The need to consider water quality in the planning of new urban development: a simulation study

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Abstract

Urban development can affect the water quality of receiving waters in the catchment in which the development takes place. To illustrate this the effect of the development of the city of Botshabelo in the upper Modder River catchment on the trophic status of the Mockes Dam – Mazelspoort Barrage systems is modelled by using the OECD modelling approach to predict the future trophic status of the system for different phosphate loadings and hydrological conditions. The system is predicted to become eutrophied and severe problems due to phytoplankton are expected, especially under low and average river flow conditions. However, in wet years, and in the case of large volumes of effluent being discharged in the future, low hydraulic residence times may prevent severe algal problems. The turbidity of the river system is not expected to limit phytoplankton populations; in fact turbidity is expected to decrease with time. This could lead to the growth of benthic and planktonic algae, as well as submerged macrophytes, which may interfere with the recreational use of the river system. The study illustrates that town and regional planners should consider the water quality effects of new urban development in proposals for development.

Introduction

The high growth rate of the South African population results in rapid urbanization (e.g. Bolitho, 1976) and the development of large new urban centres such as Botshabelo in the Orange Free-State or Ekangala in the Transvaal. These new urban developments are often situated in the catchments of rivers feeding into important water supply reservoirs; consequently, the effects of treated effluents emanating from these urban centres on the water quality of receiving waterbodies should possibly be considered in the planning of such developments.

The Rusfontein-Mockes-Mazelspoort reservoir system, situated in the upper reaches of the Modder River (Figure 1, Table 1), is utilized as a potable water supply for the Bloemfontein metropolitan area. Mazelspoort is also an important recreational resort for the area. The development of the city of Botshabelo in the catchment of the upper Modder River system could therefore be utilized as a case study to predict the consequences of new urban development on the trophic status of reservoirs receiving effluent and to evaluate the need for considering water quality when planning new urban developments.

Eutrophication results in the undesirable growth of algae (phytoplankton) and/or macrophytes, and leads to increased water purification costs, interference with recreation, loss of livestock and potential health hazards when the water is used for potable purposes (Toerien, 1977; Vollenweider, 1981; Jones and Lee, 1982a; Falconer *et al.*, 1983; Walker, 1983). Since models are now available in South Africa to predict changes in trophic status of reservoirs (e.g. Grobler and Silberbauer, 1984; Grobler, 1985), these models can be used to evaluate the impact of urban development on eutrophication-related water quality in a specific catchment.

The purpose of this study is to predict the impact of treated sewage effluents from Botshabelo on the trophic status of Mockes Dam and Mazelspoort Barrage using the modelling approach described by Grobler and Silberbauer (1984). This was done to illustrate the need to consider water quality aspects when planning new urban development.

Materials and methods

The modelling approach

A lack of data on runoff, water levels, total phosphorus (TP) loads and chlorophyll concentrations in Mockes Dam and Mazelspoort Barrage necessitated the use of an eutrophication model requiring little input data. Therefore the Organization for Economic Cooperation and Development (OECD) eutrophication modelling approach (Jones and Lee, 1982a), modified for South African reservoirs (Grobler and Silberbauer, 1984) and incorporating the trophic status classification system developed for South African reservoirs (Walmsley, 1984), was used. The methods employed are described and discussed extensively by Grobler and Silberbauer (1984) and Grobler (1985).

TABLE 1
MORPHOLOGICAL AND HYDROLOGICAL DATA FOR RUSFONTEIN DAM, MOCKES DAM AND MAZELSPOORT BARRAGE

Reservoir	FSL⁺ $m^3 \times 10^6$	Mean depth m	Catchment area km^2	MAR⁺⁺ $m^3 \times 10^6$	Mean water retention time a
Rusfontein	76	6,5	950	35	2,2
Mockes	6	1,8	2 960*	106*	0,06
Mazelspoort	0,8	2,0	3 059**	106*	0,008

⁺Full supply level
⁺⁺Mean annual runoff
*Includes catchment area of Rusfontein and Mockes dams
**Includes outflow from Rusfontein and Mockes dams

Important assumptions

In the OECD modelling approach, catchment-reservoir systems are assumed to be in steady state. Therefore, apart from the assumptions inherent in the OECD modelling approach (OECD, 1982; Grobler and Silberbauer, 1984), the following assumptions

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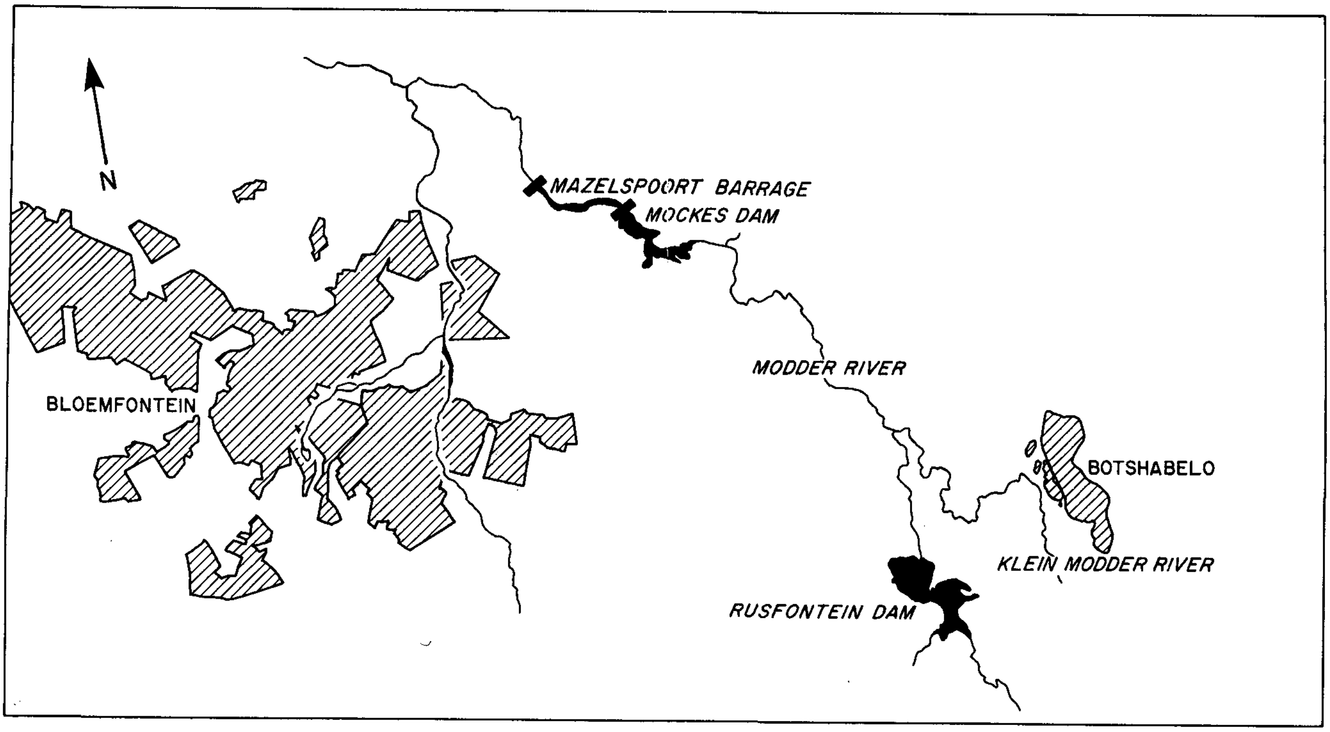

Figure 1
Schematic map of the upper catchment area of the Modder River.

had to be made about the Rusfontein-Mockes-Mazelspoort system of reservoirs:

- It was assumed that Rusfontein Dam could be treated as a point source which has an effluent volume equal to its mean annual runoff (35×10^6 m^3 a^{-1}) with mean total phosphorus (P) concentration of 60 mg m^{-3} (extrapolated from data for Bloemhof Dam; Grobler, 1985).

- In view of its very short retention time (1,4 to 14 d for runoff varying from 2 to 0,2 times the mean annual runoff (MAR)), the water quality in Mazelspoort Barrage was assumed to be essentially identical to that in Mockes Dam, about 5 km upstream of it.

- The water retention time in Mockes Dam (Table 1) was assumed, at all times, to be sufficient for algae to reach their full biomass potential allowed by the TP concentration in the water. This assumption is probably false for periods during which runoff exceeds the mean annual runoff because the water retention time at MAR is already only 22 days, which approaches the minimum retention time required for preventing wash-out of algal populations from reservoirs (e.g. Walmsley, 1980). The extent to which algal populations, adapted to shorter water residence times, could develop is unknown.

Scenarios

The sewage from Botshabelo is now treated by means of a system of maturation ponds from which the effluent is used for irrigation. It can therefore be assumed that no sewage effluent now reaches Mockes Dam. However, it is expected that a sewage treatment plant with a capacity of 20 Mℓ d^{-1} will soon be commissioned. Provision is also being made for this plant to be extended in stages of 20 Mℓ d^{-1} (Marx, 1985). All, or some, of the effluent from the new sewage treatment plant will reach Mockes Dam via the Klein Modder River.

In view of the uncertainty about the rate at which effluents from the new sewage works will be increasing (Marx, 1985) it was decided to simulate the trophic response of Mockes Dam assuming effluent volumes starting at zero, rapidly increasing to about 27 Mℓ d^{-1} (10×10^6 m^3 a^{-1}) and thereafter increasing at 5% per annum for 30 years to reach 118 Mℓ d^{-1} (43×10^6 m^3 a^{-1}). These projections were not intended to be forecasts of the effluent volumes that can be expected at specific times in future but rather to cover the range of possible conditions. Because the planned sewage treatment plant at Botshabelo will incorporate phosphate removal, the mean P concentration of the effluent was assumed to be 1 mg ℓ^{-1}. This is a conservative estimate, since to comply with the 1 mg ℓ^{-1} P standard for 95% of the time, an average concentration of about 0,4 mg ℓ^{-1} in the effluent is required.

Grobler and Silberbauer (1984) showed that hydrological conditions can have a major effect on the impact of point source loads on the trophic status of reservoirs. Therefore, simulations were done for three hydrological regimes, i.e. annual runoff equal to 20% (dry), 100% (normal) and 200% (wet) of the mean annual runoff (MAR). An analysis of runoff records for this hydrological region showed that runoff less or equal to 20% of the MAR can be expected to occur for 18% of the time, less or equal to the MAR for 80% of the time and greater than 200% of the MAR for 20% of the time.

Criteria

Walmsley (1984) suggested that South African impoundments experience no algal-related problems when the mean annual chlorophyll concentration is between 0 and 10 μg ℓ^{-1}. Surface scums develop when it is between 10 and 20 μg ℓ^{-1}, nuisance conditions develop between 20 and 30 μg ℓ^{-1}, and severe nuisance conditions develop at about 30 $\mu g\ \ell^{-1}$. Grobler and Silberbauer (1984) postulated that if the predicted frequency of severe nuisance conditions is less than 21% of the time, they will probably not warrant the introduction of control measures; if it is 21 to 40% of the time they will probably warrant control; and if greater than 40% they will definitely require the introduction of control measures.

Walmsley (1980) suggested that normal phytoplankton populations will not maintain themselves (washout will occur) when the hydraulic residence time decreases below about 22 d.

TABLE 2
PROJECTION OF THE FUTURE TROPHIC STATUS OF MOCKES DAM ASSUMING P LIMIT = 1,0 mg ℓ^{-1} AND RUNOFF = 0,2 TIMES MEAN ANNUAL RUNOFF

Characteristic	Year 1980	1990	2000	2010	2020
Rusfontein P t/a	2	2	2	2	2
Sewage P t/a	0	10	16,3	26,5	43,2
Non-point P t/a	3,2	3,2	3,2	3,2	3,2
Total P load t/a	5,2	15,2	21,5	31,7	48,4
[P] mg/m³	116	276	351	444	550
[chlorophyll] mg/m³	19	38	46	56	66
% of year with severe nuisance conditions	17	40	50	61	73
*water retention time (d)	117	79	66	52	38

*Calculated on full supply level of Mockes Dam and Mazelspoort Barrage

TABLE 3
PROJECTION OF THE FUTURE TROPHIC STATUS OF MOCKES DAM ASSUMING P LIMIT = 1,0 mg ℓ^{-1} AND RUNOFF = MEAN ANNUAL RUNOFF

Characteristic	Year 1980	1990	2000	2010	2020
Rusfontein P t/a	2	2	2	2	2
Sewage P t/a	0	10	16,3	26,5	43,2
Non-point P t/a	23,8	23,8	23,8	23,8	23,8
Total P load t/a	25,8	35,8	42,1	52,3	69,0
[P] mg/m³	199	256	288	335	399
[chlorophyll] mg/m³	29	36	39	44	51
% of year with severe nuisance conditions	30	37	42	48	55
*water retention time (d)	23	21	20	19	17

*Calculated on full supply level of Mockes Dam and Mazelspoort Barrage

TABLE 4
PROJECTION OF THE FUTURE TROPHIC STATUS OF MOCKES DAM ASSUMING P LIMIT = 1,0 mg ℓ^{-1} AND RUNOFF = 2 TIMES MEAN ANNUAL RUNOFF

Characteristic	Year 1980	1990	2000	2010	2020
Rusfontein P t/a	2	2	2	2	2
Sewage P t/a	0	10	16,3	26,5	43,2
Non-point P t/a	56,3	56,3	56,3	56,3	56,3
Total P load t/a	58,3	68,3	74,6	84,8	101,5
[P] mg/m³	247	277	296	323	364
[chlorophyll] mg/m³	(35)	(38)	(40)	(43)	(47)
% of year with severe nuisance conditions	(36)	(40)	(43)	(46)	(51)
*water retention time (d)	12	11	11	10	10

*Calculated on full supply level of Mockes Dam and Mazelspoort Barrage.
( )These values are probable overestimates of actual conditions because washout of algal cells was ignored in the models used to simulate them.

Results

The predicted response of water quality variables of Mockes Dam to increasing P loads from point sources in its catchment is shown for dry (Table 2), normal (Table 3) and wet conditions (Table 4). With no contribution from point sources to the P load on Mockes Dam (1980), chlorophyll concentrations are expected to be fairly low in dry years (19 $\mu g\ \ell^{-1}$) with the result that severe nuisance conditions are expected at a low frequency (Table 2). Under normal and wet conditions, an increased frequency of severe nuisance conditions is predicted since P loads (derived from non-point sources), and hence P concentration in the reservoir, increase with increasing runoff (Tables 3 and 4). However, during high runoff conditions the chlorophyll concentrations, and therefore the frequency at which severe nuisance conditions are experienced, will probably remain low because the water retention time in Mockes Dam is likely to be 12 days or less and algal concentrations are likely to be greatly reduced by washout.

The predicted effects of the contribution to the P load from the planned sewage treatment plant at Botshabelo on Mockes Dam are shown for effluent volumes equal to 27 $M\ell\ d^{-1}$ (approximately in year 1990), 45 $M\ell\ d^{-1}$ (approximately in year 2000), 73 $M\ell\ d^{-1}$ (approximately in year 2010) and 118 $M\ell\ d^{-1}$ (approximately in year 2020). The impact of the increased point source P loads on the trophic status of the reservoir system is illustrated if the chlorophyll concentrations (and the corresponding frequency of severe nuisance conditions) predicted for 1980 are compared with those predicted for the years 1990 to 2020 (Tables 2 to 4). In dry and normal years, non-point sources already contribute sufficient P to result in nuisance conditions for 19 to 30% of the time. However, as soon as the sewage treatment plant is in operation and contributes to the P load on Mockes Dam, severe nuisance conditions are expected to occur for more than 40% of the time.

Discussion

The discharge of treated sewage effluents from Botshabelo into the Klein Modder River is predicted to result in undesirable eutrophic conditions in Mockes Dam and Mazelspoort Barrage *even if a 1 mg ℓ^{-1} P standard is enforced.* However, if the standard is complied with, severe nuisance conditions should only arise after effluent volumes reach the magnitude predicted for 1990; but, eventually, nuisance conditions could be experienced 50% of the time. If the phosphate standard is not applied, severe nuisance conditions might be expected even before 1990 (possibly as soon as discharges of treated effluent are made).

The Modder River is turbid as a result of suspended sediments and it is possible that algal (phytoplankton) growth might be limited by light (because of reduced light penetration caused by suspended sediments) rather than nutrient availability. In such a case, the effluent discharge would result in increased quantities of nutrients but not algae. Such a condition is thought to occur in the impoundments of the Buffalo River (Hart, 1982). However, extensive studies on Wuras Dam (Stegmann, 1982), a shallow turbid impoundment 80 km south of Bloemfontein, showed that its phytoplankton population exceeded the criteria of Walmsley (1984) for eutrophied impoundments. No reason can be identified to expect that the response of Mockes Dam might differ from that of Wuras Dam (both being in the same geographical area), except that shorter hydraulic residence times in Mockes Dam might result in lower algal populations. This postulate must be investigated further.

The total dissolved solids (TDS) content of the streams of the upper Modder River system is low (Toerien *et al.*, 1983) but may increase because the effluents from Botshabelo will have a higher TDS concentration than the natural runoff. Grobler *et al.* (1983) reported that increased TDS concentration in the lower Vaal River, has resulted in increased transparency (reduced suspended sediments) of the system and it is possible that the same may happen in the Modder River system (Toerien *et al.*, (1983), provided evidence of such an interaction at Mazelspoort). Treated (clear) water is also supplied to Botshabelo, and the effluents should not contain appreciable quantities of suspended sediments. Dilution of the natural river flow with effluents low in suspended sediments should result in an increased transparency.

If the transparency of the water increases, the presence of plant nutrients (as a result of effluent discharge), could stimulate the growth of benthic and planktonic algae, as well as submerged or floating macrophytes. Such growth could interfere with the recreational uses of the river system. This postulate should also be investigated further.

The regular monitoring of chlorophyll concentrations at the Mazelspoort Water treatment plant should be initiated as soon as possible. This will provide a base line against which future trophic changes can be evaluated (Jones and Lee, 1982b), In addition, a survey should be undertaken of the present river vegetation (aquatic and riparian).

Large quantities of water will probably flow through the upper Modder River systems as effluent discharges from Botshabelo increase. From a water economy point of view it would be sensible to use water first in Botshabelo and thereafter to use the effluents to augment the supply to Bloemfontein. The consequences of such a 'cascading' use on other aspects of the water quality of the river system must be timeously investigated in order to permit optimal planning.

From this study it follows that water quality deterioration is expected in the Modder River system as a result of future effluent disposal from the urban development at Botshabelo and the question could be raised whether such impacts were adequately enough considered in the planning actions which led to the urban development. These eutrophication-related water quality problems which are in future expected for a considerable period of each year, demonstrate the need for town and regional planners to consider the water quality effects of urban development and associated effluent disposal systems in planning.

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