Changes in turbidity as a result of mineralisation in the lower Vaal River

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Abstract

Highly significant correlations were determined between annual mean values of turbidity (NTU), electrical conductivity (EC) and sodium adsorption ratio (SAR) of the lower Vaal River. A non-linear regression NTU = 1959 - (EC, mS/m) + 9,6 which explained 64% of the variance of turbidity, was derived and can be used for predictions for the lower Vaal River. The extinction coefficient (k, m^{-1}) of Bloemhof Dam was related to turbidity according to k = 0,127 (NTU) + 0,55. Thus, the photic zone depth of the lower Vaal River can be predicted for different mineralisation (= EC) levels. Future water quality management procedures need this information.

Introduction

Securing sufficient water supplies of high quality for the Pretoria-Witwatersrand-Vereeniging-Sasolburg (PWVS) complex, as well as for other users of Vaal River water, will be a considerably more challenging task in future than it has been in the past (Herold, Mileikonsky, Hall and Midgley, 1980). One contributing factor is the mineral pollution of the Vaal Barrage and the river downstream from the Barrage (Herold *et al.*, 1980).

The photic zones of turbid South African surface waters are strongly dependent on the turbidity of the water (e.g. Walmsley, 1980; Walmsley and Bruwer, 1980; Walmsley, Butty, Van der Piepen and Grobler, 1980; Stegmann, 1982). Lower turbidity in the lower Vaal River will therefore increase the depth of the photic zone in the system and might have a number of ecological implications for the system.

The total cation concentration and the ratio of monovalent to divalent cations of water determine the stability of sediment suspensions, and hence their turbidities (Grobler, Davies and Young, 1981). The increasing mineralisation of the Vaal River would thus result in a lowered turbidity in the water of Bloemhof Dam (Grobler *et al.*, 1981).

The purpose of this paper is to explore the relationships between parameters of salinity and turbidity in the lower Vaal River (the Vaal River downstream of Vaal Dam - Figure 1) and to evaluate their possible ecological consequences. For this purpose use was made of historical water quality data obtained from the Rand Water Board.

Theoretical Considerations

Turbidity and Suspended Sediment

The turbidity in the lower Vaal River can be considered to be a function of suspended sediment concentration only (Grobler *et al.*, 1981). The particles suspended in the water in the lower Vaal River are mainly a mixture of clays originally from the erosion of soils in the river drainage basin. It is reasonable to assume that the clay particles suspended in the water in the lower Vaal River are of a very fine nature because all the coarser particles settle out relatively rapidly whenever the water is impounded e.g. in Vaal Dam and Vaal Barrage. This assumption was confirmed by a particle size analysis of suspended sediment in Bloemhof Dam showing that 55% of the particles has a diameter of less than 0,1 μm (Grobler, *et al.*, 1981).

When particles settle out from a water column, the suspended sediment concentration, and hence turbidity, is decreased. The rate of sedimentation is proportional to the square of the particle radius (Baver, 1956) and the settling rate decreases exponentially with reduced particle size. At particle sizes of approximately 0,1 μm in radius, the settling rate is so low that factors opposing settling (e.g. mixing of the water column) result in a suspension that is stable for all practical purposes (= in steady state).

Dispersion and Flocculation of Clay Particles

Clay particles are negatively charged aluminium silicate crystals (Grim, 1968). When suspended in water they have a layer of cations adsorbed on them (Wiklander, 1964) and the width of this layer is a function of the clay type and the type as well as concentration of the cation adsorbed on the clay. For a given clay type the cation layer increases in width if the cation is weakly adsorbed, e.g. sodium, and decreases if the cation is strongly adsorbed, e.g. calcium and magnesium. The width of the cation layer is also determined by the concentration of cations present in the water phase. A high cation concentration causes a "crowding" of cations on the surface of the clay particles thus reducing the width of the double layer. The situation could therefore arise that a weakly adsorbed cation e.g. sodium when present in a large enough concentration, could decrease the width of the cation layer.

The zeta potential is a measure of the nett negative charge on a clay particle in suspension (Jenny and Reitemeier, 1935). An increase in the width of the double layer results in a relatively high zeta potential whereas a decrease in the width of the double layer results in low zeta potentials. Particles in suspension with similar charges repel each other whereas particles with no or very small charges on them tend to coalesce as a result of frequent collisions. Clay particles with a high zeta potential therefore tend to be stable in suspension because the clay remains in a dispersed state and the individual particles with a generally small size do not settle easily. However, should the zeta potential be lowered, either due to the adsorption of relatively more divalent cations than monovalent cations or because of increased cation concentration (both mono- and divalent) in the suspen-

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sion, the individual clay particles will tend to coalesce and form flocs of a much larger size. These flocs can settle more rapidly and readily resulting in a relatively unstable suspension.

Electrical Conductivity and Sodium Adsorption Ratio

The zeta potentials of clay particles and hence the stability of a suspension of clay particles depends on the relative proportion of divalent to monovalent cations adsorbed on the clay and the concentration of cations present in the suspension. In order to quantify the effect of each of these factors they have to be measured quantitatively. Analysing for adsorbed cations on clay in order to determine the relative proportions of monovalent and divalent cations is a tedious procedure. Therefore an empirical approach has been used by means of which the relative concentrations of cations in solution has been related to the relative concentrations of exchangeable cations on clays (Richards, 1954) defined as the sodium adsorption ratio (SAR). The SAR can be expressed as:

$$SAR = Na^{+}/(Ca^{++} + Mg^{++})^{1/2}$$

with the concentration of cations in solution measured in moles/ℓ.

The effect of increasing the SAR of the water is to increase the exchangeable sodium percentage on the clay particles, and increasing the zeta potential which will result in a more stable suspension. The opposite is also true, i.e. a lower SAR will result in the adsorption of more divalent cations, a lowering of the zeta potential and an unstable suspension.

The electrical conductivity (EC) of water serves as a reliable indicator of the quantity of dissolved minerals, and can therefore be used as a relative measure of monovalent or divalent cation concentration. EC is used as a measure of total cation concentration for the purposes of this study.

Sampling Points and Water Quality Data

Reports of the Rand Water Board from 1968 to 1981 provided simultaneous data at four sampling points (V2, V7, V17 and V18) in the lower Vaal River (Figure 1). Information on salinity (as EC), SAR (calculated from the data) and turbidity (as NTU) allowed their interrelationships to be investigated.

At first it was postulated that mean values based on winter data (April to September) would reflect steady state conditions better than annual means because the latter values could have been distorted by summer floods. However, little difference was observed between winter and annual means, and the latter were used in further calculations because they were based on more observations. Mean annual values were calculated independently for each sampling station.

Results and Discussion

Relationships between turbidity, EC and SAR

The temporal variation of mean annual EC, SAR and turbidity for each of the sampling stations are depicted in Figures 2 to 4, respectively. The turbidity of the Vaal River decreased downstream of the Vaal Dam (Figure 5 contains the data for 1979, but all years showed a similar pattern). This decrease could have resulted from sedimentation of suspended sediment as the water travelled downstream, but because a sharp decrease in turbidity occurred between sampling points V2 and V7 and only a gradual decrease between points V7 and V18, sedimentation (= clearing) was obviously not only a function of river distance but also of other phenomena such as changes in the level of mineralisation in the river.

EC and SAR increased sharply between points V2 and V7

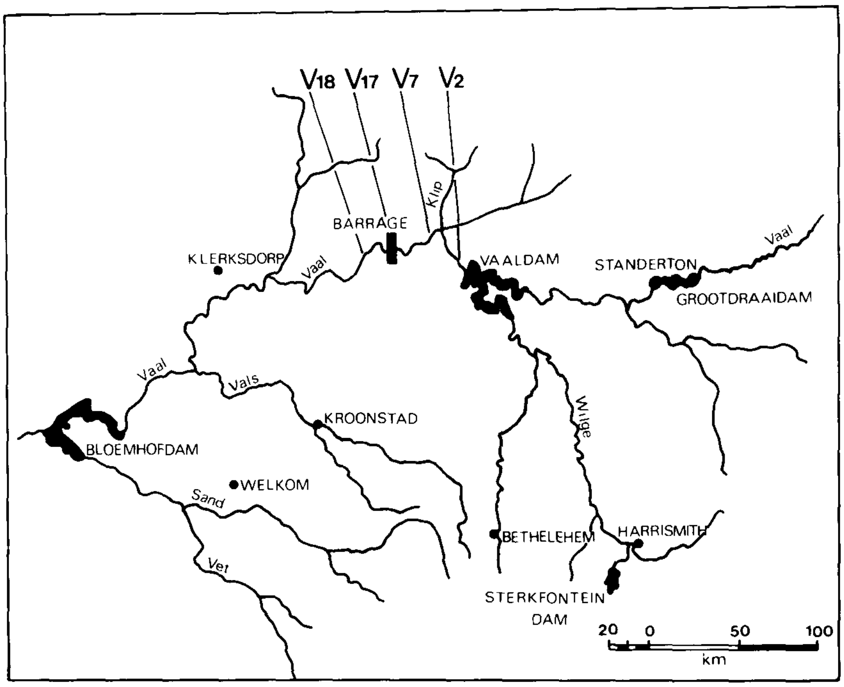

Figure 1
Sampling stations on the lower Vaal River.

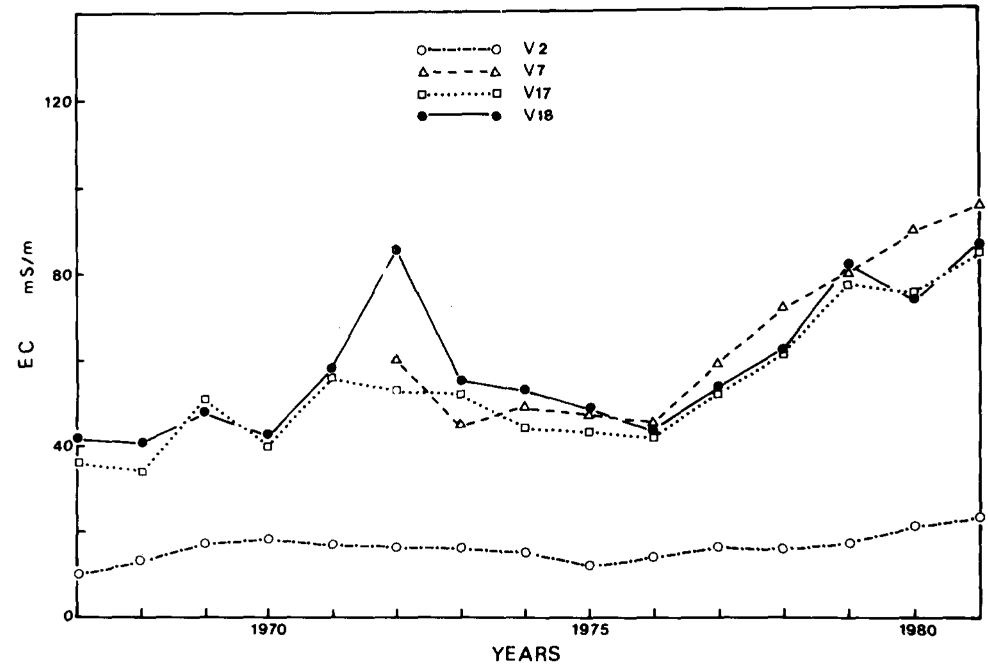

Figure 2
Annual mean electrical conductivity (EC) values for the different sampling stations on the lower Vaal River.

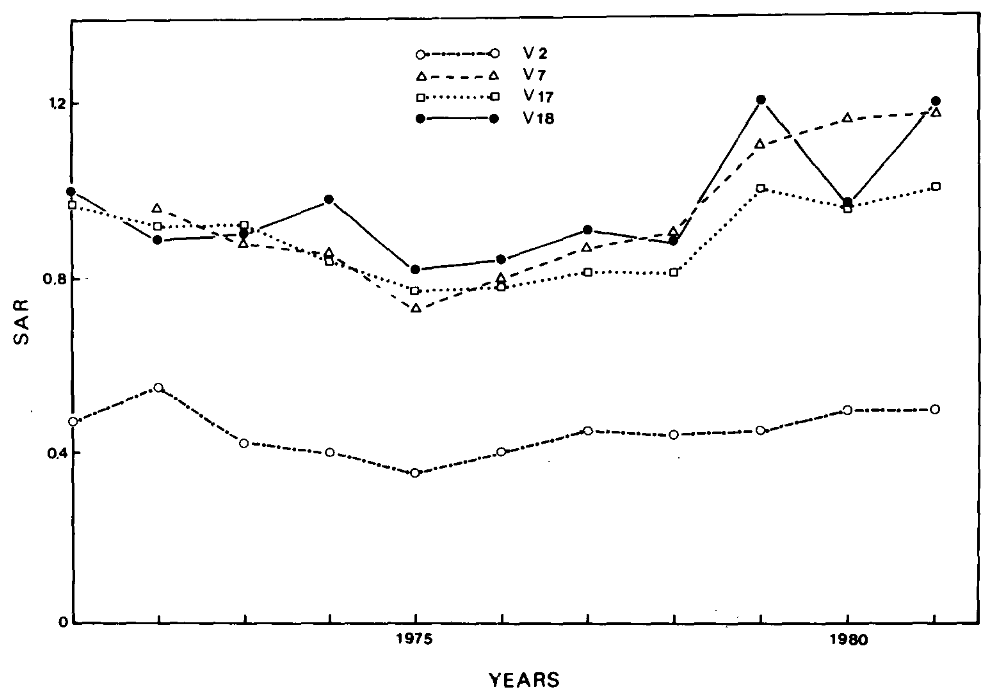

Figure 3
Annual mean sodium adsorption ratio (SAR) values for the different sampling stations on the lower Vaal River.

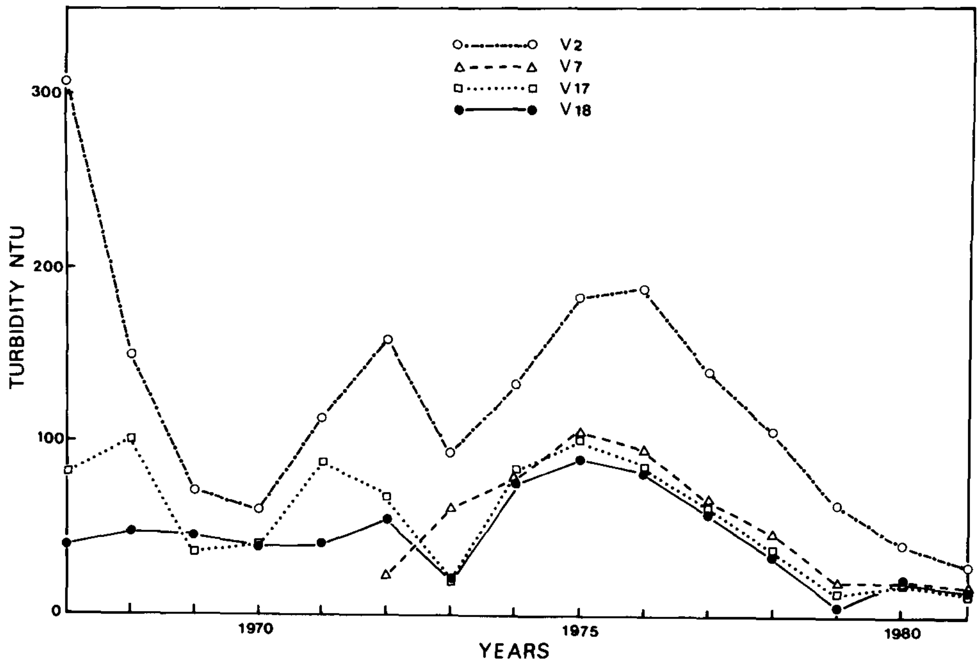

Figure 4
Annual mean turbidity values for the different sampling stations on the lower Vaal River.

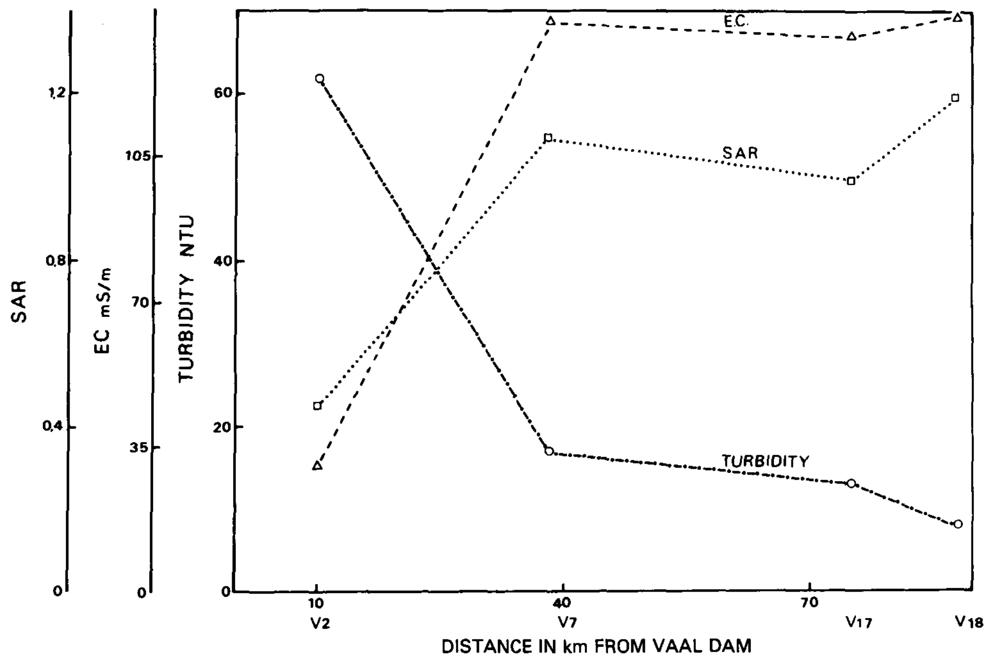

Figure 5
The relationships between sodium adsorption ratio (SAR), electrical conductivity (EC) and turbidity with river distance from the Vaal Dam.

(Figure 5), probably as a result of the mineralising influence of the Klip River (Herold *et al.*, 1980). Turbidity (using mean annual data pooled for all stations) was negatively correlated with EC and SAR ($p < 0,01$) whilst EC and SAR were positively correlated ($p < 0,01$) with one another (Table 1). Either EC or SAR could be used as the first independent variable in a stepwise, multiple regression analysis (done according to Nie, Hull, Jenkins, Steinbrenner and Bent, 1975) with turbidity. In each case about 60% of the variance was explained by the first independent variable and addition of the second independent variable added insignificantly to the explanation of variance. This pointed to a high degree of interdependence between EC and SAR. The interdependence between EC and SAR is not unsuspected because the way SAR is defined implies that a proportional increase in sodium, calcium and magnesium will result in an increased SAR due to the fact that the sodium concentration is divided by the square root of calcium plus magnesium concentrations.

As pointed out under the theoretical considerations increased cation concentrations, indicated by increased EC, should enhance flocculation of clay particles and should therefore result in a reduction of water turbidity due to an increased settling rate of suspended clay particles. Therefore turbidity should be negatively correlated with EC. An increase in SAR, however, points to relatively more monovalent than divalent cations being adsorbed on the clay particles which should favour deflocculation of particles with resultant lower settling rates and therefore higher levels of water turbidity could be expected. In this study turbidity was negatively correlated with EC (as expected) and with SAR (contrary to expectations). The deviation of the SAR-turbidity relationship from theory can be explained by the fact that SAR values varied proportionally much less than the EC values (SAR ranged from 0,35 to 1,21 whereas EC ranged from 12,3 to 95 mS/m). Because there is a measure of interdependence between EC and SAR in terms of the definition of SAR, it can be expected that when EC is the major factor controlling turbidity it might result in a spurious positive correlation between SAR and turbidity. It was accepted that this was the case with the particular data set on the lower Vaal River and SAR in further statistical analyses were ignored.

Flocculation of clay particles is prevented if the zeta potentials remains above certain critical levels (Baver, 1956) and therefore a non-linear relationship can be postulated between turbidity and EC. A hyperbolic relationship was found (Figure 6, Table 2) although a linear relationship between turbidity and EC also explained a large portion of the variance (Table 2). The non-linear equation is proposed for estimating turbidity as a function of EC in the lower Vaal River because of the better fit obtained with the hyperbolic regression and because it follows the theoretical considerations. At very low EC values, turbidities of > 100 NTU and at high EC values, turbidities of about 10 NTU can be expected in the Vaal River (steady state values in flowing waters).

TABLE 1
CORRELATION COEFFICIENTS SHOWING THE DEPENDENCE OF TURBIDITY (T), EC AND SAR ON EACH OTHER

EC	SAR	T (as NTU)
EC (mS/m)	0,94**	−0,76**
SAR		−0,75**

**Significant at p = 0,01

TABLE 2
REGRESSION EQUATION AND RELEVANT STATISTICS FOR TURBIDITY AS DEPENDENT AND EC (LINEAR) AND 1/EC (NON LINEAR) AS INDEPENDENT VARIABLES

LINEAR
Turbidity (NTU) = 145,6 (EC, mS/m) − 1,62
n = 55, r = 0,070, $r^2 = 0,49$, F-Statistic = 50,41**

NON-LINEAR
n = 55, r = 0,80, $r^2 = 0,64$, F-Statistic = 92,4**

**Significant at p = 0,01

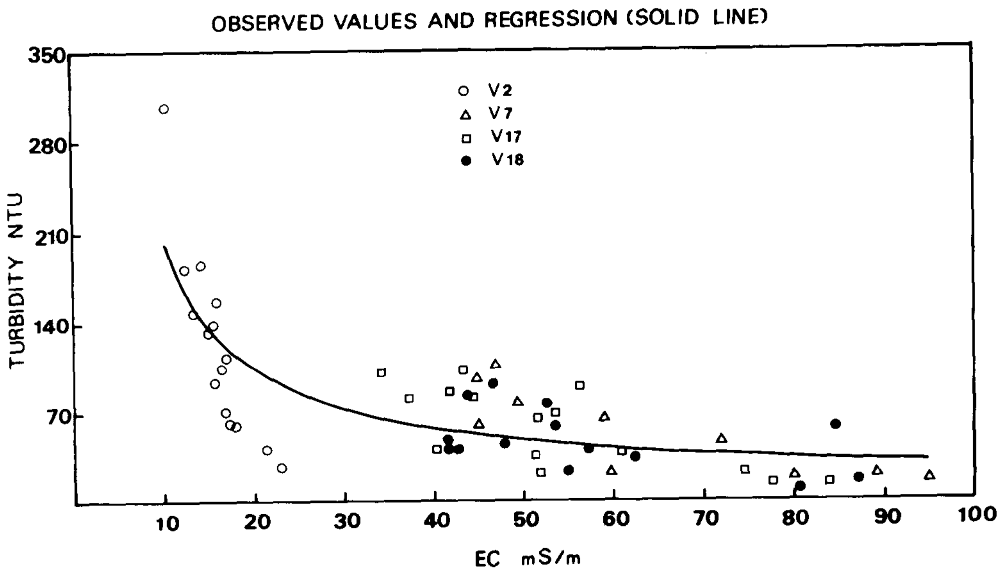

Figure 6
Relationship between turbidity and electrical conductivity (EC) in the lower Vaal River. Turbidity = 1959/EC + 9,6.

Relationship between turbidity and light regime

The major ecological implication of decreased turbidity is a change in the light regime of aquatic ecosystems. Walmsley *et al.* (1980), Walmsley and Bruwer (1980) and Stegmann (1982) have all reported highly significant correlations between the extinction coefficients of light and turbidity of different South African waterbodies (Table 3). A series of light penetration measurements (extinction coefficient from 2,5 to 6,0 per m) at different turbidities (15 to 44 NTU) in Bloemhof Dam, enabled the relationship between the extinction coefficient and turbidity of a water body on the lower Vaal River (Table 3) to be quantified.

TABLE 3
RELATIONSHIPS BETWEEN EXTINCTION COEFFICIENTS (k, m^{-1}) AND TURBIDITY (NTU) FOR A NUMBER OF SOUTH AFRICAN WATERBODIES

Waterbody	Relationship	r^2	n	Reference
Bloemhof Dam	$k = 0{,}127T + 0{,}55$	1,00	5	This study
Wuras Dam	$k = 0{,}073T + 1{,}43$	0,94	78	Stegmann (1982)
Lindleyspoort	$k = 0{,}082T + 0{,}84$	0,90	74	Walmsley (1980)
Buffelspoort	$k = 0{,}149T + 0{,}51$	0,59	76	Walmsley (1980)
Rust der Winter	$k = 0{,}10T + 0{,}44$	0,70	43	Walmsley and Bruwer (1980)

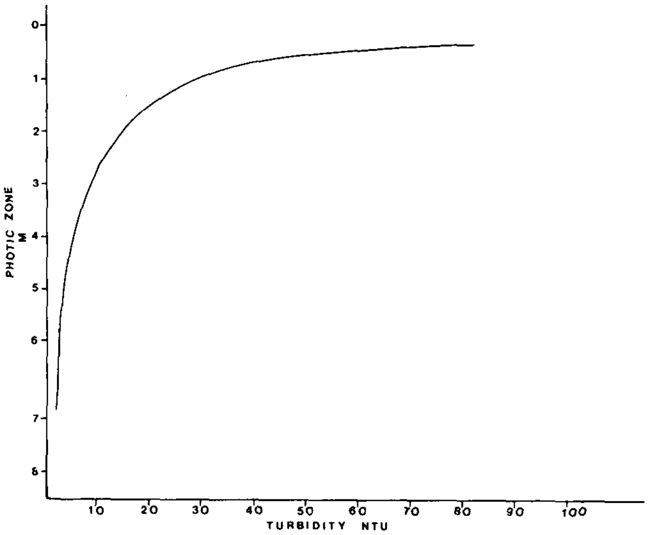

Figure 7
The probable relationship between photic zone and the turbidity of the lower Vaal River.

The photic zone can be defined as the depth to which 1% of incident light penetrates into a waterbody (e.g. Talling, 1971). The photic zone depth at different turbidities that could be expected in the lower Vaal River was calculated from the extinction coefficient/turbidity relationship for Bloemhof Dam (Table 3) and the results are presented in Figure 7. The depth of the photic zone at high turbidity increases relatively slowly as turbidity decreases to approximately 30 NTU. Further decreases in turbidity would, however, result in rapid increases in the photic zone depth of the lower Vaal River. The turbidities of Bloemhof Dam at present range between 15 and 28 NTU during the dry part of the year (unpublished results). Increased mineralisation resulting in decreased turbidities, could result in relatively large increases in the depths of the photic zones both in the flowing and standing waters of the river.

The mean chlorophyll *a* concentration of Bloemhof Dam in 1978 was 22,5 μg/ℓ (Bruwer, 1980), and in the 1980 to 1981 period it was 19 μg/ℓ (unpublished results). Planktonic production in the impoundment is high since Walmsley and Butty (1982) judged that annual mean clorophyll *a* values which exceed 11,0 μg/ℓ indicate eutrophic conditions. Increases in the photic zone would enhance planktonic production in Bloemhof Dam as well as elsewhere in the lower Vaal River system.

One metre of depth represents about 27% of the total surface area (at full supply level) of Vaalharts weir (a small impoundment in the lower Vaal River) and about 21% of the surface area of Bloemhof Dam when it is 50% full (the level at which it is operated most of the time is substantially less than its full supply level). Should the photic zone depth be increased by one metre in these systems, enormous areas will become available for colonisation by benthic primary producers, especially rooted submerged plants such as *Potamogeton* and *Ceratophyllum* spp. Similarly most parts of the river containing flowing water will be available for benthic colonisation when turbidities are 10 NTU or less. This might explain the large stands of such plants which already occur in the lower Vaal River and indicate their increased growth potential in the future.

Concluding Remarks

The lower Vaal River is the final recipient of effluents emanating to the South of the Witwatersrand and is subject to mineralisation (Institute for Water Pollution Control, 1969; Herold *et al.* 1980) and eutrophication (Bruwer, 1980). As the metropolitan complex in the PWVS area increases, mineralisation and eutrophication of the river will probably also increase.

Increased mineralisation will result in decreased turbidities and hence enlarged photic zones. Eutrophication creates a suitable nutrient environment for the rapid growth of primary producers such as phytoplankton, benthic algae, rooted and floating macrophytes. Reduced light penetration under high turbidity will limit the growth of all primary proucers except the floating macrophytes and probably the emergent macrophytes. Thus mineralisation will increase the growth of phytoplankton, benthic algae and rooted, submerged macrophytes in the lower Vaal River.

Since stands of submerged macrophytes are visible in virtually the whole length of the lower Vaal River and phytoplankton causes problems in water treatment plants (Bruwer, C.A. – personal communication), a mineralisation-eutrophication-primary producer relationship probably already exists in the river. The presented results suggest that this relationship will intensify in future.

Since macrophytes tend to block the inlets of pumps and interfere with recreation while phytoplanktons cause water treatment problems, an intensified relationship is of concern to future water quality management of the lower Vaal River. More information is needed about the photic zones, the sizes and dynamics of the primary producer populations and the nutrient status of the lower Vaal River.

Acknowledgements

We thank Dr Chris Viljoen of the Rand Water Board for this historical water quality records, Mrs H. Daneel and Mrs V. Koch for technical assistance and Mrs R. Koch for typing the manuscript.

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