent to currently available phosphate detergents, and that replacement products cost more. They remain adamant that it will cost the consumer less if phosphate is removed at the sewage works rather than from detergents (De Jong, 1985).

Estimates of costs and benefits associated with the banning of detergent phosphates in South Africa are given in Table 3. If the removal of the salts added by way of the chemicals used to remove detergent phosphorus from the wastewater is ignored, the cost-benefit ratio for banning detergent phosphate is expected to be 15:1. If salt removal is taken into account this ratio is estimated to be 3:1, i.e. it is still expected to be in favour of not banning detergent phosphate. Consequently, this management strategy for eutrophication control should be considered with circumspection before practical implementation in South Africa.

Notwithstanding the above, preparatory action has already been taken by the South African authorities in that the Water Amendment Act of 1984 (Government Gazette, 1984b) empowers the Minister of Water Affairs to force manufacturers of consumer goods to specify the contents of their products as well as alter or completely remove certain components should this be deemed necessary. The legal infrastructure therefore exists to force detergent manufacturers to specify the phosphorus content of their products, as well as to reduce or completely remove the phosphorus containing compounds.

Nonpoint sources

Nonpoint sources of phosphorus comprise *inter alia* the following: effluents from non-sewered populated areas, urban runoff, runoff from both cultivated and uncultivated land, ground water and both wet and dry atmospheric precipitation. Because of the many and varied origins of nonpoint source phosphorus, as well as the large number of factors which may control these sources, the general approach to quantify nonpoint phosphorus loads has been by means of unit area exports (Sonzogni *et al.*, 1980 and Beaulac and Reckhow, 1982).

Rast and Lee (1983) developed "national average" phosphorus export coefficients for the USA (Table 4), giving an idea of relative contributions for different watershed land uses. However, phosphorus export coefficients reported for Southern African catchments are highly variable (e.g. Kröger, 1981 and Thornton and Walmsley, 1982). Grobler and Silberbauer (1985) investigated the factors responsible for the uncertainty associated with export coefficients for seven South African catchments. They found that the spacial variance in the export coefficients could be largely accounted for if catchments were grouped according to their geological characteristics and whether or not a particular catchment contained mainly point or nonpoint sources. Temporal variation could be explained by fitting regression equations of phosphorus export as a function of runoff.

Atmospheric wet precipitation and dry fallout of phosphorus is generally low, e.g. Sonzogni and Lee (1974) reported 0,02 and 0,08 g P m^{-2} a^{-1} respectively, for the USA. Simpson and Kemp (1982) reported atmospheric deposition of 0,06 g P m^{-2} a^{-1} for an urban area (Pinetown, South Africa) and Bosman and Kempster (1985) reported 0,06 g P m^{-2} a^{-1} for a mixed catchment (Roodeplaat Dam catchment, South Africa). Lower values can be expected for undisturbed rural areas and higher values in the proximity of fertilizer factories.

Lake bottom sediments can be a significant nonpoint source of phosphorus, particularly in shallow reservoirs where wind can induce considerable mixing, resulting in resuspension of bottom sediments to the water column (Grobler, 1985). Studies of the bottom sediments from Hartbeespoort Dam have identified and quantified some of the factors controlling the flux of phosphorus to or from the sediments (NIWR, 1985). These include: the presence or absence of oxygen, phosphorus concentration, temperature and pH of the water, as well as the history of the sediments (episodes of dehydration and rewetting). Quantification and modelling of sediment resuspension in an impoundment as a whole is made nearly impossible because of the complexity of mixing forces which cause sediment resuspension. Nonetheless the net flux of phosphorus either to or from suspended sediments can be estimated by phosphorus mass balances for an impoundment. Initial indications are that these fluxes are considerable and may become significant when external loads are reduced to a level where the water phosphorus concentration is less than the equilibrium phosphorus concentration of the sediment.

TABLE 3
COST BENEFIT ESTIMATES (1983) FOR BANNING OF DETERGENT PHOSPHATES VERSUS REMOVAL OF PHOSPHORUS AT WASTEWATER TREATMENT WORKS

Item	Annual Cost ($R \times 10^6$ a^{-1})	
	Cost	Benefit
Additional Cost Items:		
• 10% increase in detergent cost	22,7	
• 5% decrease in life-cycle		
– of washing machines	3,8	
– of washable fabrics	62,5	
Perceived Benefits:		
• Reduced cost for chemical P removal		4,7
• Reduced cost for biological P removal		1,2
• Reduced salt load (saving to produce effluent with equivalent TDS)		22,5
Cost benefit without desalination (15:1)	89,0	5,9
Cost benefit with desalination (3:1)	89,0	28,4

TABLE 4
"NATIONAL AVERAGE" WATERSHED PHOSPHORUS EXPORT COEFFICIENTS (AFTER RAST AND LEE, 1983)

Watershed Land Use	Watershed Total Phosphorus Export Coefficient (g P $m^{-2}a^{-1}$)
Urban	0,1
Rural/agriculture	0,05
Forest	0,005 – 0,01
Atmosphere	0,025

Conclusions

- In South Africa severe eutrophication and the attendant problems of excessive algal and plant growth are experienced in reservoirs in catchments which contain major point sources of phosphorus.
- Accurate and reliable information on phosphorus loads is a prerequisite for the planning and management of a eutrophication control programme. Since the degree of control and its cost are linked to the type of phosphorus sources, accurate information of the relative contributions from the various sources is required. Unfortunately to date accurate phosphorus load data has only been collected in South Africa for a few research impoundments. Since phosphorus control legislation is now being enforced in sensitive catchments and

will affect many impoundments, rivers and streams, collection of this information for all or at least the most important of these water bodies is necessary. This information should be used to assess the actual phosphorus load reduction brought about by the introduction of the effluent phosphate standard; serve as a basis for prediction of the trophic response of water bodies; and also serve as a basis for deciding on additional or alternative measures should the present phosphorus control strategy not have the desired effect.

- Knowledge on the dynamics of phosphorus in river systems is limited and needs to be developed in order to allow meaningful management of point source phosphorus loads to minimize their impact on rivers and impoundments. Eutrophication management models which incorporate phosphate transformations and removal in river systems, as well as the positional and bio-availability of phosphorus in impoundments, need to be developed.
- Nonpoint sources of phosphorus do not at present constitute a major problem, but they may become of greater importance once the effluent phosphate standard has been fully implemented.
- To date control of nonpoint source derived phosphorus has received little attention in South Africa. Appropriate control techniques developed overseas (IJC, 1980) should be considered. One technique which appears to hold significant potential is pre-impoundment (Twinch and Grobler, 1986).
- A preliminary assessment of the costs and benefits associated with the banning of detergent phosphates in South Africa indicates that the costs associated with such a ban probably far outweigh the benefits. This assessment was based on limited information and should therefore be further refined in order to ensure that this preliminary conclusion is indeed justified.

Acknowledgement

This paper was published with the permission of the Water Research Commission.

References

BEAULAC, M.N. and RECKHOW, K.W. (1982). An examination of land-use nutrient export coefficients. *Wat. Resour. Bull.* **18** 1013-1024.

BOSMAN, H.H. and KEMPSTER, P.L. (1985) Precipitation chemistry of Roodeplaat Dam catchment. *Water SA* **11**(3) 157-164.

DE JONG, G.A. (1985) Detergents, the consumer and the environment. *Proceedings of the International Conference on Management Strategies for Phosphorus in the Environment*, Lisbon, 1-4 July 1985, 11-23.

EKAMA, G.A. and MARAIS, G.v.R. (1984) Preliminary investigation for the optimization of the Cape Flats sewage purification works. Research Report No. W50, University of Cape Town.

EWPCA, (1985) Lakes pollution and recovery. *Proceedings of International Congress of the European Water Pollution Control Association*, Rome, 15-18 April 1985.

GOVERNMENT GAZETTE (1984a) Requirements for the Purification of Waste Water or Effluent, *Government Gazette* **227**(991) 12-17.

GOVERNMENT GAZETTE, (1984b) Water Amendment Act, Act No 96 of 1984. *Government Gazette* **229**(9330) Article 23, Subarticle (3) 37.

GROBLER, D.C. (1985) Phosphorus budget models for simulating the fate of phosphorus in South African reservoirs. *Water SA* **11** 219-230.

GROBLER, D.C. and SILBERBAUER, M.J. (1984) Impact of eutrophication control measures on the trophic status of South African impoundments. Water Research Commission. Report No. 130/1/84.

GROBLER, D.C. and SILBERBAUER, M.J. (1985) The combined effect of geology, phosphate sources and runoff on phosphate export from drainage basins. *Water Research* **19**(8) 975-981.

HEYNIKE, J.J.C. and WIECHERS, H.N.S. (1986) Detergent phosphates and their impact on eutrophication in South Africa. Report of the Water Research Commission.

IJC (1980) Phosphate management for the Great Lakes: Final report of the Phosphorus Management Strategies Task Force. Winson, Ontario, 99-106.

JOHANNESBURG (1982) *1982 Annual Report*, Laboratory Branch, City Health Department, City Council of Johannesburg.

KERDACHI, D. and ROBERTS, M.R. (1985) Operation and performance of Pinetown's Umlaas works. Paper presented at the IWPC Durban Conference, 27-30 May 1985.

KRÖGER, A.D. (1981) Point and diffuse source phosphorus loading of rivers and impoundments in the Durban-Pietermaritzburg region. Dept. of Environment Affairs. Technical Report No. TR 117.

MAKI, A.M., PORCELLA, D.B. and WENDT, R.H. (1984) The impact of detergent phosphorus bans on receiving water quality. *Water Research* **18**(7) 893-903.

NIWR (1985) The limnology of Hartbeespoort Dam. Report by the National Institute for Water Research, CSIR, to the Water Research Commission.

RAST, W. and LEE, G.F. (1983) Nutrient loading estimates for lakes. *J. Env. Engng. Div. Am. Soc. Civ. Engng.* **109** 502-517.

SIMMONS, B.L. and CHENG, D.M.H. (1985) Rate and pathways of phosphorus assimilation in the Nepean River at Camden, New South Wales. *Wat. Res.* **19**(9) 1089-1095.

SIMPSON, D.E. and KEMP, P.H. (1982) Quality and quantity of stormwater runoff from a commercial land-use catchment in Natal, South Africa. *Wat. Sci. Tech.* **14** 323-338.

SONZOGNI, W.C. and LEE, G.F. (1974) Nutrient sources for Lake Mendota – 1972. *Transactions of the Wisconsin Academy of Science Arts Letters* **62** 133-164.

SONZOGNI, W.C., CHESTER, G., COOTE, D.R., JEFFS, D.N., KONRAD, J.C., OSTRY, R.C. and ROBINSON, J.B. (1980) Pollution from land runoff. *Environ. Sci. and Technology* **14** 148-153.

SSO (1985) Phosphate data in the Hartbeespoort Catchment. Report by Stewart, Sviridov and Oliver, Consulting Engineers, to the Water Research Commission, May.

TAYLOR, R., BEST, H.J. and WIECHERS, H.N.S. (1984) The effluent phosphate standard in perspective; Part I: Impact, control and management of eutrophication. *IMIESA* **9**(10) 43-56.

THORNTON, J.A. and WALMSLEY, R.D. (1982) Applicability of phosphorus budget models to Southern African man-made lakes. *Hydrobiologia* **89** 237-245.

TOERIEN, D.F. (1977) A review of eutrophication and guidelines for its control in South Africa. Special Report WAT 48, National Institute for Water Research, CSIR, Pretoria, South Africa.

TWINCH, A.J. and GROBLER, D.C. (1986) Pre-impoundment as a eutrophication management option: a simulation study at Hartbeespoort Dam. *Water SA* **12**(1) 19-26.

WALKER, A.R.P. (1985) Personal communication.

WALKER, W.W. (1983) Significance of eutrophication in water supply reservoirs. *J. Am. Wat. Wks. Ass.* **75** 38-42.

WIECHERS, H.N.S., LOUW, A.S., THIRION, N.C. and BRODISCH, K.E.U. (1984) Upgrading of biological filter sewage purification processes for phosphate and nitrogen removal. *Water SA* **10**(4) 205-210.

WIECHERS, H.N.S. and BEST, H.J. (1985) Environmental phosphorus management in South Africa. *Proceedings of Int. Conf. on Management Strategies for Phosphorus in the Environment*, Lisbon, Portugal, 1-4 July.

WPCF (1983) Nutrient Control: Manual of Practice FD-7: Facilities Design. Water Pollution Control Federation, Washington, DC., pp. 5-8.

WRC (1984) Theory, design and operation of nutrient removal activated sludge processes. Water Research Commission publication.

WRC (1985) Interim guidelines for chemical removal of phosphates from municipal wastewaters. Draft report to Water Research Commission.