Water quality management in the context of future climate and development changes: a South African case study
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ABSTRACT
Globally, water resources are being over-utilised; a situation exacerbated by degenerating water quality of rivers. To achieve sustainable management of water resources, uncertainty under climate change and development must be considered. A companion study was the first to incorporate uncertainty within water resources development scenario modelling for a catchment in South Africa using the Water Evaluation and Planning (WEAP) model. That study is extended in the current study by considering water quality in the form of nutrients and salinity. The WEAP model was calibrated against available observed data for the period 1999–2005. Using the calibrated WEAP model, driven by flow predicted using downscaled climate change models and projected future development, water quality was simulated for the years 2046–2065. Future simulations indicated marginally increased dilution capacity as well as increased nutrient inputs. It is evident that WEAP suffers major limitations in its water quality simulation capacity. Adaptive management along with continual monitoring as a strategy to cope with uncertainty associated with climate change and development is recommended. The shortcomings identified within WEAP in the current study were the motivation for the development of a new water quality decision support system specific to the requirements of water management in southern Africa.
Key words | catchment modelling, climate change, decision-making uncertainty, water quality

INTRODUCTION
While in the past water resource management has focussed on water quantity, water quality issues are increasingly becoming more important. This is because there is a continual decline of water quality of freshwater resources globally (Zimmerman et al. 2008), and from a human use perspective, generally resulting in increasing costs associated with water treatment and a decline in availability of usable water.

While increasing population and economic development are to blame for increasing pollution of freshwater resources, it is likely that future climate change will exacerbate water quality problems. Therefore, the development of management and adaptive measures for managing water quality should collectively take future developmental and climate change effects into account. Doubts over data, models and impacts of economic and social factors all contribute to increasing uncertainty associated with the results of modelled future scenarios (Hughes et al. 2011). Therefore, uncertainty needs to be incorporated into water resource planning so as to facilitate adaptive planning (Pappenberger & Beven 2006; Beven & Alcock 2012).

The aforementioned management measures are critically required for southern Africa, where water resources are particularly vulnerable due to inherent variability of the climate and general over-allocation of water resources (Walmsley et al. 1999; DWA 2013). Few studies have attempted to quantify the combined effects of future development and climate change on water resources in southern Africa (Mantel et al. 2015), and although a few
modelling studies on potential climate change effects on water quantity in Africa (for example, De Wit & Stankiewicz 2006), and a few international reviews and studies on potential effects of climate change on water quality exist (for example, Wilby et al. 2006; Whitehead et al. 2009), research into future river water quality is not well represented within the literature.

Mantel et al. (2015) presented the first study incorporating the joint effects of development and climate change within future scenario modelling for managing freshwater resources for a catchment in southern Africa. The aforementioned study used an application of the Water Evaluation and Planning (WEAP) model (Sieber & Purkey 2007) for the Amatole system in the Eastern Cape, South Africa that consists of three catchments. In the Mantel et al. (2015) study, individual as well as collective effects of climate change and development were assessed for the near future (2046–2065) under lower, intermediate and upper development for development scenarios, and the A2 emissions scenario for climate change scenarios. The current study presents the water quality component of the Mantel et al. (2015) study, and therefore aims to quantify future changes to water quality under projected development and climate change for the near future in southern Africa, using the Amatole system as a case study. The study by Mantel et al. (2015) incorporated prediction uncertainty in water quantity modelling and water availability by considering multiple global climate models (GCMs) and various future development scenarios. Because flow is a driver of water quality, this uncertainty is carried through to the water quality modelling considered in the current study, and therefore, to a certain degree, the current study similarly considers uncertainty. The study by Mantel et al. (2015) is key to the current study as it provides the water quantity (flow) data used to drive water quality simulations. From this point onwards, the Mantel et al. (2015) paper will be referred to as the ‘companion study’ to the current study.

**STUDY AREA**

A detailed description of the study area is available in the companion study, and a summary is provided here. Figure 1
depicts the subcatchment boundaries, rivers, dams and towns/cities within the Amatole system. The Amatole system consists of three river catchments, namely the Buffalo, Nahoon and Kubusi river catchments. The main (seven) dams are described in the companion study, and are also visible within Figure 1. The majority of observed data are available for the Buffalo River catchment (see Figure 1). Since observed data are necessary for accurate calibration within water quality modelling, the current study limits reporting of calibration to historical water quality and simulation of future water quality to within the Buffalo River catchment, with the assumption that broad catchment trends in water quality would be of relevance to the other catchments within a water quality management context.

The rivers on the system can be described as relatively short (approximately 125 km from headwaters to sea) with few tributaries and a low maximum order of four (Strahler 1957). Rainfall occurs throughout the year, although the majority occurs during summer. The upper catchments on the system are considerably wetter than the middle and lower catchments, for example, the upper Buffalo River catchment receives 1,500–2,000 mm a⁻¹ and the middle receives 500–625 mm a⁻¹. The seasonal rainfall pattern for the upper and middle Buffalo River catchment is depicted in Figure 2. The geology of the region is dominated by marine sediments resulting in surface waters in the region being naturally saline. The middle and lower Buffalo River exhibit the most serious water quality problems, being highly eutrophic because of input from overloaded waste water treatment works (WWTWs) and point and diffuse input from the King Williams Town region. Water hyacinth (Eichhornia crassipes) is an ongoing problem in Laing Dam, while Microcystis blooms have in addition been reported within the catchment.

MODEL

The WEAP model (Sieber & Purkey 2007) was used in the current study. A more detailed description of the model is available in the companion study, but in summary, WEAP is a ‘water accounting’ model that can be used to investigate different scenarios of water use and resource development (Yates et al. 2009). WEAP provides relatively rudimentary water quality modelling functionality, and simulates fewer processes than more complicated models such as QUAL2 K (Pelletier et al. 2006) or CE-QUAL (Cole & Buchak 1995). WEAP is capable of modelling the concentration of water quality constituents in a river using simple mixing, first-order decay equations, or by linking to the US EPA water quality model QUAL2 K (Pelletier et al. 2006). The linkage to QUAL2 K is not ideal, as a temporal and spatial disconnect between the two models exists, with WEAP being useful to model water quantity on a catchment scale and typically at a monthly time step. QUAL2 K on the other hand, is a local level water quality model suitable for modelling highly detailed water quality in a short stretch of a river, and at an hourly time step. QUAL2 K requires a great deal of observed data to be suitably calibrated. Neither water quality model can simulate water quality in reservoirs. WEAP however, does have the advantage of being able to support management scenario functionalities, as the model explicitly represents waste water and water treatment infrastructure by their capacities and cost (Assaf & Saadeh 2008). In the current study, the built-in water quality functions of WEAP were used.

Data used

Within the current study, WEAP was run on a monthly time step. Data used to model water quantity under current and future scenarios are outlined in the companion study, but a short summary is provided here.
Calibration of water quantity for historical conditions

Historical rainfall and evaporation/temperature data were obtained from the South African WR2005 database (Middleton & Bailey 2008). WEAP used these data to generate natural hydrology using a built-in rainfall–runoff module. Consideration of reservoirs on the system as well as current water demands allowed WEAP to simulate altered hydrology. Current water demands for the system were obtained from DWAF (2008) and were divided into three demand areas for simplification, namely the upper, middle and lower catchment, and are summarised in the companion study. The present day (current) demand was used in WEAP as a stationary demand for the modelled years 1921–2005. The WEAP application for the Amatole system in addition considered water losses due to evapotranspiration by invasive plants and water reticulation losses (see the companion study for more information). Calibration of stream flows was achieved using observed data for 11 gauging stations on the system.

Generation of water quantity for future scenarios

Daily rainfall and minimum and maximum daily temperatures were obtained from nine statistically downscaled GCMs (see the companion study for more information) for the SRES A2 emission (business as usual) scenario (IPCC 2000) for the near future (2046–2065). The near future water requirements were estimated from the available data on expected increases in water demands for the years 2005–2030, and are categorised into three possible development trajectories, namely lower, intermediate and upper development. More information is presented in the companion study, but in summary, the upper, intermediate and lower development scenarios envisaged a 100, 33 and −6% change in demand as compared to the current, respectively.

Calibration of water quality for historical conditions

It was decided to model electrical conductivity (EC) as indicative of salinisation, as well as the nutrients NO₂-N + NO₃-N and PO₄-P for the following reasons:

(1) The Amatole system is naturally saline, and higher salinities due to human impacts increase costs of treatment.

(2) Eutrophication is a major water quality problem within the system, caused by excessive nutrient inputs.

(3) The chosen water quality variables are fairly well represented within the historical monitoring data, facilitating calibration of the model.

WEAP allows a first-order decay coefficient to be associated with the non-conservative modelled nutrients (NO₂-N + NO₃-N and PO₄-P). Due to the approach used within WEAP, these coefficient values are applicable across the entire modelled catchment, i.e. they cannot be adjusted according to specific subcatchments, unless that sub-catchment is modelled separately. Observed water quality data, where available, were used to estimate water quality signatures of tributary and WWTWs inflows. Water quality signatures associated with irrigation return flow were adjusted to within a reasonable range during the calibration process. The first-order decay rates were adjusted during the calibration process. As a measure of the calibration success, a Nash–Sutcliffe efficiency value (Nash & Sutcliffe 1970) is reported within each calibration.

Generation of water quality for future scenarios

All water quality signatures and parameters were kept the same as determined during the calibration process. Average values of observed data were used to specify water quality concentrations from WWTWs in the future scenarios. The assumption made was that changes to water quality in the future would be driven by changes in flow, i.e. assuming that processes affecting water quality signatures would remain constant in the future. As an example, the degree of irrigated land may change in the future, leading to increases or decreases in irrigation return flow, but it was assumed that the water quality signatures associated with the irrigation return flow would remain constant. This assumption was additionally made with WWTWs return flows, with increases or decreases in return flow predicted according to population growth estimates, but an assumption was made that the treatment efficiencies of the WWTWs would remain the same.

While the companion study generated future water quantity development scenarios for lower, middle and upper development, the future water quality development scenarios reported on in the current study only considered intermediate development, in the interest of limiting the
range of results presented to within a reasonable amount, and also because this is the most likely future development scenario. Uncertainty in water quality is reported in a simplistic manner, where the uncertainty range for a particular variable in a particular month within the simulation is specified as the range between the maximum and minimum values obtained across all downscaled GCMs.

RESULTS

Calibration of the WEAP model to historical water quality data (1999–2005)

The calibration of the WEAP model to historical conditions for streamflow is described in the companion study. Table 1 shows the water quality flow signatures chosen for various inflows to the catchment. All values were determined through examining the available data and calculating the average, except for those parameter values marked with an “a” in Table 1, which were determined by calibrating simulated water quality data against observed data. These latter values were obtained by comparing simulated water quality results on a monthly time scale, to the average monthly observed data for selected points in the catchment. Observed historical monitoring data were only available for the upper, middle and lower Buffalo River catchments, and therefore, calibration results are only shown for these points on the Buffalo River.

Figure 3 shows the calibration results for EC. The simulations for the upper and lower catchment appeared to have obtained a reasonable estimation of salinity (Figure 3(a) and 3(c)), as confirmed by relatively good Nash–Sutcliffe efficiency values obtained when comparing simulated EC values to observed. The simulations of EC for the middle catchment were not as good, with the seasonal signal within the simulation being slightly different to that of the observed (see Figure 3(b)) and consequently, the Nash–Sutcliffe efficiency value obtained was not as favourable.

The first-order decay rate for PO$_4$-P, as evident in Table 1, was chosen to obtain as good a fit as possible to observed data within the middle catchment. The middle catchment was the focus, as this is the region where the most serious eutrophication issues occur. The water quality simulation method employed by WEAP applied this value to the entire modelled catchment. While a fairly good simulation of observed water quality was obtained for the middle catchment (Figure 4(b)), the model drastically undersimulated PO$_4$-P for the upper catchment (Figure 4(a)). A fairly variable seasonal simulation of PO$_4$-P was obtained for the lower catchment, whereas the observed seasonal trend appeared fairly stable and uniform (Figure 4(c)). The Nash–Sutcliffe efficiency values obtained reinforced the visual assessment of the model fit, indicating that WEAP overestimated processes affecting PO$_4$-P concentrations within the upper catchment, whereas simulations for the lower catchment were too variable in relation to the observed, and a more accurate simulation was obtained for the middle catchment.

Simulated NO$_3$-N + NO$_2$-N appeared fairly representative of the observed data for the lower catchment (Figure 5(c)), while less accurate simulations were obtained for the upper and middle catchments (Figure 5(a) and 5(b), respectively). This visual assessment was confirmed by the Nash–Sutcliffe values obtained for each respective calibration.
Water quality simulation of all climate change scenarios under the intermediate development scenario

Because of the variable accuracy of model calibrations obtained for water quality, it was decided to present modelled future scenario simulations only for the sites which obtained relatively good model calibrations. These sites were the upper, middle and lower catchments for salinity, the middle catchment for phosphate and the lower catchment for nitrate plus nitrite.

Generally, the seasonal trend evident within simulations of salinity for the upper catchment under future development and climate change were consistently lower than that of the current trend with a relatively narrow uncertainty band (see Figure 6(a)). The seasonal salinity trend evident within the future simulations for the middle catchment showed a slightly broader uncertainty band, and was slightly lower than the current over the wet season, but generally similar to the current over the dry season (Figure 6(b)). The seasonal salinity trend evident within the future simulations for the lower catchment appeared to show relatively less uncertainty and was consistently lower than the current trend over the entire year (Figure 6(c)).

No simulations of PO₄-P were attempted for the upper and lower catchment as the calibrations for these regions were particularly inaccurate (see Figure 4(a) and 4(c)). The seasonal PO₄-P trend evident within the future simulations for the middle catchment showed generally higher concentrations over much of the year except for part of the wet season (Figure 7).

No simulations of NO₃-N + NO₂-N were attempted for the upper and middle catchment as the calibrations for these regions were particularly inaccurate (see Figure 5(a) and 5(b)). For the lower catchment, the seasonal trend evident within future simulations of NO₃-N + NO₂-N showed
relatively high uncertainty, especially over the dry winter months. In general, the future simulations were similar to the current, although there was a slight increase in concentration as compared to the current trend evident over the dry season within the simulations of some GCM scenarios (see Figure 8).

**DISCUSSION**

**Calibration of the WEAP model to historical water quality data**

The simulations obtained for salinity (EC) during the calibration were generally representative of the observed data. Salinity parameters were estimated using the available WWTWs and industrial effluent data (see Table 1). The Amatole System is a naturally saline catchment, and is underlain by marine derived geology, from which approximately 65% of the salt load in the system originates (O’Keefe et al. 1996). These inputs were represented in the model by time series of observed data obtained from gauges on the tributaries of the Buffalo River.

The simulations of PO$_4$-P by the model obtained a good representation of observed data for the middle catchment. The strategy taken within the current study was to calibrate the model simulations of nutrients to the observed data within the middle catchment, as this part of the catchment is most seriously affected by eutrophication. However, a fairly large first-order degradation coefficient was selected to sufficiently remove PO$_4$-P from the river

![Figure 4](https://iwaponline.com/jwcc/article-pdf/7/4/775/373130/jwc0070775.pdf)
The high degradation coefficient indicates that phosphate is rapidly taken out of the middle catchment of the river, possibly because the river is phosphate limited (Wiechers & Heynike 1999). This could be due to various factors, such as uptake by algae and adsorption to inorganic sediment. However, this rapid removal of PO₄-P is evidently not applicable to the upper catchment. Since WEAP applies a common degradation coefficient to the entire modelled catchment, and not to specific parts of the catchment, the model simulations of PO₄-P were severely underestimated in comparison to the observed data for the upper catchment. In general, the upper catchment is much less impacted by nutrients than the middle and lower catchments. Therefore, eutrophication does not occur within the upper catchment, and there is no major uptake of nutrients by algae and macrophytes. In addition, the water temperature within the upper catchment is considerably lower than that in the middle and lower catchment (O’Keefe et al. 1990), resulting in the processes affecting nutrient concentration, such as decomposition and algal growth for example (Chapra 1997), being reduced. These mean that phosphates are
likely taken out of the upper catchment at a lower rate than in the middle and lower catchment.

The relatively stable seasonal PO₄-P trend evident in the observed data for the lower catchment (Figure 4(c)) is likely due to the effects of the Laing Dam upstream of this section. The dam is known to act as a sink for various water quality variables. The simulated seasonal trend generated by the WEAP model (Figure 4(c)) is much more variable than the observed because WEAP does not simulate water quality in reservoirs, and would therefore not register the nutrient sink function of Laing Dam.

The simulations of NO₃-N + NO₂-N by the model generally obtained a good representation of observed data for the lower catchment, whereas simulations for the upper and middle catchment were not as accurate. As in the case for PO₄-P but to a lesser degree, the first-order degradation coefficient used in the model was chosen to obtain as accurate a representation of observed data as possible for the middle and lower catchments, as these are the most impacted regions of the river. This means, as with PO₄-P, that the simulations of NO₃-N + NO₂-N were slightly lower than that of the observed for most of the year. Simulations of
NO\textsubscript{3}-N + NO\textsubscript{2}-N for the middle catchment were additionally not very accurate, with the model overestimating NO\textsubscript{3}-N + NO\textsubscript{2}-N over the dry season in particular. If a higher degradation coefficient had been chosen, then the simulations over the wet season would have fallen below that of the observed. The simulations of NO\textsubscript{3}-N + NO\textsubscript{2}-N for the lower catchment were generally relatively good, both for the seasonal distribution and frequency distribution.

**Water quality simulations for future development and climate change**

The future simulations show consistently lower salinity as compared to the current for the upper catchment. This trend is not as obvious within the middle catchment, except over the wet season. In the lower catchment, the simulations are noticeably and consistently lower than the current. These results appear to indicate that salinity can be expected to decrease under future climate change, most likely due to the increased amount of water in the system, thereby increasing dilution. The difference as compared to the current is most apparent within the lower catchment, probably because Laing Dam acts as a sink, thereby further decreasing the salinity.

The results of future simulation for PO\textsubscript{4}-P in the middle catchment probably reflect a greater human demand for water as extractions and a concurrent increased waste water return flow under the intermediate development scenario. The simulations of future PO\textsubscript{4}-P concentrations are in particular higher than the current over the dry season, when return flows are expected to dominate the total flow in the system, and dilution capacity of the river is at its lowest. The relatively broad uncertainty bands of the future simulations perhaps indicate that flow drivers have a more variable effect on non-conservative water quality variables, as degradation coefficients as well as dilution has to be considered.
The future simulations for NO$_3$-N + NO$_2$-N were generally similar to the current, except for a slight increase indicated over the dry season. As was shown for salinity, both increased flow (and therefore dilution capacity) as well as the sink effects of the upstream dam may act to counteract increased input of NO$_3$-N + NO$_2$-N due to increased development under the intermediate development scenario.

**General trends evident in future water quality due to climate change**

In brief, the water quality simulation results for future climate change and intermediate development appear to indicate a slightly increased dilution capacity within the Buffalo River. This assertion is supported by the simulations of salinity. However, the simulations for the nutrients appear to show that the increased dilution capacity is nullified by the increased inputs of nutrients under the intermediate development scenario. The results of water quality within the lower Buffalo River catchment by WEAP must be viewed with caution, as the WEAP model is not capable of simulating water quality in reservoirs.

**Limitations of WEAP for water quality modelling**

The current study has highlighted the limited utility of WEAP as a water quality decision support system (WQDSS). The built-in water quality procedures of WEAP are much too simplistic, with single first-order degradation coefficients for non-conservative variables being used to simulate the aggregated effects of multiple processes such as decomposition and algal uptake. The model requirement of a single degradation coefficient value for each non-conservative variable to be applied globally across the entire modelled catchment is unrealistic, as rates of processes affecting non-conservative variables tend to change from the upper to lower catchment. While WEAP can communicate with QUAL2 K as a water quality modelling tool, there is a spatial and temporal resolution disconnect between the two models, with WEAP finding utility as a catchment level model that is typically run at a monthly time scale or more, whereas QUAL2 K is typically applied to a short stretch of river at an hourly time scale, and requires a large amount of observed data for calibration. In addition, WEAP cannot simulate water quality in reservoirs. This is a major shortcoming of the model, especially within the current study, as it brings into question the validity of the water quality results within the lower catchment, as an upstream reservoir, namely Laing Dam, is known to have a dramatic effect on water quality.

Although WEAP cannot simulate water quality in as much detail as more sophisticated water quality models, the main utility of WEAP lies in its functionality as a systems model, representing natural and modified flow, and then explicitly linking flows to water quality. As a scenario modelling tool, WEAP can additionally be used to investigate cost scenarios.

During a study in 2012 on climate change adaptation measures for bulk water suppliers in South Africa (Hughes et al. 2014), the identified shortcomings of WEAP as a WQDSS led to the development of a new WQDSS called the Water Quality Systems Assessment Model (WQSAM) (see Slaughter et al. 2012, 2015; Slaughter & Hughes 2014). WQSAM links seamlessly to systems models that are routinely used in South Africa, and it is hoped that WQSAM can provide a more comprehensive water quality modelling facility than WEAP, while maintaining some of the benefits of systems modelling provided by WEAP.

**WEAP as a WQDSS: recommendations for water quality management within the Amatole system**

As previously mentioned, few studies have attempted to quantify the combined effects of future development and climate change in regards to water quantity, and to an even greater extent, water quality. Assaf & Saadeh (2008) used WEAP to develop a decision support system for the upper Litani basin in Lebanon, and focussed on biological oxygen demand within water quality management planning.

Various recommendations for water quality management resulted from the use of WEAP as a WQDSS within the Amatole system (Hughes et al. 2014). These included the extension of water quality variables routinely measured by the governmental water management agency to include chlorophyll and microbial water quality, indicative of concerns over eutrophication and faecal contamination, respectively. In addition, yearly assessments of the vertical profiles of various variables within dams would be useful...
for modelling and management. Importantly, since the management of WWTWs are a major challenge within the region, routine monitoring of effluent return flows could be viewed as a ‘low-hanging fruit’ within attempts to meet environmental and user water quality objectives. Given the high uncertainty associated with model predictions of climate change and development scenarios, a general recommendation of the Hughes et al. (2014) study was that continual monitoring is required, both from a water quantity and quality point of view. Continual monitoring is required to determine which trajectory the state of the water resource is following, so as to facilitate adaptive management.

CONCLUSIONS

The current study has demonstrated that consideration of future climate change and development within water quality simulations is associated with a large degree of uncertainty. From a water resources management perspective, adaptive management alongside continual monitoring is one approach to deal with the uncertainty. The current study has in addition highlighted the limitations of WEAP as a WQDSS. These limitations have motivated for the development of a new WQDSS designed specifically for South African water resource management requirements.

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REFERENCES


