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The development of a Water Quality Systems Assessment Model (WQSAM) and its application to the Buffalo River Catchment, Eastern Cape, South Africa

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Abstract: Water law in South Africa subscribes to the Integrated Water Resources Management (IWRM) paradigm by seeking to provide equitable access of water to all users including the ecosystem. The management of water resources to be in line with IWRM policies is seen to be a major challenge in South Africa due to increasing demands, problematic water quality impacts and concerns over future climate change and development impacts. Because of limited resources within water resources management, simple models may be more useful than complex models (Young et al. 1996). An existing yield model, the Water Resources Modelling Platform (WReMP) is well established within water resource management in South Africa, and this study outlines the development of a Water Quality Systems Assessment Model (WQSAM) that is specifically designed to interface with the water quantity inputs and outputs of WReMP. WQSAM has been designed to give useful predictions of water quality using the available observed data, and uses an approach that is oriented to risk management. WQSAM includes modules for simulating water quality variable inputs from diffuse source and point sources as well as the fate of water quality variables in-stream and within reservoirs. Future developments include the application of WQSAM to the Amatola system in the Eastern Cape, South Africa. WQSAM will include Thresholds of Potential Concern (TPCs), as well as a Decision Support System (DSS) specific to the Amatola system.

Keywords: *Water Quality Systems Assessment Model; Buffalo River, South Africa*.

1 INTRODUCTION

1.1 Water law and IWRM in South Africa

Integrated Water Resources Management (IWRM) is a paradigm that aims to be integrative and holistic, considering the needs of various stakeholders, including the ecosystem (Anderson et al. 2008). Within the context of South Africa, the National Water Act (Act 36 of 1998) was created in order to ensure that scarce and unevenly distributed water resources are managed in a sustainable way for the benefit of all users. In this way, the National Water Act subscribes to the IWRM paradigm.

The IWRM paradigm has received criticism both locally and internationally for not being able to deliver the desired results (Jonker 2007; Garcia 2008; McDonnel 2008). It is possible to implement IWRM at the constitutional and associated strategic and policy levels, as is evident by the creation of the National Water Act in

South Africa. However, there are major obstacles to implementing IWRM at the operational level. Possible reasons for this include lack of resources, such as trained personnel and funding within management agencies. This problem is especially acute within the South African Department of Water Affairs (DWA). The conceptual basis for IWRM, especially within the context of management of local water resources, and what this means for implementation, is something that must be clearly defined before managers can embrace IWRM. One major obstacle to implementing IWRM is the lack of both water quantity and quality data, and this has implications for the availability of models that can give reliable management predictions. This problem is particularly pertinent to South Africa, although it is also applicable globally. Within South Africa, while there are daily observed flow data available for main river stems, flow data are often not available for tributaries. Corresponding water quality data are scarce in comparison, and are collected on a temporal scale ranging from twice-weekly to once every few years.

1.2 The Pitman, WReMP and WQSAM models

Within the context of water resource management in South Africa, simpler models that are easier to understand, and that can give accurate model predictions using the available observed data, may be more appropriate than complex models. The definition of 'accurate' will be largely determined by specific management issues that put different demands on the accuracy of model results. Most management decisions in South Africa would be concerned with identifying situations where certain thresholds of potential concern (TPCs) for flow or water quality are exceeded, and not with identifying specific values for flow or water quality at any particular time.

The Pitman model is monthly time step rainfall-runoff model, first developed in the 1970s (Pitman 1973). The model conceptualises the natural water balance of river basins, and incorporates parameters to control these model processes (Hughes et al. 2010). The output of the Pitman model with revised surface – ground water routines (Hughes 2004) includes simulations of surface runoff depth, interflow runoff depth, ground water volume, upstream inflow volume, direct abstractions, pool volume, abstractions from dam volume, and downstream flow volume.

The yield model that was used in this study is called the Water Resources Modelling Platform (WReMP) (Mallory et al. 2011). WReMP accepts incremental flow from the sub-catchments, typically generated by the Pitman model, and models the user extractions, return flows and reservoir yields along the modelled system.

Both the WReMP model and the Pitman model are similar in that they perform a water mass-balance. However, while the Pitman model simulates natural flow, the WReMP model adds another level of modelling by incorporating human demands.

The development of the Water Quality Systems Assessment Model (WQSAM) stems from a Water Research Commission (WRC) project entitled 'Developing climate change adaptation measures and decision-support system for selected South African water boards'. A case study catchment within this project was the Amatola region in the Eastern Cape, South Africa.

A water accounting model called WEAP (SEI 2001) was initially investigated but was found to be inadequate. After discussion with management at a water board workshop (Amatola Water Board, East London, South Africa 2011), it was felt that the WEAP model is limited, too complicated, and there would be limited acceptability of the model from water resource managers. In addition, WEAP does not simulate water quality within impoundments.

An existing water quality model called the Impoundment Management and Planning Assessment Model (IMPAQ) (DWA 1998) that was developed in the

1990s was identified. However, many shortcomings within the IMPAQ model were identified, the most important being: 1. no indication of uncertainty; 2. A more rigorous method of patching missing water quality data was identified; 3. IMPAQ works on a monthly time scale, however, a model that works on a daily time scale is required to simulate non-conservative variables; 4. IMPAQ does not simulate nitrogen species which are important water quality variables affecting eutrophication.

It was therefore decided that the Water Quality Systems Assessment Model (WQSAM) would be developed, building on the work done in IMPAQ, but focussing on model outcomes that are more pertinent to management of South African water resources, such as the identification of periods of TPCs. A decision support system will also be built into WQSAM, where TPCs will be incorporated, and management responses suggested by the model.

1.3 Aims and scope

This paper aims to outline the modular structure of WQSAM. WQSAM's relationship with the WReMP model will also be discussed. At this stage, the model development has not reached completion hence model simulation results are not yet available for presentation.

2 MODEL STRUCTURE

2.1 WQSAMs relationship with the WReMP model

WQSAM accepts monthly flow data output from the WReMP model. The WReMP model is essentially a water accounting model that assigns natural flow to users, and simulates return flows back to the river, and is especially relevant for simulating the yield of reservoirs, and exploring possible user restrictions during limiting flow. The representation of the system by WQSAM is very much dependant on that of the WReMP model. The WReMP model conceptually represents the modelled system by means of nodes, which are connected by inflow and outflow channels.

The WQSAM model is dependent on the model structure of WReMP. Some consideration therefore has to be given within the model structure of WReMP if output of the WReMP model is to be used within WQSAM.

The WQSAM model structure mirrors that of WReMP and therefore, the WQSAM model setup for any region will use the same nodal and channel setup as the corresponding WReMP model. Important differences between the two models relate to WQSAM's functionality as a water quality model and decision support system.

2.2 The modular structure of WQSAM

A decision was taken during the development of the WQSAM model, that the model would take a modular structure. This is to facilitate easier maintenance and updates of sections of the model, and also to allow different functionalities within the model to be used in isolation, or imported to other applications.

2.2.1 Disaggregation of monthly to daily simulated flow

While WReMP works on a monthly time scale, a decision was made to operate WQSAM on a daily time scale. This is to facilitate the in-stream fate processes of non-conservative water quality variables such as nutrients, and also to take into account the effect of transient events on water quality, such as short but intense rainfall events. A method of disaggregating daily simulated flow from monthly simulated flow exists, and will be adapted to take a modular form within WQSAM.

2.2.2 Disaggregation of flow into surface, interflow and groundwater flow

Natural flow within a river can originate from surface runoff, interflow and groundwater flow. These different flow components may contain varying water quality signatures. For example, ground water flow may have a higher salinity signal, depending on the geology of the catchment, and surface runoff may have varying water quality signals, depending on the land use/cover composition of the catchment. The WReMP model does not attempt to break total flow down into flow components. Therefore, a baseflow disaggregation method (Hughes et al. 2003) will be used to achieve an estimate of the individual flow components.

2.2.3 Routing of water quality loads between nodes and simulation of instream processes

The WQSAM model representation of the modelled catchment consists of nodes and channels. Processes affecting water quality are simulated within the nodes. Some nodes will be flagged as receiving diffuse sources of nutrients or salts, if these nodes represent regions in the modelled catchment where agricultural land or urban land is situated. Some nodes will also simulate return flows from industry or WWTWs. Reservoirs are a particular type of node that contains specialized water quality simulation processes. Nodes are connected by channels. Channels have an attribute indicating the channel length. In-stream processes are implemented within the channels, such as the chemical processes affecting nitrogen, sedimentation of nutrients and uptake of nutrients by flora and evaporation. The instream processes depend on the travel time of water within the channel. Instream processes simulated in the channels include ammonification and nitrification (Chapra 1997) by using first order reaction equations. The travel time of non-conservative water quality variables within the channels affect the fate of these variables. Travel time is calculated using the Manning Equation (Chapra 1997). The model calculates the Manning's Roughness and reach depth for each non-zero flow using a simple iterative method. This is to estimate average flow velocity given flow.

The loads of water quality variables are routed from upstream nodes to downstream nodes along the shared channels. A sequential process of stepping through all the nodes in the system, from upstream to downstream is done within each time step.

2.2.4 Simulation of diffuse and point sources of water quality variables

Slaughter (2012) developed a simple nutrient model that attempts to model the relationship of nutrient concentration with flow. Historical monitoring daily flow and available nutrient concentration data (NO_2 + NO_3 and PO_4) from DWA gauging sites were analysed for relationships. It has been noticed in the literature, that nutrients from diffuse sources have a relationship of increasing concentrations with increasing flow, while those derived from point sources, have a decreasing concentration with increasing flow (Bowes et al. 2008). Nutrients derived from diffuse sources are mobilized by runoff from the catchment and therefore increase instream with increasing flow (Hughes and van Ginkel 1994), while nutrients derived from fairly constant point source effluent flow are diluted by increasing insteam natural flow.

The point source model attempts to mirror the scatter of observed nutrient data points in relation to flow at low flows. The model generates two uniformly distributed random numbers to achieve this scatter. This is justified by the assumption that WWTWs effluent has the properties of effluent flow and nutrient concentration that vary greatly over time and independently. The model generates an envelope curve that indicates the maximum expected instream – nutrient concentration originating from point sources for any given flow. Figure 1 is an example for data obtained from a flow and water quality gauging station showing a distinct point and diffuse source signature.

The diffuse source component of the model is statistical, and attempts to fit a curve to the residual ratios (observed nutrient concentration / point source envelope curve). Essentially, the model attempts to fit a regression equation to the residual ratios and estimate 90% prediction limits to represent the uncertainty in the diffuse part of the model. An example is given in Figure 1.

2.2.5 Simulation of reservoirs

Modelling of water quality within impoundments can be complicated as processes operating in the vertical direction in addition to the longitudinal and horizontal direction have to be considered, such as movement of toxicants from the sediment to the water column, distinct boundaries within the water column delineated by differences in temperature and salinity, and anoxia at deeper levels within a reservoir.

Impoundment models such as CE_QUAL-W2 have already been investigated within South Africa (DWA 1997; DWA 1998) and a simple reservoir module is being developed for incorporation in WQSAM which is modelled on the most important processes affecting water quality identified within reservoirs. This simplified reservoir model will be a mixing model with the total load of a water quality variable being the sum of three components: 1. in the Water Column; 2. stored in the biota (phytoplankton and macrophytes for example); 3. stored in the sediment.

Processes highlighted for inclusion include the effect of macrophytes such as Water Hyacinth and turbidity on water quality. Specific effects of climate change such as potential changes to dominant algal species will also be investigated.

2.3 TPCs and the DSS

It is envisaged that WQSAM will incorporate Thresholds of Potential Concern (TPCs) as well as a decision support system (DSS) outlining management options to deal with scenarios where thresholds are exceeded. The thresholds values are guided in majority by ecological water quality and flow requirements, as well as the present state of the modelled system.

3 CASE STUDY

WQSAM will be applied to the Amatola system, consisting of the Nahoon and Buffalo Rivers, as well as a transfer scheme from the Wriggleswade Dam on the Kubusi River, into both the Buffalo and Nahoon Rivers (see Figure 2).

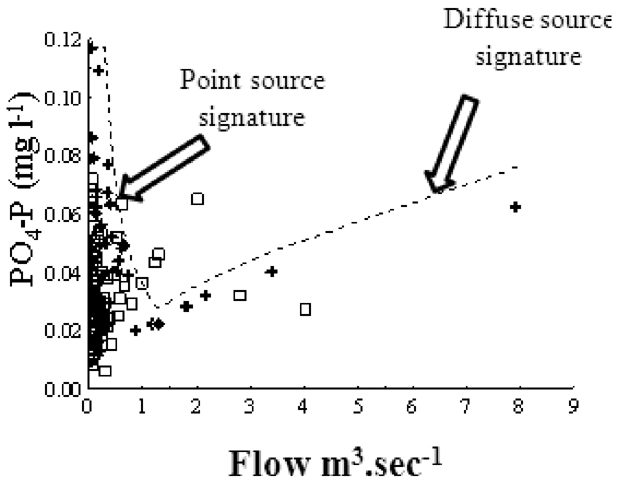

Figure 1. Point and diffuse source model applied to historical monitoring data from a DWA gauging site.

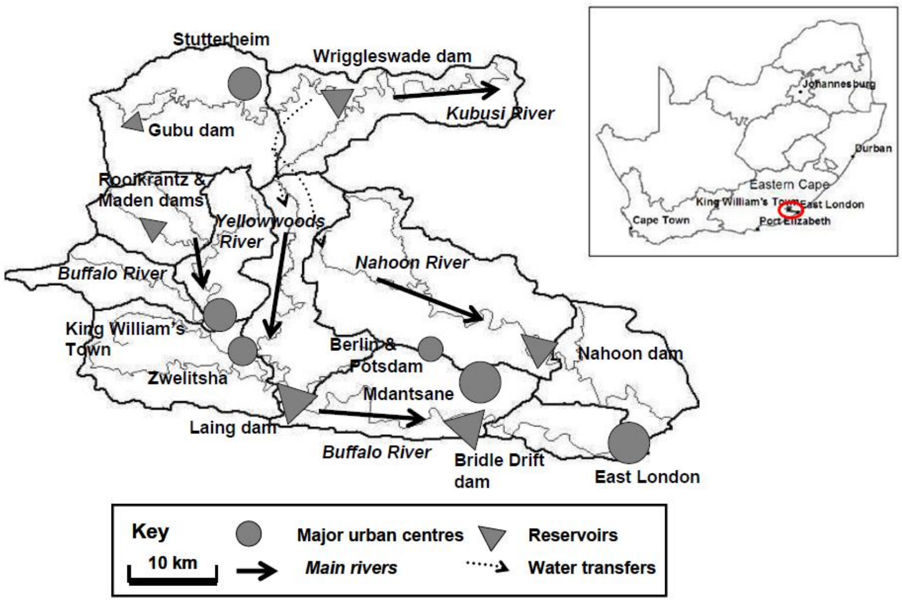

Figure 2. Map of the Amatola system in the Eastern Cape, South Africa

The Buffalo River is a short river (125 km) originating in the forested Amatole Mountains and running in a south easterly direction to the sea (O'Keefe at al. 1996).

In total, there are four relatively major dams within the Amatola system. These are the Rooikrantz Dam in the upper reaches of the Buffalo River, the Laing and Bridle Drift Dams on the middle and lower reaches of the Buffalo River, and the Nahoon Dam on the Nahoon River. Generally, water quality in the upper reaches of the Amatola system is fairly good, with some small impacts by rural communities and agriculture. Water quality degenerates within the middle reaches with the influence of various industries and waste water treatment works (WWTWs) releasing effluent into the river. Laing Dam and Bridle Drift Dam experience water quality problems such as eutrophication, faecal bacteria contamination and toxic metal contamination. The rivers in this region tend to be relatively salty because of the influence of marine sedimentary rocks within the catchment.

4 DISCUSSION

WQSAM has been designed in a way to attempt to resolve management challenges in water resource management. Management of water resources in South Africa is limited by resources. The design of WQSAM has taken these limitations into account as much as is possible. The model's simplicity and ability to provide useful model simulations from a management perspective, using the available historical flow and water quality monitoring data, is one such context specific consideration. WQSAM in addition incorporates uncertainty, which is essential for providing managers with an indication of risk associated with management decisions.

The inclusion of non-conservative water quality variables into the WQSAM model simulation necessitated a daily model operated time step.

The design of WQSAM took a modular format with relatively separate development of several model modules, including the monthly – daily flow disaggregation module, the in-stream fate module, the point and diffuse source modules, the baseflow separation module and the reservoir module. The modular design used facilitates easier maintenance and updating of the modules, and facilitates re-use of the modules within other applications.

5 CONCLUSIONS AND RECOMMENDATIONS

Within the context of water resource management in South Africa, the development of a model such as WQSAM is perhaps a foregone conclusion, as there is currently a great management need for such a model. This paper presents the initial development of a Water Quality Systems Assessment Model WQSAM. The value of the model in addressing many of the current water resource management shortcomings in South Africa is presented. While many of the model components are at an advanced stage of completion, the reservoir module is still at a conceptual stage, and will present some challenges.

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