Control options for river water quality improvement: A case study of TDS and inorganic nitrogen in the Crocodile River (South Africa)

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Abstract

Using a simple conceptual dynamic river water quality model, the effects of different basin-wide water quality management options on downstream water quality improvements in a semi-arid river, the Crocodile River (South Africa) were investigated. When a river is impacted by high rates of freshwater withdrawal (in its upstream reaches), and receives polluted side-stream inflows and wastewater effluent discharges (in the middle reaches), river water quality can deteriorate seriously over time. This study focused on two water quality problems: Progressive increases in the concentrations of total dissolved solids (TDS) as a measure of salinity, and the concentrations of nitrate-plus-nitrite and ammonia (as inorganic nitrogen) as a measure of eutrophication. Based on a low-flow analysis for the period prior to construction of the Kwena Dam (1960 to 1979), the 7d low flows that could be expected to occur every 10 years (7Q10) are generally very low ($< 0.5\ m^3 \cdot s^{-1}$), both in the upstream (Montrose Weir) and the downstream (Kruger National Park) sections of the Crocodile River. During such critical periods of low river flow, very low effluent standard limits would be required to prevent adverse river water quality. However, these options are not economically feasible. Furthermore, inflows from the highly polluted tributary stream, the Kaap River, which drains an area where considerable gold mining takes place, govern water quality in the Crocodile River downstream of the Crocodile-Kaap confluence. Subsequently, two additional water quality control options (setting limits for maximum water withdrawal and low-flow augmentation) were analysed. The results show that a decrease in maximum water withdrawal could reduce the TDS concentration. Furthermore, controlling water release patterns from a dam at the Montrose Weir can have a remarkably positive effect on the downstream river water quality. On the basis of the 1989/90 monitoring data, a minimum flow of $5\ m^3 \cdot s^{-1}$ at the Montrose Weir can reduce concentrations of TDS and ammonia nitrogen by about 20% and 60%, respectively, in the Kruger National Park (at the downstream point of the considered river). However, this management option does not reduce nitrate nitrogen concentrations. The proposed model used in this study is relatively simple and can be used as a tool for the evaluation of short-term (monthly) basin-wide water quality management options.

Keywords: Dynamic model; flow regulation; water quality management; tank in series model

Introduction

As the demand for water increases in line with human population pressure and economic development activities, river ecosystems will continue to deteriorate unless they are managed in a sustainable way. The main causes for this, particularly in their downstream reaches, are related both to water quantity and water quality. The problem related to water quantity (e.g. the occurrence of extremely low flows) is governed by both natural events (drought) and human-induced factors (e.g. large upstream freshwater withdrawals). Because it reduces the dilution capacity of the river, high levels of water withdrawal or loss from upstream river sections or tributaries can considerably affect the water quality of downstream river reaches. High upstream water losses result in the reduction of dry weather flows. In turn, reduced flows can cause accelerated sedimentation and increases total dissolved solids (TDS) concentrations in downstream reaches of the river (Qader, 1998; Mokhlesur et al., 2000). Many other studies have also shown that extremely low flows can have severe effects on river ecosystems, e.g. the failure of natural reproduction processes of many fish species, declining fish yields, and reduced biological productivity (Dubinina and Kozlitina, 2000). In addition, reduced flows also have adverse effects on benthic macro-invertebrate communities, either through direct changes in habitat and flow hydraulics, or through indirect changes in water quality (Caruso, 2002).

While methods for basin-wide water quantity controls are well established, though not yet fully implemented, similar considerations are less common for optimum water quality management. When an extreme low-flow event is combined with inflows from highly polluted tributaries or wastewater effluents, there will be a dramatic decline in the water quality status of downstream river reaches. To deal with problems of this nature, the setting of effluent quality standards and non-point source pollution regulations are usually ineffective. Hence, additional cost-effective control options must be considered.

The objective of this study was to investigate a range of possible management control strategies for the Crocodile River, which receives several inflows from polluted side-streams and also experiences high levels of water withdrawal. Salinity and eutrophication are the major water quality problems in this river. Using a conceptual dynamic hydrological model, the seasonal dynamics of TDS (as a measure of salinity) and inorganic nitrogen concentrations (nitrate plus nitrite and ammonia, as measures of eutrophication), were simulated in the downstream reaches of the Crocodile River, and the results were compared with monitoring data.

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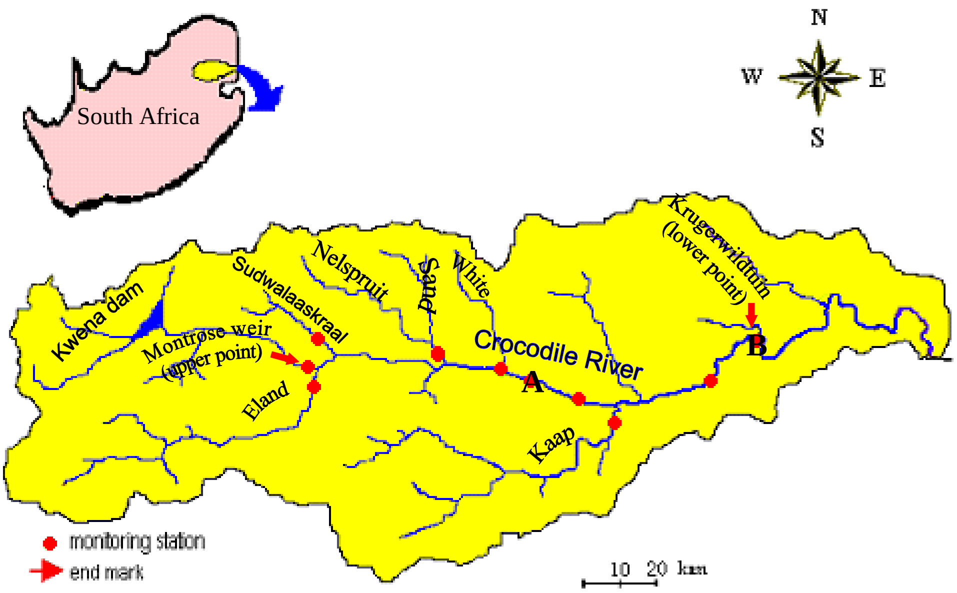

Figure 1
Crocodile River basin and water quality monitoring stations: The model considers only the distance between two arrows (about 153 km); mark A (82 km) and B (153 km) are the monitoring sites where the model was calibrated

Study area

DWAF (1995) provides a summary of the Crocodile River catchment characteristics and hydrology as is summarised here. The Crocodile River is situated in Mpumalanga Province in the north east of the Republic of South Africa (see Fig. 1). It is a relatively large river basin with a total main-stem river length of approximately 320 km draining a catchment area of about 10 450 km^2. Annual rainfall varies from 1 200 mm in the mountainous western and central parts of the catchment, to less than 600 mm in the drier eastern Lowveld. The mean annual precipitation over the catchment is approximately 880 mm. The catchment falls within the summer rainfall zone of South Africa and approximately 85% of the annual rainfall is received as convective thunderstorms during the warm to hot summer months of November to March. The mean annual runoff (MAR) in the whole catchment is 1 446 × 10^6 m^3. However, the hydraulic characteristics of the river have also been changed by the construction of dams and afforestation and abstraction. The Kwena Dam (capacity = 167 × 10^6 m^3) was constructed at a point some 40 km upstream of the upper point of the study site in order to regulate the river flows. Generally, water is released from this dam during the dry winter months to ensure that a minimum flow of 7 m^3·s^{-1} reaches irrigation farmers along the middle and lower reaches of the Crocodile River in the Lowveld, and to help flush out wastewater effluent discharges from the towns of Nelspruit and Malelane in the middle reaches of the catchment. Apart from the Kwena Dam, seven more medium-sized dams exist in the catchment, as well as over 200 small farm dams. The quantities of water abstracted for irrigation, as well as the decreased inflows caused by increased afforestation, have resulted in a marked decline in winter flows from many tributaries and the main stem of the Crocodile River. Moreover, mean annual potential evaporation losses for the catchment ranging between 1 800 to 2 000 mm, exceed the mean annual precipitation by a wide margin and considerable quantities of water are lost via evaporation. These high water losses have had a considerable impact on water quality in the downstream river reaches.

It is also indicated that water quality in the Crocodile River is influenced not only by direct human interventions, but also by natural phenomenan such as climate and geology (DWAF, 1995). Geological processes such as chemical weathering contribute some chemical ions but indicated to be far less (<1%) than the contributions from soil erosion and land use. The primary effect of climate on water quality is expressed through the effects of rainfall seasonality on the timing and duration of high or low river flows. High summer rainfalls with discrete storm events result in sudden increases and decreases in runoff, causing rapid changes in river water levels and suspended sediment concentration. In contrast, river flows decline gradually to very low levels during the dry winter months, and the lowest flow levels are usually less than 10% of the average flows recorded in the dry season. This decrease in flow, combined with relatively high rates of evaporation (>100 mm/month), causes a gradual increase in the concentration of dissolved salts present in the lower reaches of the river.

Such natural problems can be aggravated when a low flow is combined with a high load of point and/or non-point source pollution that can exceed the so-called "dilution capacity" of the river. TDS concentrations in the Crocodile River increase markedly after its confluence with the Kaap River, which drains an extensive area of active and abandoned gold mines. Subsequently, the lower reaches of the Crocodile River (downstream from the Kaap River confluence) have poor water quality due to agricultural runoff and return flows, as well as additional mining activities (Kleynhans, 1999). Any additional freshwater withdrawals in the upstream reaches during periods of extremely low flow can cause a further increase in salinity and deterioration of water quality.

Furthermore, the study of the Fish Assemblage Integrity Index (FAII) in the Crocodile River has indicated the potential impact of human influence in the downstream section of the catchment (Kleynhans, 1999). It has been indicated that the relative FAII score per fish habitat segment decreases longitudinally in the Crocodile River. The FAII calculation is based on rating the individual species in terms of intolerance, frequency of occurrence and health. Then the relative FAII score (the ratio of expected and observed FAII scores) is used to classify the integrity class of the fish habitat segment. The integrity class is "unmodified" or "natural condition" if the relative FAII score is 90 to 100%, "largely modified" if it is 80 to 89%, "moderately modified" if it is 60 to 79%, "largely modified" if it is 40 to 59%, "seriously modified" if it is 20 to 39%, and "critically modified" if it is less than 19%. It is also indicated that the progressive and longitudinal decline of the relative FAII per fish habitat segment along the lower reaches of the catchment is related not only to altitude but also to agricultural and domestic runoff, industrial effluents (in the middle of the catchments, from Montrose to the Kaap River confluence) and mining activities (in the lower catchment downstream of the Kaap River confluence).

The current flow-release pattern from the Kwena Dam also has a dramatic effect on attempts to improve water quality in downstream river reaches. Water is generally released from the dam to ensure that a minimum flow of 7 $m^3 \cdot s^{-1}$ reaches irrigation farmer along the river in the Lowveld but does not follow the natural flow pattern of the river.

Besides, water quality criteria are not explicitly considered in the flow-release pattern. Such flow modifications imposed by the Kwena Dam have already been reported to decrease the biodiversity of fish in reaches downstream of the Kwena Dam (State of the Crocodile River, 2001).

In this study, consideration was focused on the 153 km long central section of the Crocodile River (see Fig. 1), between Montrose Weir (upper point) and Kruger National Park (lower point), as this is the section that is under greatest human influence. This section represents the most sensitive portion of the river, where nitrate and ammonia concentrations often exceed the recommended maximum limits of 0.5 $mg \cdot l^{-1}$ (nitrate) and 0.03 $mg \cdot l^{-1}$ (ammonia) for oligotrophic systems (DWAF, 1993; Ashton et al., 1995). In certain years, the TDS concentration also exceeds the water quality objective for irrigation (>260 $mg \cdot l^{-1}$, for sensitive crops) (DWAF, 1993).

Methods

Model formulation

In order to control further deterioration of river water quality caused by high levels of upstream water abstraction and by downstream contributions of polluted inflows in the downstream reaches of the river, two alternative control strategies were considered. The first alternative chosen was to set a maximum limit to the volume of water withdrawn at the upstream point. Water is abstracted from the main river or its tributaries for irrigation, industry and domestic water supply. Most of this water will be lost through evaporation and very little may return to the river. High rates of water withdrawal at the upstream point or from tributaries in the upper reaches can cause an increase in TDS concentrations in the downstream reaches of the river. This is due to the fact that the volume of water reaching the downstream sections of the river is too low to dilute the inflows from polluted side-streams and effluent discharges. In such cases, a relatively simple dynamic water quality model consisting of completely mixed tanks in series can be applied as indicated in the following general mass balance formulation of one such tank:

$$\frac{dVC}{dt} = Q_{in}C_{in} - \left(Q_e + Q_{wd} + ET \cdot A\right) \cdot C - rV \qquad (1)$$

$$Q_e = \alpha h^{\beta} \qquad (2)$$

where:

V = volume of the tank [m^3]
C_{in} = inflow concentration [$g \cdot m^{-3}$]
C = outflow concentration [$g \cdot m^{-3}$]
Q_{in} = inflow rate [$m^3 \cdot d^{-1}$]
Q_e = outflow rate [$m^3 \cdot d^{-1}$]
Q_{wd} = rate of water withdrawal from the tank [$m^3 \cdot d^{-1}$]
ET = water loss by evapotranspiration [$m \cdot d^{-1}$]
A = surface area of the river tank [m^2]
r = reaction rate [$g \cdot m^{-3} \cdot d^{-1}$]
h = hydraulic depth at a time t for rectangular cross-section [m] = V/A
β, α = parameters estimated from stage flow relations [-]
t = simulation time step [d]

In Eq. (1), stated variables such as V, C, Q_{in}, Q_e Q_{wd}, ET and h vary with time, and the ordinary differential equation should be solved numerically. The overall reaction rate r is obtained from the simplified version of the River Water Quality Model number 1 (RWQM1) (Reichert et al., 2001) as summarised here. This model is a set of equations that can be implemented in any convenient modelling and simulation software e.g. AQUASIM (Reichert, 1998) and WEST® (Vanhooren et al., 2002). In this study, the biochemical processes included in the model are aerobic growth of heterotrophs with ammonia and nitrate, aerobic respiration of heterotrophs, anoxic growth of heterotrophs with nitrate, anoxic respiration of heterotrophs, growth of nitrifiers, aerobic respiration of nitrifiers, hydrolysis of particulate organic materials, adsorption of phosphate and desorption of phosphate. Stoichiometric coefficients were determined using a simple standard mass composition for organic substances considering the elemental C, H, O, N and P, and charge balances. The conversion rates were all formulated with Monod-type limitation factors. In this study, the stated variables include the concentrations of dissolved oxygen, inorganic nitrogen (ammonia (NH_4 + NH_3) and nitrite (NO_2) plus nitrate (NO_3)), inorganic phosphorus (HPO_4 + SH_2PO_4), soluble readily biodegradable chemical oxygen demand (COD) and microbial biomass (nitrifiers and heterotrophs). This type of modelling approach has the advantage that it is compatible with standard wastewater treatment plant modelling and hence can be used for integrated water quality studies in the future. Detailed information regarding the simplified reaction rate term r in Eq. (1) is given elsewhere (Deksissa et al., 2001). As TDS is not involved in the biochemical reaction, it is considered as a conservative substance, and hence the value of r in the general mass balance (Eq. 1) is zero for TDS. Therefore only transport of this substance is accounted for in the model.

The proposed model requires the daily time steps of flow and chemical water quality variables indicated above. When only the seasonal dynamics of water quality are of interest, monthly time step data can also be applied.

Using the WEST® modelling and simulation software (Hemmis NV, Kortrijk, Belgium) (Vanhooren et al., 2002), the complete tank in series model is illustrated in Fig. 2. The physical details of each river section are given in Table 1.

The proposed model is formulated on the basis of the following key assumptions:

- Only the pollution loads from the major tributaries and the upstream end of the main river were considered. As it was difficult to collect suitable water quality information for the tributary rivers, the contributions of minor tributaries were assumed to be relatively negligible. This assumption, however, should be tested by future field studies.
- The rate of water withdrawal in the upstream river reaches is time varying (high during the dry season and low during the wet season) because the high water abstraction for irrigation mainly occurs during the dry season.

Model calibration and validation

On the basis of data provided by South African Department of Water Affairs and Forestry (DWAF), the model was calibrated and validated for the river section between Montrose Weir and Kruger

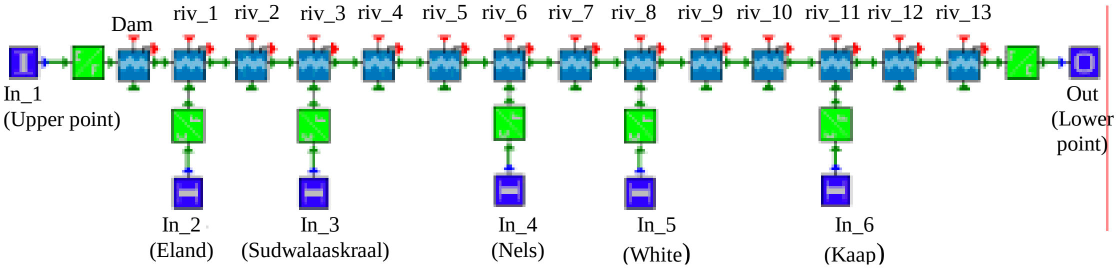

Figure 2
Completely mixed tanks in series model in the WEST® modelling and simulation software; riv_1 to riv_13 are river reaches that are further subdivided into 4 to 5 tanks; "Dam" is the hypothetical reservoir as a control volume; In_2 to In_6 are major tributaries

TABLE 1
River segmentation into completely mixed tank in series (CMTS)

Name	Monitoring station	Reach length (km)	Cumulative length (km)	Tank length (km)	Number of CMTS
riv_1	Montrose Weir – Section 1	4	4	4	1
riv_2	Section 1 - Sudwalaaskraal River	8	12	4	2
riv_3	Sudwalaaskraal River – Section 1	5	17	5	1
riv_4	Section 1 – Section 2	20	37	5	4
riv_5	Section 2 - Boschrand	20	57	5	4
riv_6	Boschrand – Section 1	4	61	4	1
riv_7	Section 1– Goede Hoop	16	77	4	4
riv-8	Goede Hoop – Karino Weir	5	82	5	1
riv_9	Karino Weir – Weltevrede	16	98	4	4
riv_10	Weltevrede – Kaap River	10	108	5	2
riv_11	Kaap River – Section 1	5	113	5	1
riv_12	Section 1 – Malelane Bridge	20	133	5	4
riv_13	Malelane Bridge–KrugerNat Park	20	153	5	4
	Sum				**33**

National Park. The measured data collected in 1987 and 1988 were used for calibration, whereas the model was validated with independent data collected in 1989 and 1990. The only data available in the main stem of the Crocodile River and its tributaries include daily flow rate and monthly water quality variables such as ammonia nitrogen, nitrate plus nitrite nitrogen inorganic phosphorus and TDS. Subsequently, a trial-and-error procedure was used to calibrate the hydraulic component of the model (by 'tuning' the amount of water lost per length of each river reach until the best agreement was obtained between the simulated and measured data sets).

Model application and water quality management options

Setting maximum water withdrawal

During low flow periods, setting maximum water withdrawal can prevent the further water quality deterioration caused by high upstream fresh water withdrawal. The low-flow periods in rivers are widely used for traditional water quality modelling as the design condition (likely worst-case scenario) for waste load allocation studies (Chapra, 1997). The lowest continuous flow for a 7d period that would be expected to occur every 10 years (also called the "7Q10" flow) is generally accepted as the standard design flow for waste load allocation studies, as it incorporates a high level of assurance against risk. The typical set of procedures used to analyse 7Q10 has been described in Chapra (1997). Based on such a low-flow analysis for the Crocodile River, we can estimate the instream flow requirements (ecological reserve) and overall maximum water withdrawal that includes water supply for irrigation, industries or domestic supplies, and the reserve water flow required for river ecosystems. The maximum water withdrawal can be defined as the difference between the discharge in a low water base year and the discharge critical for fish reproduction (Dubinina and Kozlitina, 2000). The instream flow requirement varies from river to river and region to region. Hence, the South African Building Block Methodology (BBM) (King and Louw, 1998; Rowntree and Wadeson, 1998) is considered to be appropriate for the determination of instream flow requirements in river ecosystems located in semi-arid and arid regions. As it is not the intention of this study to determine the critical instream flow requirements, the rate of water withdrawn was obtained after model calibration. The rate at which water is withdrawn per unit length of each river reach ($m^3 \cdot m^{-1} \cdot d^{-1}$) is one of the model parameters whose real values should be obtained by calibrating the model with real monitoring data.

Low-flow augmentation and water-release patterns from the reservoir

Low-flow augmentation is generally required when dry season

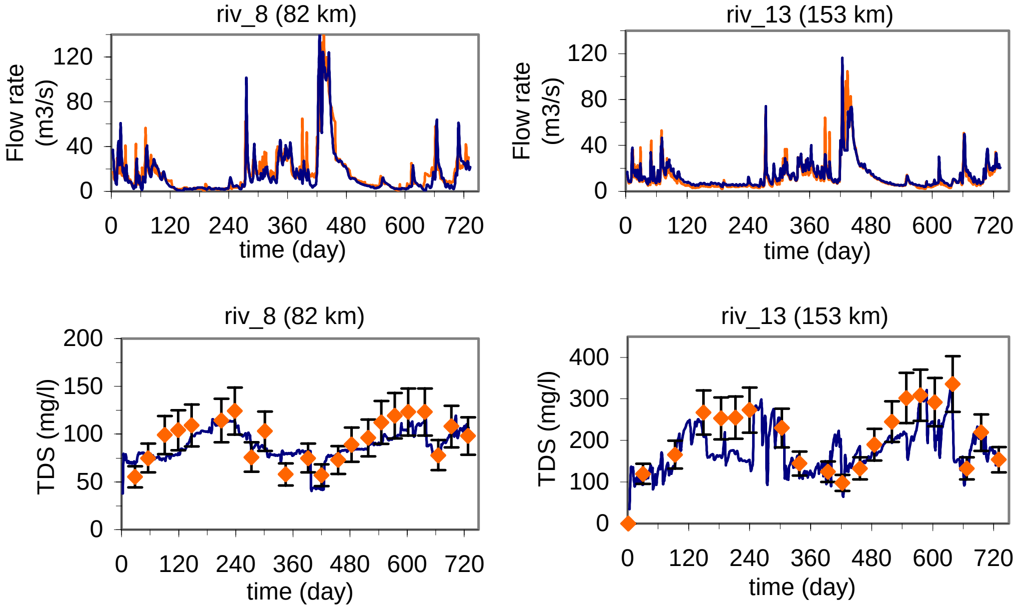

Figure 3
Model calibration: comparison of measured and simulated data sets of TDS concentrations and river flow rate at 82 and 153 km

river flows are lower than those required in the downstream segments of a catchment. During the dry season, most South African rivers are characterised by low flows, or zero flows in the case of highly seasonal rivers. As a consequence, river water quality in the reaches downstream of many wastewater treatment works is usually very poor due to the lack of dilution (Dickens and Graham, 1998). Thus, reservoir releases, one of the most important traditional forms of low-flow augmentation, can also be considered.

Because reservoirs always modify river flow patterns and alter or interrupt the river continuum, they are frequently viewed as imposing strongly negative impacts on the aquatic environment (Ward and Stanford, 1983; Avakyan and Iakovleva, 1998). Despite these negative views, some studies have also indicated that reservoirs or impoundments can improve downstream water quality conditions; for example, impoundments that receive agricultural runoff and urban effluents generally cause an improvement in water quality downstream for most of an annual cycle (Palmer and O'Keeffe, 1990). Therefore, reservoirs can have both positive and negative impacts depending on their mode of operation and the prevailing downstream river water quality conditions. Indeed, reservoirs offer an important potential management tool if the relationships between modes of reservoir operation and the resulting influence on water quality can be understood (Straskraba, 1994).

Deriving and using appropriate reservoir operation rules therefore offer an important opportunity to improve water quality in downstream river reaches. If the flow release from a dam does not follow the natural flow seasonality patterns, it can and does result in dramatic ecological changes. However, using dynamic storage and release patterns, at least some semblance of natural seasonality can be simulated. This can be formulated in such a way that the flow pattern should follow the general trend of natural flow patterns in the catchment. The algorithm for the governing equation of the general water balance in the control volume (dam) can be formulated as follows:

$$\frac{dV}{dt} = Q_{in} - Q_e \qquad (3)$$

Q_e = Q_{max} if $Q_{in} > Q_{max}$ to store some water during the wet season

= Q_{min} if $Q_{in} < Q_{min}$ to supplement the low flow during dry season

= Q_{in} if $V < 0$ to avoid negative output (specific for the model)

= $Q_{min} + \Phi(Q_{in} - Q_{min})$ if $Q_{min} < Q_{in} < Q_{max}$ for seasonal trends

where:

Q_{min} and Q_{max} are, respectively, the minimum and the maximum outflow rate required to release from the reservoir;

Φ is the fraction ranging from 0 to 1 depending on the volume of water required to be released.

As indicated in the last expression in Eq. (3) for Q_e, changes in the outflow rate (Q_e) will depend on changes in the inflow rate (Q_{in}). In this way the general natural flow pattern can be maintained, albeit at a lower level than normal during high (wet season) flows because some water must be stored for low-flow augmentation. The value for Q_{max} must overlap, or coincide with, the timing of natural maximum flows (see Fig. 8). The magnitude of the maximum and minimum flow released from the reservoir depends on the capacity of the storage capacity of the reservoir, the design capacity of the outflow control structure(s) and stream-flow requirements for sediment transport. The following conditions are considered:

- the maximum flow released should be set so that the flow is large enough to restore the natural size of the river channel by removing fine sediments and any other detritus deposited during low flows; and
- the remaining stored water volume should be sufficient to maintain the minimum flow required for fish passage and water quality targets during low-flow periods of the year.

Despite the fact that there is insufficient information for the calculation of exact values of the above flows, the usefulness of this approach can be demonstrated by choosing Q_{min} on the basis of the water quality target of TDS and inorganic nitrogen, and setting Q_{max} during high flow such that the remaining stored water volume is sufficient to maintain the minimum flow required during low flows. The influence of the above proposed new flow pattern on downstream water quality (i.e. downstream of the Kaap River confluence) was also evaluated.

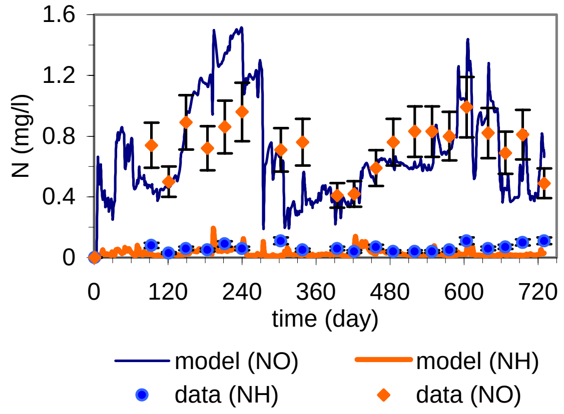

Figure 4
Model calibration for inorganic nitrogen: ammonia (NH) and nitrate plus nitrite (NO) at the lower end (153 km)

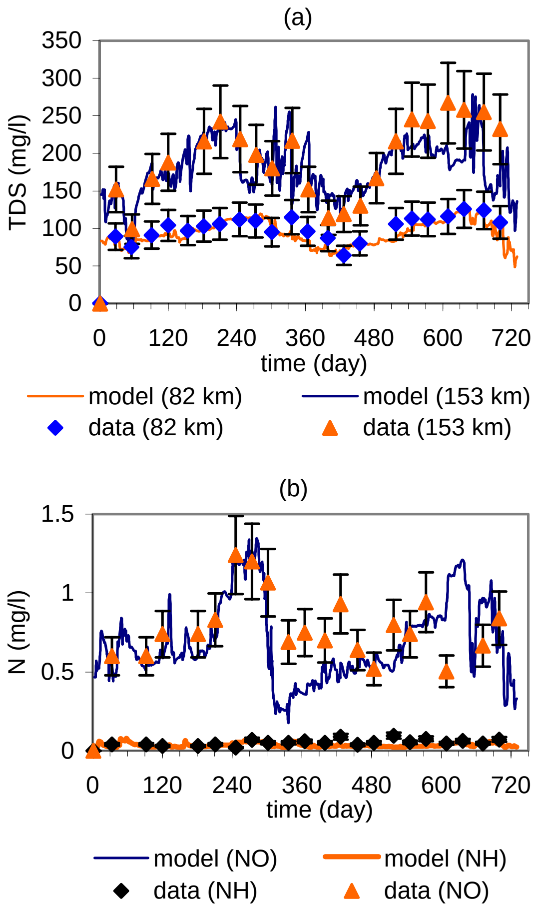

Figure 5
Model validation: comparison of measured and simulated data sets for (a) TDS concentrations at 82 and 153 km and (b) Nitrogen concentration at 153 km

Results and discussion

On the basis of monitoring data collected in 1987/88, the results of the model calibration are presented in Figs. 3 and 4. The results indicate that trends of the predicted data sets show good agreement with the measured data sets for river flow rate and the concentra-

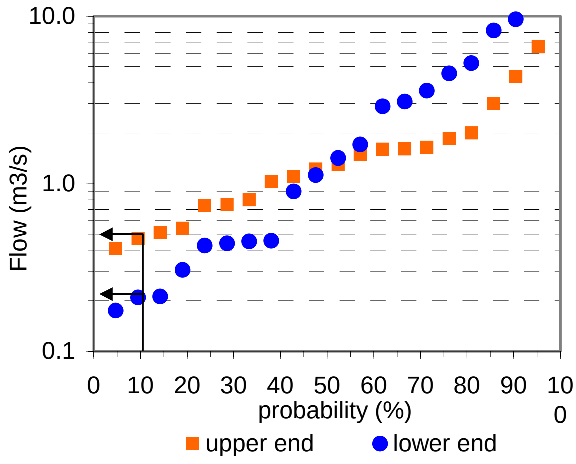

Figure 6
Low flow analysis (1960-1979) for the two sites of Crocodile River: Upper end (0 km) and lower end (153 km); Arrows indicate the value of 7Q10, the minimum flow that occurs every 10 years; probability is the cumulative probability of occurrence of the corresponding low flow rate

tions of TDS and inorganic nitrogen. The best fit was obtained with the minimum and maximum water withdrawal set at 2 and 4 $m^3 \cdot m^{-1} \cdot d^{-1}$, respectively. The estimated water use in 1997 was 580 × $10^6 m^3 \cdot a^{-1}$ (State of the Crocodile River, 2001). By normalising this against the total length of the main-stem Crocodile River (320 km) the amount of water lost is approximately equivalent to 5 $m^3 \cdot m^{-1} \cdot d^{-1}$. This is comparable with the calibrated values. The model was also calibrated for inorganic nitrogen, using nitrate plus nitrite nitrogen (NO_2-N+NO_3-N) and ammonia nitrogen (NH_4-N). The general trend of the model predictions agrees well with the measured data sets within 20 % error (see Fig. 4). Though there are only limited data available (few monthly water quality data), the calibration result for nitrogen is quite satisfactory.

The model was validated using data from 1989/90; once again, the predicted data sets agreed well with the measured data sets (see Fig. 5). Like the calibration result, the model can describe measured the data set within 20 % error. Note that the nutrient load due to possible point effluent discharge and other small tributaries is not included in the model input. Thus, a higher accuracy of the model prediction will require the availability of many more detailed data, a feature that is seldom possible in practice.

Using 20 years of flow data prior to dam construction (1960 to 1979), the low-flow analysis (7Q10) results are indicated in Fig. 6. The 7Q10 flows of the Crocodile River were calculated, and the 7Q10 flow at the upper point (0. 47 $m^3 \cdot s^{-1}$) is higher than that of the lower point (0.21 $m^3 \cdot s^{-1}$). This indicates considerable water losses along the river length.

Dubinina and Kozlitina (2000) have indicated that the 90% and 95% probability of exceeding the corresponding river flow can be used as the critical low base flow and the critical ecological flows, respectively. In Fig. 6, these values correspond to 10% and 5% probability of occurrence, respectively. Based on this method, the value of the critical base flow and critical ecological flows at the lower end of the study site (as is seen in Fig. 6) are 0.21 and 0.17 $m^3 \cdot s^{-1}$, respectively. It should be noted that these critical low flows are clearly far too low to dilute the wastewater effluent discharges and Kaap River inflows in the lower reaches of the Crocodile River. Thus, the above statistical approach is not applicable to rivers in arid and semi-arid regions, where the 95% probability may indicate the likely low flow during drought periods. Furthermore, any additional water abstraction during such critical low flows can accentuate and accelerate further river water quality deterioration. The impact of the maximum rates of water withdrawal from the upstream section of the main river on water quality in the downstream section of the Crocodile River was investigated in this study. Using the "pre-dam" flow data from 1989/90, an increase or decrease in the maximum rate of water withdrawal by approximately 30% (1 $m^3 \cdot m^{-1} \cdot d^{-1}$) caused an average increase or decrease in TDS concentrations of some 4% during low flow periods at the lower point (153 km), but no significant change was observed in nitrogen concentrations (see Fig. 7). This depicts that decreasing the water withdrawal by 1 $m^3 \cdot m^{-1} \cdot d^{-1}$ can reduce the TDS concentration but it is not significant as compared to the 20% error of the model calibration for TDS concentration (see Fig. 3). However, it still indicates a trend. Setting an overall limit on the maximum permissible volume of water that can be withdrawn from the river basin during critical low flows can at least help to reduce further water quality deterioration caused by increased quantities of total dissolved salts. Efficient water use can reduce the necessary rate of water withdrawal. For example, using a covered irrigation canal instead of an open canal can reduce water loss by evaporation. Similarly, surface (flood) irrigation systems waste nearly two-thirds of the water used because of evaporation and seepage. Given that almost 50 % of the water used in the Crocodile River basin is used for irrigation, this offers an opportunity to achieve considerable reductions in water losses.

In addition to its use in setting the maximum limits for water withdrawal, low-flow augmentation was found to be an important management option. The concept of low-flow augmentation used in this study implies the storage of enough water during the wet season (high flow) and then releasing the stored water during the dry season in order to regulate or supplement low flow. The low flow is supplemented not only on the basis of water quantity required for different uses (e.g. irrigation, domestic and industrial supplies) but also for the desired water quality target. With the minimum and maximum outflow rate set to about 5 $m^3 \cdot s^{-1}$ and 7 $m^3 \cdot s^{-1}$ respectively, the dynamics of water stored in the control dam (a hypothetical dam at Montrose Weir) are illustrated in Fig. 8. The proposed minimum outflow is maintained as long as the reservoir storage volume is larger than zero. If the storage volume is equal to or less than zero, it indicates the so-called "alarm level" at which there is no longer enough water available for low-flow augmentation.

The minimum flow (at Montrose Weir) that maintains the target water quality (< 260 $mg \cdot l^{-1}$ for TDS in irrigation water for sensitive crops; < 0.5 $mg \cdot l^{-1}$ for nitrate nitrogen, and < 0.03 $mg \cdot l^{-1}$ for ammonia nitrogen) at the lower point of the study area (153 km) was investigated in this study. The result (see Fig. 9) shows that, with a minimum flow of 5 $m^3 \cdot s^{-1}$ at the upper point of the study site, low-flow augmentation can improve the general downstream water quality (with the exception of nitrite plus nitrate nitrogen concentrations, which are higher in the outflow of the control reservoir than in its inflow (see Fig. 9). During low-flow periods, the controlled flow releases can reduce salinity (TDS concentration) by 20%, and ammonia nitrogen by 60% at the lower point. However, in the middle of the river section (at about 82 km from the upper point), the concentrations of ammonia nitrogen were reduced by 80%, but there was no significant difference in TDS concentrations. Such a large reduction of ammonia concentrations in the middle of the river section is due to dilution and nitrification processes.

This method (low-flow augmentation or controlled flow re-

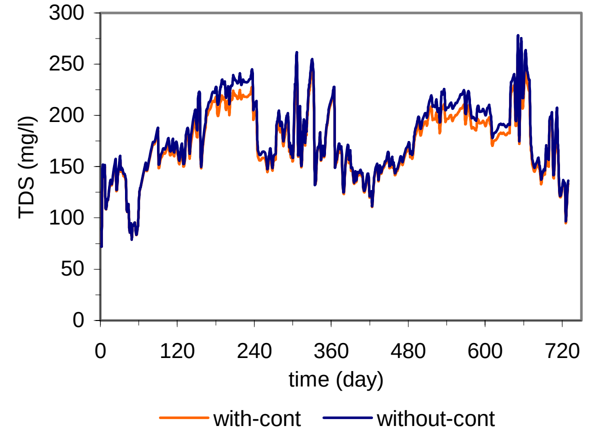

Figure 7
The effect of 30% reduction of water withdrawal on TDS concentration at 157 km: with reduction of water withdrawal (with-cont) and without the reduction of water withdrawal (without-cont)

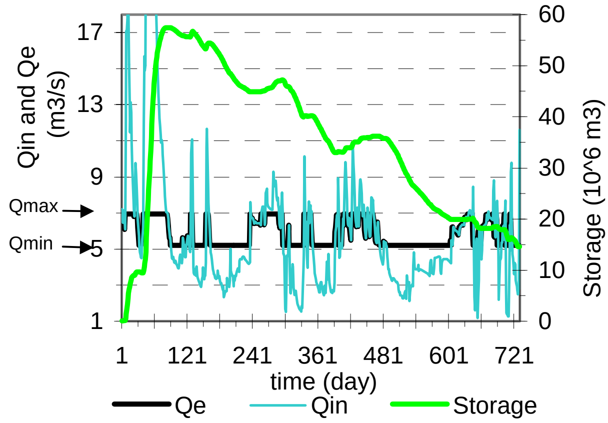

Figure 8
Controlling water release from the dam (hypothetical) at the Montrose Weir (upper point)

lease) can thus improve downstream water quality in TDS and ammonia nitrogen concentrations in the downstream section of Crocodile-Kaap confluence. According to an earlier study, water released from an impoundment that received agricultural runoff and urban effluents could generally improve the water quality of downstream reaches, with the exception of nitrate concentrations (Palmer and Keeffe, 1990). Whilst at least a minimum concentration of phosphorus is required for the growth of nitrifiers, the nitrification process in the reservoir is governed mainly by the available concentration of ammonia and dissolved oxygen, as well as by water temperature. The Palmer and O'Keeffe study shows that as long as these three conditions are satisfied, an increase in the hydraulic residence time of water stored in the reservoir can increase the concentration of nitrate nitrogen in the reservoir. It is therefore up to the water resource manager to decide which water quality parameters should be considered first (e.g. nitrate or ammonia).

In this study, the proposed control strategy seemed to be a useful and cost-effective management option because the existing reservoir (Kwena Dam) could be used. The only change would be the water release pattern from the dam, which has to be adjusted

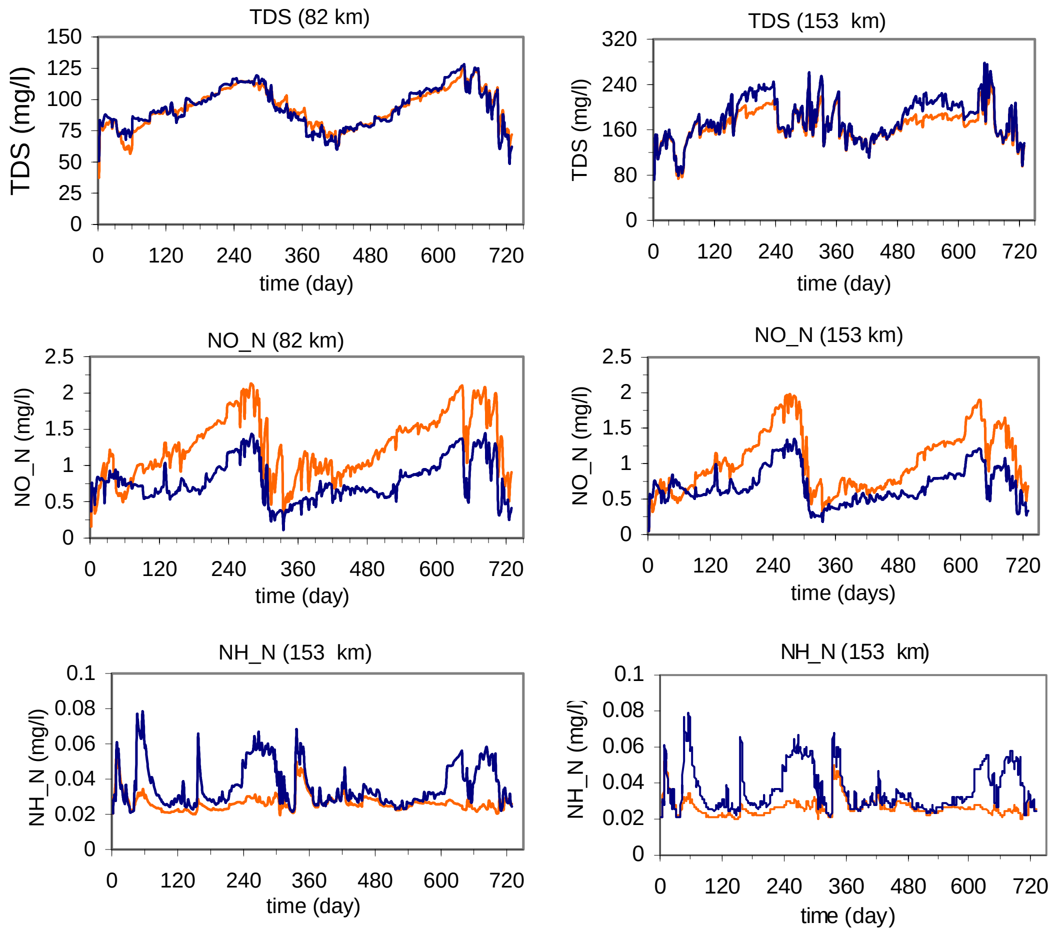

Figure 9

The effect of low flow augmentation on the concentrations of TDS, nitrate plus nitrite nitrogen (NO_N), and ammonia nitrogen (NH_N) in the downstream sections of the river at 82 and 153 km: Light lines for augmented, and dark lines for non-augmented low flows

according to the required target water quality in the downstream reaches of the river. The highly polluted tributary stream (the Kaap River), with water quality that has been adversely affected by mining activities and agricultural runoff, can be diluted to improve water quality in the downstream section of the Crocodile River. In the Kaap River, on the basis of data collected in 1989/90, ammonia nitrogen is greater than 0.03 $mg \cdot l^{-1}$ for most of the time, whereas nitrate nitrogen concentration is greater than 0.6 $mg \cdot l^{-1}$, and TDS concentration can reach about 700 $mg \cdot l^{-1}$ during low flows). The adverse impacts of the Kaap River and the Nelspruit and Malelane wastewater effluents can be controlled by strict adherence to effluent discharge standards and by controlling water releases at the upstream point. Importantly, the general water balance should be conserved, so enough water should be stored during the rainy season so that it can be used for later low-flow augmentation during the dry season. If insufficient rain falls during the preceding rainy season and insufficient water is stored in the control volume or reservoir, another alternative must be considered. In such a case, the second approach, namely that of setting a strict limit on the quantity of water that can be withdrawn could reduce the adverse effects associated with extremely low flows.

Conclusions and recommendations

In this study, different water quality management alternatives were evaluated by using the proposed model. Based on the results obtained, two catchment-based water quality control strategies can be proposed for further testing and possible use on a routine basis. The first proposed control strategy focuses on setting strict maximum limits for water withdrawal during periods of low flow, and ensuring that there is always a minimum river flow available to maintain the target water quality during the dry season. This method is applicable when rivers do not normally experience frequent extremely low flows. When rivers experience frequent low flows, for example in arid and semi-arid regions, low-flow augmentation by an upstream reservoir can be proposed as the second control strategy. In this second control strategy, the relationships between reservoir operation and the resultant river water quality in downstream reaches should be well understood. As shown, regulating the flow pattern of water released from the Kwena Dam can achieve a remarkable reduction in the TDS and ammonia nitrogen concentration in the lower reaches of the Crocodile River. Ideally, the augmented flow pattern should follow or mimic the seasonal pattern of unregulated river flows. Based on flow data for 1987 to1990, the minimum flow at the upper point of the Crocodile River study site should be at least 5 $m^3 \cdot s^{-1}$ so that the salinity (TDS) and ammonia concentrations in downstream reaches can be improved. Importantly, one should also note that the proposed management options are not a stand-alone solution to guarantee the defined water quality objectives. Thus, in addition to the proposed management option, effluent quality standards and diffuse pollution regulation should always be considered. This study has shown that the proposed model has great potential for use as a basin-wide water quality management tool. The model used in this study is relatively simple and can be used for short-term (monthly) predictions of TDS and inorganic nitrogen concentrations.

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