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Applying SWAT to predict orthophosphate loads and trophic status in four reservoirs in the upper Olifants catchment, South Africa

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Abstract

Excessive phosphate loading in the upper Olifants River, South Africa has resulted in widespread eutrophication and associated ecosystem health impacts. The majority of sewage treatment works (STWs) are operating poorly and are likely an important source of bioavailable orthophosphate (OP) in the catchment. The Soil Water Assessment Tool (SWAT), was used to identify important sources of OP loading in the catchment and predict changes in the trophic status of four reservoirs associated with three STWs effluent OP standards; (current average of 4 mg L^{-1} and standards of 1 and 0.1 mg L^{-1}). Naish-Sutcliffe and PBIAS statistics showed good model performance for simulations of flow and OP loading using a multi-site calibration and validation approach. Key sub-catchments responsible for high OP loading were identified. Three of the four reservoirs are heavily impacted by OP loading originating from STWs. Two reservoirs show mean annual OP concentrations indicative of eutrophic conditions and a 1 mg L^{-1} effluent standard would reduce concentrations to well within the mesotrophic range. There was little difference in OP loads and concentrations associated with the 1 and 0.1 mg L^{-1} effluent standard, indicating that attention to nonpoint sources would be required to realise any benefit associated with the strictest effluent standard. Regression analyses and associated 95 % prediction limits between simulated OP loads and concentrations for all effluent treatment scenarios from 2002 to 2010 allowed for the quantification of OP loading that would ensure a specific trophic status in each reservoir. This study is one of the first to apply SWAT in simulating OP loading and concentrations in large reservoirs and its application in South Africa provides further support for its utility throughout a wide a geographical area.

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1 Introduction

Nutrient pollution and the proliferation of algal blooms associated with eutrophication is considered to be one of the greatest threats to water quality in South Africa (van Ginkel, 2011). Phosphorus is the limiting nutrient in freshwater systems and anthropogenic inputs thereof are the most important driver with regards to managing eutrophication in lakes, reservoirs and rivers (Carpenter et al., 1998; Mainstone and Parr, 2002). While total phosphorus is most commonly used as an indicator of trophic status in reservoirs and lakes, it is well known that ortho-phosphate (OP) is the most available form of phosphorus and is the primary driver of algal productivity in freshwater systems (Reynolds and Davies, 2001). OP concentrations have showed an increasing trend in most primary catchments across South Africa (de Villiers and Thiar, 2007). Nonpoint source agricultural runoff containing nutrients derived from fertilizer and manure and point source effluent originating from sewage treatment works (STWs) are typically the most important sources of phosphorus pollution in freshwater systems (Hart et al., 2004; Jarvie et al., 2006). Furthermore, mining and the concurrent removal of vegetation and exposure of bare soil and rock to weathering and soil erosion also results in the potential for relatively high losses of naturally occurring phosphorus in the soil, similar to what would be expected at large construction sites (Carpenter et al., 1998).

Water quality in the upper Olifants catchment, located in the Mpumalanga Province of South Africa, is significantly impacted by a number of land use activities occurring in the catchment (Dabrowski and De Klerk, 2013). The catchment is currently the most important source of coal in the country (Hobbs et al., 2008) and also supports associated coal-fired power stations, metallurgical industries and large urban towns as well as dryland agriculture and cattle production in grassland areas. The majority of STWs are operating at a poor standard, releasing high volumes of partially treated effluent into river reaches (DWA, 2010). The effects of these intensive anthropogenic activities have been most pronounced in the Loskop Reservoir, located at bottom of the catchment, where water quality has steadily declined (Dabrowski et al., 2013). In particular,

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area (Fig. 1). Discharge was measured constantly at each station and expressed as total monthly flow. OP samples were collected at frequencies ranging from once to 4 times per month. Corresponding monthly loads were calculated based on the multiple regression methodology using the FLUX 32 programme (Walker, 1996) which was designed for estimating constituent loads from intermittent quality data and continuous flow data. Model calibration and uncertainty analysis was done using the SUFI-2 optimization programme within the SWAT-CUP software (Abbaspour, 2011). In SUFI-2, uncertainty of input parameters are depicted as uniform distributions, while model output uncertainty is quantified by the 95 % prediction uncertainty (95 PPU) calculated at the 2.5 and 97.5 % levels of the cumulative distribution of output variables obtained through Latin hypercube sampling (Abbaspour et al., 2007). SUFI-2 starts by assuming a large parameter uncertainty (within a physically meaningful range), so that the measured data initially falls within the 95 PPU, then decrease this uncertainty in steps until two rules are satisfied: (1) the 95 PPU band brackets “most of the observations” (indicated by the p -factor, where values are between 0 and 1, with 1 indicating 100 % of the data is bracketed by the PPU) and (2) the average distance between the upper (at 97.5 % level) and the lower (at 2.5 % level) parts of the 95 PPU is smaller than the standard deviation of the measured data (indicated by the r factor, where a value of less than 1 is considered acceptable). A balance between the two rules ensures bracketing most of the data within the 95 PPU, while seeking the smallest possible uncertainty band. The above two measures were used to quantify the strength of calibration accounting for the combined parameter, model, and input uncertainties. For flow calibration, sensitive parameters influencing peak and base flow (Neitsch et al., 2002; White and Chaubey, 2005) were used to calibrate flow simulations for the calibration stations. Two iterations were performed, with 1000 simulations performed in each iteration. The final parameter ranges identified after the second iteration were considered to be the calibrated parameter ranges providing the best simulation solution for the observed data at all calibration stations (Table 2).

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In addition to the uncertainty parameters, further goodness of fit was quantified by the Naish-Sutcliffe (NS) coefficient between observed data and the best simulation identified by the SUFI-2 algorithm. The values of R^2 range from 0 to 1. If the R^2 values are less than or close to 0, the model simulation is taken as an indication of poor or unacceptable performance. The closer the values get to 1, the more perfect the model simulation. Moriasi et al. (2007) indicate that a value greater than 0.5 for these variables constitutes an acceptable simulation model. Percent bias (PBIAS) is the average tendency of the simulated data to be larger or smaller than their observed counterparts (Moriasi et al., 2007), and was also used to compare model outputs. For flow, PBIAS statistics indicating variation (a) between 15 and 25 % (b) between 10 and 15 % and (c) less than 10 % are considered satisfactory, good and very good, respectively.

Considering that OP loads were estimated from infrequent monitoring data, we did not anticipate a good temporal comparison between monthly measured and predicted loads. It was however important that predicted loads fell within the range of measured loads. Calibration of parameters influencing OP loading was performed manually and only the PBIAS statistic was used to evaluate model predictions, with the emphasis on achieving a good comparison between average measured and predicted loads. For nutrient loads, PBIAS statistics indicating variation (a) between 40 and 70 % (b) between 25 and 40 % and (c) less than 25 % are considered satisfactory, good and very good, respectively (Moriasi et al., 2007).

2.4 Model validation

Model validation was performed through comparing simulated data to measured data retrieved from additional DWA monitoring stations (validation stations) occurring within the catchment (Fig. 1). Measured data from these validation stations were not used to calibrate the model. The same statistics used in assessing model calibration were used to assess model validation.

2.5 Model application

The calibrated model was used to; (a) predict monthly and mean annual OP loading in the upper Olifants catchment (b) identify important sub-catchments responsible for high loading of OP and (c) estimate OP loading and concentrations in the four large reservoirs located in the catchment. Simulated monthly and mean annual OP concentrations were compared to available measured data from each of the reservoirs to determine model accuracy. In addition, two point source load reduction scenarios were simulated by reducing OP effluent concentrations (and derived loads) at each STW from 4 mg L^{-1} to 1 (current national phosphate effluent standard) and 0.1 mg L^{-1} , respectively. The effect of these reduction scenarios was evaluated by comparing predicted mean annual OP concentrations (for each year from 2002 to 2010) to OP water quality guidelines (DWAF, 1996) that identify thresholds associated with a trophic status (i.e. oligotrophic, mesotrophic, eutrophic and hyper-eutrophic). Each simulation for each scenario generated a load prediction and associated mean annual OP concentration for 9 annual time-steps (2002 to 2010), with each time step accounting for prevailing hydrological conditions for that year. The data points for all scenarios (27 in total), were analysed by linear regression (using STATISTICA, version 12) and the associated 95 % prediction limits were used to identify the range of OP loads that would ensure that mean annual OP concentrations in each reservoir would remain within a specific trophic status.

3 Results and discussion

3.1 Flow simulations

In general, flow simulations at calibration stations compared well to measured flow records and peak flow events were within maximum peaks measured at flow gauging stations across the catchment (Fig. 2). The r factor for calibration and validation stations for most catchment areas was below 1 indicating low uncertainty associated

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with model predictions. Stations located in the Wilge catchment (B2H014 and B2H007) area had r factor values above 1 indicating higher uncertainty associated with model outputs. The proportion of measured data bracketed by the 95 PPU band was relatively high for the B1H004, B1H005 and B2H014. Apart from B2H014 area, NS statistics for all calibration stations were above 0.49, indicating a satisfactory simulation (Table 3). The NS for the B1H004 area was particularly good (0.79). PBIAS statistics for these calibration stations were also considered as satisfactory, falling below 25 %, with good and very good values obtained for B1H005 and B1H012, respectively. NS and PBIAS values for B2H014 were poor (below 0.5 and above 25 % respectively). With the exception of B1H002, NS statistics for the validation stations were slightly lower than for calibration stations across (Table 3). PBIAS statistics were slightly better at validation stations than at calibration stations.

Results therefore indicate that the model provides a satisfactory representation of flow characteristics in the upper Olifants catchment. The SWAT model has been successfully applied to simulate hydrology in other African countries (Baker and Miller, 2013; Schuol et al., 2008) as well as in two South African catchments (Andersson et al., 2011; Govender and Everson, 2005). The hydrological results of this paper therefore provide further evidence to the applicability of the SWAT model in a wide range of climatic and geographical conditions. Discrepancies between predicted and measured flows are most likely related to input uncertainty associated with rainfall data. The upper Olifants catchment falls within a summer rainfall region which is characterised by isolated, scattered thunder showers. This results in highly variable rainfall patterns across the catchment. For example, peak flows were generally over-predicted during 2002 and 2003, particularly at B1H012 and B1H005, where rainfall monitoring stations were absent further up in their respective catchments. In these instances, SWAT retrieves rainfall data from the weather station in closest proximity to the sub-catchment (e.g. weather stations located close Delmas and Middelburg) which have a good possibility of not being representative of rainfall conditions further upstream. Flow stations in closer proximity to weather stations, (e.g. B1H002, B1H004 and B1H019) did not show

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particular, STWs located in the upper reaches of the Wilge and Steenkoolspruit and lower reaches of the Klein-Olifants rivers contribute high loads to the catchment. The Steenkoolspruit, draining an area of 1342 km² contributed similar loads to those originating from the Wilge River, a significantly larger river in terms of discharge, draining an area of 4007 km². This further emphasises the impact of STWs in this catchment, resulting in high nutrient loading in the Olifants River relatively high up in the system.

No other studies have applied SWAT to predict nutrient input in South Africa and only one other example exists for the rest of Africa. Kimwaga et al. (2012) implemented the model to predict the effectiveness of best management practices on reducing nonpoint-source pollution to Lake Victoria, however no calibration of the model simulations were performed. Results of this study therefore represent one of the first to be conducted in South Africa and indeed Africa. A number of other studies have successfully applied SWAT to predict total phosphorus and nitrate loading (Grizzetti et al., 2003; Lam et al., 2010; Poudel et al., 2013; Ullrich and Volk, 2009). Fewer studies have however focussed on the prediction of OP loads. In fact, a study by Daloğlu et al. (2012), which modelled long-term loading of dissolved reactive phosphorus (DRP) to Lake Erie is claimed to be first long-term detailed analysis of DRP using SWAT. Results of this study therefore further lend support to the ability of the model to make realistic predictions of OP loading in large catchments. Considering the importance of OP in driving eutrophication in lakes and reservoirs (Reynolds and Davies, 2001), the implication of these results is that the model can be used to estimate the impact of different management scenarios on trophic status in reservoirs in the catchment.

3.3 Point source vs. nonpoint source contributions

Predicted OP loading resulted in realistic OP concentrations in the four reservoirs that compared favourably to measured values (Fig. 5). PBIAS statistics indicated that simulated concentrations were within an acceptable range of measured concentrations, particularly in the Witbank and Bronkhorstspruit reservoirs. Temporal patterns of OP concentrations in Bronkhorstspruit reservoir in particular, are indicative of point source

Middelburg reservoir receives significantly lower loads of OP than the Bronkhorstspruit reservoir, even though the catchment area upstream of the Bronkhorstspruit reservoir is slightly smaller (Fig. 1). STWs in this catchment are therefore responsible for significant loading of OP in the reservoir. The importance of point sources in the catchment can again be illustrated by the effect of the STW effluent reduction scenarios on loading in the reservoirs. Implementation of a 1 mgL^{-1} phosphate effluent standard would result in similar loading in the Middelburg and Bronkhorstspruit reservoirs. This represents an approximate 77 % reduction in loading in the Bronkhorstspruit reservoir. A similar effluent standard in the catchment area upstream of Middelburg reservoir would have relatively little effect on loading, again emphasising the importance of nonpoint sources in this catchment. The effluent standard would result in an approximate 50 % reduction in the Witbank reservoir leading to a situation where point and nonpoint sources would contribute equally to OP loading in the reservoir. The greatest reduction in terms of total load would be realised in the Loskop reservoir. A 1 mgL^{-1} effluent standard would result in a mean annual load of approximately 13 900 kg (representing a 61 % decrease), resulting in nonpoint sources becoming the most important driver of OP loading in this reservoir. A 0.1 mgL^{-1} effluent standard would result in further reductions in Loskop and Bronkhorstspruit reservoirs, although the difference between the 0.1 and 1 scenario is far smaller than the difference between the current and 1 mgL^{-1} scenario. This indicates that the 1 mgL^{-1} scenario is potentially the most effective in making a large impact on OP reductions. Furthermore the fact that nonpoint sources play more a of a significant role in the 1 mgL^{-1} scenario indicates that the impact of alternative best management practices should be investigated in addition to enhanced effluent treatment options. The extent of OP load reductions is also dependent on the desired state of the resource. In this respect the impact of OP loading on trophic status provides a valuable means of quantifying maximum allowable loading in a catchment. Such an approach is widely used in the estimating Total Maximum Daily Loads (TMDLs) for pollutants in the USA (Borah et al., 2006).

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dard across the catchment would be more than sufficient to meet this objective. While eutrophication in large water bodies can be reversed by decreasing inputs of phosphorus, rates of recovery are highly variable among water bodies and often the eutrophic state persists and recovery is slow (Carpenter et al., 1998). This is largely because of the effective recycling of accumulated phosphates within the water body. However, a recent study found Loskop reservoir to be sensitive to phosphorus loads and, together with the fact that trophic status was considered to be on the threshold of eutrophic, load reductions would most likely result in a switch in trophic status to mesotrophic (Oberholster et al., 2013). The Bronkhorstspruit reservoir is most heavily affected by OP loading, with all current STW scenario predictions falling well into the eutrophic range. Implementation of either effluent reduction scenarios would result in considerable decreases in annual loading and a trophic status that falls well within the mesotrophic range. An approximate 50 % reduction in loads would result in 95 % of mean annual loads resulting in mean annual concentrations that fall within the mesotrophic range. The Witbank reservoir has only one mean annual concentration value above the eutrophic range and most mean OP concentrations fall within the mesotrophic range. The overlap in data points associated with the 0.1 and 1.0 mgL⁻¹ scenarios indicates that the implementation of the strictest effluent guideline would not have a significant benefit over the 1.0 mgL⁻¹ scenario. As highlighted previously, the influence of nonpoint sources in this catchment area would mask the added benefit derived from a 0.1 mgL⁻¹ standard. Results indicate that the current mean annual loading of 8700 kg (Fig. 7), while sufficient to maintain a mesotrophic status, is close to the load threshold of approximately 10 000 kg, above which less than 95% of mean annual OP values would fall in the mesotrophic range (Fig. 8). All mean annual OP concentrations fall well within the mesotrophic range at Middelburg reservoir. Furthermore there is a lot of overlap in mean annual OP concentrations associated with all STW scenarios (including the current scenario of 4 mgL⁻¹). This is indicative of the fact that nonpoint source pollution is the primary driver behind OP concentrations in the dam and any treatment options in STWs further upstream, are unlikely to influence trophic status and OP con-

centrations to a significant extent. The regression model developed for the Middelburg reservoir provides an opportunity to estimate the potential load contributions from the feedlot to make up for the model under prediction. A mean annual OP concentration of 0.015 mg L^{-1} (current measured concentration) would correspond to an average OP loading of 5750 kg (Fig. 8), which is almost 4000 kg higher than the current predicted load (Fig. 6). This implies that management of feedlot effluent in this catchment would make the most significant impact on OP loading for this reservoir.

4 Conclusions

This study comprises the first comprehensive application of SWAT to predict nutrient loading in a South African and African catchment and is one of the first in the world demonstrating the use of the model in predicting OP loading and associated concentrations in reservoirs. Overall the model was able to generate good spatial and temporal simulations of flow throughout the catchment, with validation stations generating similar goodness of fit statistics to calibration stations. Discrepancies in flow profiles could largely be explained by the lack of weather data for large areas of the southern and south eastern parts of the catchment and the addition of a weather station in this area would undoubtedly improve flow and OP simulations in the catchment. The model did not provide good temporal predictions of OP loading at a monthly time step, which can be attributed to the paucity of monitoring data at calibration stations. There was however good correspondence between the range of simulated and measured values over a monthly time step with little variation in the average tendency of simulated values to be larger or smaller than measured values. As a result mean annual OP loading at calibration and validation stations compared very well with mean annual measured loads.

While model simulations can be significantly improved, it is important to note that, in contrast to the majority of studies that use a single site at the catchment outlet for calibrations; multiple, un-nested sites were used in the calibration and validation

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procedure in this study. The observed simulations and associated statistics therefore provide a reasonable representation of hydrology and OP loading in multiple locations at varying spatial scales throughout the catchment area. The method used in this study therefore ensures greater confidence in the effectiveness of management interventions in most locations throughout the catchment. A drawback of this method is that calibration using multiple sites introduces more constraints on the process, making calibration challenging (White and Chaubey, 2005). For example the poor statistics observed at monitoring stations in the Wilge catchment, indicate that the input parameters used to calibrate the model for the larger upper Olifants catchment are not a good representation of conditions in this part of the catchment and separate input parameterization of this section of the catchment may be necessary to account for hydrological variation.

Most importantly the model was able to provide realistic estimates of OP concentrations in four different reservoirs of varying sizes, and allowed for the estimation of OP loading ranges that could be linked to trophic status categories. This study therefore provides promising evidence of applying the SWAT model in South African conditions and improving decision making with regards to formulating catchment management plans designed to improve ecological health and water quality through implementation of realistic management goals. In 1980, an OP standard of 1.0 mg L^{-1} was introduced in South Africa, with the specific aim of controlling eutrophication in sensitive catchments. The widespread occurrence of eutrophication in South African water bodies would indicate that this standard has apparently had little effect (Walmsley, 2000). However these observations do not take into account the fact that many STWs across the country are most likely not meeting this standard in the first place. Nevertheless, past and recent studies have emphasised the importance of reducing the current OP effluent standard of 1 mg L^{-1} to a stricter standard of 0.1 mg L^{-1} (Dickens et al., 2010; Rossouw, 1990). Results from this study highlight that in some instances a 0.1 mg L^{-1} effluent standard is unlikely to have an effect if nonpoint sources are not adequately managed and that at least for reservoirs in the upper Olifants catchment, a 1.0 mg L^{-1} effluent standard

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Table 1. Sources of input data for application of the SWAT model in the upper Olifants catchment.

Data Type	Source	Description
DEM	ASTER/GDEM (2012)	Digital Elevation Model 30 × 30 m
Soil	Middleton and Bailey (2008)	Soil data for South Africa from the WR2005 project
Land Use	SANBI (2009)	Land Cover Classifications
Agricultural Census Data	STATSSA (2002)	Census data on area and production of crop types per magisterial district in South Africa
Weather Data	ARC (2011)	Records from five precipitation, air temperature, solar radiation, relative humidity and wind speed gauges over a 10 yr period (2000–2010) were used in the model
Point Source Concentrations	DWA (2011a)	Limited data on point source emissions of ortho-phosphate
Point Source Volumes	DWA (2009)	Information on design and actual capacity for effluent volumes for each STW in the catchment

Table 2. Calibrated parameter ranges and final fitted values used to simulate flow and orthophosphate loading in the upper Olifants catchment.

Parameter	Description	Range	Fitted value
Flow:			
CN2 ¹	SCS Runoff curve number	0.81–1.13	0.9
ALPHA_BF	Baseflow alpha factor (days)	0.44–1.35	0.76
GW_DELAY	Groundwater delay time (days)	0–314	214
GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur (mm H ₂ O).	2482–7457	3568
REVAPMN	Threshold depth of water in the shallow aquifer for percolation to the deep aquifer to occur (mm H ₂ O)	87–363	157
GW_REVAP	Groundwater revap coefficient	(0.16)	0.16
ESCO	Soil evaporation compensation factor	0–0.62	0.02
CH_N2	Manning <i>n</i> value for the main channel	0.07–0.22	0.19
ALPH_BNK	Baseflow alpha factor for bank storage (days)	0–0.55	0.09
SOL_AWC*	Soil available water storage capacity (mm H ₂ O/mm soil)	0.61–1.14	0.97
SHALLST	Initial depth of water in the shallow aquifer	60–687	489
DEEPST	Initial depth of water in the deep aquifer	218–2073	1733
Ortho-phosphate ² :			
BC4	Rate of constant decay of organic phosphorus to dissolved phosphorus (1 day ⁻¹)		0.05
USLE_P	USLE equation support practice factor		0.5
RS2	Benthic sediment source rate for OP in the reach at 20 °C (mg OP m ⁻³ day ⁻¹)		0.08
AI2	Fraction of algal biomass that is phosphorus (mg P mg ⁻¹)		0.16
PPERCO	Phosphorus percolation coefficient (10 m ³ Mg ⁻¹)		15.1
PHOSKD	Phosphorus soil partitioning coefficient (m ³ Mg ⁻¹)		159

¹Default SWAT parameters for land uses multiplied by specified fitted value.²No parameter ranges are defined as SWAT-CUP was not used to calibrate orthophosphate loads.

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Table 3. Uncertainty and goodness of fit statistics for flow and ortho-phosphate loading at calibration and validation stations in the upper Olifants catchment, South Africa.

	Calibration Stations			
	B1H004	B1H005	B1H012	B2H014
Flow:				
<i>p</i> factor	0.62	0.19	0.56	0.79
<i>r</i> factor	0.48	0.28	0.64	1.98
NS	0.79	0.49	0.56	0.18
PBIAS	21.53	12.80	1.36	36.08
Ortho-phosphate:				
PBIAS	−19	−41.45	2.4	26.92
	Validation Stations			
	B1H002	B1H019	B1H021	B2H007
Flow:				
<i>p</i> factor	0.25	0.24	0.16	0.89
<i>r</i> factor	0.40	0.35	0.3	2.74
NS	0.50	0.45	0.42	0.31
PBIAS	19.86	−17.43	6.5	13.49
Ortho-phosphate:				
PBIAS	36.94	−15.67	−3.19	56.73

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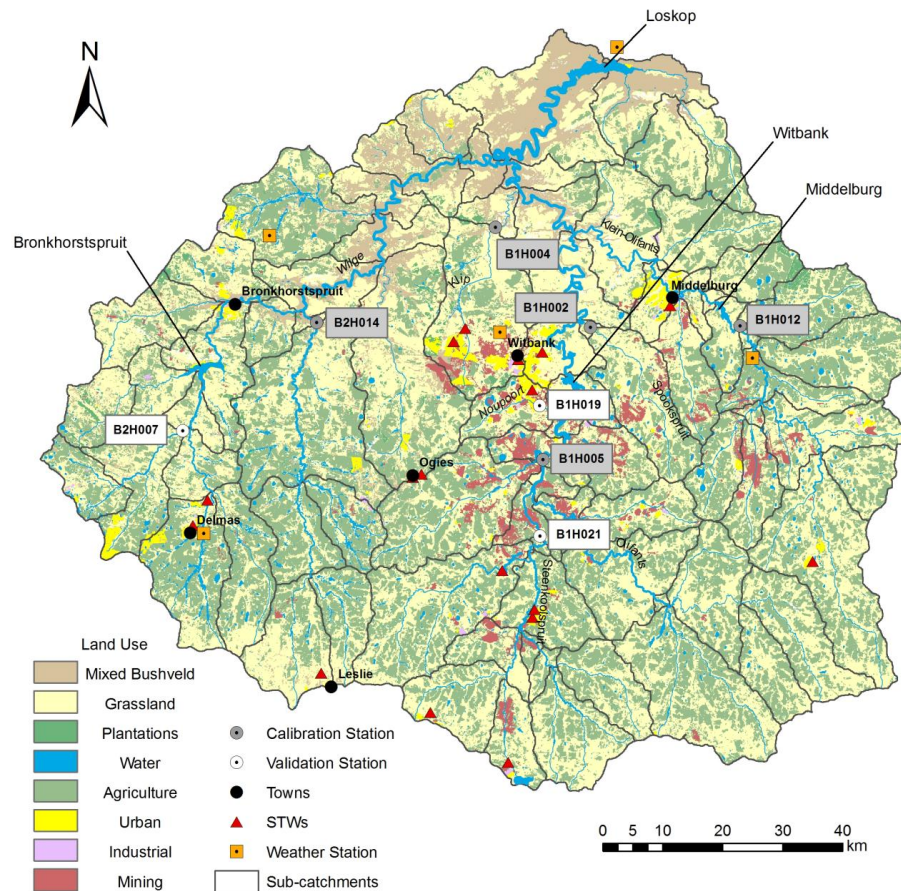


Fig. 1. Sub-catchments (delineated by the SWAT model) and location of sewage treatment works (STWs), weather stations and DWA flow and water quality monitoring stations in the upper Olifants catchment.

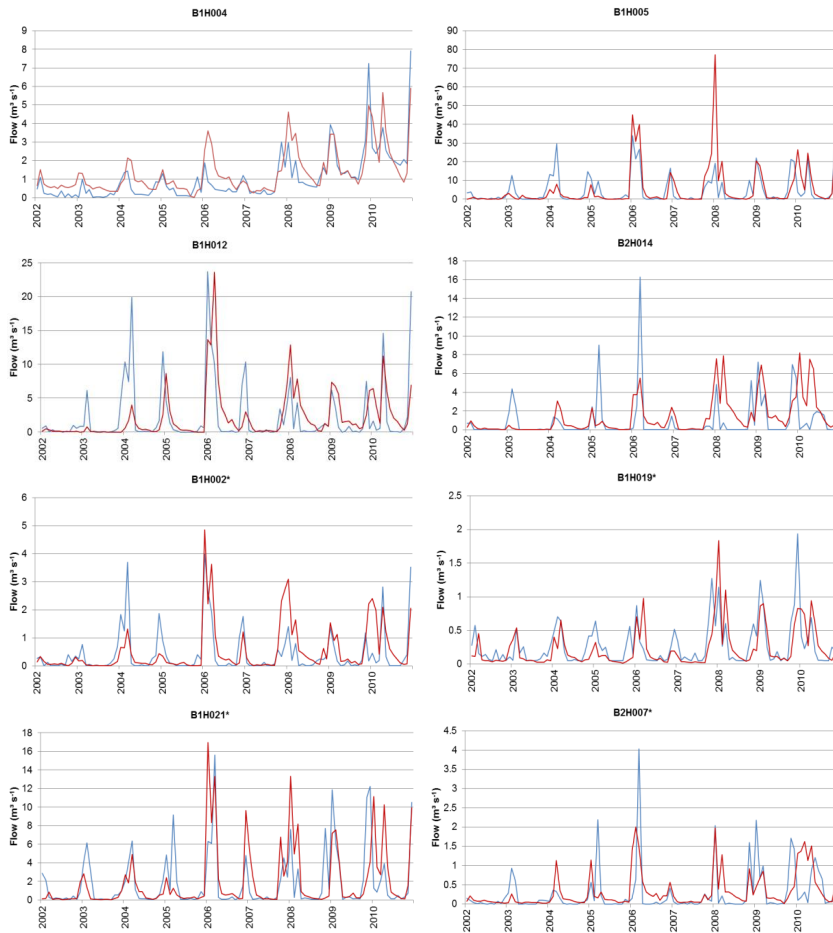


Fig. 2. Predicted (red lines) and measured (blue lines) monthly flow at calibration and corresponding validation (indicated by *) monitoring stations located in the upper Olifants catchment.

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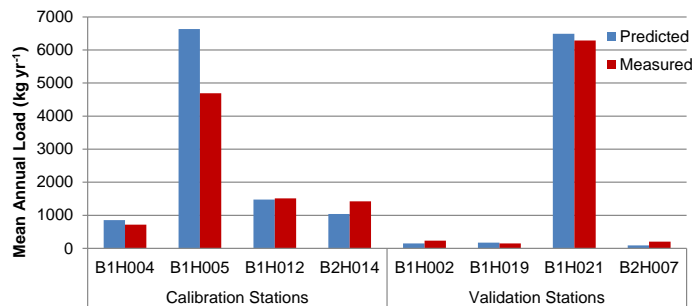


Fig. 3. Predicted and observed mean annual orthophosphate loads at calibration and validation monitoring stations located in the upper Olifants catchment from 2002 to 2010.

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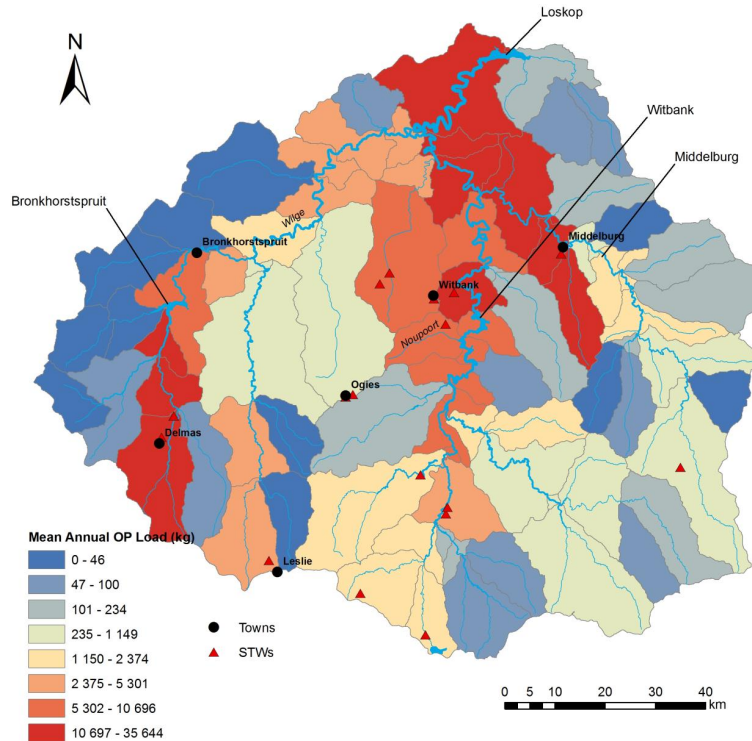


Fig. 4. Mean annual OP loads associated with three STW effluent scenarios entering four reservoirs in the upper Olifants catchment (horizontal lines indicate nonpoint source contributions to mean annual OP loads per reservoir).

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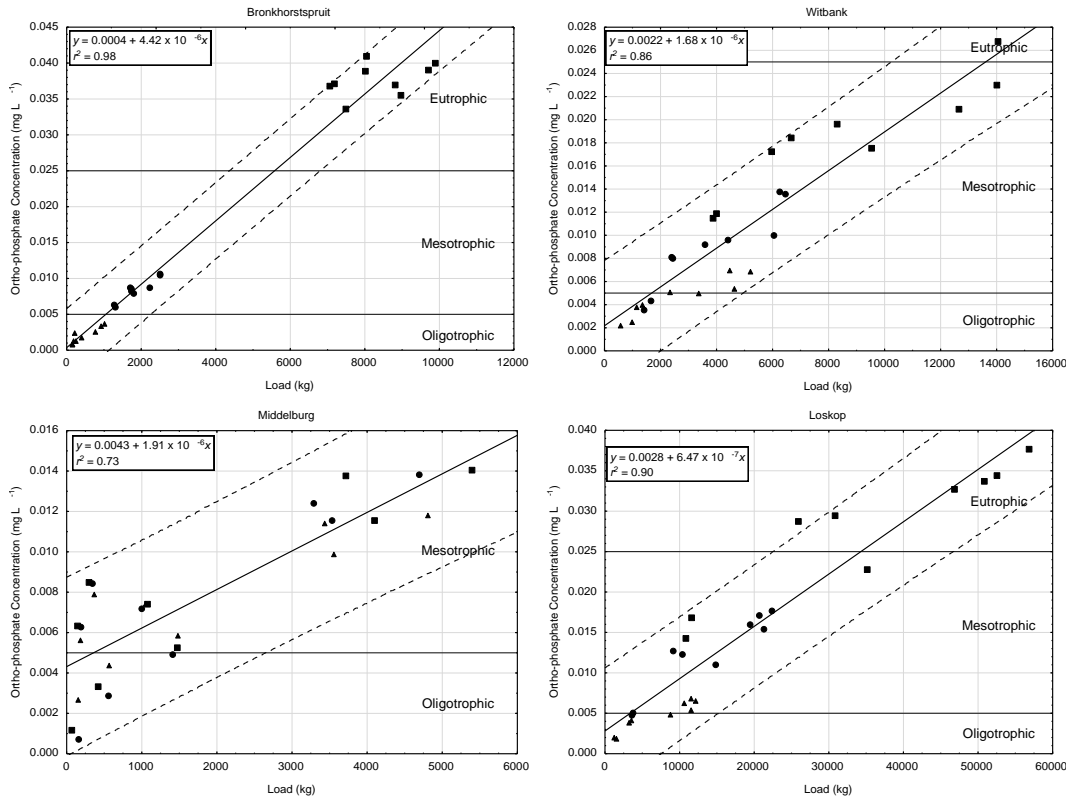


Fig. 8. Linear regression plots of ortho-phosphate loads and concentrations associated with three sewage orthophosphate effluent standards (4 mg L^{-1} – ■ 1 mg L^{-1} – ●; 0.1 mg L^{-1} – ▲) in four reservoirs located in the upper Olifants catchment for the years 2002 to 2010 (dotted lines represent 95 % prediction limits).

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