A review of sediment/water quality interaction with particular reference to the Vaal River system

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Abstract

Sediment effects water quality in many ways. Visually, the most obvious effect is that of increasing turbidity. In the lower Vaal River this effect is being countered by the increasing salinity. A greater light penetration results in extensive blooms of rooted underwater macrophytes in sections of the lower Vaal River, but could also increase the likelihood of phytoplankton blooms.

Sediment modifies the impact of pollution on the aquatic environment. Sorption of pollutants on sediments alters their fate and their positional- and bio-availability in the aquatic environment. Sediment is one of the important sinks for pollutants in the aquatic environment; however, under certain circumstances pollutants can be remobilized. These effects of sediment on water quality are of major importance in systems, such as the Vaal River, which carry large sediment loads. Planning and management should take these into account.

Most management-oriented water quality models ignore important effects of sediment – pollutant interaction on water quality. This poses a serious limitation to the application of these models to sediment-rich systems, such as the Vaal River and research to rectify this is suggested.

Introduction

The Vaal River system (Fig. 1) is the most important South African water resource. It supplies water to the Pretoria-Witwatersrand-Vaal (PWV) metropolitan complex in which about 40% of South Africa's population resides and which accounts for more than 50% of the gross national product. Below this region the Vaal River system also supplies water to the Western Transvaal and Orange Free State gold fields, various small towns and the Vaalhartz Irrigation Scheme. Along its whole length the Vaal River is also heavily utilized as a recreational resource (Bruwer *et al.*, 1985). The river is already fully exploited and water is imported from the Tugela River basin to meet water demands. Several ambitious schemes to further augment water supplies to the PWV region are being planned (Badenhorst, 1985). As the water demand in the Vaal River rises the volume of effluents returned to the river also increases. For example, it is projected that by 1997 the contribution of effluents to water supply in the Vaal River will be about equal to the supply from Sterkfontein Dam and by 2005, about equal to the supply from Vaal Dam (Badenhorst, 1985). Effluents will therefore increasingly affect water quality, especially in the lower Vaal River (between Barrage and Douglas Weir).

Water resource managers have placed a high priority on maintaining and improving water quality in the Vaal River system. For example, the Rand Water Board, which is responsible for managing part of the system, has set a phosphorus (P) standard of about 0,5 mg P ℓ^{-1} for effluents discharged near its intakes (Viljoen, 1986), compared to the 1 mg P ℓ^{-1} standard operational in other sensitive catchments. In view of Vaal Dam's importance as a national water resource, the Directorate of Water Pollution Control of the Department of Water Affairs (Best, 1985) decided not to grant any permits to exceed the general P standard for effluents in the Vaal Dam catchment, despite predictions by Grobler and Silberbauer (1985a) that the standard is unlikely to have noticeable effects on water quality in Vaal Dam.

Sediment is an important pollutant in many freshwater systems (Golterman *et al.*, 1983). In South Africa, the greatest direct economic impact of sediment is the reduction of reservoir storage capacity through sedimentation, which is estimated at 1% per annum in high erosion hazard regions. Besides the loss in storage capacity, sedimentation also results in the deterioration of reservoir basin characteristics such as higher evaporation area: capacity ratios. In addition, sediment in the aquatic environment also affects water quality through sorption and release of pollutants (Baker, 1980; Felz, 1980; Jennet *et al.*, 1980); through changing the transparency of water (Kirk, 1985); and through affecting, in various ways, the habitat and feeding of benthic and pelagic organisms (Hynes, 1970; Brinkhurst, 1974; Sorensen *et al.*, 1977; Bruton, 1985; Melack, 1985). In this paper the authors discuss some of the effects that sediment has on water quality in the Vaal River system and the implications for management of water quality.

Sources of sediment

Sources of sediment include catchment soils, stream banks and channel beds, atmospheric deposition and detritus (Logan, 1981). The properties of sediments in waterbodies generally differ from those of their sources as a result of differential transport to and chemical transformation in the aquatic environment. Differential transport results in sediments becoming enriched with respect to finer particles. For example, sediment transported in South African rivers consists mainly of particles less than 0,2 mm in diameter (Rooseboom, 1978). Fifty five per cent of the bottom sediment in Bloemhof Dam consists of particles less than 0,1 μm in diameter (Grobler *et al.*, 1981). Chemical transformation causes changes in the chemical and physical properties of sediments, i.e. their sorption capacity (Logan, 1981).

The interaction between catchment characteristics, climate and population pressure, determines the sediment yield from drainage basins (Dooge, 1984). Rooseboom (1978) estimated that the total sediment delivery from South Africa, Lesotho and Swaziland amounts to between 100 and 150 million t a^{-1}. Sediment yields vary from less than 10 to more than 1 000 t km^{-2}.a^{-1} in specific catchments. Rooseboom (1978) delineated areas with similar sediment yield potentials on the basis of soil type, geomorphology and geology. The average sediment yeild for the Vaal River drainage basin was estimated to be between 100 and 150 t km^{-2}.a^{-1}. Phosphorus (P) export from nonpoint sources in

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catchments with sedimentary geological formations (e.g. the Vaal River catchment), is considerably higher than from catchments with mainly igneous geology (Dillon and Kirchner, 1975; Grobler and Silberbauer, 1985b). This is partly a result of the higher sediment yields from catchments with sedimentary geology (Grobler and Silberbauer, 1985b).

The effect of sediment on turbidity and light penetration

The presence of suspended sediment in water is the major cause of the high turbidity of the water of the Vaal River and limits light penetration (measured as the depth to which a Secchi disk can be seen) into the water column (Grobler *et al.*, 1981). High turbidity usually reduces the aesthetic quality of water (Kirk, 1985) but in South Africa, where waters are naturally turbid, this is probably not of great importance. The mean Secchi depth of Vaal Dam is about 0,1 m (Howard, 1986) and it increases downstream to about 0,6 m at Bloemhof Dam (Rossouw, 1986). It is about 0,8 m at Douglas Weir near the confluence of the Vaal and the Orange Rivers (Fig. 1).

Reduced light penetration limits the potential for primary production by phytoplankton and rooted macrophytes because the depth of the photic zone (the zone in which enough light is available for plants to photosynthesize) is limited. For example, it was found that the trophic response of reservoirs, measured as the mean annual chlorophyll concentration, was lower per unit P in turbid than in clear water reservoirs (Walmsley and Butty, 1980; Smith, 1982). An important implication of the highly non-linear relationship between the depth of the photic zone and turbidity (Fig. 2) is that small decreases in turbidity, once the turbidity is below about 30 NTU, can cause a dramatic increase in the depth of the photic zone and, consequently, in the primary production potential of the system. In a system enriched with plant nutrients, such as the Vaal River system, high suspended sediment concentrations can therefore be considered an advantage because nuisance blooms of phytoplankton or underwater rooted macrophytes are prevented (Grobler *et al.*, 1983). Data provided by Howard (1986) and Rossouw (1986) indicate that reduced light penetration, as shown by a mean Secchi depth of 0,1 m for Vaal Dam compared to 0,6 m for Bloemhof Dam, may be one of the factors responsible for the lower mean chlorophyll concentrations observed in Vaal Dam (about 1 $\mu g\ \ell^{-1}$ compared to about 27 $\mu g\ \ell^{-1}$ in Bloemhof Dam). Despite much higher observed P concentrations in Vaal Dam (mean total P of 0,143 mg ℓ^{-1} and mean dissolved P of 0,061 mg ℓ^{-1}) than in Bloemhof Dam (mean total P of 0,060 mg ℓ^{-1} and dissolved P of 0,022 mg ℓ^{-1}) chlorophyll concentrations in Vaal Dam are much lower.

In Vaal Dam turbidities are expected to decrease mainly as a consequence of Vaal River water being diluted with increasing volumes of water with comparatively low suspended sediment concentration being imported from other catchments. For example, at a sampling station near the wall of Sterkfontein Dam, through which water is obtained from the Tugela River basin, the mean Secchi depth was found to be 2,13 m (Dörgeloh, 1986) compared to 0,1 m in Vaal Dam. Similarly, water to be imported from the planned Lesotho Highlands Water Scheme is expected to have much lower suspended sediment concentrations than Vaal River water (Rooseboom, 1985).

The effects of salinity on turbidity and light penetration

Salinization is a major water quality problem in the lower Vaal

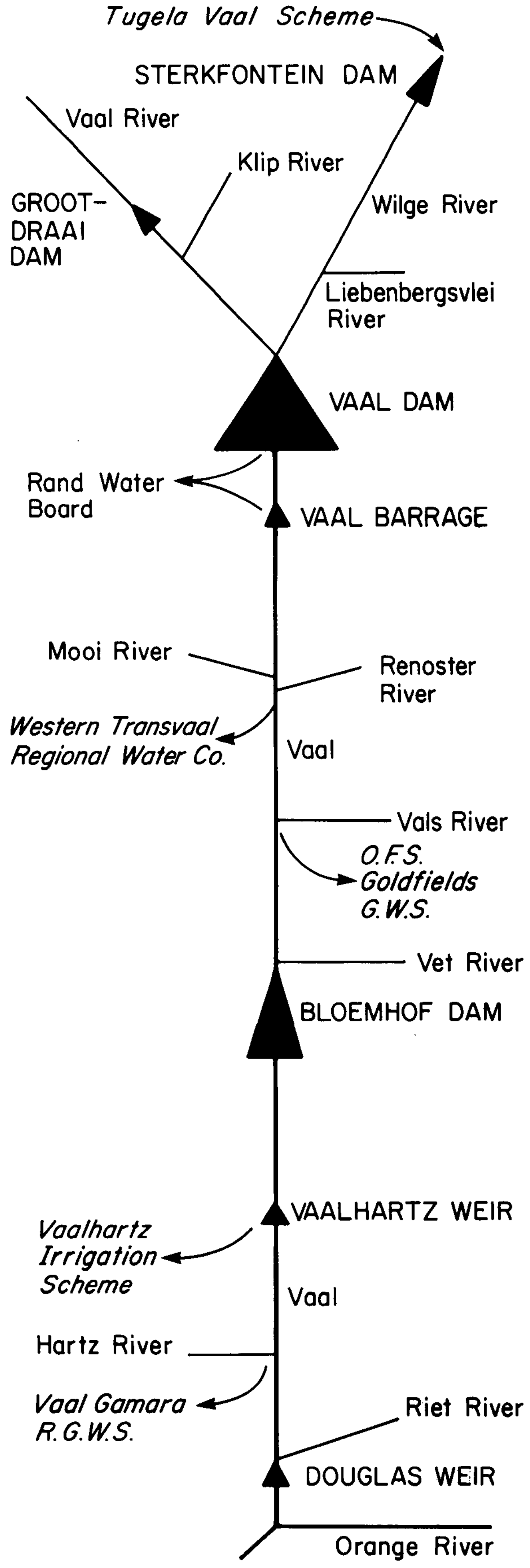

Figure 1
Schematic diagram of the Vaal River system showing major reservoirs and points where water enters or is abstracted from the system.

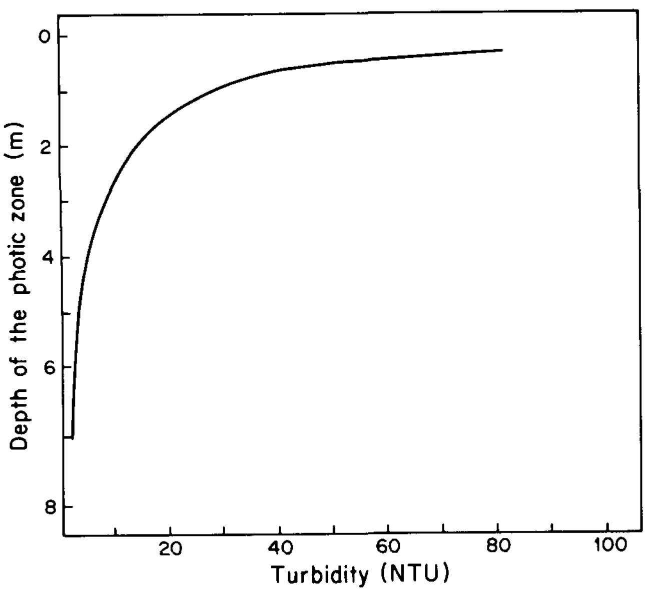

Figure 2
A plot of the depth of the photic zone as a function of turbidity in the lower Vaal River system shows the sharp increase in the depth of the photic zone as turbidity drops to lower than 30 NTU (taken from Grobler et al., *1983).*

River system as a result of increasing amounts of mining, industrial and domestic effluents and irrigation return flow entering the system. Increasing salinity has been shown to cause the flocculation of suspended sediment (Grobler *et al.*, 1981) and Grobler *et al.* (1983) related reduced turbidity in the lower Vaal River system to increased salinity (Fig. 3).

In the lower Vaal River salinity is expected to increase. If the management option of blending effluents with Vaal Dam water is used to keep the salinity (as TDS) of the water at Rand Water Board intakes to below 300 mg ℓ^{-1}, the expected average TDS concentrations at Bloemhof Dam are 490, 560 and 650 mg ℓ^{-1} by 1990, 2000 and 2010 respectively (Herold, 1986). Grobler *et al.* (1983) predicted that increasing salinization of the lower Vaal River would lead to increased photic zone depths and, consequently, to increases in phytoplankton and rooted aquatic macrophyte biomass. Evidence of this already happening in sections of the lower Vaal River system can be found in Bruwer *et al.* (1985).

Sediments as a sink for pollutants

Sediments and suspended particulate matter play an important part in the dynamics of organic and inorganic compounds in the aquatic environment (Felz, 1980; Wakeham and Farrington, 1980). Highly charged clay particles are responsible for the sorption of both cations and anions (Grobler *et al.*, 1981) and the organic matter associated with the sediment particles is largely responsible for the ability of sediment to adsorb uncharged organic compounds (Karickhoff, 1983). Therefore, pollutant concentrations in sediment usually increase with decreasing particle size (Dossis and Warren, 1980). The adsorptive properties of sediment result in the accumulation of pollutants in the sediment. For example, sediments in Bloemhof Dam contain about 330 mg P kg^{-1} (Grobler and Davies, 1981) compared to an average soluble P concentration in the water of about 0,02 mg P ℓ^{-1} (Rossouw, 1986). On a mass basis the P concentration in the sediment is 16 500 times higher than in the water. The same phenomenon was observed for heavy metals and organic pollutants in other river systems (Hite and Lopez-Avila, 1980; Jennet *et al.*, 1980) and has been shown to apply to heavy metals in the lower Vaal River system (Bruwer *et al.*, 1985).

The ability of sediment to concentrate pollutants results in it

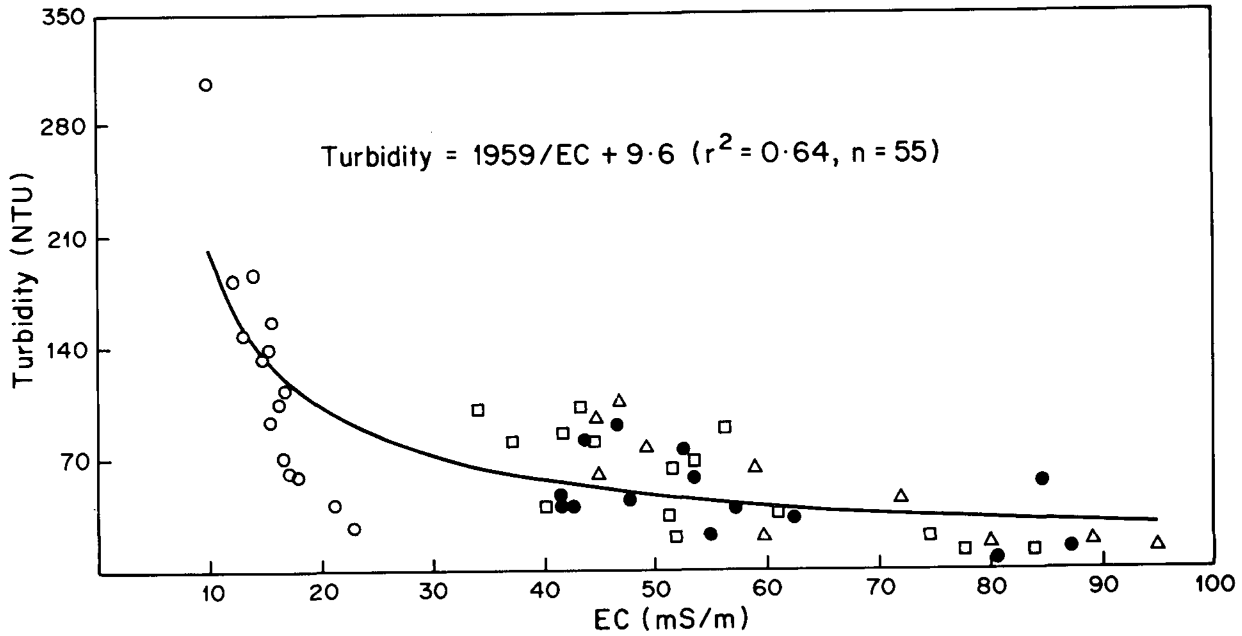

Figure 3
Diagram showing the effect of salinity (measured as electrical conductivity (EC)) on turbidity in the lower Vaal River (taken from Grobler et al., *1983).*

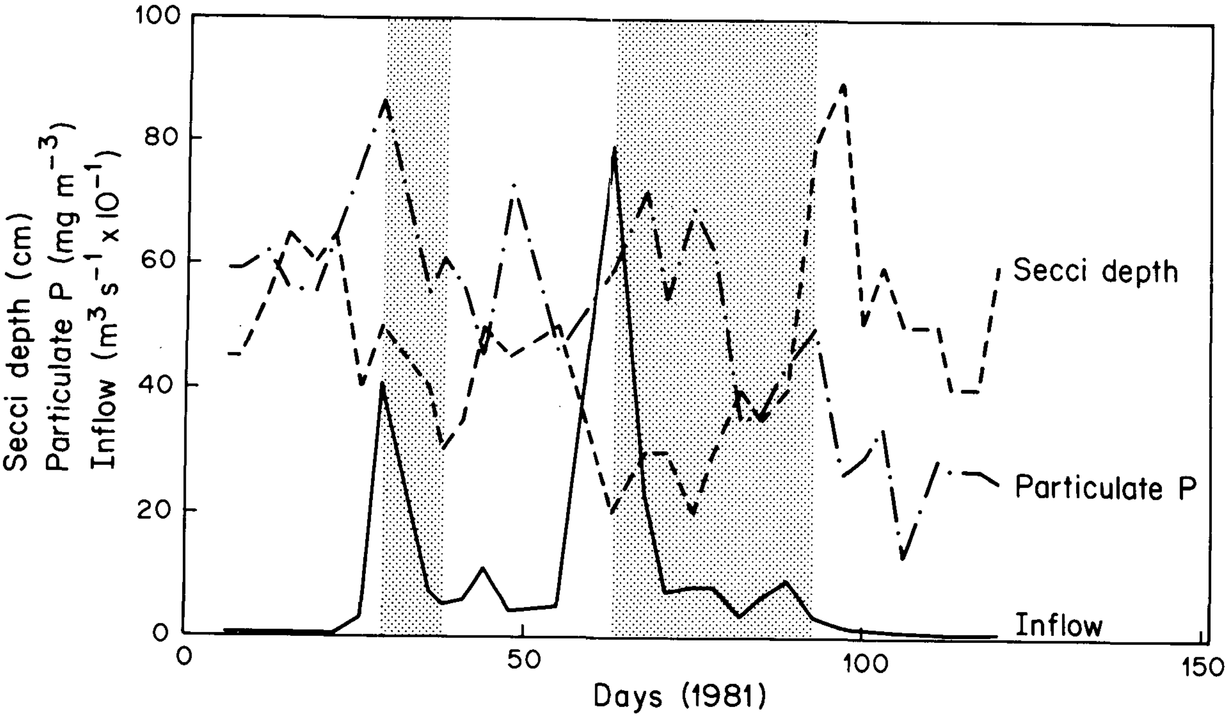

Figure 4
Time series plots of Secchi depth, particulate P concentration and inflow for Bloemhof Dam. The shaded regions highlight times at which there were rapid increases in Secchi depth and decreases in particulate P after major floods (taken from Rossouw, 1986).

acting as a major sink for pollutants in the aquatic environment because, when suspended sediment particles settle, adsorbed pollutants are removed from the water column (Stabel and Geiger, 1985). Under quiescent conditions most particles greater than 1 μm settle fairly rapidly (in several minutes to about an hour; Ferrara, 1983). Rossouw (1986) showed that a large amount of P entering the reservoir during a major flood was rapidly lost from the water column because of sedimentation (Fig. 4). Twinch and Grobler (1986) suggested that the comparatively large losses of P in association with sedimentation, can be utilized as an auxiliary method of controlling the P loading on reservoirs. Pre-impoundments or detention basins, acting as settling basins, could be highly effective for controlling water quality in systems, such as the Vaal River, which carry large sediment loads.

Sediments as a source of pollutants

Pollutants removed from the water by the settling of sediment can under some circumstances be returned to the water column. Several mechanisms are responsible for the remobilization of pollutants associated with sediments i.e. desorption, dissolution, mineralization, ligand exchange and enzymatic hydrolosis. These processes are affected by environmental factors such as redox potential, pH, temperature and turbulence and depend on dynamic equilibria between the concentrations of pollutants in the pore-water and the sediment. The remobilized pollutants return to the water column through various transport processes i.e. diffusion, wind-induced turbulence, gas convection and bioturbation (Boström *et al.*, 1982; Richardson, 1985; Ryding, 1985).

Redox controlled dissolution and diffusion of pollutants from the sediment pore-water to the overlying water are considered the dominant remobilization processes in waterbodies in which an anaerobic hypolimnion develops. Silberbauer (1981) showed that the bottom sediments present in the Vaal River system released large quantities of P, Fe and Mn to the water column under anaerobic conditions (Fig. 5). In shallow waterbodies, wind-generated waves disturb bottom sediments and cause resuspension of sediments with their adsorbed pollutants. In such cases the remobilization processes may take place whilst the sediment is suspended in the water column. Weaver (1981) showed that individual wind events resuspended bottom sediments in the littoral zone in Bloemhof Dam (Fig. 6) and Rossouw (1986) showed that mean particulate P concentrations in Bloemhof Dam were at times doubled (from 0,03 to 0,06 mg ℓ^{-1}) as a result of resuspension of sediments during high-wind events.

Waterbodies in the Vaal River system are generally shallow and seldom develop anaerobic hypolimnia. Resuspension rather than chemical release, could therefore be the dominant mechanism for returning pollutants to the water column. Because resuspension is seldomly incorporated in either sophisticated (e.g. Rossouw, 1986) or simple (Grobler, 1985) water quality models, accurate simulation of the fate of pollutants in these systems is difficult. For instance, Grobler (1985) showed that a simple P budget model could not adequately simulate P concentrations in Bloemhof Dam during periods when the amount of P in the reservoir was controlled by internal recirculation as a result of resuspension of sediment.

The biota play a definite role in the remobilization of pollutants (Ryding, 1985). However, the importance of their role is still uncertain. Pollutants are absorbed from sediments by benthic (bottom) organisms to an appreciable extent and then become available for uptake by predators (Wakeham and Farrington, 1980). These pollutants might then be concentrated in the food chain. It is also known that bacteria can transform highly

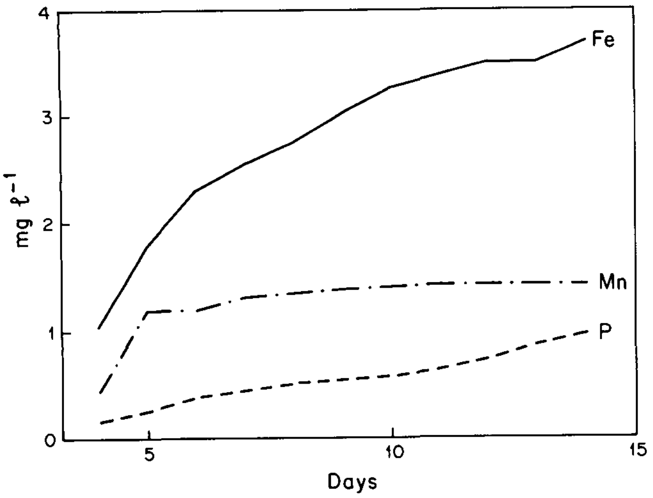

Figure 5
Release of Fe, Mn and P under anaerobic conditions for bottom sediments collected at Bloemhof Dam (taken from Silberbauer, 1981).

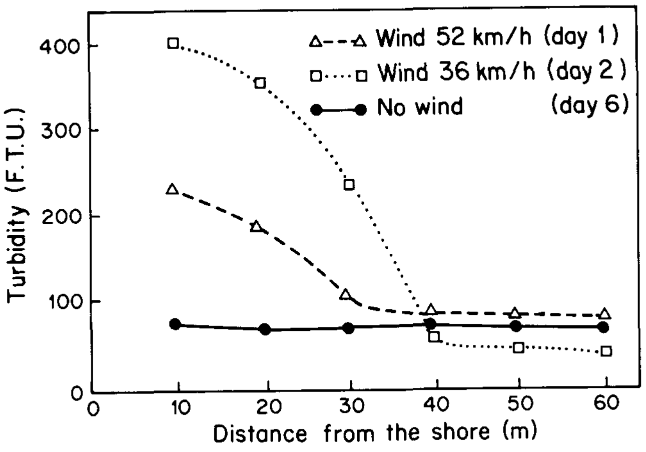

Figure 6
Turbidity profiles in Bloemhof Dam on days with different wind strengths demonstrate the effect of wind on the resuspension of bottom sediments in the littoral zone (taken from Weaver, 1981).

immobile forms of pollutants such as mercury and lead to highly mobile forms e.g. through methylation (Jennet *et al.*, 1980). Another way in which biota may affect the remobilization of pollutants is through disturbing the bottom sediments. Bottom feeding fish species disturb sediments through their feeding behaviour which involves picking up bottom sediments and blowing it out (Lamarra, 1975). The fish population in the lower Vaal River system consists mainly of bottom feeders such as *Labeo capensis*, *L. umbratus* and *Cyprinus carpio* (Bruwer *et al.*, 1985; Rossouw, unpublished data). The authors believe that the feeding behaviour of these fishes enhances the resuspension of bottom sediments in the Vaal River system.

Sediments and pollutant transport

The majority of pollutants originates from point sources, such as effluent discharged from industries, mines and domestic wastewater treatment plants. However, the important contribution of non-point sources, such as runoff from agricultural land, has recently been recognized (Sonzogni *et al.*, 1980; Beaulac and Reckhow, 1982; Grobler and Silberbauer, 1985b). Sediment is derived from non-point sources and, therefore, the effect of sediment on other pollutants can greatly modify the impact of pollution from point sources. For instance, phosphorus which is discharged mainly in the dissolved state from point sources, is converted to the particulate state in rivers (Grobler and Silberbauer, 1985b).

The immobilization of pollutants through sorption by riverine sediments and biota (e.g. Simmons and Cheng, 1985) and their remobilization under conditions such as major floods, create considerable difficulty in relating the water quality in receiving waterbodies to effects of pollutant discharge (Dobolyi and Jolankai, 1985; Twinch *et al.*, 1986). For example, in the Crocodile River, which flows into Hartbeespoort Dam, only about 50% of the P load contributed by point sources actually reaches the reservoir (Wiechers and Best, 1985; Twinch *et al.*, 1986). Sorption of pollutants onto the river sediments might only represent a temporary storage of pollutants because most of them could be transported to receiving waterbodies during major floods. Research aimed at testing this hypothesis in several South African catchments is now being initiated by various organizations.

Sediments and pollutant availability

The effect of pollutants on organisms in the aquatic environment, is determined by the positional- and bio-availability of the pollutant in question. The bio-available fraction refers to that portion of the total amount of a pollutant present in a system which is potentially available for uptake by the organism in question (Grobler and Davies, 1979). Positional availability (Chapra, 1982), in contrast, refers to that fraction of the total amount of pollutant in a system to which an organism is exposed by virtue of the spatial distribution of the organism and/or pollutant. In order to determine the actual availability of a pollutant its positional availability first has to be determined and then the fraction that is bio-available, of what is positionally available, has to be determined.

The fraction of pollutant bound to sediment particles, is usually assumed to be less bio-available than the dissolved fraction (Grobler and Davies, 1979; Rast and Lee, 1983), mainly because its chemical activity is reduced by sorption onto the sediment. The bio-availability of pollutants adsorbed onto sediment can differ markedly, depending on sediment characteristics. Only about 20% of the P bound to sediment is generally bio-available (Rast and Lee, 1983). However, Grobler and Davies (1981) showed that almost all of the inorganic P bound to sediments originating in catchments with sedimentary geology (such as the Vaal River drainage basin) was bio-available. In contrast, only about 30% of the inorganic P bound to sediments originating from catchments with igneous geological formations, was bio-available.

The positional availability of a pollutant is also much affected by sorption onto sediment. Most of the sediment carried in rivers settles fairly rapidly when the water is impounded. The pollutants bound to the settled sediment are then trapped in the bottom of the reservoir. Pollutants trapped in this way are not positionally available to organisms living in the water column. However, resuspension or remobilization may make these pollutants positionally available. Their bio-availability will then determine to what extent the pollutants will affect organisms living in the water column.

Discussion

The Vaal River system has always been naturally turbid due to suspended sediment (hence it's name) and it is a system in which sediment has had a major effect on water quality. Some of these effects are beneficial e.g.:

- reduced light penetration prevents or reduces the occurrence of nuisance blooms of phytoplankton and rooted macrophytes;
- sorption of pollutants to sediment particles reduces their positional- and bio-availability.

However, on occasion the bottom sediments can act as sources of pollutants. The topography of the Vaal River drainage basin is generally very flat, hence its waterbodies are usually rather shallow. In such systems anaerobic hypolimnia are unlikely to develop and the dominant process likely to be responsible for remobilization of pollutants is resuspension of bottom sediments during high-wind events or as a result of high flows.

It is expected that the Vaal River system will become less turbid as a result of increasing salinization and as a result of importation of comparatively clear water from other drainage basins. A reduction in sediment concentrations in the Vaal River will reduce the capacity of the system to assimilate pollutants thereby increasing the impact of pollution on water quality. This is already notable in the case of eutrophication in the lower Vaal River. In view of the much higher P concentrations now being observed in Vaal Dam compared to Bloemhof Dam the authors believe that Vaal Dam will experience eutrophication problems should its water transparency increase from the present Secchi depth of 0,1 m to about 0,6 m as is the case in Bloemhof Dam. Such a clearing of the water in Vaal Dam is likely to result from importation of clear water from other catchments. The authors have observed that once water transparency has increased to such an extent that underwater plants become established, they will cause further clearance of the water through adsorption of the remaining suspended sediment. Algae have the ability to flocculate clay (Avnimelech *et al.*, 1982) and therefore, once large algal blooms start to develop the clearing process will probably be accelerated.

Different parts of the river system will probably be impacted by different land use patterns. The upper Vaal River (above Grootdraai Dam) might be affected by mining and agricultural activities, and salinization might take place over the long term. The main impacts in the Wilge River catchment will remain agricultural activities and the importation of water from other catchments. Below Standerton the Vaal River will increasingly be subject to eutrophication, whilst urban/industrial development, power generation and mining activities will increase salinization and industrial pollution above the Vaal Dam. Although there are few point sources of nutrients in the Vaal River drainage basin upstream of Vaal Dam (Grobler and Silberbauer, 1984) it seems, from the observed P concentrations in Vaal Dam, that nonpoint sources should be considered as a major source of nutrients in that part of the catchment. Because nonpoint source pollution originates over a broad area and because its control is usually not the concern of a single jurisdictional authority, it is not easy to manage (Vigon, 1985; Chesters and Schierow, 1985). However, in the North American Great Lakes region considerable success in controlling nonpoint source pollution has been achieved through the practice of minimum tillage (Sonzogni, 1985). Integrated catchment management along the lines suggested by Braune *et al.* (1985) should therefore be considered.

Below the Vaal Dam the impact of the continued expansion of the PWV region will steadily increase. More effluents and pollutants will reach the river, and the reduced suspended sediment concentration in the water will maximise the negative effects of eutrophication and toxicants etc. Thus the lower Vaal River (below the Vaal Barrage) will bear the brunt of changing water qualities, and Bloemhof Dam as the major impoundment should be severely affected. The impoundment is already infested by the water hyacinth (*Eichhornia crassipes*) and most, if not all, of the negative effects of eutrophication could eventually be experienced there.

The Vaal River system is crucial to the future development of South Africa's water resources and therefore research which will allow the water quality in this system to be predicted in response to various management options, should receive a high priority. The management-oriented eutrophication models currently used for predicting the impact of P control measures on water quality in South Africa reservoirs, ignore the effect of water turbidity on modifying the trophic response of waterbodies to nutrients and ignore important aspects of the positional- and bio-availability of P in reservoirs. This poses limits to their usefulness in predicting the trophic status of reservoirs in systems, such as the Vaal River, which carry large sediment loads and in which sorption of pollutants onto sediment can drastically alter their impact on water quality (Grobler, 1985). The authors believe that research on:

- the role of sediment in determining the fate of pollutants and in affecting the positional- and bio-availability of pollutants; and
- the effect of turbidity on the trophic response of waterbodies in the Vaal River system

should receive a high priority.

Concurrently, management-oriented models which allow the effects of positional and bio-availability of pollutants and the effect of turbidity to be taken into account in predictions need to be developed.

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