Predicting water quality associated with land cover change in the Grootdraai Dam catchment, South Africa

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(Received 23 May 2014; accepted 27 June 2015)

The Grootdraai Dam catchment forms part of the Vaal River system, which is deemed to be the ‘workhorse’ of South Africa as it is located within the economic heart of the country. The status of water quality within the catchment is an important characteristic that needs to be investigated extensively due to its importance to the country’s future economic growth. Intricate relationships between land cover and specific water quality parameters were quantified and unique model equations were formulated to predict water quality in the region. Urban and mining developments should be re-evaluated due to the accompanied significant hydrological consequences.

Keywords: water quality; land cover; Grootdraai Dam catchment; South Africa; prediction

Introduction

The quality of the world’s water resources and the accompanied freshwater and coastal ecosystems have been negatively affected by primarily anthropogenic factors due to increased nutrient loading and, in some cases, pathogens within these affected water bodies, to name two. Changes in land cover have consequently led to the loss of biodiversity through the modification, fragmentation or loss of habitats, the degradation of the soil and water resources, and the overexploitation of endemic or native species (Deelstra, Oygarden, Blankenberg, & Eggestad, 2011; Meador & Goldstein, 2003; Rothenberger, Burkholder, & Brownie, 2009; Seeboonruang, 2012). Population pressures and intensified economic activity in sub-basins have altered land-use patterns and generated water pollution (Jung, Lee, Hwang, & Jang, 2008; Tong & Chen, 2002; Wilson & Weng, 2010).

The relationship between land use and water quality within different regions or catchments has been widely researched across the world (Jung et al., 2008; Wilson & Weng, 2010). Extensive research has been completed on the relationships between land cover or land-use change and different water quality parameters. Consequently, studies have progressed from identifying relationships to predicting water quality in relation to land cover change or determining and comparing the accuracy or uncertainty of various river water quality modelling techniques such as the partial least squares (PLS) regression model (Baker, 2011; Hall, Germain, Tyrrell, & Sampson, 2008; Huang & Klemas, 2012; Li, Gu, Lui, Han, & Zhang, 2008).

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South Africa is a semi-arid country with inefficient management of water that results in overall deterioration in its quality. This persists even though water is described as a vital resource in maintaining life and sustaining agriculture, manufacturing, transportation and other economic activities (Ashton & Haasbroek, 2002; DEAT, 2005; Helmschrot & Flugel, 2002; Kadewa, Moyo, Mumba, & Phiri, 2005; King, Maree, & Muir, 2009; Usali & Ismail, 2010).

The current and anticipated growth rates of the population and trends in future socio-economic development indicate that South Africa's freshwater resources will be unable to sustain the current patterns of water use and discharge. This has consequently led to numerous water supply problems across the whole country. At present, multiple water management areas are experiencing a water deficit. The natural ecosystems as well as the region's and the country's freshwater resources are put under immense pressure by various sectors and users, which lead to the overall deterioration of water resources (Ashton, Hardwick, & Breen, 2008).

This study has consequently focused upon the quantification of these relationships between selected water quality parameters and land cover change with the application of a partial least squares (PLS) regression to formulate model equations for the prediction of water quality and possibly assist with the development of a presently lacking science-policy interface. This study, therefore, puts forward a practical application of these formulated model equations for the prediction of water quality within a specific catchment. It presents the importance of the formulation of the PLS model equations to promote informed and accurate decision-making within the water management sector. It also presents a practical application of these within a catchment that has been plagued by immense land cover change due to mining and urban developments accompanied with poor and uninformed decision-making processes.

Study area

The Grootdraai Dam catchment, which is the main focus of this research paper, is situated within the Upper Vaal Water Management Area and located at the upper reaches of the Vaal River, which is considered to be the main water source for the central industrial, mining and metropolitan regions in South Africa (Figure 1). The Grootdraai Dam catchment together with the rest of the Vaal River catchment serves six of the nine provinces of the country, and is consequently of great importance in terms of the environmental, social and economic spheres (Bertasso, 2004; DWAF, 2004). The region is presently plagued by numerous applications for prospected mining rights and urban sprawl, which may be accompanied by immense degradation of the region's freshwater resources.

The natural landscape of the Grootdraai Dam catchment has therefore been transformed and manipulated physically and chemically in order to meet society's needs. The changes of land cover have been accompanied by various impacts on a specific region's hydrological responses and ultimately its water resources. Increasing demands from society as well as economic pressures have been accompanied with further land cover changes within the region and have recently contributed to water availability and water quality problems within the catchment (Attua, Ayamga, & Pabi, 2014; Warburton, Schulze, & Jewitt, 2012).

Research done on the Grootdraai Dam catchment was found to be minimal. Most research has focused upon the identification of causes and consequences of water

Figure 1. Location of the Grootdraai Dam catchment within the Vaal River catchment, South Africa.

degradation within the catchment with a primary focus upon mining operations as well as on other water quality problems such as acid mine drainage (McCarthy, 2011; Van Steenderen, Theron, & Hassett, 1987).

The predominant methodologies implemented by previous research have been a combination of qualitative and quantitative methods. Qualitative methods, which include literature and observations, were aimed at describing the current state of the larger Vaal River catchment as well as the development of management plans to be implemented by authorities. Quantitative methods included basic descriptive statistics aimed at identifying possible pollution sources and areas of concern. This research therefore proposed that the interactions between hydrological responses, in terms of water quality, and land use needs to be quantified for the catchment or region to improve upon its water resource planning and management through the application of PLS regression analysis and formulated model equations. The formulated PLS regression model equations would therefore enable the prediction of the selected water quality parameters in relation to a change in land cover and can hopefully aid in the development of a science–policy interface.

This research investigated the hydrological responses, in terms of water quality, in the case of land cover change within the Grootdraai Dam catchment due to its ecological, social and economic importance, but also for its definite widespread negative cumulative impacts on the environment and human health. Relationships and unique model equations were established, formulated and applied in a possible future land cover change scenario to predict the future water quality of the catchment, which has not been completed for the catchment by any previous research. The results can ultimately be used to determine what sustainable measures need to be taken in terms of land cover change and identify possible policy changes that need to be taken to promote a more sustainable Grootdraai Dam catchment and ultimately the larger

Vaal River catchment through improving informed decision-making and management processes.

Methods

The research made use of rainfall, evaporation, water flow and water quality data for the period July 2000–June 2012 as well as land cover data for 1994, 2000, 2005 and 2009 to establish the hydrological responses in terms of water quality in the case of land cover change.

Rainfall, water flow and evaporation data

The rainfall data were obtained from the South African Weather Service for the period July 2000–June 2012. Daily readings were used to calculate the average for the month. The average monthly rainfall figures were obtained for each of the two weather stations. Sample stations with long periods of no recorded data were excluded to ensure good-quality data and sound results. Water flow, as well as evaporation data, were obtained from the Department of Water Affairs (DWA) for July 2000–June 2012. The daily average water flow rate (m^3/s) was measured at all the river water flow sample stations over this period. Monthly water flow and evaporation values were calculated for each of the stations. Sample stations with large data inconsistencies, as well as long periods of no recorded data, were excluded to ensure good quality and accurate data.

Water quality data

Water quality data were obtained from all the available Rand Water (water services provider for the Upper Vaal WMA) at sample points situated in the Grootdraai Dam catchment for the same period. A total of 12 water-quality sample stations were used and provided a complete dataset of water quality data for this research. The locations of these are set out in [Figure 2](#).

The water quality data obtained from these sampling points were measured monthly, weekly and, in some cases, daily throughout the year, but at no scheduled time and on no fixed day or week. A monthly average was calculated for each of the water quality parameters used at each station.

Sampling stations with inadequate data recordings were excluded. They were excluded in the case of the station having recorded fewer than four measurements within a year. Some water quality sampling stations were also not included in this research due the station having measured fewer than four parameters with fewer than four recorded measurements within a year. The ‘Four by Four’ (4×4) rule was therefore followed. It ensures that only sampling stations that regularly monitor the relevant parameter are included and eliminates stations with only three monitoring phases per year. This research was therefore limited to these sampling stations that had adequate replication in an attempt to ensure high-quality data and representation within the Grootdraai Dam catchment.

A wide variety of water quality parameters was used in order to obtain a holistic and accurate view of a water body’s water quality in terms of environmental and human health. Water quality parameters to be used in this research were selected according to a selection process and were selected according to the following rules:

Figure 2. All the available Rand Water quality sampling stations used within the Grootdraai Dam catchment.

- The water quality parameter needs to have available national or regional water quality indices or guidelines.
- The water quality parameter must have been commonly measured and reported by Rand Water's water quality sampling stations within the Grootdraai Dam catchment.
- The water quality parameter needs to have a representation percentage of a minimum of 100%, 50% in the case of biological parameters, within the Grootdraai Dam catchment.
- Water quality parameters characterized by the occurrence or measurement of non-detectable values needs to be excluded due to the possibility of bias.

This research made use of relevant national and regional water quality standards and guidelines. The Vaal Dam in-stream water quality guidelines were predominantly used. In the event of a water quality parameter not having a regional standard, the appropriate South African national water quality standard was used and indicated accordingly. Water quality parameters were therefore excluded on the basis of the availability of international, national and regional guidelines. Subsequently, a total of 14 water quality parameters were identified, according to the described rules, for this research and include the following:

- Physical parameters: pH and electrical conductivity (EC).
- Chemical parameters: alkalinity, calcium, chloride, sodium, magnesium, nitrate, sulphate, ammonia, phosphate and chemical oxygen demand (COD).
- Biological parameters: dissolved oxygen (DO) and dissolved organic carbon (DOC).

The relevant national and regional water quality standards and guidelines were applied in the establishment of water quality status of the Grootdraai Dam catchment. The colour

Table 1. Applied colour classification of water quality standard.

Water quality standard	Colour class
Ideal
Acceptable
Tolerable
Unacceptable

classification was used according to the relevant water quality standards and catchment guidelines, as shown in [Table 1](#).

Land cover data

National land cover data were obtained from the Agricultural Research Center (ARC) for 1994, 2000, 2005, while land cover data for 2009 were obtained from the South African National Biodiversity Institute (SANBI) (ARC, 2005; SANBI, 2009). These land cover datasets were developed to establish the land cover for the whole of South Africa (no other datasets are available) and were consequently used in order to establish land cover changes for the Grootdraai Dam catchment. The land cover data from 1994 were included in the research to obtain a baseline land cover characteristic for the catchment. Land cover data from 2000, 2005 and 2009 were used in the PLS correlation and regression analysis.

The national land cover data used the Standard Land Cover Classification Scheme as the reference system to compile a 49-class legend. This full classification scheme is based on a hierarchical framework designed to suit the South African environment and incorporates known land cover types, which can be identified in a consistent and repetitive manner from high-resolution satellite imagery such as LandSat TM and SPOT (Thompson, 1996).

In their turn, the class definitions ensured that the data were standardized, and that broad generic classes were subdivided into more specific user-defined subclasses. The classification used by the land cover data was designed to conform to internationally accepted classification standards and conventions to ensure cross-border compatibility and integration with existing national and international land cover classification systems and datasets.

This research made use of the five-class legend used by the 2005 land cover dataset in order to describe the land cover. The seven-class legend for the land cover of 1994, 2000 and 2009 needed to be converted into the five-class legend used for 2005 during data analysis in order to obtain uniformity. The five land-cover classes were based on Level I and II classes and include the following:

- Urban build-up.
- Forestry and Plantations.
- Mining.
- Cultivated.
- Other (Natural, Degraded and Water bodies).

The five class-legend land cover was used to establish the land cover change over the period and ultimately to determine relationships between water quality and land cover.

Note that the 'other' land cover class constitutes natural, degraded and water bodies land cover classes. 'Other' land cover is predominantly constituted of natural land cover followed by water bodies and degraded land cover classes.

Shortcomings were also identified regarding the use of national land cover data supplied by ARC and SANBI. These included possible inaccuracies as well as low spatial resolution or cell size regarding the 2005 land cover dataset. The accuracy of the land cover data could have been decreased due to the project being completed by multiple stakeholders. Over- or under-estimations of land cover or the inaccurate identification of land cover could therefore have taken place (Burrough, 1990; Thompson, 1996). A logical error test was completed through the completion of a sensitivity analysis between the datasets to establish whether significant errors were present. A sensitivity test was completed by ARC between 1994, 2000 and 2005. Consequently, this research completed a sensitivity analysis regarding land cover classes between the 2005 and 2009 datasets. Very few errors were however identified through this testing process. Errors were corrected when necessary.

Mixed classes or classification structure is also a recognized limitation of land-use data. Mixed classes or classification structure were not a limitation in this study due to the use of a hierarchical classification design namely the Standard Land Cover Classification Scheme for Remote Sensing Applications in South Africa, as described previously (Lo & Yeung, 2002; Longley, Goodchild, Maguire, & Rhind, 2005; Thompson, 1996).

Data analyses

Temporal analyses and basic descriptive statistical analyses (data summaries) were completed on average monthly rainfall, water flow, evaporation and water quality data to identify significant variations and possible relationships between all the mentioned variables for July 2000–June 2012. Rainfall and evaporation data measured by the weather and evaporation sampling stations were correlated with water quality data from water quality stations located within close proximity thereof. Water flow data measured by the water flow sampling stations were correlated with water quality data measured by the water quality sampling stations located at the same location or downstream of the applicable water flow sampling station.

A temporal trend analysis was also completed between water quality and land cover for the periods 2000, 2005 and 2009 upon which the PLS model equations are built on. The independent variables were therefore the land cover classes and the dependent variables, and the selected water quality parameters. A multivariate statistical analysis in the form of PLS correlation and regression analysis was completed between the selected water quality parameters and the five class-legend land cover for 2000, 2005 and 2009. The PLS analysis is a proven effective variance-based structural equation model approach recommended for small sample sizes or in the case when the number of explanatory variables exceeds the number of observations and a high level of multicollinearity (Ibrahim & Wibowo, 2013a; Nasser & Wisenbaker, 2003). The use of PLS is recommended as it addresses multivariable problems such as the ill-effect of multiplex between variables (Ibrahim & Wibowo, 2013a, 2013b; Lou, Zhao, Chen, & Zhao, 2009; Singh, Jakubowski, Chidister, & Townsend, 2013).

The application of the PLS analysis enabled the prediction of water quality according to land cover changes with the development of a PLS regression model and associated algorithm. PLS regression models therefore facilitated the establishment of

unique equations for each water quality parameter at each water quality sampling station.

Average concentrations were calculated for each selected water quality parameter in terms of the period over which the land cover dataset was established. The average annual concentration levels of the water parameters of the studied region were therefore calculated for 2000, 2005 and 2009 (includes full seasonal year, i.e., July 2000/2004/2008–June 2001/2005/2009), and paired with the land cover class percentages for those same time periods. This was completed for each water quality sampling station.

A PLS correlation and regression analysis was completed between the percentage of each specific land cover class and the calculated concentration level of each of the selected water quality parameters at each water quality station for 2000, 2005 and 2009 to establish the respective relationships between the land cover classes and the selected water quality parameters.

An overall average was calculated with the use of all the water quality sampling stations for each of the identified water quality parameters, for 2000, 2005 and 2009 to coincide with land cover data, to obtain a generalized water quality status as well as to formulate a generalized model equation for the Grootdraai Dam catchment as a whole. PLS regression model equations were established to quantify the overall hydrological responses for each selected water quality parameter to land cover change and to predict the concentration levels of these parameters in the event of such change. The root mean square error (RMSE), which is a standard statistical metric to measure model performance in some geoscience studies such as air quality and other geosciences, was used in this research to indicate the average model performance for each model equation as it assists in providing a holistic view of the error distribution (Chai & Draxler, 2014).

These model equations are consequently used to predict the specific concentration of all the identified water quality parameters according to the percentage land cover in the Grootdraai Dam catchment. A simulation was completed to quantify and predict concentrations of the selected water quality parameters in accordance with a possible land cover change scenario for 2015, 2020, 2030 and 2050.

It should be noted that these formulated model equations were based on only three periods (2000, 2005 and 2009) due to limited datasets. Furthermore, there could also be instances of multicollinearity in these model equations due to high correlation amongst the explanatory values themselves. These are therefore identified shortcomings that can be improved upon in future research with the completion of the 2014 land cover dataset which will enable the validation of these formulated model equations. Note that the adjusted R^2 value and the RMSE value needs to be taken into account for each individual model equation as the accuracy of these models vary and is not uniform.

Results and discussion

The water quality of the Grootdraai Dam catchment is of concern in light of the tolerable and unacceptable water quality standards. The quality of the water in this catchment has been degraded and its standard is of concern due to some of the water quality parameters proving to be either tolerable or unacceptable in terms of the Vaal Dam in-stream water quality guidelines.

Table 2. Average monthly concentrations of the selected water quality parameters in the Grootdraai Dam catchment in terms of the Vaal Dam in-stream water quality guidelines and standards.

Water quality parameter	Grootdraai Dam
pH (pH units)	7.90
EC (mS/m)	42.66
Alkalinity (CaCO ₃ mg/l)	136.56
Calcium (mg/l) ^a	26.18
Chloride (mg/l)	23.89
Sodium (mg/l) ^a	25.91
Magnesium (mg/l) ^a	16.87
Nitrate (mg/l)	0.79
Sulphate (mg/l)	39.07
Ammonia (mg/l)	1.63
Phosphate (mg/l)	0.88
COD (mg/l)	29.40
DO (mg/l) ^b	5.31
DOC (mg C/l) ^a	8.77

Notes: ^aAccording to national domestic-use water quality guidelines.

^bAccording to national aquatic ecosystems water quality guidelines.

Water quality

The Grootdraai Dam catchment is characterized by tolerable standards of EC and DO as well as unacceptable standards of alkalinity, ammonia, phosphate and COD, as indicated in [Table 2](#).

The water quality of the Grootdraai Dam catchment varies significantly across the region. On account of its very poor water quality across the range of some of the selected water quality parameters, this catchment poses significant challenges, with the hydrological conditions here generally being considered to be a matter of concern. The main areas of concern proved to be those regions located in close proximity to or downstream of urban built up areas (includes industrial areas), mining as well as cultivated land cover. These areas should therefore be seen as areas of major concern and should consequently be monitored closely for future changes to ensure that the quality of the water in this catchment would not be degraded even further.

Land cover

Firstly, rainfall, evaporation and water flow data were included in the research as these variables may have an influence on water quality. A Pearson correlation as well as a PLS correlation analysis were completed between these variables to determine the significance of their effects on water quality. The research found that the effects of rainfall, evaporation and water flow are not significant over the time period ($p < 0.05$; $n = 132$). The research subsequently concluded that land cover will have the most predominant and significant impact on water quality as it is the main determinant regarding the type and significance of the relationships and is consequently the main focus.

Figure 3. Land cover within the Grootdraai Dam catchment, 2009.

As indicated in Figure 3, the Grootdraai Dam catchment is dominated by cultivated land. This land cover class constituted 82.97% of the total land cover in 2009. This was followed by the 'other' land cover category, which constituted 16.06% (10.49% of which was natural and 2.67% of which consisted of water bodies), mining land, which constituted 0.45%, and forests and plantations, which constituted less than 0.001% of the total land cover.

As shown in Figure 4, the catchment has undergone various land cover changes since 1994 and illustrates the catchment's dynamic nature. There was an upward trend in the urban built-up land cover class from 1994 to 2000, which has subsequently experienced a decline that may be due to the region having focused upon agricultural activities. The forestry and plantations land cover class has declined to such an extent that it no longer features in the catchment. In terms of mining, the catchment has generally experienced consistent growth, but also a decline. These trends will change in future, however, owing to the numerous prospected mining operations planned for this catchment. The cultivated and the 'other' land cover category experienced upward as well as downward trends. It should be noted that the immense decrease and increase of certain land cover classes such as cultivated and 'other' land cover from 2005 to 2009 were flagged as outliers and these values were adjusted accordingly to ensure accuracy within the analysis.

Quantifying hydrological change

It was established that the catchment is experiencing tolerable to unacceptable concentration levels of EC, COD, alkalinity, ammonia and phosphate. The recent temporal trends in the water quality within the catchment have shown an increase from 2009 in the concentration levels of EC, alkalinity, calcium, nitrate, sulphate and ammonia. The main possible agents for the raised concentrations of these water quality parameters were

Figure 4. Land cover trends within the Grootdraai Dam catchment, 1994–2009.

determined by establishing the relationships between the relevant variables, as indicated in Table 3. Values highlighted in bold are different from zero with a significance level $\alpha = 0.05$, $n = 3$.

The very few significant relationships were found between water quality and land cover change within the Grootdraai Dam catchment. Negative relationships of

Table 3. Partial least squares (PLS) correlation matrix obtained between land cover classes and the selected water quality parameters for the Grootdraai Dam catchment.

Variables	Urban built-up	Forestry and Plantations	Mining	Cultivation	Other
Urban built-up	1.000	0.975	0.895	0.360	-0.480
Forestry and Plantations	0.975	1.000	0.971	0.557	-0.662
Mining	0.895	0.971	1.000	0.739	-0.822
Cultivation	0.360	0.557	0.739	1.000	-0.991
Other	-0.480	-0.662	-0.822	-0.991	1.000
Ph	0.968	0.888	0.753	0.113	-0.244
EC	-0.396	-0.183	0.056	0.715	-0.616
Alkalinity	-0.815	-0.667	-0.470	0.247	-0.117
Calcium	-0.998	-0.986	-0.919	-0.413	0.530
Chloride	0.979	1.000	0.967	0.544	-0.650
Sodium	0.983	0.918	0.797	0.181	-0.310
Magnesium	-0.964	-0.999	-0.981	-0.594	0.695
Nitrate	0.711	0.849	0.950	0.912	-0.958
Sulphate	-0.568	-0.373	-0.140	0.564	-0.449
Ammonia	-0.629	-0.443	-0.216	0.499	-0.379
Phosphate	0.984	0.922	0.802	0.190	-0.319
COD	1.000	0.980	0.905	0.381	-0.500
DO	0.944	0.994	0.992	0.647	-0.742
DOC	0.714	0.542	0.326	-0.397	0.271

significance were found between calcium and urban built-up, as well as magnesium and forestry and plantations. Positive relationships of significance were established between COD and urban built-up, as well as between DO and forestry and plantations.

This research did however establish that an increase in the extent of the ‘other’ land cover category – issuing from the transformation of cultivated, urban built-up, as well as mining land cover classes – was found to be accompanied by undesirable and, in some cases, insidious effects. Furthermore, it was found that the buffering properties of the catchment tend to decline in tandem with the constant transformations (and re-transformations) that the land cover undergoes, especially in the case of the ‘other’ category. As a result, an increase in the extent of the ‘other’ land cover category within the catchment is expected to contribute to further degradation in the quality of the water in the catchment and needs to be highlighted.

The Grootdraai Dam catchment is currently showing a declining degree of resilience towards land cover change. Driving forces such as economic pressure, together with the further transformation of the ‘other’ land cover category into mining and urban built-up land cover, undesirable negative effects would be brought to bear on the surrounding water bodies.

Thus, the proclamation of numerous mining developments within the catchment is worthy of careful attention. In the event of the closure of a mine, it is of prime importance that the correct decommissioning measures be enforced to limit future challenges regarding the quality of the water within the catchment.

Model equations were established for each water quality parameter within this drainage region in terms of the land cover class proportions (percentages), as given in [Table 4](#). These equations could be used, in association with the current trends in land cover change and in management practices, to predict the future concentration levels of these water quality parameters.

Predictions could therefore be made with a good amount of certainty and accuracy on future pH, calcium, chloride, magnesium, nitrate, ammonia, phosphate, COD and DO concentration levels within the Grootdraai Dam catchment due to the high adjusted R^2 values, indicating strong correlations between variables, and low RMSE values indicating low standard errors in these models. Model equations with a high adjusted R^2 value and a low RMSE value can therefore be used as a guideline when trying to predict changes in water quality due to land cover change and can also be incorporated in the development of a science–policy interface.

Future of the Grootdraai Dam catchment

The Grootdraai Dam catchment is experiencing an increase in the extent of its ‘other’ land cover category. This might develop into a situation that would be the direct opposite of the current conditions in the region – on account of the seemingly periodic nature of the relationship between the ‘other’ land cover category and the cultivated land cover class. As a result of future economic growth and development pressures, and of the approval granted by the numerous prospected mines, this catchment could experience an increase in urban built-up land, mining as well as cultivated land cover.

The following scenario was developed in terms of these assumed economic developmental trends and with the approval of the prospected mines in the catchment. It assumes a constant increase of 1% per year in the areal extent of the urban built-up land cover class, as well as in mining land cover. [Table 5](#) presents the results for this scenario, which were obtained with the application of the model equations as given in [Table 4](#).

Table 4. Model equations and the respective adjusted R^2 values and root mean square error (RMSE) values for each of the selected water quality parameters related to each land cover class for the Grootdraai Dam catchment.

Water quality parameter	Model equation	R^2	RMSE
pH	$\text{pH} = 10.62 - 02 \times \text{Urban built-up} + 9.75 - 02 \times \text{Forestry and Plantations} + 0.22 \times \text{Mining} + 1.28 - 03 \times \text{Cultivation} - 1.57 - 03 \times \text{Other}$	0.61	0.099
EC	$\text{EC} = 48.27 - 03 \times \text{Urban built-up} + 1.86 - 02 \times \text{Forestry and Plantations} + 4.18 - 02 \times \text{Mining} + 2.44 - 04 \times \text{Cultivation} - 2.99 - 04 \times \text{Other}$	0.00	1.000
Alkalinity	$\text{Alkalinity} = 140.99 - 0.55 \times \text{Urban built-up} - 1.76 \times \text{Forestry and Plantations} - 3.95 \times \text{Mining} - 2.31 - 02 \times \text{Cultivation} + 2.82 - 02 \times \text{Other}$	0.26	1.000
Calcium	$\text{Calcium} = 28.41 - 0.27 \times \text{Urban built-up} - 0.86 \times \text{Forestry and Plantations} - 1.93 \times \text{Mining} - 1.13 - 02 \times \text{Cultivation} + 1.38 - 02 \times \text{Other}$	0.87	0.415
Chloride	$\text{Chloride} = 21.05 + 0.29 \times \text{Urban built-up} + 0.93 \times \text{Forestry and Plantations} + 2.10 \times \text{Mining} + 1.23 - 02 \times \text{Cultivation} - 1.50 - 02 \times \text{Other}$	0.96	0.258
Sodium	$\text{Sodium} = 23.92 + 0.26 \times \text{Urban built-up} + 0.84 \times \text{Forestry and Plantations} + 1.89 \times \text{Mining} + 1.10 - 02 \times \text{Cultivation} - 1.35 - 02 \times \text{Other}$	0.68	0.740
Magnesium	$\text{Magnesium} = 17.70 - 0.11 \times \text{Urban built-up} - 0.34 \times \text{Forestry and Plantations} - 0.76 \times \text{Mining} - 4.46 - 03 \times \text{Cultivation} + 5.45 - 03 \times \text{Other}$	0.98	0.067
Nitrate	$\text{Nitrate} = 3.03 - 02 \times \text{Urban built-up} + 7.86 - 02 \times \text{Forestry and Plantations} + 0.18 \times \text{Mining} + 1.03 - 03 \times \text{Cultivation} - 1.26 - 03 \times \text{Other}$	0.88	0.038
Sulphate	$\text{Sulphate} = 40.98 - 0.146 \times \text{Urban built-up} - 0.47 \times \text{Forestry and Plantations} - 1.06 \times \text{Mining} - 6.17 - 03 \times \text{Cultivation} + 7.54 - 03 \times \text{Other}$	0.03	1.000
Ammonia	$\text{Ammonia} = -0.34 - 02 \times \text{Urban built-up} - 7.99 - 02 \times \text{Forestry and Plantations} - 0.18 \times \text{Mining} - 1.05 - 03 \times \text{Cultivation} + 1.28 - 03 \times \text{Other}$	0.07	0.382
Phosphate	$\text{Phosphate} = 3.39 - 02 \times \text{Urban built-up} + 8.62 - 02 \times \text{Forestry and Plantations} + 0.19 \times \text{Mining} + 1.13 - 03 \times \text{Cultivation} - 1.38 - 03 \times \text{Other}$	0.68	0.075
COD	$\text{COD} = 28.04 + 0.20 \times \text{Urban built-up} + 0.66 \times \text{Forestry and Plantations} + 1.47 \times \text{Mining} + 8.60 - 03 \times \text{Cultivation} - 0.01 \times \text{Other}$	0.85	0.350
DO	$\text{DO} = 13.83 - 03 \times \text{Urban built-up} + 0.03 \times \text{Forestry and Plantations} + 6.21 - 02 \times \text{Mining} + 3.63 - 04 \times \text{Cultivation} - 4.43 - 04 \times \text{Other}$	0.99	0.003
DOC	$\text{DOC} = 8.81 + 4.66 - 03 \times \text{Urban built-up} + 1.50 - 02 \times \text{Forestry and Plantations} + 3.37 - 02 \times \text{Mining} + 1.97 - 04 \times \text{Cultivation} - 2.41 - 04 \times \text{Other}$	0.13	0.049

Table 5. Predictions of water quality parameter concentrations in the event of a 1%/year increase in urban built-up land cover within the Grootdraai Dam catchment showing water quality colour classification indicators in terms of the Vaal Dam in-stream water quality guidelines.

(a) Prediction of land cover (%)

Land cover class	2015	2020	2030	2050
Urban built-up	1.53	6.53	16.53	36.53
Forestry and Plantations	0.00	0.00	0.00	0.00
Mining	0.50	1.06	2.17	4.40
Cultivation	79.97	71.91	74.00	56.40
Other	18.00	20.50	7.30	2.67

(b) Prediction of concentration levels of water quality parameters

Water quality parameter	2015	2020	2030	2050	R ²	RMSE
pH (pH units)	7.82	7.99	8.41	9.16	0.61	0.099
EC (mS/m)	44.99	48.55	62.45	72.29	0.00	1.000
Alkalinity (CaCO ₃ mg/l)	145.55	153.21	171.35	204.24	0.26	1.000
Calcium (mg/l) ^c	31.70	32.65	34.90	38.97	0.87	0.415
Chloride (mg/l)	21.63	26.09	36.66	55.84	0.96	0.258
Sodium (mg/l) ^c	26.33	29.57	37.23	51.14	0.68	0.740
Magnesium (mg/l) ^c	17.57	20.23	26.51	37.90	0.98	0.067
Nitrate (mg/l)	1.07	0.85	0.32	0.00	0.88	0.038
Sulphate (mg/l)	42.51	50.71	70.12	105.33	0.03	1.000
Ammonia (mg/l)	0.29	0.21	0.00	0.00	0.07	0.382
Phosphate (mg/l)	0.62	0.52	0.30	0.00	0.68	0.075
COD (mg/l)	24.46	24.87	25.85	27.62	0.85	0.350
DO (mg/l) ^d	5.83	5.36	4.26	2.25	0.99	0.003
DOC (mg C/l) ^c	10.50	10.02	8.89	6.83	0.13	0.049

Notes: ^cIn terms of the national water quality guidelines for domestic use.

^dIn terms of the International European Union water quality standards.

From Table 5, we can conclude that the water in the Grootdraai Dam catchment will become more alkaline should there be a gradual increase in the extent of urban built-up and mining land cover according to the predicted pH values. Furthermore, owing to an increase in mining operations, the catchment is also expected to experience an increase in its sulphate concentrations, which will reach tolerable standards in 2020. Certain water quality parameters such as nitrate, ammonia, phosphate, as well as DOC, are expected to decline in tandem with these developments. The complete transformation of the ‘other’ land cover class into urban built-up, mining, as well as cultivated land cover, would cause the catchment to record unacceptably high concentration levels of pH, EC, alkalinity, sulphate and DO, but also tolerable standards of chloride. In turn, these would lead to various environmental impacts and might cause economic growth and development to occur at a slower pace in future. The factors behind such a scenario would be the

inhibition of certain industrial, mining and agricultural activities on account of scaling and the high alkalinity levels of the water, thereby precluding its use.

Conclusions

South Africa has limited natural water resources and is water stressed. The Vaal River catchment is part of the Vaal River system, which is deemed to be the 'workhorse' of South Africa as it is located within the economic heart of the country. The Grootdraai Dam catchment located within this Vaal River system helps supply water resources to all the major economic activities within the economic hub of the country and is fully exploited in terms of its water availability. The status of water quality within the catchment is therefore an important characteristic that needs to be investigated and monitored extensively due to its prime importance for the economic growth of the country. The degradation of the region's water quality will consequently decrease the availability of water in the catchment and have widespread environmental, social, as well as economic consequences and impacts.

Some relationships of varying significance were found between land cover change and the identified significant water quality parameters and it supports previous findings which illustrate that a change in land cover will be associated with hydrological responses but it affects water quality parameters at varying degrees and with different reactions. The hydrological changes associated with a specific water quality parameter will be dependent on the physical characteristics of the catchment as well as on the type of land cover and land use in terms of land use. These characteristics will in turn determine the type of hydrological response in terms of positive or negative relationships, the significance of the relationships and, lastly, which significant water quality parameters will change the most.

The establishment of these relationships has enabled the quantification of water quality change in the event of an increase or decrease of specific land cover classes. The future water quality conditions can therefore be predicted with the use of the formulated PLS model equations according to land cover change.

The future water quality of the Grootdraai Dam catchment and the Vaal River catchment as a whole will be affected significantly with the approval of the numerous prospected mines and the accompanied urban built-up areas within the catchment. This research therefore concludes that even the gradual increase of these land cover classes will have significant negative effects on the catchment's water quality and should be carefully considered or managed. In the event of the approval of these prospected mines, the catchment will experience tolerable to unacceptable standards of EC, alkalinity, nitrate, sulphate, phosphate COD and DO within the next couple of years. The tolerable and unacceptable concentrations of these water quality parameters will have widespread effects in terms of the environment and may inhibit future economic growth due to the water being of an unusable nature.

In the event of a rapid increase of mining land cover, which will be associated with the approval of the prospected mines, it will have even more significant and disastrous effects on the region's environment and economic spheres. It is therefore of prime importance that these developments be carefully considered if the region is to avert a water predicament.

The water quality of the Grootdraai Dam catchment as well as the Vaal River catchment as a whole can therefore be improved upon. The implementation of regular monitoring, creation of water-quality and land-cover databases, which in turn will promote and facilitate improved water management practices, informed decision-making processes as well as cost-effective measures can as a result promote the sustainability of

the Vaal River catchment as a whole. To avert a predicament in the not too distant future, the approval of the prospected mines, especially in the Grootdraai Dam catchment, needs to be reconsidered and re-evaluated as these developments will have significant and detrimental environmental, social and economic effects on the region as well as on the country. The development of a science–policy interface will also assist greatly by promoting informed decision-making and can aid in the aversion of a water predicament.

Acknowledgements

The authors would like to thank the South African Weather Service for rainfall data, the Department of Water Affairs for evaporation and water flow data, Rand Water for water quality data, the Agricultural Resource Centre for 1994, 2000 and 2005 land cover, and the South African National Biodiversity Institute for the 2009 land cover dataset.

References

- ARC (Agriculture Resource Centre). (2005). Land cover for South Africa. Pretoria, South Africa: ARC.
- Ashton, P. J., & Haasbroek, B. (2002). Water demand management and social adaptive capacity: A South African case study. Johannesburg: CSIR: Division of Water, Environment and Forestry Technology.
- Ashton, P. J., Hardwick, D., & Breen, C. M. (2008). Changes in water availability and demand within South Africa's shared river basins as determinants of regional social–ecological resilience. In M. J. Burns & A. V. B. Weaver (Eds.), *Exploring sustainability science: A Southern African perspective*, 279–310. Stellenbosch: Stellenbosch University Press.
- Attua, E. M., Ayanga, J., & Pabi, O. (2014). Relating land use and land cover to surface water quality in the Densu River basin, Ghana. *International Journal of River Basin Management*, 12 (1), 57–68. doi:[10.1080/15715124.2014.880711](https://doi.org/10.1080/15715124.2014.880711)
- Baker, B. (2011). A decision support tool for predicting water quality based on land cover (Master's Thesis). Nicholas School of the Environment of Duke University, Durham, NC.
- Bertasso, A. (2004). Ecological parameters of selected helminth species in *Labeobarbus aeneus* and *Labeobarbus kimberleyensis* in the Vaal Dam, and an evaluation of their influence on indicators of environmental health (Unpublished MSc short dissertation). Rand Afrikaans University, Johannesburg, South Africa.
- Burrough, P. A. (1990). *Principles of geographical information systems for land resource assessment*. Oxford, UK: Clarendon Press.
- Chai, T., & Draxler, R. R. (2014). Root mean square error (RMSE) or mean absolute (MAE)? – Arguments against avoiding RMSE in the literature. *Geoscience Model Development*, 7, 1247–1250. doi:[10.5194/gmd-7-1247-2014](https://doi.org/10.5194/gmd-7-1247-2014)
- DEAT (Department of Environmental Affairs and Tourism). (2005). *National State of the Environment Report*. Pretoria: Government Printer.
- Deelstra, J., Oygarden, L., Blankenberg, A. B., & Eggstad, H. O. (2011). Climate change and runoff from agricultural catchments in Norway. *International Journal of Climate Change Strategies and Management*, 3, 345–360. doi:[10.1108/17568691111175641](https://doi.org/10.1108/17568691111175641)
- DWAF (Department of Water Affairs and Forestry). (2004). *Internal Strategic Perspective: Upper Vaal Water Management Area*. Compiled by PDNA, WRP Consulting Engineers (Pty) Ltd, WMB and Kwezi-V3 on behalf of the Directorate: National Water Resource Planning, 2004 (Report No. P WMA 08/000/00/0304). Department of Water Affairs and Forestry, South Africa
- Hall, M., Germain, R., Tyrrell, M., & Sampson, N. (2008). *Predicting future water quality from land use change projections in the Catskill–Delaware watersheds*. New York, NY: The State University of New York College of Environmental Science and Forestry and the Global Institute of Sustainable Forestry Yale University School of Forestry and Environmental Studies.
- Helmshrot, J., & Flugel, W. A. (2002). Land use characterisation and change detection analysis for hydrological model parameterisation of large scale afforested areas using remote sensing. *Physics and Chemistry on the Earth*, 27, 711–718. doi:[10.1016/S1474-7065\(02\)00055-4](https://doi.org/10.1016/S1474-7065(02)00055-4)

- Huang, J., & Klemas, V. (2012). Using remote sensing of land cover change in coastal watersheds to predict downstream water quality. *Journal of Coastal Research*, 283, 930–944. doi:[10.2112/JCOASTRES-D-11-00176.1](https://doi.org/10.2112/JCOASTRES-D-11-00176.1)
- Ibrahim, N., & Wibowo, A. (2013a). Predictions of water level in Dungun River Terengganu using partial least squares regression. *International of Basic and Applied Sciences*, 12, 1–7.
- Ibrahim, N., & Wibowo, A. (2013b). Partial least squares regression based variables selection for water level predictions. *American Journal of Applied Sciences*, 10, 322–330. doi:[10.3844/ajassp.2013.322.330](https://doi.org/10.3844/ajassp.2013.322.330)
- Jung, K., Lee, S., Hwang, H., & Jang, J. (2008). The effects of spatial variability of land use on stream water quality in a costal watershed. *Paddy Water Environment*, 6, 275–284. doi:[10.1007/s10333-008-0122-1](https://doi.org/10.1007/s10333-008-0122-1)
- Kadewa, W., Moyo, B. H. Z., Mumba, P., & Phiri, O. (2005). Assessment of the impact of industrial effluent on water quality of receiving rivers in urban areas of Malawi. *International Journal of Environmental Science and Technology*, 2, 237–244. doi:[10.1007/BF03325882](https://doi.org/10.1007/BF03325882)
- King, N. A., Maree, G., & Muir, A. (2009). Freshwater systems. In H. A. Strydom & N. D. King (Eds.), *Fuggle & Rabie's Environmental management in South Africa* (2nd ed.). Johannesburg: Juta.
- Li, S., Gu, S., Lui, W., Han, H., & Zhang, Q. (2008). Water quality in relation to land use and land cover in the upper Han River Basin, China. *Catena*, 75, 216–222. doi:[10.1016/j.catena.2008.06.005](https://doi.org/10.1016/j.catena.2008.06.005)
- Lo, C. P., & Yeung, A. K. W. (2002). Concepts and techniques of geographic information systems: Chapter 4. Upper Saddle River, NJ: Prentice Hall.
- Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2005). *Geographic information systems and science: Chapter 6* (2nd ed.). Hoboken, NJ: Wiley.
- Lou, B., Zhao, Y., Chen, K., & Zhao, X. (2009). Partial least squares regression model to predict water quality in urban water distribution. *Systems Transactions Tianjin University*, 15, 140–144. doi:[10.1007/s12209-009-0025-2](https://doi.org/10.1007/s12209-009-0025-2)
- McCarthy, T. S. (2011). The impact of acid mine drainage in South Africa. *South African Journal of Science*, 107, 1–7. doi:[10.4102/sajs.v107i5/6.712](https://doi.org/10.4102/sajs.v107i5/6.712)
- Meador, M. R., & Goldstein, R. M. (2003). Assessing water quality at large geographic scales: Relations among land use, water physicochemistry, riparian condition and fish community structure. *Environmental Management*, 31, 504–517. doi:[10.1007/s00267-002-2805-5](https://doi.org/10.1007/s00267-002-2805-5)
- Nasser, F., & Wisenbaker, J. (2003). A Monte Carlo study investigating the impact of item parceling on measures of fit in confirmatory factor analysis. *Educational and Psychological Measurement*, 63, 729–757. doi:[10.1177/0013164403258228](https://doi.org/10.1177/0013164403258228)
- Rothenberger, M. B., Burkholder, J. M., & Brownie, C. (2009). Long-term effects of changing land use practices on surface water quality in a coastal river and lagoonal estuary. *Environmental Management*, 44, 505–523. doi:[10.1007/s00267-009-9330-8](https://doi.org/10.1007/s00267-009-9330-8)
- SANBI (South African Biodiversity Institute). (2009). *Land cover for South Africa*. Pretoria, South Africa: SANBI.
- Seeboonruang, U. (2012). A statistical assessment of the impact of land uses on surface water quality indexes. *Journal of Environmental Management*, 101, 134–142. doi:[10.1016/j.jenvman.2011.10.019](https://doi.org/10.1016/j.jenvman.2011.10.019)
- Singh, A., Jakubowski, A. R., Chidister, I., & Townsend, P. A. (2013). A MODIS approach to predicting stream water quality in Wisconsin. *Remote Sensing of Environment*, 128, 74–86. doi:[10.1016/j.rse.2012.10.001](https://doi.org/10.1016/j.rse.2012.10.001)
- Thompson, M. W. (1996). A standard land cover classification scheme for remote sensing applications in South Africa. *South African Journal of Science*, 92, 34–42.
- Tong, S. T. Y., & Chen, W. (2002). Modeling the relationship between land use and surface water quality. *Journal of Environmental Management*, 66, 377–393. doi:[10.1006/jema.2002.0593](https://doi.org/10.1006/jema.2002.0593)
- Usali, N., & Ismail, M. H. (2010). Use of remote sensing and GIS in monitoring water quality. *Journal of Sustainable Development*, 3, 228–238. doi:[10.5539/jsd.v3n3p228](https://doi.org/10.5539/jsd.v3n3p228)
- Van Steenderen, R. A., Theron, S. J., & Hassett, A. J. (1987). The occurrence of organic micro-pollutants in the Vaal River between Grootdraai Dam and Parys. *Water S.A.*, 13, 209–214.
- Warburton, M. L., Schulze, R. E., & Jewitt, G. P. W. (2012). Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology*, 414–415, 118–135. doi:[10.1016/j.jhydrol.2011.10.028](https://doi.org/10.1016/j.jhydrol.2011.10.028)
- Wilson, C., & Weng, Q. (2010). Assessing surface water quality and its relation with urban land cover changes in the Lake Calumet Area, Greater Chicago. *Environmental Management*, 45, 1096–1111. doi:[10.1007/s00267-010-9482-6](https://doi.org/10.1007/s00267-010-9482-6)