Chemical pollution assessment and prioritisation model for the Upper and Middle Vaal water management areas of South Africa

B. Dzwairo and F. A. O. Otieno

ABSTRACT

A chemical pollution assessment and prioritisation model was developed for the Upper and Middle Vaal water management areas of South Africa in order to provide a simple and practical Pollution Index to assist with mitigation and rehabilitation activities. Historical data for 2003 to 2008 from 21 river sites were cubic-interpolated to daily values. Nine parameters were considered for this purpose, that is, ammonium, chloride, electrical conductivity, dissolved oxygen, pH, fluoride, nitrate, phosphate and sulphate. Parameter selection was based on sub-catchment pollution characteristics and availability of a consistent data range, against a harmonised guideline which provided five classes. Classes 1, 2, 3 and 4 used ideal catchment background values for Vaal Dam, Vaal Barrage, Blesbokspruit/Suikerbosrant and Klip Rivers, respectively. Class 5 represented values which fell above those for Klip River. The Pollution Index, as provided by the model, identified pollution prioritisation monitoring points on Rietspruit-W:K2, Natalspruit:K12, Blesbokspruit:B1, Rietspruit-L: R1/R2, Taaibosspruit:T1 and Leeuspruit:L1. Pre-classification indicated that pollution sources were domestic, industrial and mine effluent. It was concluded that rehabilitation and mitigation measures should prioritise points with high classes. Ability of the model to perform simple scenario building and analysis was considered to be an effective tool for acid mine drainage pollution assessment.

Key words | acid mine drainage, assessment and prioritisation model, classification, Pollution Index, rehabilitation, Upper and Middle Vaal water management areas

B. Dzwairo (corresponding author)
Durban University of Technology,
Institute for Water and Wastewater Technology,
P. O. Box 1334, 4000,
South Africa
E-mail: *ig445578@gmail.com*

F. A. O. Otieno
Durban University of Technology,
Deputy Vice Chancellor: Technology,
Innovation and Partnerships,
P. O. Box 1334, 4000,
South Africa

INTRODUCTION

Blacksmith's Report (Harris & Andrew 2011) lists mercury, lead, pesticides and chromium as being among the world's top ten toxic products, whose sources are various economic activities like mining, tannery and agriculture. The problem is not the activities themselves as these sustain national gross domestic product (GDP), but non-existent or weak global environmental monitoring and mitigation plans, the consequences of which are environmental disasters that started hundreds of years ago. Their negative effects are envisaged to continue into the unforeseeable future and urgent mitigation measures are required now. The same report also lists 20 declared environmental pollution-causing economic activities. Among these, mining occupies first (artisanal gold mining), sixth and seventh (mining and ore processing) position on the list. All three processes specifically result in production of complex mine effluent and solid waste, which eventually generate acid mine drainage (AMD) through interaction with air and water.

Benedetto *et al.* (2005) described AMD as one of the most serious environmental problems that the mining industry has ever created. In South Africa, Zilles *et al.* (2002) arguably declared AMD to be the single most significant threat to the country's environment. Apart from the mine dumps which continuously create harsh acidic and chemically toxic ecosystems, a major environmental concern of

doi: 10.2166/wh.2014.017

pollution from AMD is severe impacts on aquatic life (Wei *et al.* 2011; Kruse *et al.* 2012).

AMD and sewage effluent continue to threaten South African ecosystems despite existence of the National Environmental Management Act No. 107 of 1998 (DEAT 1998). Mining management creates a huge challenge with regards compliance with water quality guidelines or objectives. In addition to this challenge, a wide array of parameters has to be tested before decisions are made regarding pollution trending and health statuses of these ecosystems. In such cases, a model that enables construction of an index simplifies presentation of results as the index can summarise in one value or concept the array of parameters that are analysed (Couillard & Lefebvre 1985; Wepener *et al.* 2005; Abrahão *et al.* 2007). A Pollution Index that allows proper identification of contamination sources, in addition to prioritisation for rehabilitation and mitigation, promotes sustainable environmental management, and can further assist in checking legal compliance of parameter values.

Water quality guidelines are invaluable for monitoring environmental impacts. The process of deriving these guidelines at catchment or sub-catchment level has a long history in South Africa. Several ecosystem health indicators have been proposed and evaluated but they have their specific shortfalls, which is why the process is ongoing (DWAF 1996, 2007; Roux *et al.* 1996; Slaughter 2005; Dzwairo *et al.* 2011b). Examples of ecosystem health indicators are the Salinity Index (DWAF 2007) and the Ecological Functionality by Dzwairo *et al.* (2011b).

The Ecological Functionality was specifically developed for the Upper and Middle Vaal water management areas (U&MVWMAs). It uses water quality guidelines of predefined boundary conditions and electrical conductivity (EC) as surrogate for chemical pollution. The index is simple and can be used for rapid assessments because EC is measured in normal routine assessments, thus no additional complex testing is required. It, however, does not account for microbial pollution, which is a problem in environments that are impacted by domestic effluent pollution, a drawback of this index.

The Salinity Index is not standardisable for use in other environments since any environmental impacter can contribute to the salinity value. Further, the Department of Water Affairs' (DWA) 1996 guidelines contain very detailed information, which is a drawback where everyday use in local settings requires simplified guidelines.

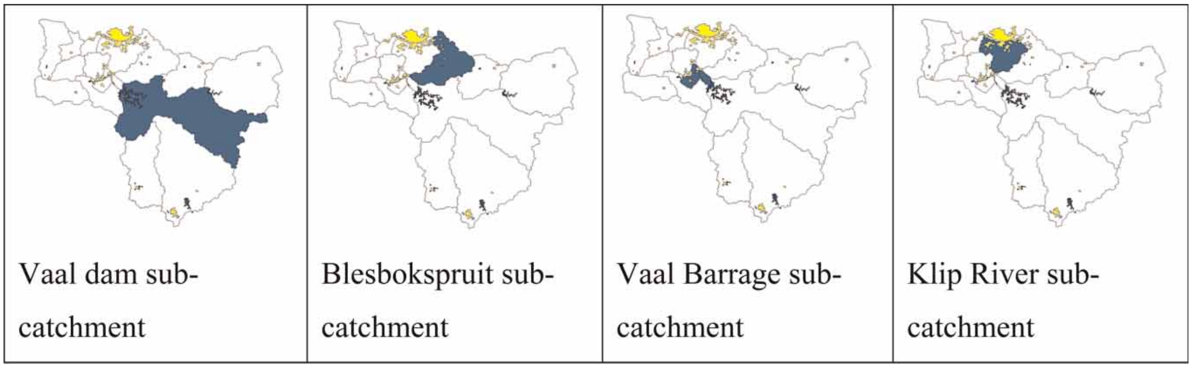
On the other hand, the Soil and Water Assessment Tool now incorporates a water quality module QUAL2E which makes it possible to quantify relative impacts of alternative catchment management practices on water quality. Paliwal *et al.* (2007) noted that although the model incorporates hydrological calculations and data preparation, they require relatively good modelling techniques. Thus it does not find general use in catchment management.

Another example is the resource water objectives (RWOs) which describe the health status of a sub-catchment by taking into account its specific pollution impacts. Use of this model in the Upper Vaal WMA assigns the lowest RWOs values to Vaal Dam. Klip River is assigned the highest values while Blesbokspruit/Suikerbosrant Rivers and Vaal barrage RWOs values fall in-between those for Vaal Dam and Klip River. The sub-catchments are shown in Figure 1. The model presents a major limitation in that it is impossible to adapt it or compare pollution trends across the sub-catchment boundaries because the guidelines are catchment-specific.

A harmonised guideline could serve as a baseline to make comparisons based on the same set of objectives, and is thus proposed in this study. The guideline could further provide a management dispensation based on equity, especially for potable water treatment utilities and other stakeholders that use the same SANS 241 potable water standard, in addition to meeting the Blue Drop criteria (DWAF 2009). A pollution assessment and prioritisation model could then be constructed, based on the harmonised guideline, for trans-boundary sub-catchment pollution assessments and prioritisation to support mitigation and rehabilitation activities.

STUDY AREA

South Africa suffers from water stress while its existing water resources are under pressure to meet a growing demand (Haji 2011) from agriculture, mining and domestic use sectors. To add to this pressure, the ecosystem is considered to be extremely negatively impacted in specific locations since many years ago (Steÿn *et al.* 1976; Pieterse


Vaal dam sub-catchment

Blesbokspruit sub-catchment

Vaal Barrage sub-catchment

Klip River sub-catchment

Figure 1 | Upper Vaal WMA showing the four sub-catchments (Rand Water 2012).

et al. 1987; Cloot & Le Roux 1997; Winde & Jacobus van der Walt 2004; DWAF 2007; Dzwairo 2011; Durand 2012).

This paper focuses on U&MVWMAs that are part of the Vaal basin. The Vaal River, which flows from east to west, is a very strategic and important source of water in these WMAs. Land use as at 2009 for the U&MVWMAs is shown in Figure 2 and data were sourced from the DWA. Mines, including degraded land, occur close to or among the urban built-up areas, which exposes humans to toxic effluent and dust from mining activities.

Water requirements are, however, augmented by flow from Lesotho (Lesotho Highlands Water Project) and this helps to flush pollution towards downstream into MVWMA and beyond.

This paper reports on development of a simple model to assess and prioritise pollution across the two WMAs using data for 2003 to 2008 and 21 monitoring points (Figure 3). It also provides a method for adapting the index system to a drinking water treatment plant's water quality assessment.

The highly developed UVWMA contributes nearly 20% towards South Africa's GDP (Dzwairo 2011). Klip River, Suikerbosrant and Rietspruit-L drain mining areas, resulting in pollutants flowing into the Vaal River. Interventions are thus necessary to ensure that good quality water is available to support the WMA's land use.

The MVWMA's northern regions are also impacted by mining activities and the resultant pollution loads flow via

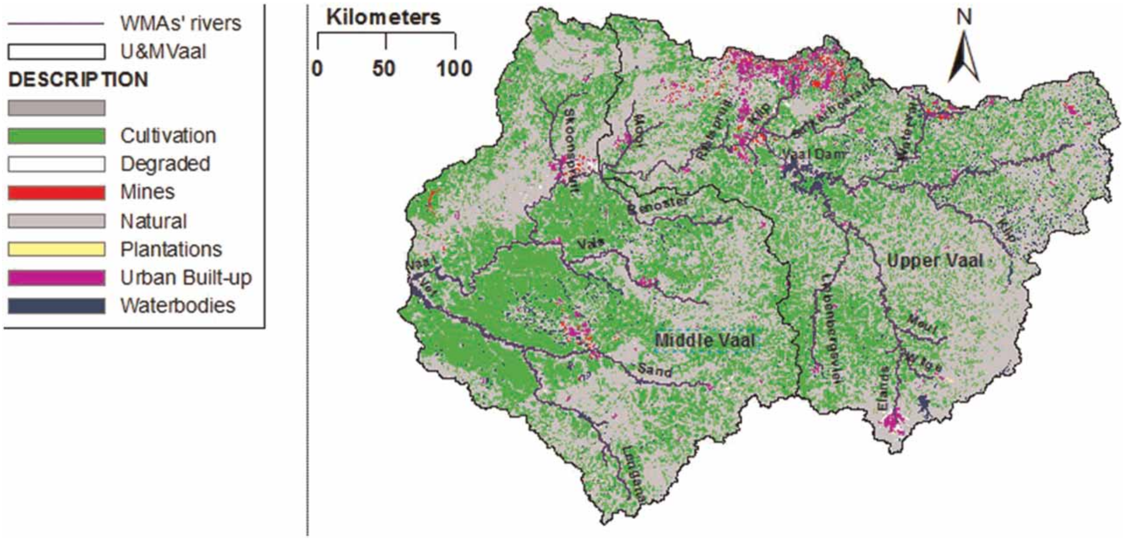


Figure 2 | Upper and Middle Vaal WMAs' land use as at 2009 (map was developed from data which were sourced from DWA).

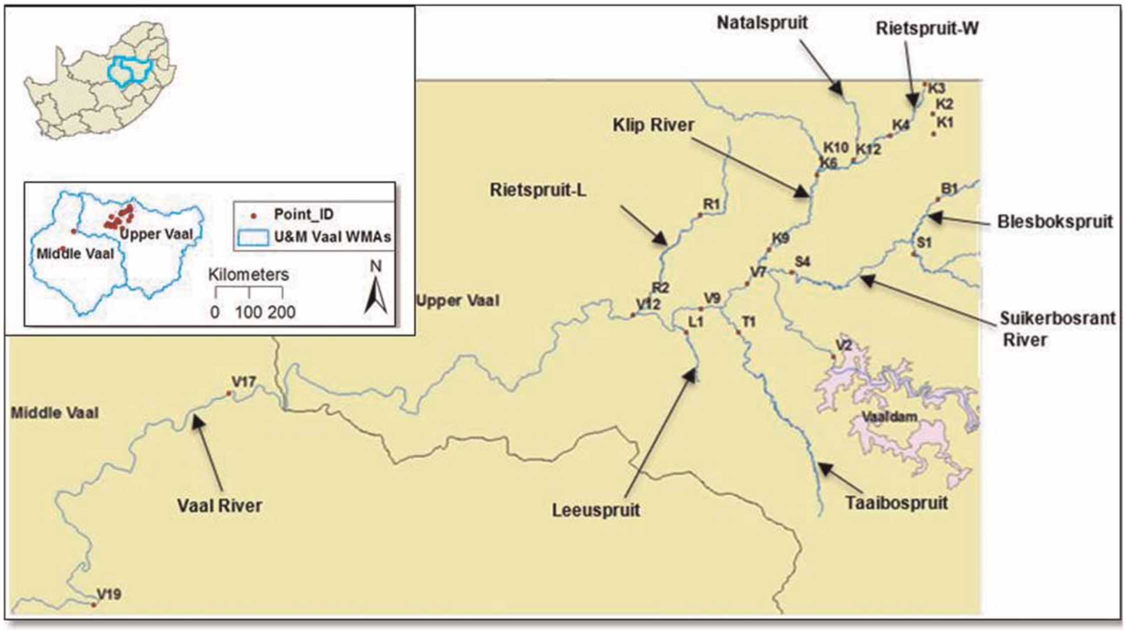


Figure 3 | Pollution assessment Point_IDs on specific rivers in U&MVWMAs (base maps were developed from data which were sourced from DWA).

tribuatries into the Vaal River. Despite the stated pollution problems, mining generates about 45% of that WMA's GDP (DWAF 2003; Dzwairo 2011), with a total 4% being its contribution towards the country's GDP (Dzwairo 2011).

MATERIALS AND METHODS

Harmonised in-stream water quality guideline

A harmonised in-stream water quality set of guideline values was required as a basis for constructing the model equations. The harmonised in-stream water quality guideline (Table 1), which is made up of RWOs values, was adapted for this purpose.

The nine parameters representing pollution sources were determined in earlier studies for the study area (Dzwairo *et al.* 2011a, 2012). They act as surrogates for pollution sources in the U&MVWMAs, thus: ammonium, chloride, EC, dissolved oxygen, pH, fluoride, nitrate, phosphate and sulphate. Dzwairo *et al.* (2011a) specifically considered availability of data, pollution sources in the study area, and data reduction techniques like factor analysis. The data reduction and factor analysis processes employed sensitivity analysis techniques as various parameters were evaluated for inclusion in the best parameter set.

Model calibration

Model calibration consisted of changing values of the input parameters to match field conditions within the acceptable harmonised in-stream water quality guideline criteria. Ideal catchment background values of the RWOs were employed for this process. Vaal Dam ICB values represented class 1 as the least impacted ecosystem while Klip River was assigned class 4. The ICBs for Vaal Barrage and Blesbokspruit/Suikerbosrant Rivers were assigned classes 2 and 3, respectively. Class 5 represented a category for values which fell above those for Klip River. The lower and upper limits of the RWOs defined the operational boundary within each class (Table 1).

Microsoft Excel-based IF-THEN-ELSE rule-set functions were constructed against the HIWQG values. The method was used to construct four models for each of the

Table 1 | Harmonised in-stream water quality guideline

Ideal catchment background/values for sub-catchment	Class	NH_4^+ (mg/l)	DO (mg/l)	Cl^- (mg/l)	EC (mS/m)	pH	F^- (mg/l)	NO_3^- (mg/l)	PO_4^{3-} (mg/l)	SO_4^{2-} (mg/l)
Vaal Dam	1	0.2	6	25	10	6.5–8.5	0.05	0.1	0.05	20
	Lower					6.5				
	Upper					8.5				
Vaal Barrage	2	< 0.5	> 6	< 5	< 18	7–8.4	< 0.19	< 0.5	< 0.03	< 20
	Lower	0.2			10	7	0.05	0.1		
	Upper	0.5			18	8.4	0.19	0.5		
Blesbokspruit/Suikerbosrant River system	3	< 0.1	> 6	< 80	< 45	6.5–8.5	< 0.19	< 0.5	< 0.2	< 150
	Lower			50	18	6.5				20
	Upper			80	45	8.5				150
Klip River	4	< 0.5	> 6	< 50	45–80	6–9	< 0.19	< 2	< 0.2	< 200
	Lower				45	6		0.5	0.05	150
	Upper				80	9		2	0.2	200
Above class 4 limit	5	0.5	6	80	80	$< 6; > 9$	0.19	2	0.2	200
	Lower									

Source: Adapted from Rand Water (2012).

nine parameters. Equations (1)–(4) are provided for the parameter EC

$$\text{IF}\left(\text{EC value} \geq 80\,\frac{\text{mg}}{\text{l}}\ \text{THEN Class 5 ELSE}\ \gamma\right) \tag{1}$$

$$\gamma\!:\left[\text{IF}\left(\text{AND}\left(\text{EC value} \geq 45\,\frac{\text{mg}}{\text{l}}, \text{EC value} \leq 80\,\frac{\text{mg}}{\text{l}}\right)\right)\ \text{THEN Class 4 ELSE}\ \beta\right] \tag{2}$$

$$\beta\!:\left[\text{IF}\left(\text{AND}\left(\text{EC value} \geq 18\,\frac{\text{mg}}{\text{l}}, \text{EC value} \leq 45\,\frac{\text{mg}}{\text{l}}\right)\right)\ \text{THEN Class 3 ELSE}\ \alpha\right] \tag{3}$$

$$\alpha\!:\left[\text{IF}\left(\text{AND}\left(\text{EC value} \geq 10\,\frac{\text{mg}}{\text{l}}, \text{EC value} \leq 18\,\frac{\text{mg}}{\text{l}}\right)\right)\ \text{THEN Class 2 ELSE Class 1}\right] \tag{4}$$

Weight factors

Assuming that some users in the two water management areas use untreated water from the rivers, weighting of the parameters considers human and environmental health effects of using that water (Dzwairo *et al.* 2012). In previous research by the same author, the process of deriving the weight factors was described in detail. It included developing a ranking key for effects of individual parameters on humans and the environment. These effects were categorised as death in the short term, death in the long term, immediate debilitating effects, long-term debilitating effects and effects that were of low significance. The ranking key is given in Table 2 while the sources of literature and ranking procedure are provided in Dzwairo *et al.* (2012).

The resultant normalised and aggregated factors represented overall weighting of the parameters. The values are quoted as: 0.2000 (F^-), 0.1778 (NO_3^-), 0.2000 (NH_4^+), 0.1778 (DO), 0.1556 (pH), 0.1333 (SO_4^{2-}), 0.1111 (PO_4^{3-}),

Table 2 | Human and environmental health effects ranking key

Effect	Duration	Term	Preference ordering
Death	Short term	D_{st}	5
	Long term	D_{lt}	4
Debilitating effects	Immediate	DE_i	3
	Long term	DE_{lt}	2
Low significance		LS	1

Source: Dzwairo *et al.* (2012).

0.0444 (EC) and 0.889 (Cl^-). These were multiplied by each corresponding parameter class to provide a weighted daily median. The median represented the index for that date.

Because the aim was to model at a daily time-step, water quality data (represented by the chosen nine parameters) for the 21 monitoring sites were treated for outliers and then 'patched' for missing values using series interpolation in Microsoft Excel. The data sets were then date-cubic-interpolated on Matlab (R2012b) platform to produce data with 365 days. The 29th day of February was deleted so as to create a data set of equal lengths for spatial and temporal comparisons.

The Matlab codes for interpolating a single column and for many columns are provided in Dzwairo *et al.* (2011a). These codes are invaluable for fast date-interpolation, especially because historical water quality data normally contain missing values, mainly because consistent data analysis is very expensive and also because of human error. Water quality monitoring in developing countries mainly relies on human input and intervention in specific steps. The four rule-sets in Equations (1)–(4) were thereafter applied to the pre-processed data and the result was daily indices (medians) for each of the 21 sites.

Applying the four equations on each of the parameter quality data gave nine parameter classes per day for the 6 years, for all the 21 sites. Pollution assessment and prioritisation indices at a daily time-step for 3 days only are given in Table 3. Computing indices at a daily time-step incorporates management flexibility to compute indices at any other time-steps such as weekly or yearly (Table 3).

Progressive changes in quality can be monitored easily in Microsoft Excel, and remedial actions can be suggested. Further, if the guideline values change, these can be easily incorporated into the models in the Microsoft Excel environment, which requires neither computer nor model expertise.

MODEL INTERPRETATION AND SCENARIO ANALYSIS

The pollution assessment and prioritisation model is meant to mainly aid in understanding system pollution processes in the study area in retrospect and to offer a basis for action to mitigate impacts. However, the model suffers from low goodness-of-fit. This is largely as a result of huge perturbations which are a response to natural and artificial impacts like human-induced pollution or rainfall events, etc. The resultant R^2 values are typically below 0.5. A model with a good data fit should give an R^2 value of close to or equal to 1.

However, this model finds invaluable use in scenario building and analysis in order to assess or predict the combined impacts of the nine parameters, wherever positive or negative change occurs in the environment. Trending or scenario building allows users to 'see' into the future before impacts actually happen. This can provide windows of opportunities to understand what the future scenario will be like if nothing is done to current conditions or if positive or negative change is effected. For example, undesirable modifications to quality at a specific monitoring point can be

Table 3 | Pollution Indices as medians for daily, weekly and yearly time-steps

Time	S1	B1	S4	K9	V7	T1	V9	L1	R2	V12	V17	V2	K1	K2	K3	K4	K6	K10	K12	R1	V19
1/1/03	2	3	3	3	3	3	4	2	3	3	3	2	2	4	3	3	4	3	4	3	2
1/2/03	2	3	3	3	3	3	3	2	3	3	3	2	2	4	3	3	4	3	4	3	2
1/3/03	2	3	3	3	3	3	3	2	3	3	3	2	2	4	3	3	3	3	4	3	2
Week1	2	3	3	3	3	3	3	2	3	3	3	2	2	4	3	3	3	3	4	3	2
Week 2	2	3	3	3	3	3	4	2	4	3	3	2	2	4	2	3	4	3	4	3	2
Week 3	2	3	3	3	3	4	3	2	4	3	3	2	3	4	2	3	4	3	4	3	3
2003	2	3	3	3	3	3	3	2	4	3	3	2	2	4	3	3	4	3	4	3	3
2004	2	3	3	3	3	3	3	3	4	3	3	2	3	5	3	3	4	3	4	4	3
2005	2	3	3	3	3	3	3	3	4	3	3	2	3	4	3	3	4	3	4	4	3

determined much earlier so that mitigation measures can be put in place before the changes occur.

TEMPORAL AND SPATIAL ANALYSIS

Temporal analysis (Figure 4) for 2003 to 2008 using a yearly time-step revealed that S1 index remained at 2 for all 6 years, as did V2. Trending results for sites located around the East Rand (K2, K4, K3 and K6, K10, K12 and K9) show no significant change in pollution, through the 6 years. These points were impacted mainly by AMD and in some places like K12 in Natalspruit, by poor quality sewage effluent. K1 trends show that as at 2008, good quality water passed through that point.

T1, R1, R2 and L1 indices are consistently high for the 6 years. R1 and R2 mainly channelled sewage effluent pollution from upstream wastewater treatment plants while T1 and L1 pollution characteristics indicated industrial pollution. Pollution from the Vaal tributaries impacted the Vaal River at V7, V12 (Vaal Barrage), V17 and V19 and the 6-year trends show that no positive mitigation activities occurred at any of the identified pollution sources.

In addition, the pollution was persistent towards downstream over the years. For a sub-basin that is critical to South Africa's economy, this condition is unacceptable because V2, V17 and V19 are abstraction points for potable water treatment.

Spatial trends were done using Figure 5, which mapped indices for 2003 and 2008. It can be noted that if mitigation measures are effected at just seven monitoring sites in the Upper Vaal, at B1, K12, K2, T1, L1 (to some extent), and at R2 and R1, the resultant improvement in quality is what is desirable for the Vaal River for many years. Positive effects would be noted in the Klip River at K9, Suikerbosrant River at S4 and Vaal River at V12 (at the Barrage). Taaibospruit (T1) and Leeuspruit (L1 – this point shows an improvement between 2003 and 2008 from an index of 3 to 2) to a lesser extent, polluted the Vaal River, as did Rietspruit-L through the Loch Vaal. Figure 5 also indicates that the pollution load which flowed through V12 (Vaal Barrage) originated from the Upper Vaal water management area itself, since Vaal Dam (at V2) and Suikerbosrant (at S1) indices indicate pristine environments.

East Rand, as part of South Africa's Eastern, Central and Western Basins, requires massive rehabilitation, mainly on the dysfunctional and inefficiently maintained mines and associated mine dumps, pyrite tailings and AMD. The indices will remain indicative of the problem until government steps in with grand plans. The results from the Pollution

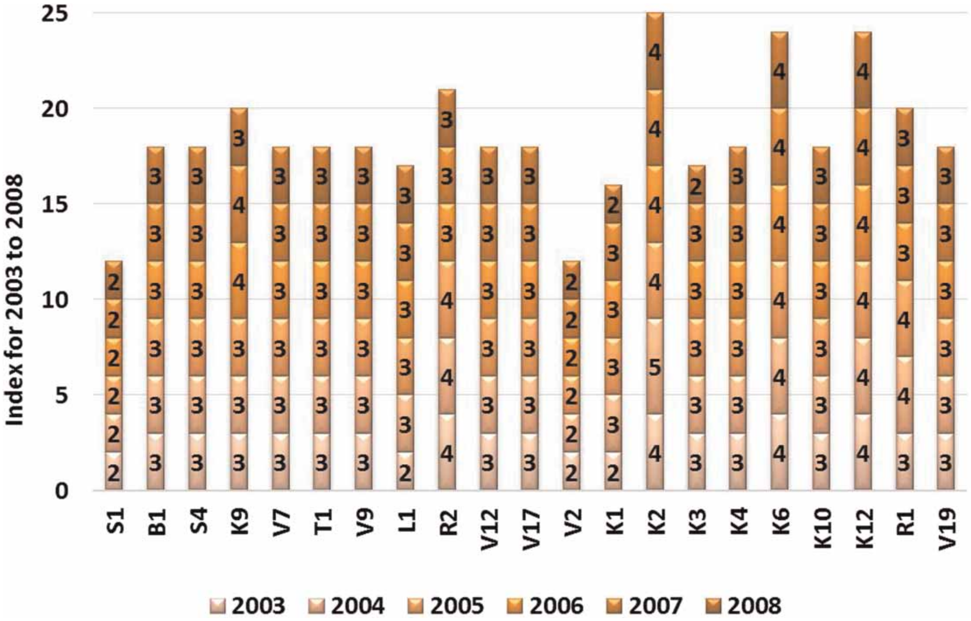


Figure 4 | Temporal analysis for the 21 monitoring sites from 2003 to 2008.

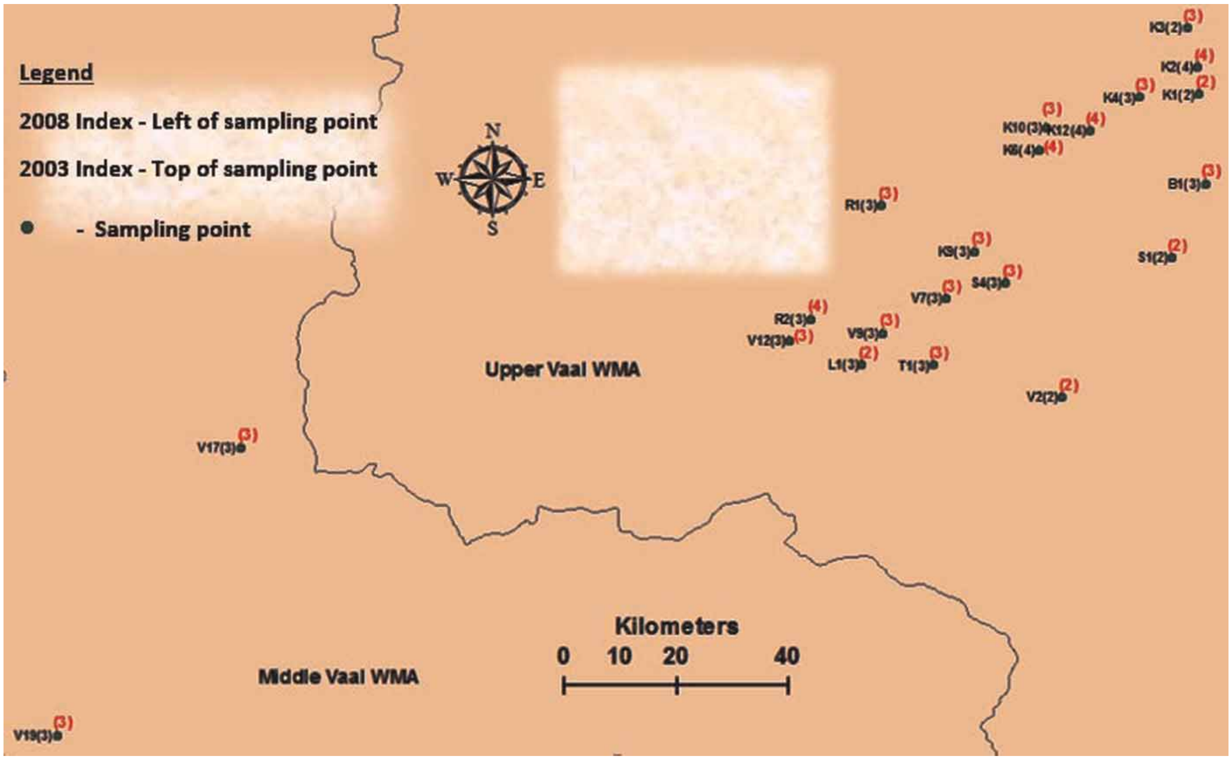


Figure 5 | Spatial analysis of pollution across catchments using the pollution assessment and prioritisation indices.

Assessment Index are in agreement with the Salinity Index that was used in DWAF (2007).

MODEL TESTING AND FLEXIBILITY WITH PARAMETER SELECTION

The model was tested for seasonal effects by carrying out a one-parameter-at-a-time (OPATAT) sensitivity analysis, a method that was specifically developed for this particular research. Observations were made on the index as its magnitude varied from baseline with each change in input value, one parameter at a time. Days 1 July 2001 and 1 January 2002 were taken to represent the dry and wet days, respectively, for a 1-year cycle.

The process of testing the model involved pretreating data for raw water that is used at a potable water treatment plant, but whose source is Vaal Dam. It is channelled to the plant through a pipeline. Additional parameters from those in the original model (Table 4) were incorporated to reflect the requirements of a potable water treatment plant in the Modified Harmonised In-stream Water Guideline in Table 4.

Table 4 | Modified harmonised in-stream water quality guideline

Ideal catchment background/Values for sub-catchment	NH_4^+ (mg/l)	Fc (CFU)	Cl^- (mg/l)	EC (mS/m)	F^- (mg/l)	NO_3^- (mg/l)	pH	PO_4^{3-} (mg/l)	SO_4^{2-} (mg/l)	Rturb (NTU)	COD (mg/l)
Vaal Dam	< 0.2	< 126	< 25	< 10	< 0.05	< 0.1	6.5–8.5	< 0.05	< 20	0–1	< 10
Vaal Barrage	< 0.5	< 126	< 5	< 18	< 0.19	< 0.5	7.0–8.4	< 0.03	< 20	1–5	< 10
Blesbokspruit/Suikerbosrant	< 0.1	< 126	< 80	< 45	< 0.19	< 0.5	6.5–8.5	< 0.2	< 150	5–10	< 20
Klip River	< 0.5	< 126	< 50	< 80	< 0.19	< 2	6.0–9.0	< 0.2	< 200	< 10	< 15

Source: Values were adapted from Rand Water (2012).

Flexibility of the model structure allowed for incorporation of faecal coliforms specifically to provide microbial assessment, which is critical in a potable water treatment plant. Turbidity was incorporated because it is the one which is used in jar tests to determine optimum coagulant dose. Chemical oxygen demand (COD) was introduced for operational optimisation.

The parameter classes were not weighted, the reason being that if the plant was monitoring for them, it meant that they were critical to human health. The rule-sets (Equations (1)–(4)) were applied to the data, which classified the 11 parameters. The two sets of parameter classes were plotted together with their indices. The indices are the medians of the daily parameter classes (Figure 6). Rturb represents raw water turbidity and COD.

OPATAT sensitivity analysis

OPATAT sensitivity analysis method works in such a way that for each parameter class which exhibits an extreme value, that is, 1 or 5, that class is assigned its extreme opposite value (class 1 will be assigned a value of 5 while class 5 will be assigned a value of 1). The difference between the original index (index_o) and the output index (index_s) from sensitivity analysis gives the residual of that analysis.

For the test sample in this paper, the sensitivity analysis was performed on the baseline data as indicated in Figure 6 using parameters with class 1 only. By raising these to maximum values, one at a time the residual was calculated. Where index_o was insensitive to the parameter class change, index_o equated to index_s, giving a residual of 0. A sensitive index_o means that the residual can become positive or negative, depending on the baseline classes where a user can decide to test for all variations including those classes whose values fell in-between 1 and 5. A point to note is that if the $\text{index}_o = 1$, lowering the maximum sub-classes does not affect the magnitude of that index_o.

The process used the following parameters for both the wet and dry seasonal dates: ammonium (Figure 7), faecal coliforms (Figure 8), chloride (Figure 9), pH (Figure 10), phosphate (Figure 11) and sulphate (Figure 12). Nitrate (Figure 13) was used for sensitivity analysis only for 1 January 2002 since nitrate exhibited a class of 1 only for that day (see Figure 6).

The residuals, which are shown in Figure 14, indicate that the models were sensitive only to the dry date parameter classes, by a magnitude of one index unit for all parameters. The wet date gave residuals of zero for all parameters. These two results highlight the influence of precipitation as run-off, on the models. The wet conditions could have also influenced the parameter classes resulting in lower pollution indices for 1 January 2001 than for 1 July 2001. The residual outcome also points to less perturbation effect on a wet day than on a dry date. On a dry date, any perturbations from

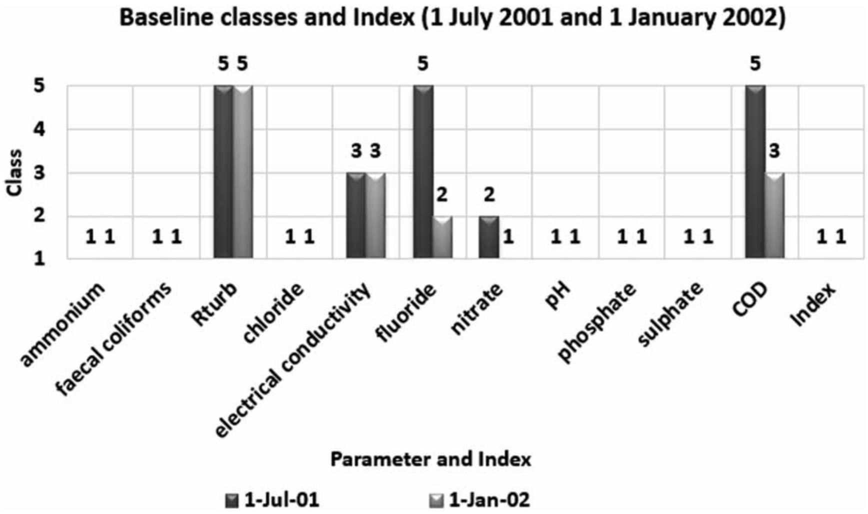


Figure 6 | Parameter classes for 1 July 2001 and 1 January 2002 plus the indices.

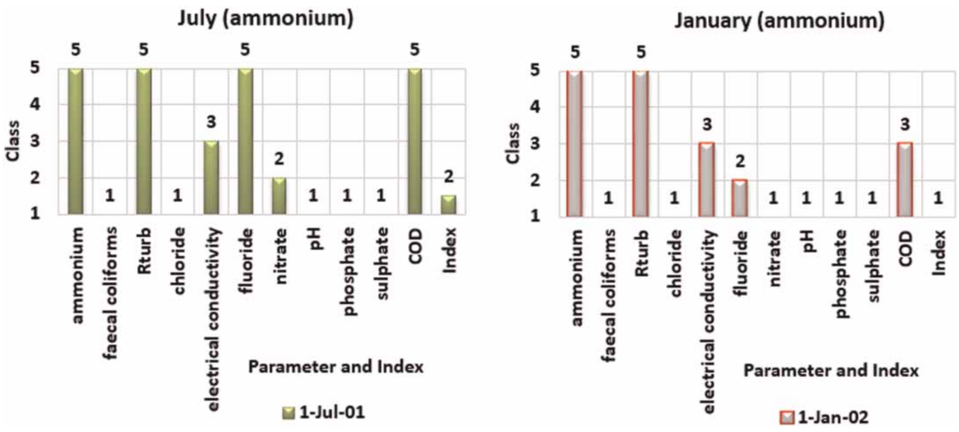


Figure 7 | Ammonium sensitivity analysis.

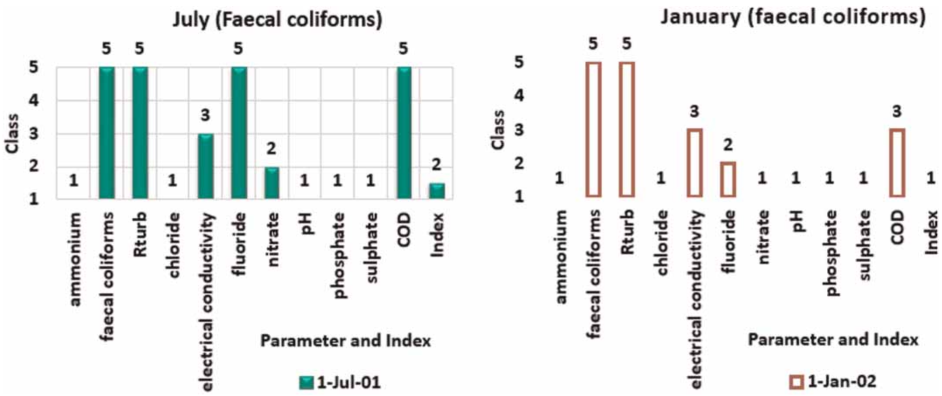


Figure 8 | Faecal coliforms sensitivity analysis.

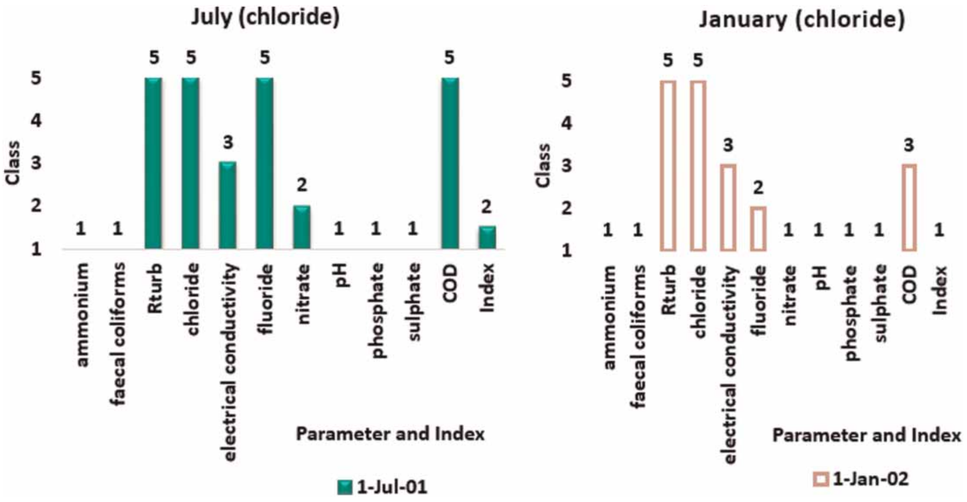


Figure 9 | Chloride sensitivity analysis.

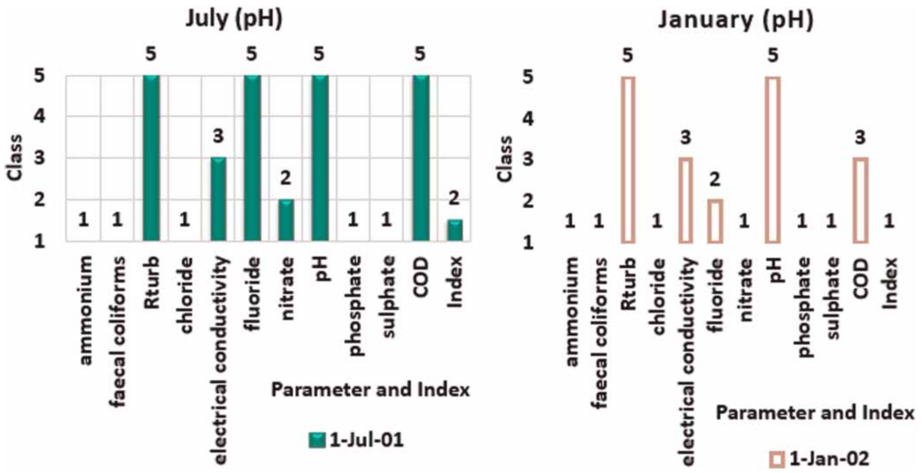


Figure 10 | pH sensitivity analysis.

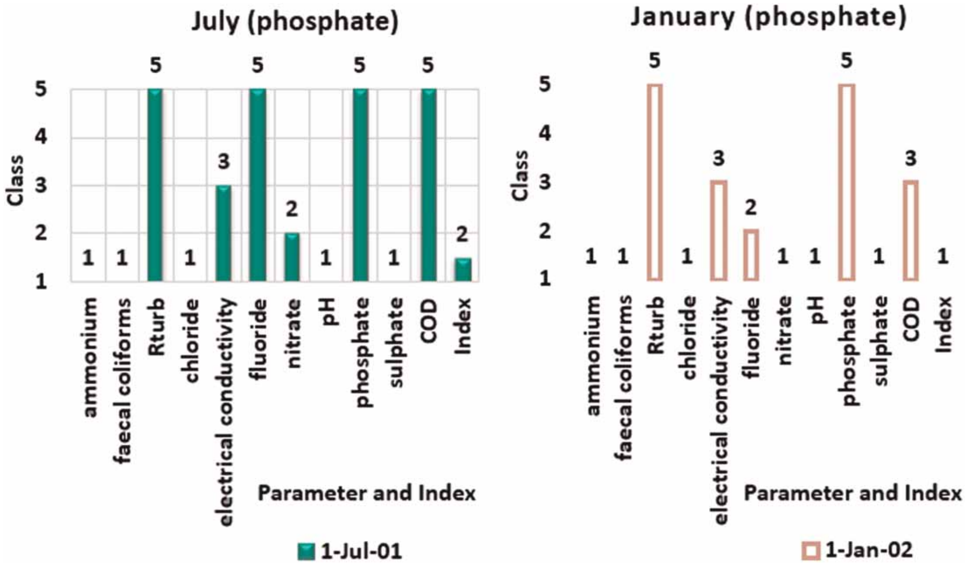


Figure 11 | Phosphate sensitivity analysis.

baseline created a residual, most likely because of the influence of lower flows on water quality.

PRIORITISATION AND MITIGATION

The environmental impacts of AMD, which is a complex challenge in the East Rand, can be minimised at three basic levels: through primary prevention of the acid-generating process; secondary control, which involves deployment of AMD migration prevention measures; and tertiary control, or the collection and treatment of effluent (Akcil & Koldas 2006). Characteristically high sulphate concentrations exhibit AMD pollution and thus this paper raises a proposal to install and operate anaerobic sulphate bioreactors for currently decanting ground water and mine dump seepage.

For environments that are not yet decanting, all efforts must be taken to keep pumping the groundwater so that it is treated at point sources, for re-use in active mines. An anaerobic sulphate bioreactor acts as an immobilised

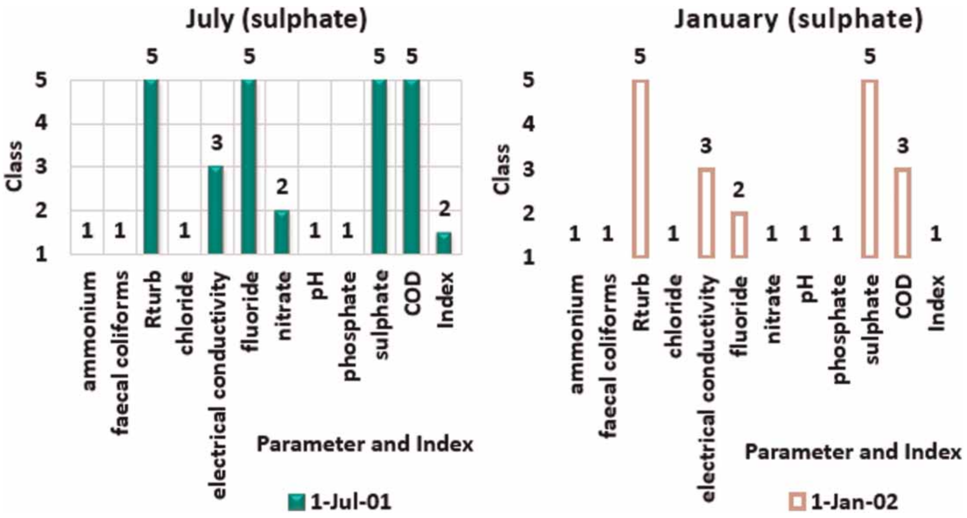


Figure 12 | Sulphate sensitivity analysis.

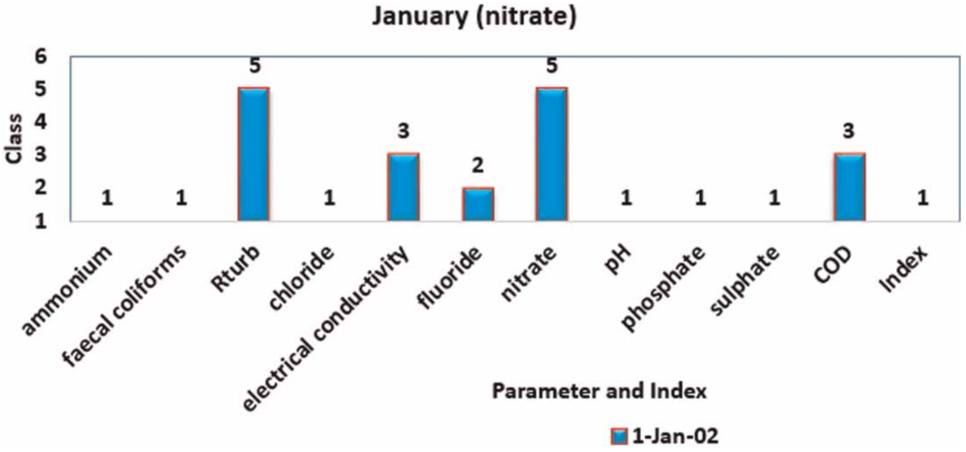


Figure 13 | Nitrate sensitivity analysis.

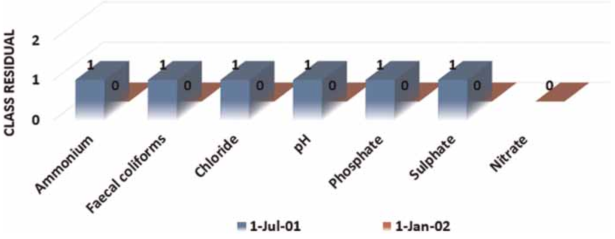


Figure 14 | Index residuals from sensitivity analysis.

bacterial bed which takes advantage of bacterial metabolic pathways that would normally occur in nature. By optimising conditions for these bacteria to utilise sulphate in a confined environment, reduction of sulphate levels is theoretically achievable, in addition to reduction of associated metals and anions. This methodology has worked elsewhere. However, it requires consistency that is equivalent to operating a wastewater treatment plant, for which unscheduled stoppages may result in wastewater spillage and subsequent pollution of surrounding environments.

It was observed that the Pollution Index was in agreement with findings in DWAF (2007), McCarthy (2011) and Durand (2012), among other papers which documented mining impacts in South Africa. Durand (2012) specifically reported about the effluent which passes by the Marievale RAMSAR site, which is located downstream of Grootvlei Mine in Springs, South Africa.

CONCLUSIONS

The pollution assessment and prioritisation model was successfully developed to provide a simple and practical method for constructing a Pollution Index. The model was tested for sensitivity using the OPATAT method that was developed for this research. Results showed that although the index was site specific, adaptation to other environments that were impacted by similar pollutants was possible, with modification of the HIWQG. In this paper, the model assessed a potable water treatment plant's raw water quality, together with calculation of residuals for indices on one wet and one dry day. Results indicated that the dry date index was sensitive to maximum change for all parameters (residual = 1) while the wet date index was insensitive to parameter change, which confirmed the influence of precipitation/flow on water quality.

The index system was used to assess water pollution levels across Upper and Middle water management area boundaries using nine parameters that represented the study area pollution sources, both spatially and temporally. Spatial analysis showed points with high indices to be: K2 on Rietspruit-W, K12 on Natalspruit, B1 on Blesbokspruit, R1 and R2 on Rietspruit-L, T1 on Taaibospruit and L1 on Leeuspruit River.

Although this paper focused on the overall daily index, parameter classification showed that major pollution sources in the study sites were domestic sewage, mine and industrial effluent. This was due to the presence of high levels of specific parameters such as sulphate (associated with mine-AMD effluent), ammonium, chloride, nitrate and phosphate (associated with sewage or its effluent), very low pH (AMD), EC (dissolved ions), and dissolved oxygen (river health and organic load). Within the study site, water flowing out of the Vaal Dam on V2 and that through Suikerbosrant River segment before confluence with Blesbokspruit, were both overall class 2 on a yearly time-step, depicting good quality water.

It was concluded that rehabilitation and mitigation measures to curb pollution should use the Pollution Index after performing scenario analysis in order to predict what could happen if rehabilitation efforts were effected. Reactors, if installed and operated on Blesbokspruit (B1) and Klip River (K9), will guarantee good quality flows into the Vaal River, at least up to before the confluences of the Vaal River with Taaibospruit and Leeuspruit. Pollution load at L1 and T1 could be minimised by installing wastewater treatment plants at the industrial sites of the polluting companies. Rietspruit-L drains sewage into Vaal Barrage and the immediate solution is rehabilitation of the treatment plants. V17 and V19 are indicator points for pollution from the Vaal River and they could benefit from clean-ups at the upstream sites.

It is recommended that the Pollution Assessment and Prioritisation Index be incorporated into the current pricing structure for raw water, as a function of water quality, in order to reflect the upstream–downstream water quality variations. This will ensure fairness of service delivery and spread of burden to consumers, based on quality requirements and equity.

The scenario analysis method (OPATAT) assumes that a monitoring point is a discrete system whose downstream impacts are affected individually by conditions at that particular monitoring point. Keeping the models simple by using a limited set of parameters compromises detailed representation but provides a practical model for everyday use at sub-catchment or even catchment level.

ACKNOWLEDGEMENTS

The financial assistance of the Department of Science Technology (DST) is hereby acknowledged. Opinions expressed and conclusions arrived at, are those of the authors and are not necessarily to be attributed to the DST. The authors would also like to thank Durban University of Technology (TUT) for hosting and co-funding this research. The Water Boards Rand Water, Midvaal Water and Sedibeng Water, DWA and the Water Research Commission are also sincerely acknowledged for provision of data and co-funding (Rand Water Professorial Chair in water utilisation at TUT).

REFERENCES

Abrahão, R., Carvalho, M., da Silva Júnior, W. R., Machado, T. T. V., Gadelha, C. L. M. & Hernandez, M. I. M. 2007 Use of index analysis to evaluate the water quality of a stream receiving industrial effluents. *Water SA* **33**, 459–465.

Akcil, A. & Koldas, S. 2006 Acid mine drainage (AMD): causes, treatment and case studies. *J. Clean. Prod.* **14**, 1139–1145.

Benedetto, J. S., de Almeida, S. K., Gomes, H. A., Vazoller, R. F. & Ladeira, A. C. Q. 2005 Monitoring of sulfate-reducing bacteria in acid water from uranium mines. *Miner. Eng.* **18**, 1341–1343.

Cloot, A. & Le Roux, G. 1997 Modelling algal blooms in the middle Vaal River: a site specific approach. *Water Res.* **31**, 271–279.

Couillard, D. & Lefebvre, Y. 1985 Analysis of water-quality indices. *J. Environ. Manage.* **21**, 161–179.

Department of Environmental Affairs and Tourism (DEAT) 1998 *No. 107 of 1998: National Environmental Management Act. Department of Environmental Affairs and Tourism*. DEAT, Pretoria.

Department of Water Affairs and Forestry 1996 *South African Water Quality Guidelines: Volume 7: Aquatic Ecosystems*. DWAF, Pretoria.

Department of Water Affairs and Forestry 2003 Middle Vaal water management area: Overview of water resources availability and utilisation. National Water Resources Strategy. BKS report no. H41409/ DWAF report no. P WMA 09/000/00/0203. Prepared by MS Basson and JD Rossouw for the Department of Water Affairs and Forestry on behalf of the Directorate: National Water Resource Planning (No. P WMA 09/000/00/0203). Pretoria, South Africa.

Department of Water Affairs and Forestry 2007 *Integrated Water Quality Management Plan for the Vaal River System*. DWAF, Pretoria.

Department of Water Affairs and Forestry 2009 *South African Drinking Water Quality Management Perfomance: Blue Drop Report*. DWAF, Pretoria.

Durand, J. F. 2012 The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province, South Africa. *J. Afr. Earth Sci.* **68**, 24–43.

Dzwairo, B. 2011 Modelling Raw Water Quality Variability in Order to Predict Cost of Water Treatment. DTech Thesis. Tshwane University of Technology: Department of Civil Engineering.

Dzwairo, B., Ochieng, G. M., Letsoalo, M. E. & Otieno, F. A. 2011a Data reduction for water quality modelling, Vaal Basin. In: *Scientific and Engineering Applications Using Matlab* (E. P. Leite ed.). Intech, Croatia, pp. 71–86.

Dzwairo, B., Otieno, F. A. O. & Ochieng, G. M. 2011b Ecological functionality of the Upper and Middle Vaal Water Management Areas. *Proceedings of the 3rd Municipal Drinking Water Quality Conference*, Cape Town.

Dzwairo, B., Otieno, F., Ochieng, G. & Bezuidenhout, J. 2012 Raw water quality weight factors: Vaal basin, South Africa. *Water Sci. Technol.* **66** (5), 1061–1068.

Haji, H. T. 2011 Impact of Climate Change on Surface Water Availability in the Upper Vaal River Basin. MTech Thesis. Tshwane University of Technology: Department of Civil Engineering.

Harris, J. & Andrew, M. 2011 The Top Ten of the Toxic Twenty. The World's Worst Toxic Pollution Problems Report (Vol.). Blacksmith Institute and Green Cross Switzerland, New York.

Kruse, N. A., Bowman, J. R., Mackey, A. L., McCament, B. & Johnson, K. S. 2012 The lasting impacts of offline periods in lime dosed streams: a case study in Raccoon Creek, Ohio. *Mine Water Environ.* **31**, 266–272.

McCarthy, T. S. 2011 The impact of acid mine drainage in South Africa. *S. Afr. J. Sci.* **107**, 01–07.

Paliwal, R., Sharma, P. & Kansal, A. 2007 Water quality modelling of the river Yamuna (India) using QUAL2E-UNCAS. *J. Environ. Manage.* **83**, 131–144.

Pieterse, A., Roos, J., Roos, K. & Pienaar, C. 1987 Preliminary observations on cross-channel and vertical heterogeneity in environmental and algological parameters in the Vaal River at Balkfontein, South Africa. *Water SA* **12**, 173–184.

Rand Water 2012 Welcome to the Reservoir: water resource information centre for the Vaal barrage and Vaal Dam catchments. Available at: http://www.reservoir.co.za/.

Roux, D. J., Jooste, S. H. J. & MacKay, H. M. 1996 Substance-specific water quality criteria for the protection of South African freshwater ecosystems: methods for derivation and intial results for some inorganic toxic substances. *S. Afr. J. Sci.* **92**, 198–206.

Slaughter, A. R. 2005 The Refinement of Protective Salinity Guidelines for South African Freshwater Resources. MSc Thesis. Rhodes University.

Steÿn, D., Toerien, D. & Visser, J. 1976 Eutrophication levels of some South African impoundments. IV. Vaal Dam. *Water SA* **2**, 53–57.

Wei, X., Wei, H. & Viadero, R. C. 2011 Post-reclamation water quality trend in a Mid-Appalachian watershed of abandoned mine lands. *Sci. Total Environ.* **409**, 941–948.

Wepener, V., van Vuren, J. H. J., Chatiza, F. P., Mbizi, Z., Slabbert, L. & Masola, B. 2005 Active biomonitoring in freshwater environments: early warning signals from biomarkers in assessing biological effects of diffuse sources of pollutants. *Phys. Chem. Earth A/B/C* **30**, 751–761.

Winde, F. & Jacobus van der Walt, I. 2004 The significance of groundwater-stream interactions and fluctuating stream chemistry on waterborne uranium contamination of streams–a case study from a gold mining site in South Africa. *J. Hydrol.* **287**, 178–196.

Zilles, J. L., Peccia, J. & Noguera, D. R. 2002 Microbiology of enhanced biological phosphorus removal in aerated-anoxic orbal processes. *Water Environ. Res.* **74**, 428–436.

First received 17 December 2013; accepted in revised form 25 March 2014. Available online 29 April 2014