MODELLING THE HYDROLOGY AND NITROGEN ASSIMILATION OF THE WAKKERSTROOM VLEI WETLAND

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted in partial fulfilment of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(Justin Walls)

20th day of October 2020 at Johannesburg

ABSTRACT

This research report presents the flow modelling of water through a wetland utilising the Australian Water Balance Model (AWBM) within Goldsim and PCSWMM. The modelling was undertaken to understand the hydrological routing and removal of nitrogen in order to potentially use this understanding to inform passive water treatment systems and emphasise one of the most valuable wetland functions, namely their ability to treat water. The AWBM and PCSWMM results both predicted flow peaks at the correct frequency when compared to observed flow data, however the peaks of the AWBM were generally of a lower amplitude than the observed data. The amplitude of the PCSWMM simulated graph peaks mimic the observed data very well. Due to the better correlation compared to PCSWMM, it is recommended to utilise the AWBM to inform water management at the Wakkerstroom Vlei, although some additional calibration would be required.

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LIST OF ACRONYMS

APES:	School of Animal, Plant and Environmental Sciences
AWBM:	Australian Water Balance Model
CHI:	Computational Hydraulics International
CTM:	Contaminant Transport Module
DEM:	Digital elevation model
DRDEU:	Daily Rainfall Data Extraction Utility
DWS:	Department of Water and Sanitation (now: Department of Human Settlements, Water and Sanitation)
NWA:	The National Water Act, 1998 (Act 36 of 1998)
PCSWMM:	Personal Computer Storm Water Management Model
RMSE:	Root mean square error
RO:	Research objective
SAWS:	South African Weather Service
SRTC:	Sensitivity-based Radio Tuning Calibration
SWMM:	Storm Water Management Model
US EPA:	United States Environmental Protection Agency
WWTP:	Wastewater treatment plant

LIST OF SYMBOLS

A1:	Partial area 1
A2:	Partial area 2
A3:	Partial area 3
BFI:	Base flow index
BS:	Quantity of water in the base flow store
C1:	Surface storage capacities 1 (corresponding to partial area 1)
C2:	Surface storage capacities 2 (corresponding to partial area 2)
C3:	Surface storage capacities 3 (corresponding to partial area 3)
Cd:	Discharge coefficient
E:	Evaporation
K_b:	Base flow recession constant
K_s:	Surface flow recession constant
N	Number of values
P:	Precipitation
$Q_{baseflow}$:	Discharge from the base flow attenuation store
Q_m	Measured spill rate
Q_p	Predicted spill rate
$Q_{surface}$:	Discharge from the surface attenuation store
R^2:	Correlation coefficient
SS:	Quantity of water in the surface store

1 INTRODUCTION

Wetlands are immensely valuable ecosystem components as they provide a number of services, including recharge of the groundwater table, flood attenuation (Acreman and Holden, 2013), habitats for fauna and flora and passive water treatment, in addition to aesthetic, recreational and educational benefits (Tsihrintzis et al., 1998). In order to prevent the mismanagement of wetlands, we need to understand them (Gopal, 1991). As hydrology is considered to be one of the most influential factors affecting wetland ecosystems (Low et al., 2016; Tsihrintzis et al., 1998; Wen et al., 2013), being able to hydrologically model flow through a wetland is a step towards understanding them.

The School of Animal, Plant and Environmental Sciences (APES) at the University of the Witwatersrand has been investigating the limits to the capacity of the Wakkerstroom Vlei in Mpumalanga, South Africa, to absorb and sequester nitrogen and phosphorus, and detoxify Escherichia coli, resulting from inputs of municipal sewage. These investigations have been ongoing since 2016 and have considered the annual water balance of the Vlei. The Wakkerstroom Vlei is part of the Wakkerstroom Wetland Nature Reserve and Joubert & Ellery (2013) state the importance of this Vlei by highlighting that it is invaluable to the immediate and downstream water users. This research therefore modelled both the hydrological and biochemical components of the Wakkerstroom Vlei specifically. This will help to inform future research and monitoring of the Vlei.

1.1 Wetlands

The Ramsar Convention on Wetlands (Ramsar, 1971) defines wetlands as “areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres.” The National Water Act (NWA) (The National Water Act (Act No. 36 of 1998), 1998) defines a wetland as “land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil". While the Ramsar definition is widely accepted throughout most of international community, the Department of Water and Sanitation (DWS) has declined to use the Ramsar definition because "the NWA caters for the characteristics of a watercourse (water quantity, biota and habitat at least) and is more practical and suitable to use in local conditions" (Department of Water and Sanitation, 2017).

The DWS have explicitly stressed that wetlands are "of national importance" as a direct result of the invaluable services they provide. However, wetlands are being degraded at unsustainable rates with several studies (Clilverd et al., 2016; Davidson, 2014; UNWWAP, 2003) reporting that more than half of the global wetland area has been lost since 1900 and corresponding concerning terms such as 'precarious' (Price et al., 2018), 'fragile' (Shanbhag and Borges, 2008; Tooth et al., 2002), 'disrupted' (Clilverd et al., 2016) and 'threatened' (Verones et al., 2013) are often used to describe their states. Bullock & Acreman (2003) assert that the management of wetlands must play a meaningful role in the integrated water resources and flood management of all river basins due to their strong influence on the hydrological cycle.

In order to manage wetlands effectively, it is necessary to first understand them because alterations to the hydrology of the watershed can substantially impact the wetlands within the catchment area and their valuable functions (Acreman and Miller, 2006). Hydrology is believed to be one of the most important factors influencing wetland ecosystems (Low et al., 2016; Tsihrintzis et al., 1998; Wen et al., 2013) with a direct impact on their physical, chemical and biological components (Arega, 2013). Furthermore, the flow rate through water courses is the single biggest factor influencing nutrient retention (Saunders and Kalff, 2001). To better understand wetlands, hydrological models are required to assess the hydrological fluctuations to consider the influences of water management policies (Wen et al., 2013).

Wetlands are able to act as sinks for numerous components, including pollution, heavy metals and nutrients (Khan and Shah, 2010), with wetlands able to retain more nitrogen than lakes or rivers (Saunders and Kalff, 2001). Nutrient imbalances can decrease ecosystem productivity (Galloway et al., 2004) or reduce biodiversity through eutrophication (Baldwin et al., 2001) and/ or acidification (Kelly et al., 1990). The selected biochemical parameter of interest for this research study is nitrogen because nitrogen is a known plant nutrient (Galloway et al., 2004) and the isotope 15N can be measured in the plants as it progresses through the wetland. Nitrogen is a common water pollutant and frequently a contaminant of concern due to its potential ability to detrimentally affect natural water systems (Lee et al., 2009) which results in the need to invest large amounts of money and resources to remove the pollutant.

1.2 Specific Objectives

The research proposed to model the Wakkerstroom wetland to understand its flow and nitrogen removal characteristics in order to understand one of the most valuable wetland functions, namely their ability to treat water. This understanding also assists with the management of the water resources of the Wakkerstroom Vlei.

The research pursued three research objectives (ROs) as described below.

1.2.1 Research Objective 1: Hydrological modelling of the Zaaihoek Dam catchment

This first RO was to hydrologically model the catchment of the Zaaihoek Dam.

1.2.2 Research Objective 2: Hydrological modelling of the Wakkerstroom Vlei

This research sought to inform the work undertaken by the APES by hydrologically modelling the retention time of the Wakkerstroom Vlei. This RO utilised the results of the modelling of the Zaaihoek Dam catchment (first RO).

1.2.3 Research Objective 3: Biochemical modelling of nitrogen through the Vlei

The intention was to create a quantitative biochemical model for nitrogen removal/ assimilation by building on the hydrological model developed as part of the second RO. However, it was necessary to make a number of simplifying assumptions to allow a qualitative model to be developed.

1.3 Limits of research

This research models the hydrological behaviour of the Wakkerstroom Vlei by using the available inflow, climate, landscape and reservoir data in order to predict the outflow rates. The biochemical model is driven by the outputs from the hydrological model. The modelling methods employed in this research are focussed on the site specific conditions and inputs, and the results are similarly site specific.

The confining dolerite dykes help to ‘confine’ the wetland boundary which simplifies the modelling process. This simplification is expected to further reinforce the likelihood that the model results are site specific.

As the only available flow data exists at the Zaaihoek Dam outlet, the hydrology of the Zaaihoek Dam catchment had to be modelled in order to enable the modelling of its sub-catchment – the Wakkerstroom Vlei catchment.

The modelling of the flow of nitrogen is based on data obtained from an APES research project (Sanderson, 2018) which unfortunately did not have the characteristics of frequent sampling. It is believed that the results obtained from the biochemical modelling component are unlikely to be suitable for use at other sites due to the nature of the water quality sampling frequency and site specific hydrological modelling.

1.4 Summary of unresolved issues

There are multiple models available which can be used to hydrologically model flows through wetlands, with no single approach appearing to be dominant. Furthermore, there are a great number of approaches for coupling other analyses with the hydrological models.

While all found studies state that they achieved a good degree of accuracy for their model, some claim that their models can be generalised to similar sites (Tsihrintzis et al., 1998; Wester et al., 2018) with one even stating that their model could be applied to other wetlands with minimal available empirical data (Mansell et al., 2000). Developing such a model, which can be applied across different wetlands, would allow it to be widely utilised for different scenarios at a variety of wetland assessments and comparative analyses.

Although such a goal may be unachievable because of the large number of variables which exist across different wetland systems, it is however one that modellers aspire to in order to avoid having to switch between different models that require lots of site specific input data. This research intended to create a model which could be extended upon in the future to become such a generic model.

A number of studies made use of certain input parameters, such as physical site specific or climatological parameters, from literature which leads to recommendations for future work to examine these parameters more closely (von Christierson et al., 2015; Li, Zhang, et al., 2015). There is limited literature that addresses the modelling of biochemical processes through wetlands in comparison to the documented literature research on wetland hydrological modelling. This contrast supports this research report because its results are expected to add to this field of knowledge.

The fact that nitrogen is a nutrient opens future opportunities to explore how nature manages nitrogen. Therefore, modelling nitrogen through the wetland is important to understand how these natural nitrogen processes could be enhanced or utilised elsewhere in the treatment of contaminated water. The Wakkerstroom Vlei has proven to be very effective at naturally removing nitrogen as the water flows through the wetland (Sanderson, 2018). Nature may therefore have more efficient and cost-effective ways in which to breakdown and/ or transform nitrogen than traditional industrial methods. This could be extremely useful for companies to save money and minimise environmental impacts as well as developing solutions to ensure receiving environments are not contaminated. It is therefore important to model the flow to understand the relationship between flow rates and the corresponding treatment efficiencies, as well as which plants (individually or jointly) allow this nitrogen management to be successful in order to be emulated elsewhere (Saunders and Kalff, 2001).

While examples of hydrological modelling of wetlands in literature are not uncommon, the modelling has hardly been conclusive except that adequate data for calibration allows most models to achieve a satisfactory level of accuracy, as can be seen in the following chapters.

2 LITERATURE REVIEW

2.1 Hydrology

Water is one of earths most precious resources and is central to many naturally occurring processes. In order to manage this valuable resource and help solve water problems, hydrology has evolved into an extremely important field of study (Bales, 2015). Chow et al., (1988) described the importance of hydrology to humans and the environment, due to its many practical uses such as; water supply, wastewater, pollution reduction, design and operation of hydraulic structure, erosion control, flood control and irrigation (Jajarmizadeh et al., 2012).

Hydrology is the study of the water cycle (Chow et al., 1988) as well as the biological, chemical and physical processes of water within this cycle, including all phases (solid, liquid and gas) of water (Marshall, 2013). Hydrology focusses on the occurrence, distribution and movement of water in nature, the interactions with earth materials and the biological processes and human activities that affect water movement, distribution and quality (Dingman, 2015; Şen, 2015). More specifically, hydrology deals with the occurrence, management, control and prediction of rainfall, drought, floods, runoff and groundwater (Şen, 2015). Engineering applies hydrology in the form of laws, calculations, and modelling in order to provide better management and control over the natural resource of water (Şen, 2015). This application can be utilised for many water sources, one of which are wetlands.

2.1.1 Wetland hydrology

Wetland hydrology is the driving force that creates and maintains wetlands and changes can affect plant composition, wildlife and wetland functions (Brown et al., 2009; Tiner, 2009) Fennessy et al., (2004) stated that the most important variable of wetland ecosystems is hydrology because it drives the formation of wetland soils and therefore the development of the biotic communities. Wetlands are created and maintained by sustained soil saturation. Fauna, flora and wetland function are affected by changes in topography, climate and other hydrological conditions (Tiner, 2009). Wetlands have long since been identified as important natural resources because they provide a large range of important services that includes water purification (Scholz and Lee, 2005;Golden et al., 2014).

Wetland hydrology is of key importance from both an ecological and engineering perspective as it describes a wetland’s specific productivity, species diversity and nutrient cycling. Scholz and Lee (2005) state the importance of understanding hydrological conditions to enable the best utilisation of wetlands for removing pollutants from the water. Technological advancement within the field of hydrology has allowed numerical and statistical calculations, and modelling to be utilised within this field (Jajarmizadeh et al., 2012).

2.2 Wetland systems modelled

A model is an approximation of a real world system, while a good model is one which is able to provide appropriately accurate results with the least complexity (Moradkhani and Sorooshian, 2009). As discussed above, hydrology is the main driver for the wetland ecosystems, and a number of examples exist in the literature where freshwater (von Christierson et al., 2015; Clilverd et al., 2016; Li, Zhang, et al., 2015; Mansell et al., 2000; Tsihrintzis et al., 1998) and tidal (Arega, 2013; Trivisonno et al., 2013; Wester et al., 2018) wetlands have been modelled.

A number of studies exist where the flow of nitrogen has been modelled through wetlands to better understand their ability to clean or polish water (Van Dam et al., 2007; Griffiths and Mitsch, 2017; Kazezyilmaz-Alhan et al., 2007), to inform policy makers (Kansiime et al., 2007) and to support water management strategies (Mayo and Bigambo, 2005).

Various research projects have made use of coupled analyses to model hydrological and other aspects such as particle transport (Arega, 2013), sediment fluxes (Kiesel et al., 2013), dissolved oxygen concentrations (Cheng et al., 2012), biogeochemical processes (von Christierson et al., 2015; Shi et al., 2018) or hydraulics (Clilverd et al., 2016; Tsihrintzis et al., 1998; Wester et al., 2018).

The various models also utilise differing numbers of dimensions to suit their needs, for example, one-dimensional (Cheng et al., 2012), two-dimensional (Arega, 2013; Clilverd et al., 2016; Li, Zhang, et al., 2015; Mansell et al., 2000; Trivisonno et al., 2013; Tsihrintzis et al., 1998), quasi-two-dimensional (Wester et al., 2018) or three-dimensional (von Christierson et al., 2015). Some of the models listed here are applicable in two- or three-dimensional space, such as the MIKE suite. With respect to model complexity, the number of dimensions does not necessarily determine the accuracy of the model outputs, but rather the suitability of the number of dimensions for the specific application.

2.3 Existing models

A number of models were found in the literature for hydrological modelling of wetlands and these include, amongst others, WETLANDS (Mansell et al., 2000), CTSS8 (Trivisonno et al., 2013; Wester et al., 2018) Link-node SWMM-EXTRAN (Tsihrintzis et al., 1998), the Personal Computer Storm Water Management Model (PCSWMM) (Charbonneau and Bradford, 2016), Flux-PIHM-BGC (Shi et al., 2018), HEC-RAS (Cheng et al., 2012), the MIKE suite of models (von Christierson et al., 2015; Clilverd et al., 2016; Li, Zhang, et al., 2015) and Goldsim (Ind, 2014).

Flux-PIHM-BGC (Shi et al., 2018) and the MIKE software suite (von Christierson et al., 2015) are both distributed models capable of undertaking coupled hydrological and biogeochemical modelling, although no literature could be found on Flux-PIHM-BGC having been used for modelling wetland flows and cycles. Goldsim (Strand et al., 2010; Vandenberg, J and Lauzon, N and Prakash, S and Salzsauler, 2011) and PCSWMM (Perrelli and Irvine, 2013) can similarly undertake coupled analyses as the user is only limited by his or her abilities to mathematically describe the processes. Goldsim is a graphical simulation software programme which was developed to undertake steady, dynamic and probabilistic modelling and can conceptually be thought of as a “visual spreadsheet” (Goldsim, 2018). PCSWMM is a GIS-based Graphical User Interface software programme which is driven by the US EPA SWMM5 engine (https://support.chiwater.com/77618/why-choose-pcswmm).

A number of model types exist for estimating runoff with varying emphasis on underlying physical mechanisms, mathematical modelling approaches and input data intensity requirements (Li, Lambert, et al., 2015). Rainfall-runoff modelling using rainfall and evaporation typically falls into one of three groups, namely, physically based, black box or conceptual (Beven, 2006). Physically based models are built on the underlying system principles and consequently very complex processes (Li, Lambert, et al., 2015), while black box models have the advantage of generally being efficient in data processing but are often restrictive as they do not take cognisance of these underlying physical mechanisms (Li, Lambert, et al., 2015). Conceptually based models fall between the physically based and black box models in terms of computational efficiency, data requirements and transparency (Li, Lambert, et al., 2015).

The Australian Water Balance Model (AWBM) is a conceptual rainfall runoff model which considers runoff from the perspective of accounting for all water entering, leaving and being stored in a system (Boughton, 2010).

Mansell *et al.* (2000) utilised a model known as WETLANDS to successfully hydrologically model a 0.4 km^2 wetland system. The model only required a few inputs and was able to fairly accurately predict the groundwater table elevations. Three years of data was used for the model calibration. The authors concluded that the model can be used as a predictive wetland hydrological model for sites which only have limited empirical data as simplifying assumptions can be incorporated.

An extremely large lake wetland catchment system of 1.62 x10^5 km^2 in China was hydrodynamically modelled (Li, Zhang, et al., 2015) using MIKE 21 to understand the residence times of the various flow components and the corresponding biochemical processes. This study made use of observed water levels, flow rates, the surface area of the lake and dye tracers to calibrate the modelling. Nine years of water level and flow data were available for this calibration. While the study successfully validated the model with a resulting correlation R^2 coefficient of between 0.79 and 0.84, it is believed that the developed model is site specific but useful for understanding the local water environment and aiding decision makers.

A study was undertaken for a 1.42 km^2 wetland system in the context of flood detention design and rehabilitation by Tsihrintzis et al. (1998). Hydrology was highlighted as the most influential factor informing wetland design and hence accurate models are required to reduce the possibility of failed designs. The SWMM-EXTAN model was utilised and calibrated using observed flow rates and water levels, with the Manning's roughness coefficient used as the calibration variable. This dynamic flow routing model is built upon the United States Environmental Protection Agency (US EPA) Storm Water Management Model (SWMM). The correlation R^2 coefficient was high (0.93) for the predicted hydrograph and the predicted water elevation in the one flow path (0.85), but poorer for another flow path (0.12). Generally, the pre-project maximum predicted conditions and observed water elevations compared better than the project predicted conditions and observed water elevations. One reason for the poorer correlation was attributed to the less frequent sampling of observed flow rates and water elevations (every three to five days over a six month period) in comparison to the modelled daily time step. It is believed that the modelling approach can be applied to other projects with the inclusion of appropriate site specific model parameters.

A project in Denmark examined a rehabilitated wetland in the context of surface-, groundwater and nitrate processes (von Christierson et al., 2015). The study highlighted the importance of wetlands in reducing nutrient loads, amongst other benefits. A "detailed eco-hydrological" model was developed to investigate the nitrate dynamics, with the calibration undertaken using observed water levels and flow rates. The researchers made use of a coupled ECO Lab/ MIKE SHE model. Reasonable calibration of the groundwater levels was obtained with the predicted levels underestimating the groundwater levels by 10 to 15cm. The area of the catchment was 254 km^2. Approximately a year's worth of data was used for calibration, but not all data were measured at the same frequency interval.

The researchers state that further work will be undertaken to determine the model's suitability for modelling larger scale catchments.

Another study utilising a coupled MIKE 11/ MIKE SHE model for freshwater wetlands was undertaken by Clilverd *et al.* (2016) for a 115 km^2 catchment. This research made use of 13 months of data of the groundwater levels for the calibration of the model, followed by 12 months of data for the validation process. The Root Mean Square Error (RMSE) approach was used to minimise the difference between the observed and predicted levels and the Nash-Sutcliffe efficiency was utilised when assessing the goodness of fit between them. This modelling was able to realise a very good correlation between the observed and predicted levels. It was unclear whether the authors believed the model could be applied to other wetland systems.

2.4 Biochemical

Nitrogen is a nutrient that plays a significant role in the eutrophication of surface waters (Moffat, 1998). Wetlands have been found to be the most efficient nitrogen remover when compared to other freshwater systems (Saunders and Kalff, 2001). Nitrogen exists in several forms in wetland systems with the main means of removal from the system being through denitrification, sedimentation and plant uptake (Saunders and Kalff, 2001). A brief summary of the various nitrogen flows and processes in wetlands is presented in **Error! Reference source not found.**.

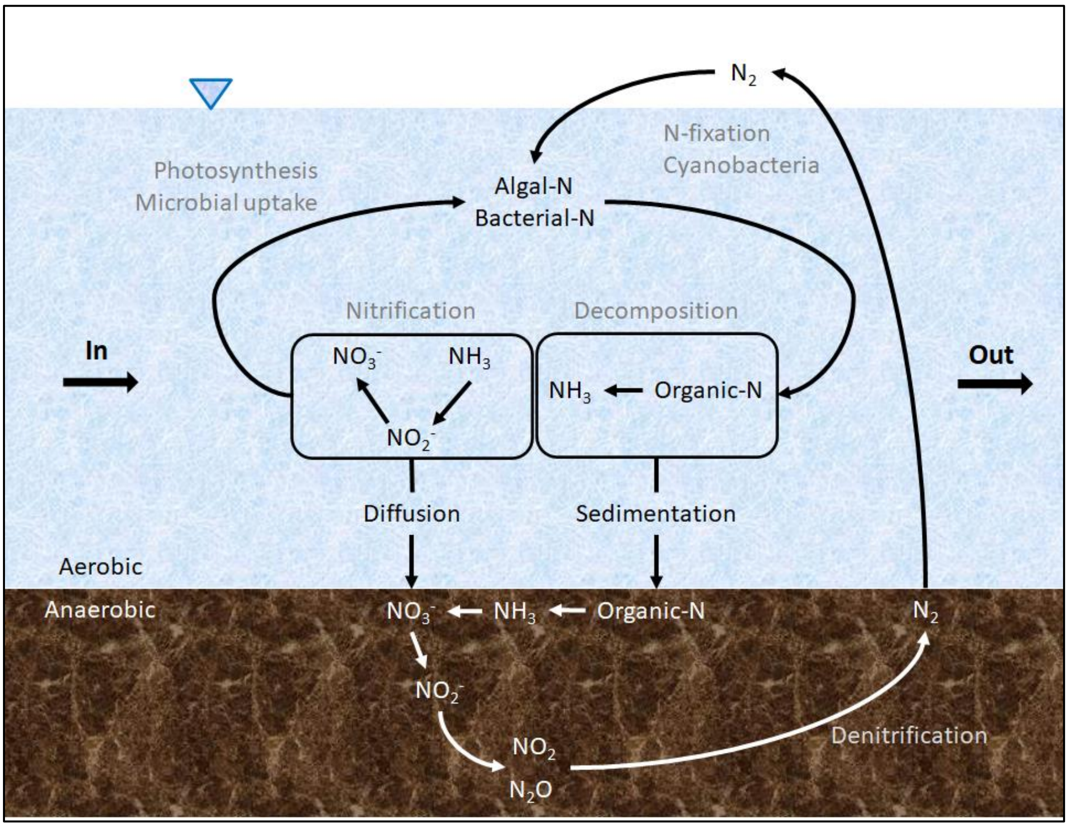


Figure 2.1 Nitrogen cycle in wetlands (Adapted from Baldwin et al. (2001))

The rate at which nutrients, specifically nitrogen and phosphorous, are taken up in wetlands is influenced by seasonal changes in vegetation (Khan and Shah, 2010). A study looking at the ability of wetlands to reduce nutrient concentrations in agricultural water by Woltemade (2000) indicated that wetlands have the ability to remove almost 70% of nitrate nitrogen. The retention time of wetlands was concluded to be the most influential factor accounting for the wetland’s removal effectiveness.

The coupled hydrological and biochemical modelling undertaken by von Christierson *et al.* (2015) included the main nitrogen removal processes prevalent in riparian wetlands, namely, nitrification, denitrification, plant uptake and processes, adsorption and mineralisation.

Kazezyilmaz-Alhan et al. (2007) used SWMM to model the hydrological process and WETSAND to model the solute transport dynamics. This modelling allowed for the surface and groundwater interactions and concluded that these interactions significantly influence wetland dynamics and should consequently be considered when modelling wetlands.

The removal of nitrogen has also been modelled using logistic equations (Van Dam et al., 2007) and built into the model with four sequential stages or vertical layers, namely papyrus mat, water, sludge and sediment. This model was calibrated using measured data from a wetland which receives effluent from a WWTP, much like the situation in the Wakkerstroom Vlei, and the resulting simulated results were found to be realistic.

2.5 Wakkerstroom Vlei

Wakkerstroom is a small town in Mpumalanga approximately 28km due east of the town of Volksrust and just north of the KwaZulu Natal border. The town is on the South African Highveld and experiences warm, wet summers and cold, dry winters. The Wakkerstroom Vlei, which will be the wetland utilised for this research, is part of the Wakkerstroom Wetland Nature Reserve, that lies northwest of the town of Wakkerstroom, refer to Figure 2.2. The Vlei is an approximately 1000ha un-channelled valley-bottom wetland in the upper reaches of the Tugela River catchment area (Joubert and Ellery, 2013).

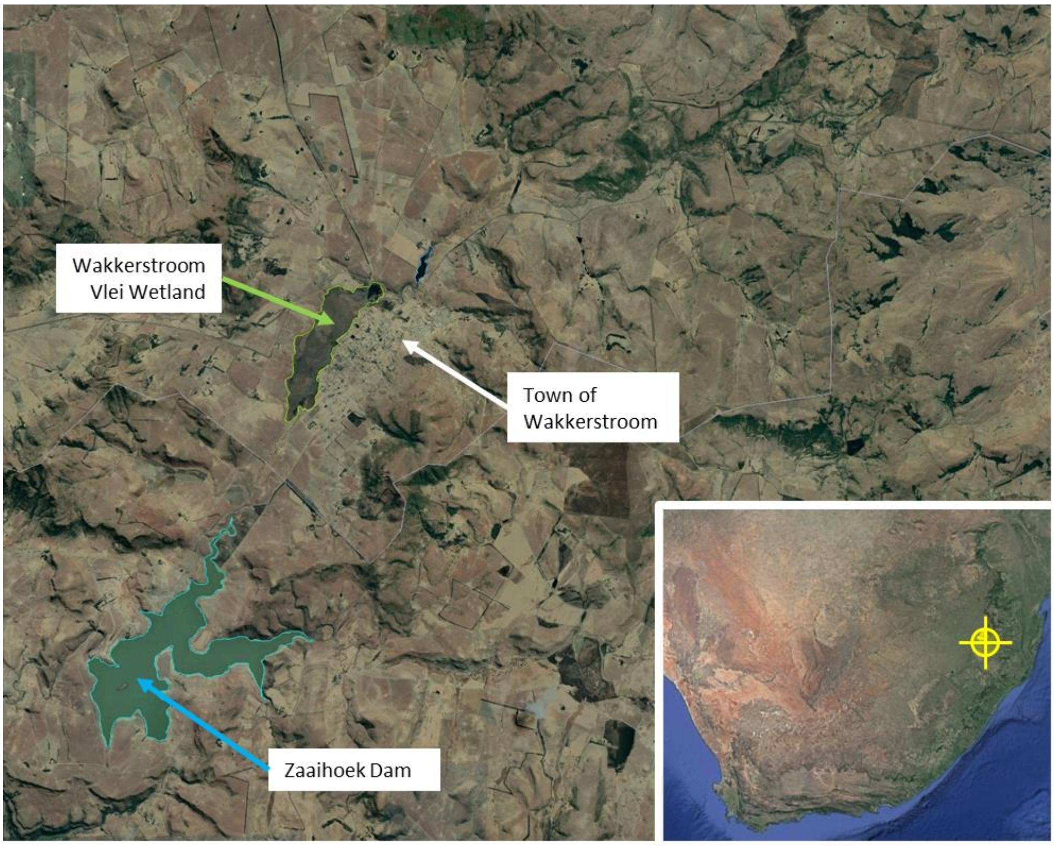


Figure 2.2 Wakkerstroom layout figure (Background images from Google (2020))

The Wakkerstroom Vlei is controlled by dolerite outcrops (Tooth et al., 2004), which are the remnants of intrusive dykes formed during the mid-Jurassic period (Duncan et al., 1997). Tooth *et al.* (2004) explain that the intrusive dolerite material, being more resistant to erosion than the sand- and mudstone material, limits the rate of erosion the contained sand- and mudstone materials. The dykes consequently cause rivers to meander and form wetland floodplains (Tooth et al., 2004). Figure 2.3 illustrates the position of the dolerite dykes relative to the Wakkerstroom Vlei. It should be noted that the dolerite intrusions can effectively be described as the main reason for the wetland existing.

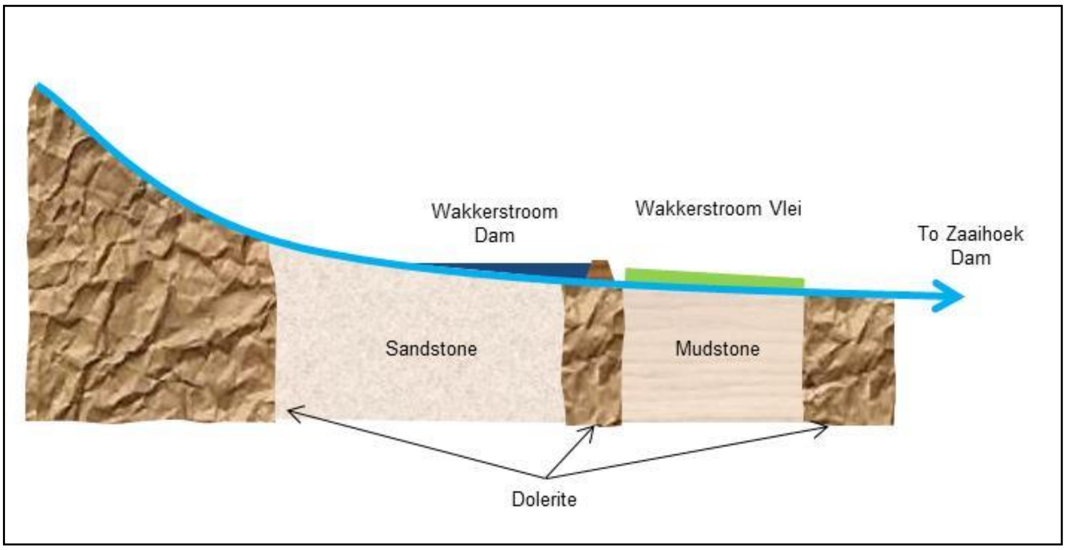


Figure 2.3 Schematic section through the Wakkerstroom Vlei (Adapted from Joubert & Ellery (2013) and Scholes (2018))

The Wakkerstroom Vlei is hydrologically maintained by rivers, as with the majority of wetlands on the Highveld (Ellery et al., 2011; Rogers, 1995). Most of the incoming flow is from the Wakkerstroom River but there are also some minor tributaries, each with their own small catchments, as well as the outflow from the local wastewater treatment plant (WWTP) near the upstream start of the wetland. The Wakkerstroom River and minor tributaries are all of a good water quality but the WWTP is discharging water with elevated nitrogen and phosphorous levels (Sanderson, 2018).

According to Joubert & Ellery (2013) it is possible to subdivide the approximately five kilometre long Wakkerstroom Vlei into three hydrogeomorphic units travelling in a downstream direction:

- 1km uppermost floodplain wetland.
- 2km un-channelled valley-bottom wetland.
- 2km lowermost floodplain wetland.

The Vlei consists of a significant number of reeds that provide considerable flow resistance, hence a high roughness coefficient (Joubert and Ellery, 2013). Joubert & Ellery (2013) also highlight that reeds combined with the moderately flat overall slope of less than 0.3%

results in the wetland having “high water purification, water storage and flood attenuation value” and is consequently invaluable to the immediate and downstream water users.

The river which flows out of the Vlei is known as the Thaka or Utaga River. The Thaka River flows in a south westerly direction into the Zaaihoek Dam approximately three kilometres downstream of the Wakkerstroom Vlei. The Zaaihoek Dam was constructed in 1988 (South African Institution of Civil Engineers, 1989) on the confluence of the Thaka and Slang Rivers. Flow gauging station V3R003 exists just below the Zaaihoek Dam.

2.6 Research assumptions

Some researchers appear to detail all of their main assumptions (von Christierson et al., 2015; Clilverd et al., 2016) while others did not state any assumptions (Kiesel et al., 2013; Trivisonno et al., 2013). The most common assumptions made in the literature are related to the simplification of boundary conditions (Arega, 2013; von Christierson et al., 2015; Clilverd et al., 2016; Mansell et al., 2000; Tsihrintzis et al., 1998; Wester et al., 2018) with the second most common assumption being that the flow through the wetland can be characterised as shallow flow (Arega, 2013; Wester et al., 2018). These two assumptions are considered adequate and appropriate for modelling flows in wetlands if the assumed boundary conditions do still realistically describe the site.

2.7 Calibration

The majority of studies which modelled flow through wetlands utilised flow parameters such as depth or flow rates (Arega, 2013; Clilverd et al., 2016; Mansell et al., 2000; Trivisonno et al., 2013; Tsihrintzis et al., 1998; Wester et al., 2018) to calibrate their models, and they generally produce good results. The calibration processes documented in the literature generally manipulated the roughness coefficients (von Christierson et al., 2015; Kiesel et al., 2013; Trivisonno et al., 2013) although some utilised flow rates (Broekhuizen et al., 2019; Perrelli and Irvine, 2013).

3 METHODS EMPLOYED TO ADDRESS THE OBJECTIVES

3.1 Considerations

Unfortunately there was no readily available flow data immediately up- or downstream of the Wakkerstroom Vlei so it was necessary to enlarge the geographical area considered in order to be able to utilise the available flow data. In light of this approach it was decided to focus the initial modelling on the flows at the Zaaihoek Dam, some 4km downstream of the Wakkerstroom Vlei, and then use the calibrated hydrologic model for the Wakkerstroom Vlei catchment to develop a predictive model. This approach of developing a predictive model for the Wakkerstroom Vlei using the Zaaihoek Dam hydrological model parameters is deemed to be appropriate as the Wakkerstroom Vlei is a sub-catchment of the Zaaihoek Dam catchment as it is similar to other studies which have reproduced predicted discharge rates for other locations within a river network (Grayson et al., 1992; Senarath et al., 2000).

Upon development of a hydrological model for the Wakkerstroom Vlei, it was possible to extend the model to also consider the flow of nutrients, and more specifically nitrogen, through the Vlei.

3.2 Data utilised for modelling

A large amount of data already exists for the Zaaihoek Dam. The available data includes:

- Measured outflow rates for the Slang River component.
- Measured flow data from the Zaaihoek Dam spillway.
- Measured rainfall and pan evaporation rates.
- Water quality data.

The initial modelling indicated that using a single meteorological station for the whole catchment was not adequate. The overall catchment was split into similar elevations zones resulting in each of the two rivers entering Zaaihoek Dam consisting of three sub-catchments. In addition to the available Zaaihoek data, additional rain gauges exist that are more appropriate for the higher reaches of the overall catchment.

Nutrient data was obtained from an Honours Research Report (Sanderson, 2018) undertaken through the APES. This research looked at the ability of the Wakkerstroom Vlei to remove nutrients and coliform contaminants by measuring the nutrient and bacterial levels in the water. These nutrient results were kindly made available for this research in order to inform the nutrient modelling through the Wakkerstroom Vlei. However, the sporadic nature of the obtained water quality data made it unfeasible to allow detailed modelling of the flow of nitrogen through the wetland.

3.3 Modelling approach

The modelling undertaken during this research looked at the large scale catchment runoff contributing to the Zaaihoek Dam. The reason for selecting this location was the availability of data from the DWS and other freely available rainfall data extraction utilities.

Once a calibrated model was generated for the Zaaihoek Dam, the Wakkerstroom Vlei hydrology was then addressed since it is a sub-catchment of the Zaaihoek Dam. Thereafter, the Wakkerstroom Vlei hydrological model was extended to consider the flow of nitrogen through the wetland.

3.4 Choice of model

Numerous software packages exist which can be used for modelling hydrological systems (Devi et al., 2015) with the main types being lumped or distributed models. In a lumped model the system is seen as a single unit, while a distributed model divides the system into smaller sets to allow parameters to vary spatially (Moradkhani and Sorooshian, 2009).

While some research have been based on utilising separate models for their coupled hydrologic analyses (Arega, 2013; Kiesel et al., 2013), we have decided to rather utilise a single model which makes use of internal coupled analyses to simplify the integration process.

The ROs stated in the previous section are not new as they were successfully undertaken by von Christierson *et al.* (2015). However, this research will utilise a two-dimensional model instead of the von Christierson *et al.* (2015) three-dimensional modelling approach.

Kazezyilmaz-Alhan *et al.* (2007) concluded that ground- and surface water interactions should be incorporated into hydrological wetland models to allow water quality components to be more accurately modelled. Due to the dolerite outcrops present (Tooth et al., 2004) the groundwater portion of the Wakkerstroom Vlei catchment was ignored. This exclusion could have negatively impacted on the accuracy of the hydrological results.

3.4.1 Australian Water Balance Model

The AWBM has been used by a number of researchers (Escobar et al., 2015; Heneker, 2002; Sharifi et al., 2004) around the world for predicting flow rates.

The AWBM considers antecedent moisture conditions by utilising the elementary bucket approach (Boughton, 2004) as presented in Figure 3.1 with runoff only taking place after the buckets, or surface stores, are full. The AWBM assumes that each catchment area can be defined by three partial areas (A1, A2 and A3) adding to unity, with each partial area having its own respective surface storage capacity (C1, C2 and C3). These partial areas with their individual storage capacities are shown in Figure 3.1a while Figure 3.1b displays the resulting rainfall-runoff relationship.

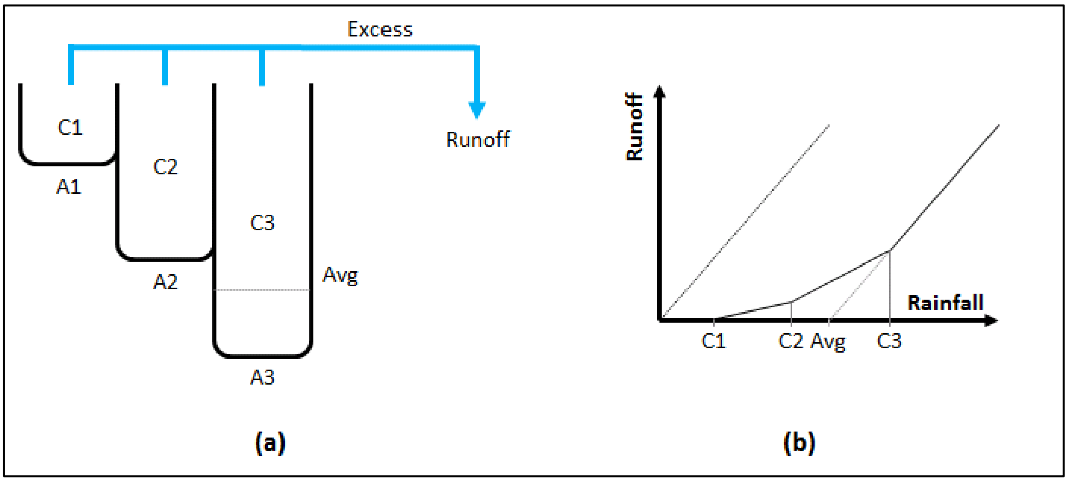


Figure 3.1 Schematic multi-bucket approach (Adapted from Boughton (1987, 2004))

The runoff indicated in Figure 3.1a is split between surface and base flow to take account of both overland and sub-surface flow, with each having an attenuation component utilising recession constants (Boughton, 2004). This split between the above and below ground components transforms the structure to the one indicated in Figure 3.2.

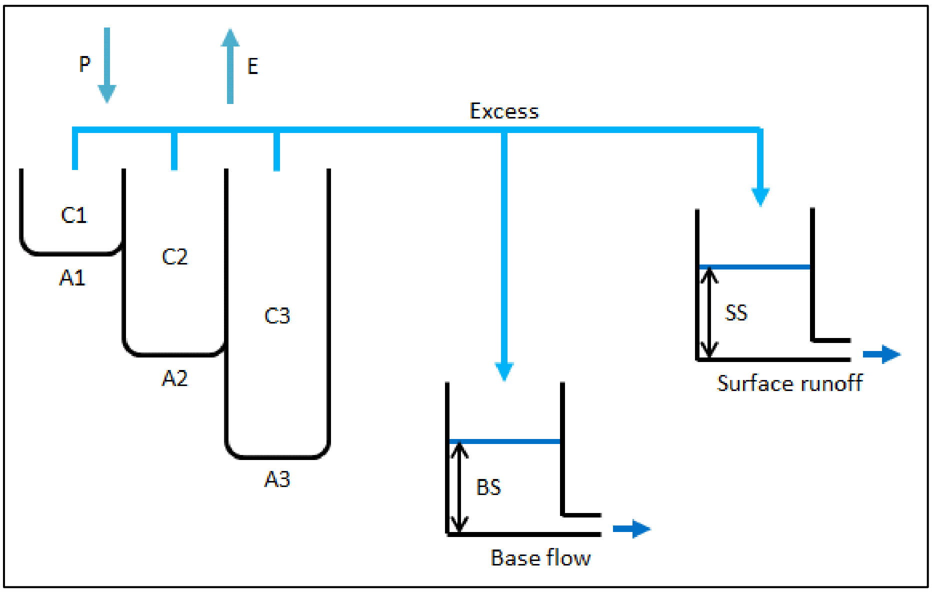


Figure 3.2 Expanded schematic of AWBM (Adapted from Boughton (2010))

The abbreviations used in Figure 3.1 and Figure 3.2 are as follows:

A1, A2 and A3:	Partial areas with different surface storage capacities
BS:	Quantity of water in the base flow store
C1, C2 and C3:	Surface storage capacities corresponding to the partial areas
E:	Evaporation
P:	Precipitation
SS:	Quantity of water in the surface store

The quantity of water in the surface store is calculated by Equation (3.1) and the discharge rates from the surface and base attenuation stores are calculated as shown by Equation (3.2) and Equation (3.3):

$$SS = Excess * (1.0 - BFI) \tag{3.1}$$

$$Q_{surface} = SS * (1.0 - K_s) \tag{3.2}$$

and

$$Q_{baseflow} = BS * (1.0 - K_b) \tag{3.3}$$

Where:

SS:	Quantity of water in the surface store
BFI:	Base flow index
$Q_{surface}$:	Discharge from the surface attenuation store
K_s:	Surface flow recession constant
$Q_{baseflow}$:	Discharge from the base flow attenuation store
BS:	Quantity of water in the base flow store
K_b:	Base flow recession constant

3.4.2 Goldsim

As discussed in Section **Error! Reference source not found.** it was identified that the Goldsim software package would be suitable for modelling the behaviour of the Vlei. Goldsim has programmed an AWBM model for free download from the Goldsim Model Library database (https://support.goldsim.com/hc/en-us/articles/115008698407-Australian-Water-Balance-Model-AWBM-). This model was used as the basis for the surface and base flow components within the overall water balance model of the Zaaihoek Dam catchment.

While the AWBM was not developed to act as a coupled model (Boughton, 2004), the inclusion of the model within Goldsim allows coupling of the hydrological processes with the relevant biochemical processes through use of the Contaminant Transport Module (CTM). A standalone academic licence (Version 12.1) was obtained from Goldsim for the purposes of undertaking this research.

3.4.3 PCSWMM

In addition to the use of Goldsim, the software programme PCSWMM was utilised to determine how the AWBM modelling within Goldsim influences the results obtained, with a discussion of the PCSWMM details included in Section **Error! Reference source not found.**. A Professional Educational single-user license of PCSWMM was obtained through the Computational Hydraulics International (CHI) University Grant Programme for the purposes of undertaking this research.

3.5 Model time step

The models can be based upon a variety of time steps, although the AWBM is limited to utilising hourly or daily steps, with the daily option often used for water management or yield assessments and the hourly option typically selected for hydraulic design or flood estimation purposes (Boughton, 2004). In numerical modelling the time step should ideally be as large as possible to reduce computational effort, without influencing the results obtained.

The selected time step of one day was checked relative to the time it takes for the whole catchment to contribute to the runoff in the form of the time of concentration calculation (Kirpich, 1940) as a relative sanity check. While calculating the time of concentration is not the same as determining the appropriate modelling time step, this was deemed to be suitable as the time of concentration was calculated to be less than day (between 190 and 670 minutes) and hence within the selected water balance modelling time step. This result indicates that the selected time step is deemed to be appropriate for the Zaaihoek Dam catchment water balance modelling.

3.6 Model components

The AWBM approaches runoff modelling by using a water balance calculation for each time step. In order to model the in- and outflows from the Zaaihoek Dam, a water balance model was similarly developed for the dam, with the components illustrated in Figure 3.3 and summarised below:

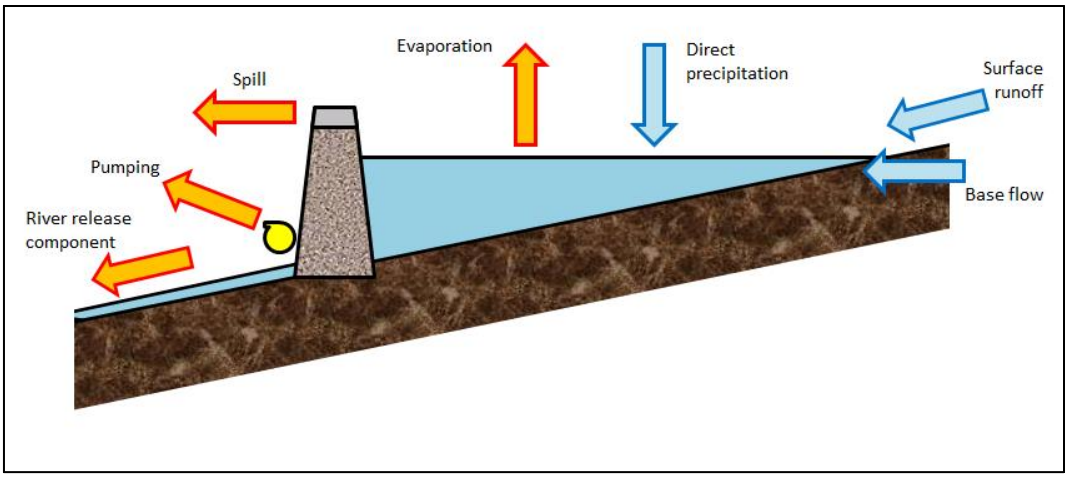


Figure 3.3 Schematic Zaaihoek Dam water balance components

Where:

Base flow:	The subsurface flow rate calculated by the AWBM model.
Direct precipitation:	Rainfall directly onto the dam.
Evaporation:	Evaporation losses from the dam surface.
Pumping:	A pumped system exists to convey water to nearby users.
River release:	Flow rate released to maintain the downstream river ecosystem.
Spill:	The rate at which water leaves the dam if the water level exceeds the spillway invert level
Surface runoff:	The surface flow rate calculated by the AWBM model.

3.7 Input parameters

3.7.1 Climate data

The Zaaihoek rainfall and evaporation data was downloaded from the DWS website (http://www.dwa.gov.za/Hydrology/ (Department of Water and Sanitation, 2019)). The evaporation data was supplied as S-Class pan values which were converted to lake evaporation rates using the pan correction factors contained in the Water Research Commission book entitled “Surface water resources of South Africa” (Midgeley et al., 1994).

The available evaporation data is monthly instead of daily but this is deemed to be appropriate for this modelling due to the lower sensitivity of the modelling to evaporation than rainfall (Chapman, 2003) which made it possible to convert the monthly figures to daily figures by dividing the total monthly value by the number of days in each month (Boughton, 2004).

Additional rainfall data for the sub-catchments was obtained from the Daily Rainfall Data Extraction Utility (DRDEU) (Kunz, 2004), Version 1.4. This software locates nearby stations and the stations with the most appropriate elevations were selected for each of the three sub-catchments. The three most appropriate stations available were owned by the South African Weather Service (SAWS):

- Skurweklip (SAWS number 0371421_W) – Utilised for the upper sub-catchment
- Groenvlei (SAWS number 0407418_W) – Utilised for the middle sub-catchment
- Barrowfield (SAWS number 0407148_W) – Utilised for the lower sub-catchment

Supplementary data for the Groenvlei and Barrowfield stations were obtained free of charge from the SAWS as part of a Disclosure Agreement for the purposes of conducting research.

Open water evaporation rates were converted to evaporation rates from wetlands based on the known reed species present in the Wakkerstroom Vlei in accordance with values documented in Mohamed et al. (2012).

3.7.2 Flow data

The pumping data, Zaaihoek spillway overflow and river component flow rates were downloaded from the DWS website (http://www.dwa.gov.za/Hydrology/ (Department of Water and Sanitation, 2019)).

The pumped flow rates were included within the AWBM by simply using an input table. However, PCSWMM is not able to handle an existing time series of outflows and so the pumped rate was incorporated by setting the pumped outflow as a negative inflow.

3.7.3 Modelling period informed by input data

Unfortunately, as the Zaaihoek Dam was only commissioned in 1988 (South African Institution of Civil Engineers, 1989), the DWS datasets generally cover from April 1988 to December 2018, while the SAWS stations were closed in late December 2010 and the DRDEU datasets were only available from January 1920 to August 2000. This resulted in the only period of data which covered both climate and flow rates being from October 1988 to August 2000. This is one month short of twelve years, which was initially split to allow the first eight years of data to be used for the calibration of the model and the remaining three years and eleven months to be used for the validation of the calibrated model. However, it was then realised that the rainfall and flow data did not match as expected, with the initial (Period A) and latter (Period C) portions having weaker correlations than the middle portion (Period B) as can be seen in Figure 3.4.

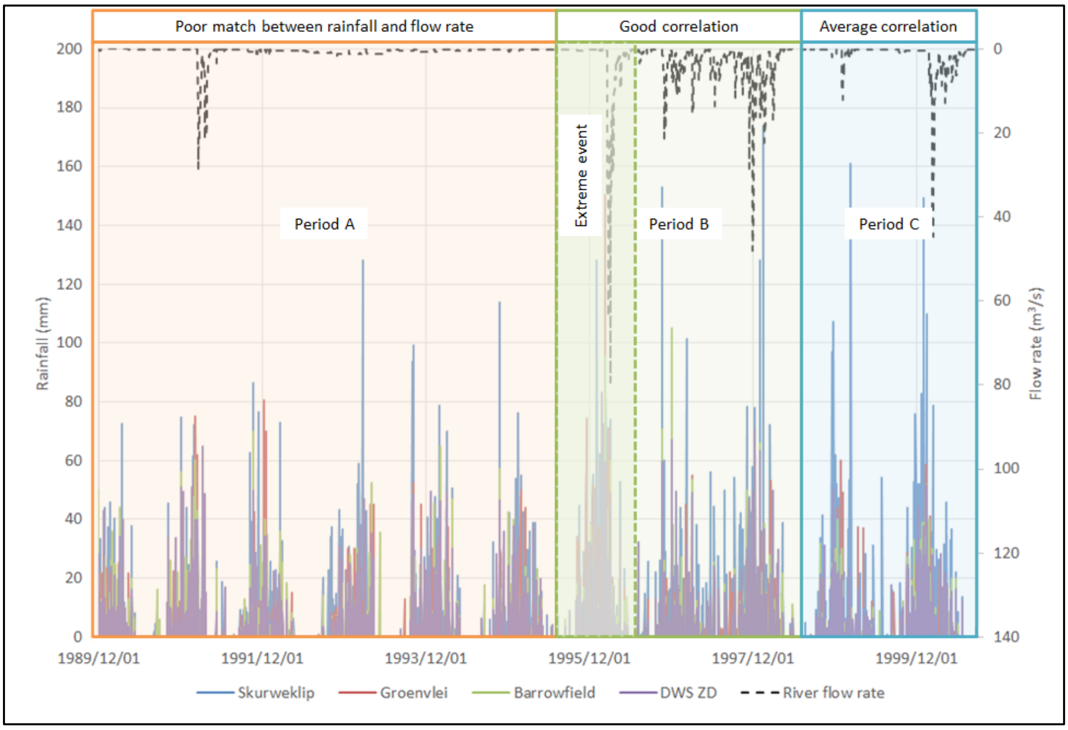


Figure 3.4 Comparison of rainfall and run-off

It was subsequently decided that instead of using a single model to calibrate and validate the results using periods with weaker correlations between rainfall and flow rate, it would be preferable to utilise two separate models covering the period of good correlation. This approach is deemed to be acceptable as shorter calibration periods of two and three years (Boughton, 2007; Makungo et al., 2010) have successfully been by other researchers, although contrasting views also exist which suggest that the accuracy improves with increasing lengths of data sets (Arsenault et al., 2018).

While the period of good correlation indicated in Figure 3.4 by the green shading includes an extreme event (>79 m^3/s resulting from the three main rain gauges recording daily rainfall depths between 73 mm and 150.5 mm) in February 1996, it was decided to run the models with and without this year of data to assess the effect of the extreme event on the calibration of the models. However, Boughton (2006) states that extreme events negatively impact upon the calibration of such rainfall runoff models.

3.7.4 Patching of climate and flow data

A couple of the datasets downloaded from the DWS site included some gaps due to a variety of reasons. The missing data portions were patched using either interpolation from the surrounding values or converting the monthly averages into daily flows. The completeness of the downloaded climate and flow data is presented below as Table 3.1

Table 3.1 Input data completeness

Data	Data source	Missing	Comments
Zaaihoek rainfall	DWS	(none)	
Zaaihoek evaporation		(none)	
Zaaihoek spill rate		(none)	
Zaaihoek river component (Slang River)		0.7% missing	Manually patched
Zaaihoek-Majuba pipeline		0.2% missing	Manually patched
Pipeline from Zaaihoek Dam		(none)	
Pipeline from Zaaihoek Dam		(none)	
Pipeline from Zaaihoek Dam		(none)	
Pipeline from Zaaihoek Dam		(none)	
Pipeline from Zaaihoek Dam		(none)	
Skurweklip rainfall	DRDEU	1.6% missing, 66.2% patched	Already patched by DRDEU prior to download
Groenvlei rainfall		1.6% missing, 58.8% patched	
Barrowfield rainfall		0.2% missing, 72.2% patched	

The downloaded DWS Slang River flow rates included the Zaaihoek overflow rates as the Slang River measuring weir is downstream of both the dam wall and dam spillway outlet.

Figure 3.5 illustrates that the flow rates measured by the measuring weir consist of both the river release component and dam spill rates.

Figure 3.5 Zaaihoek Dam release components (Background image from Google (n.d.))

In light of this, the Zaaihoek Dam spillway rates were subtracted from the Slang River flow rates to allow each component to be considered separately within the model. However, it was found that this sometimes resulted in negative flow rates (i.e. the spillway rates were sometimes larger than the Slang River rates). This is deemed to be as a result of the nature of the Slang River measuring weir being more accurate for lower flow rates and less accurate for the larger overflow rates (refer to Figure 3.6). The Slang River flow rates were patched using average flow rates based on the monthly averages for these instances where the Zaaihoek Dam overflow rates were greater than the Slang River rates.

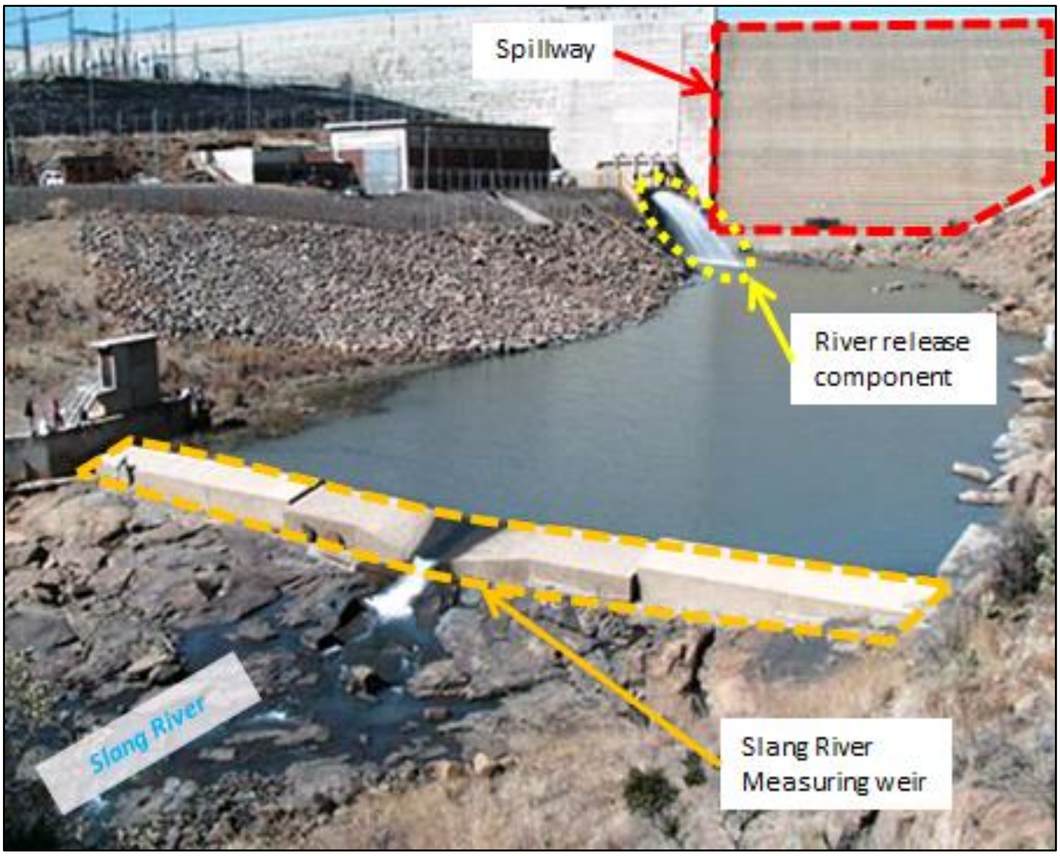


Figure 3.6 View looking upstream from the Slang River measuring weir (Source: DWS website (http://www.dwa.gov.za/Hydrology/Verified/HyImage.aspx?Station=V3H028))

3.7.5 Catchment areas

A digital elevation model (DEM) consisting of 5m contours of the overall Zaaihoek Dam catchment area was obtained (refer to Figure 3.7) from the Chief Directorate: National Geo-Spatial Information (CD:NGI) Database and the catchment boundaries were delineated within PCSWMM. The overall catchment was split into three sub elevations to better account for the large variation in height (>400 m). The PCSWMM sub-catchment delineation function was used to split the overall catchment and then each sub-catchment was linked to the appropriate rainfall station depending on whether the sub-catchment fell into the Upper, Middle or Lower category. These coloured sub-catchments are illustrated in Figure 3.8.

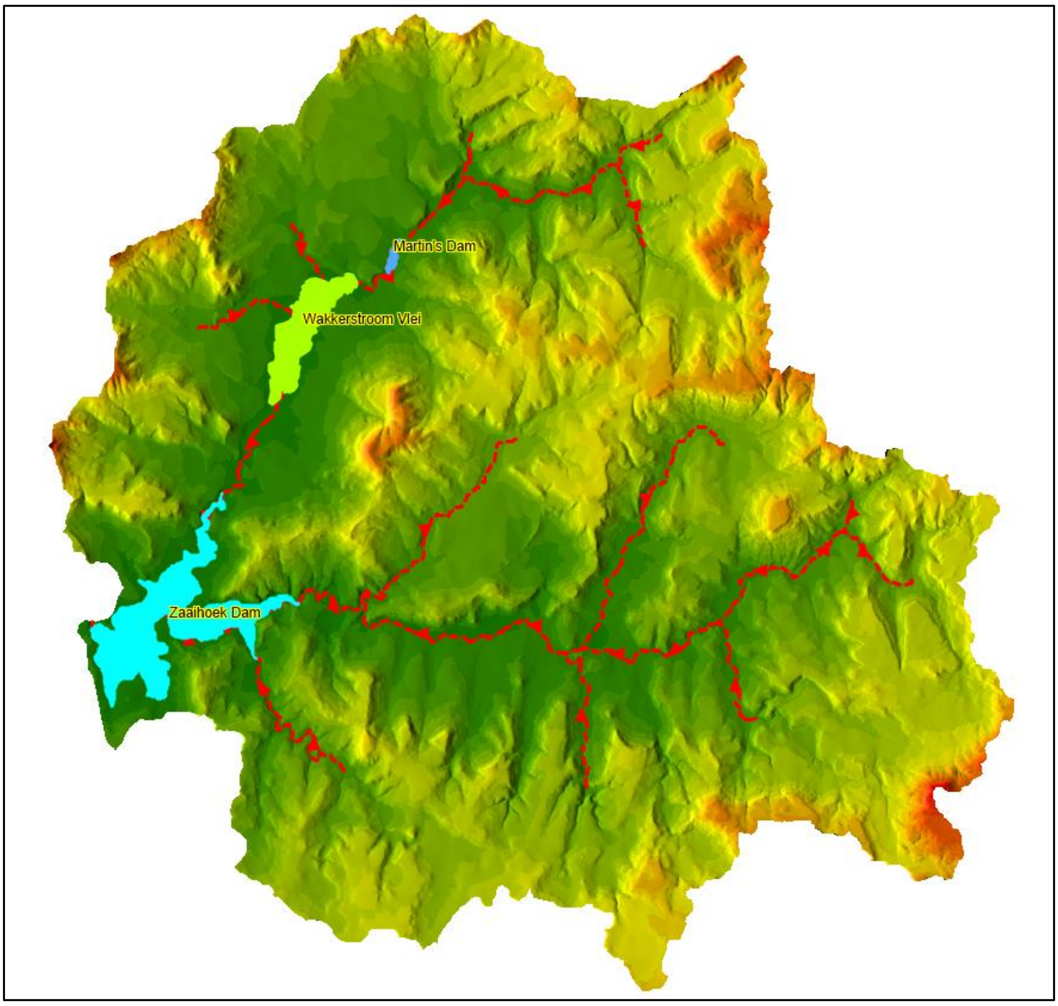


Figure 3.7 Zaaihoek Dam catchment DEM

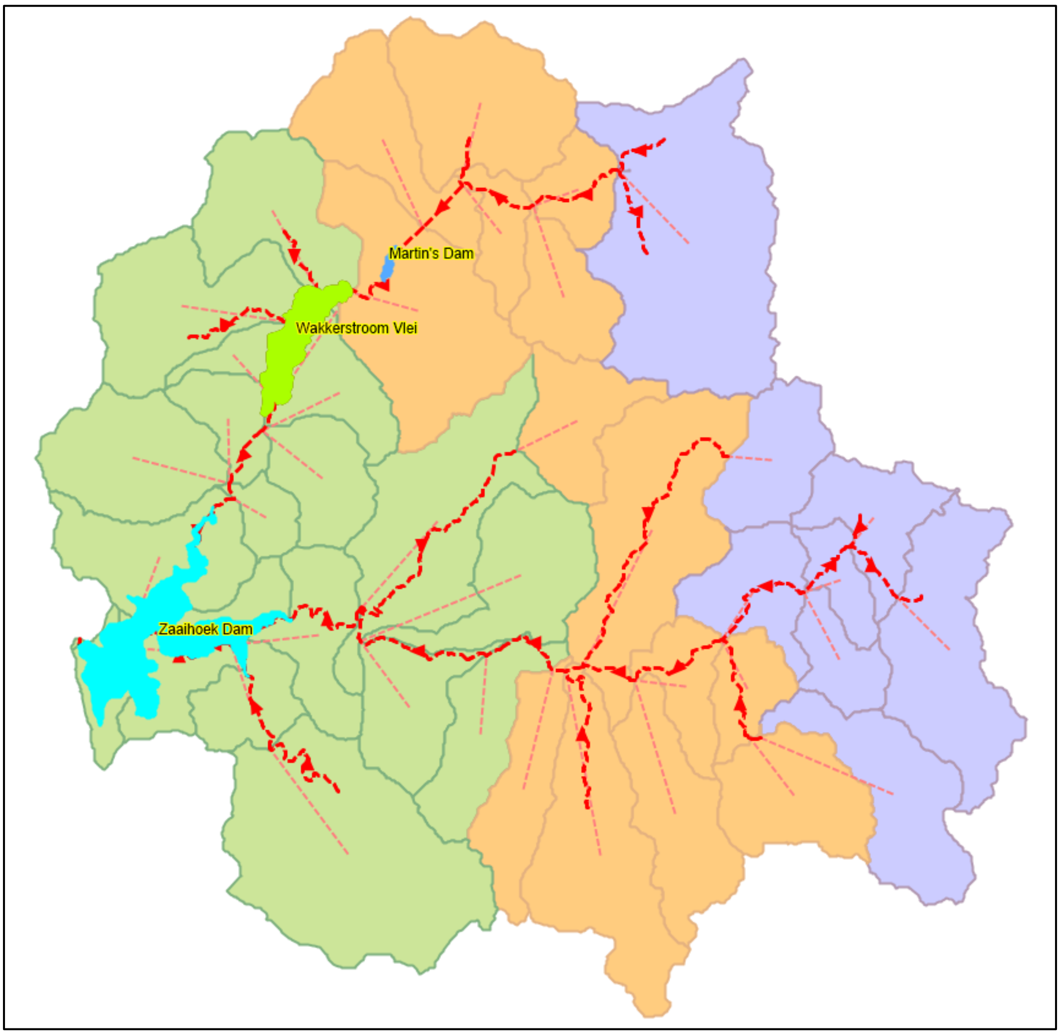


Figure 3.8 Delineation of sub-catchments

Zaaihoek Dam has two incoming rivers, namely the Slang and Thaka. The catchment of each of these rivers was divided into three sub-catchments as discussed above, with the relevant labels included in Figure 3.9.

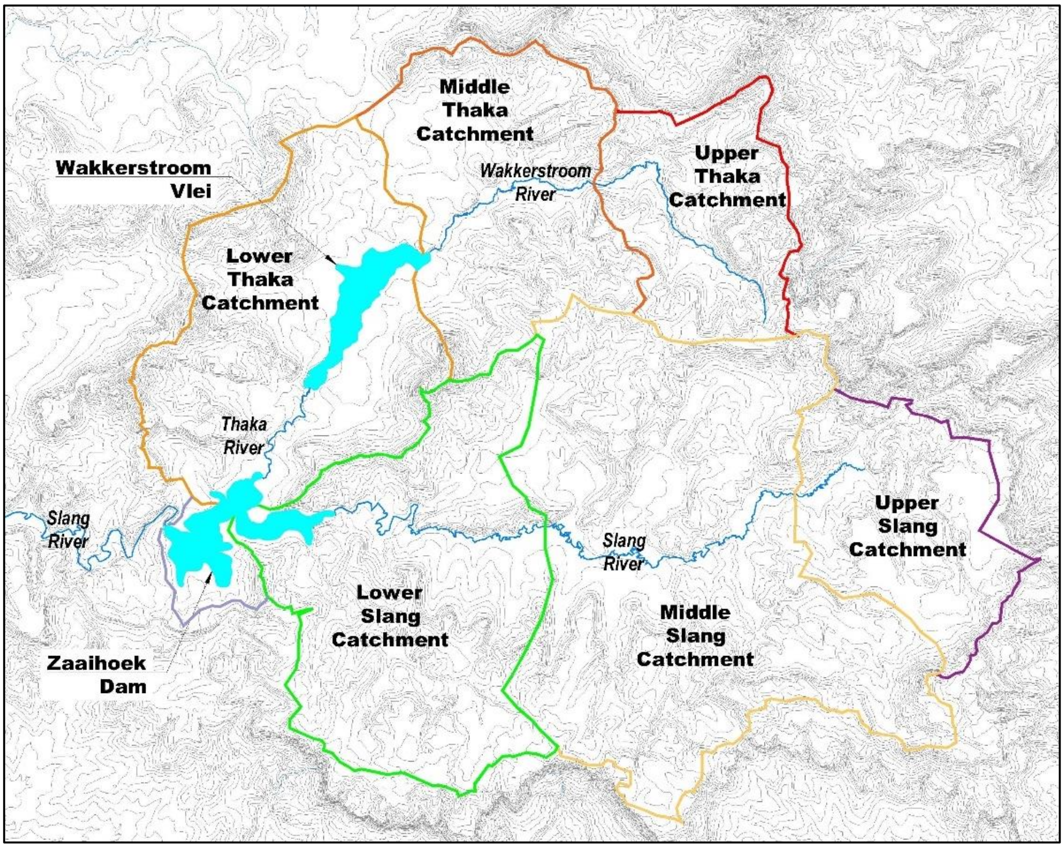


Figure 3.9 Delineation of catchments

This DEM was further processed within PCSWMM to locate flow paths and generate the irregular channel cross sections, both of which are used by the PCSWMM modelling.

3.7.6 AWBM specific input parameters

The required input parameters for the AWBM model are summarised below in Table 3.2.

Table 3.2 AWBM input parameters

Parameter	Units	Value	Source
A1		0.134	These are the default partial area fractions recommended for the AWBM which were found to be appropriate for the Zaaihoek catchment as the model is more sensitive to other input parameters.
A2		0.433	
A3		0.433	
C1	mm	12.4	C1 = 0.075 x Avg*
C2	mm	126.0	C2 = 0.762 x Avg*
C3	mm	252.0	C3 = 1.524 x Avg*
Avg*	mm	165.4	Avg = Average annual rainfall - Average annual runoff
Catchment area	km^2	617	Delineated and measured within PCSWMM
BFI		0.658	This is the default AWBM input value which was later calibrated

Kb		0.309	This is the default AWBM input value which was later calibrated
Ks		0.869	This is the default AWBM input value which was later calibrated
Zaaihoek Dam starting volume	m^3	55,365,000	Assumed to be 30% full due to the model starting in the middle of the dry season
Diameter of orifice pipe	m	1.2	The largest known diameter was selected based on available SAICE article (South African Institution of Civil Engineers, 1989)
Discharge coefficient (Cd)		0.67	Typical circular orifice discharge coefficient value
Martin’s Dam starting volume	m^3	167,323	Assumed to be 80% full
Wakkerstroom retention time	days	19	Online article**
**The average capacity is not used directly in the AWBM, but rather just to calculate the partial storage capacities (Boughton (2010))* **“IOL news website” (2018)			

3.7.7 PCSWMM specific input parameters

The modified Green-Ampt method was used to take account of infiltration. This method is based on water travelling vertically down the soil profile in a saturated layer with the wetted zone being fully saturated and the moisture content in the un-wetted zone below the wetting front being at an initial degree (United States Environmental Protection Agency, 2016). The soil in the sub-catchments was modelled as a Loamy Sand soil texture, with typical literatures values extracted from the SWWM5 User’s Guide (James et al., 2010) and converted to metric units, as provided below in Table 3.3. These input parameters were then calibrated within PCSWMM.

Table 3.3 Infiltration parameters from literature (James et al., 2010)

Parameter	Value	Units
Saturated hydraulic conductivity	29.97	mm/hr
Suction head	60.96	mm
Porosity	0.437	(fraction)
Field capacity	0.105	(fraction)
Wilting point	0.047	(fraction)

Similar to the AWBM, PCSWMM makes use of a “bucket” type model, known as *Depression Storage* which accounts for the depth of water which needs to be stored prior to the onset of runoff. The initial values were selected to be 1 mm and 2 mm for the Impervious and Pervious areas respectively. These depths were also used as calibration variables.

PCSWMM requires that the *Imperviousness* of the sub-catchments is specified. This parameter accounts for all impervious surfaces in the sub-catchment areas. The starting value was selected to be 2% based on the recommended value for rural/ agricultural areas in the SWMM Hydrology Manual (United States Environmental Protection Agency, 2016) and this was then modified during calibration of the model.

PCSWMM allows for some immediate runoff from each sub-catchment by incorporating a *Zero Imperviousness* parameter. This is the percentage of the imperviousness area which does not have any depression storage. The initial value was specified as 25% and this was then modified during the model calibration step.

The channels were modelled as having Manning's Roughness Coefficients of 0.05, which is comparable with fairly regular natural channels (James et al., 2010). The roughness coefficient of the pervious portion of each sub-catchment was based on work undertaken on overland flow hydraulics which presented a Manning's Roughness Coefficient of 0.5 (Emmett, 1970). While this value is higher than typically purported for grassed areas (0.13 to 0.24 (James et al., 2010)), it was found it be more appropriate for the modelled sub-catchments.

3.7.8 Hydraulic data

The river flow component of the Zaaihoek Dam outlet was modelled as an orifice at the base of the dam. According to an article published soon after the Zaaihoek Dam was commissioned (South African Institution of Civil Engineers, 1989), it was determined that there are four river outlet pipes from the dam, ranging in diameter from 400 mm to 1200 mm. Unfortunately, as the control operational guides of the outlet pipes were unknown, the outlet was modelled as a single 1200 mm orifice with a discharge coefficient of 0.67, although this single value was used as one of the calibration parameters to try better account for the unknown varying controls.

The other inputs included the spillway rating curve which was downloaded from the DWS database (Department of Water and Sanitation, 2019) and the stage capacity relationship for the dam which was generated by measuring the dam basin contours from the survey file. These datasets were both inserted as lookup tables.

The outlet of the Wakkerstroom Vlei storage unit was modelled as a weir with the following attributes, which were then calibrated within the model:

- The length of the weir approximately equal to the width of the Vlei.
- A discharge coefficient of 2.95 which was also used as a variable during model calibration.

3.8 Biochemical modelling

The data provided in Sanderson (2018) covered three locations, namely:

- Below Martin’s Dam (i.e. the clean stream inflow into the Wakkerstroom Vlei).
- Below the eSizamaleni sewage leak.
- At the bottom end of the Wakkerstroom Vlei.

These measured nutrient concentrations are presented as Figure 3.10. As can be seen from this figure, there are only 37 data points for each of the three locations, with some locations sampled two or three times per day towards the end of the sampling exercise. These sporadic sampling results in a dataset are unsuitable for integration with the daily time step hydrological model developed as part of this research.

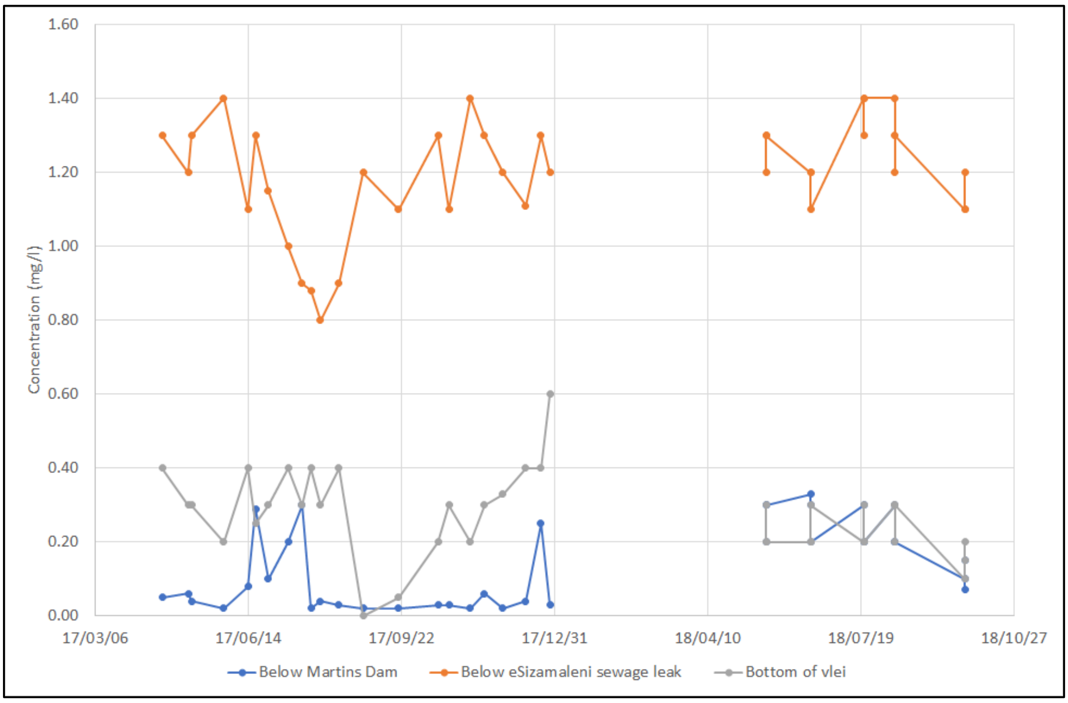


Figure 3.10 Nitrate data obtained from Sanderson (2018)

In lieu of more comprehensive data, the mean and standard deviation values were calculated for each location and then used to describe a normal distribution for the data set. These distributions were utilised within the CTM, an add-in to Goldsim, which was coupled with the calibrated hydrological model, to model the flow of nitrogen through the Wakkerstroom Vlei.

3.9 Model calibration

In the past it was more challenging to calibrate models due to limited computing power, with the calibration approach often being undertaken manually and with a limited number of variables (Senarath et al., 2000). The Goldsim and PCSWMM models were calibrated by comparing the observed and predicted flow rates and minimising the RMSE, as had similarly been done as part of the calibration of other catchment rainfall-runoff models (Hafezparast and Fatemi, 2013; Kim et al., 2007; Madsen, 2000; Makungo et al., 2010). However, it was found that the inclusion of the extremely wet period over February and March in 1996 tended to distort the calibration as the RMSE minimises the error by trying to calibrate the higher flow rates to the detriment of the lower flows, as also highlighted previously by Boughton (2006). This period was subsequently excluded from the model duration such that the modelling was undertaken between 1 July 1996 and 30 June 1998. The reason for starting the model during the dry winter period instead of the start of the hydrological year was to simplify the starting volumes of the dams.

A Water Research Commission report was found which stated that the quality of the data at the weir immediately downstream of the Zaaihoek Dam had the highest quality data for the period 1991 to 1998, but that the data “is not acceptable for verification” (Smithers et al., 2007).

3.9.1 Goldsim

The predicted overflow rates were compared against the measured overflow rates. Using a RMSE approach where the difference between the daily measured and predicted spill rates were calculated, the input parameters were calibrated using the inbuilt Goldsim optimisation function. The RMSE equation proposed by Goldsim is included here as Equation 3.1.

Equation 3.1

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(Q_{m,i} - Q_{p,i}\right)^2}{N}}$$

Where:

Q_m:	Measured spill rate
Q_p:	Predicted spill rate
N:	Number of values

The Goldsim optimisation function minimised the RMSE difference through Monte Carlo sampling of the user selected parameters within the specified ranges. The parameters included in the optimisation runs are tabulated in Table 4.1 and the RMSE setup in Goldsim has been included as Figure 3.11.

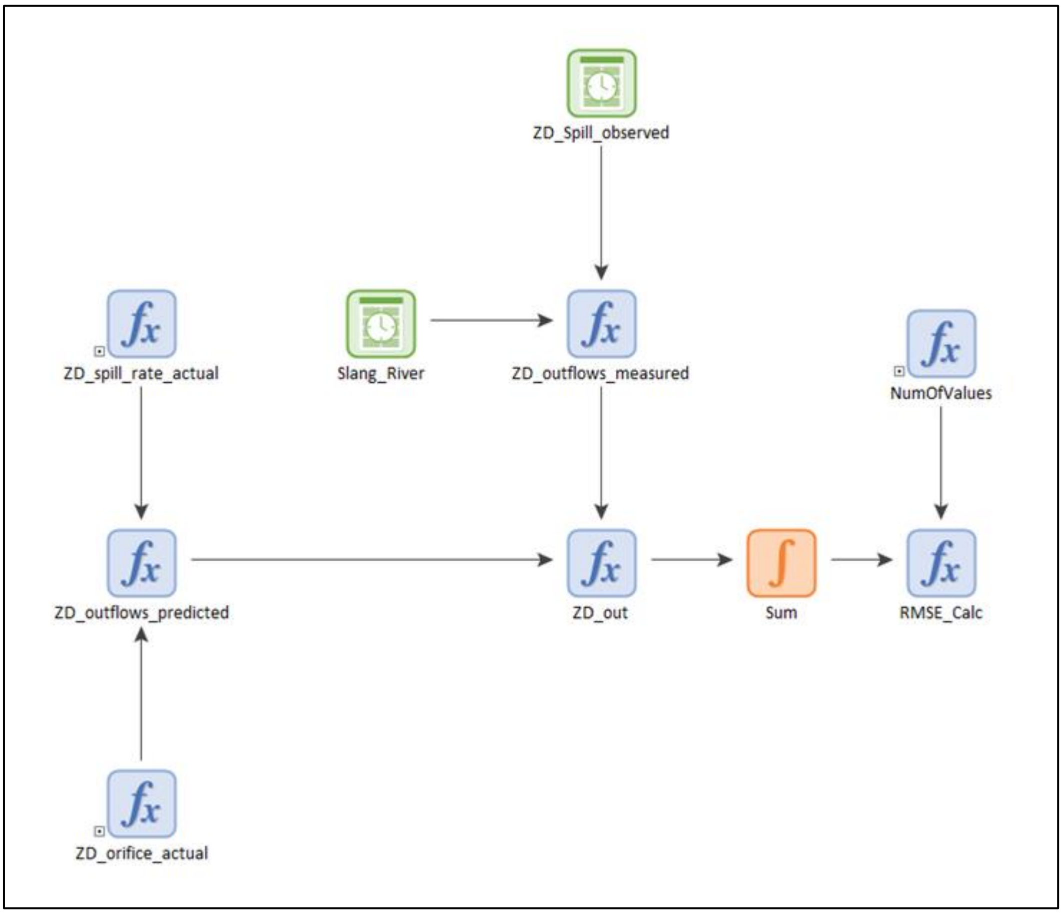


Figure 3.11 Goldsim RMSE

3.9.2 PCSWMM

The Sensitivity-based Radio Tuning Calibration (SRTC) tool was used within PCSWMM to calibrate the predicted flow rates against the observed (i.e. DWS) flow rates. This tool makes use of user selected uncertainty ranges for each parameter requiring calibration and then runs the model multiple times to assess the impacts of varying the selected variables. Upon completion of the runs, the user individually goes through each variable and adjusts the value by either using the auto-calibrate option or manually adjusting the value. Once each parameter has been adjusted and an estimated new correlation between the predicted and observed flow rates provided, the model is rerun with the adjusted values to confirm the estimated correlation. The process can be repeated as many times as desired.

Historically the majority of calibration has been undertaken manually but the advancements now afford some models the ability to utilise automatic calibration (Senarath et al., 2000).

The use of the SRTC is a combination of both manual and automatic measures as the initial steps are undertaken automatically but then the modeller still needs to adjust (or tune) each parameter individually, although the SRTC is able to assist with the automatic calibration of each one individually. However, the automatic calibration of a particular parameter happens in isolation of the others, so it is necessary to re-run the newly calibrated model to confirm whether or not the expected correlations match or improve upon the estimated correlation parameter.

3.10 Validation

Following on from the mismatched rainfall and flow data described above, the software package, PCSWMM, was used to validate the Goldsim AWBM. This approach of validation does not validate the model in terms of the modelled catchment but does validate the model in terms of modelling accuracy.

4 RESULTS AND DISCUSSIONS

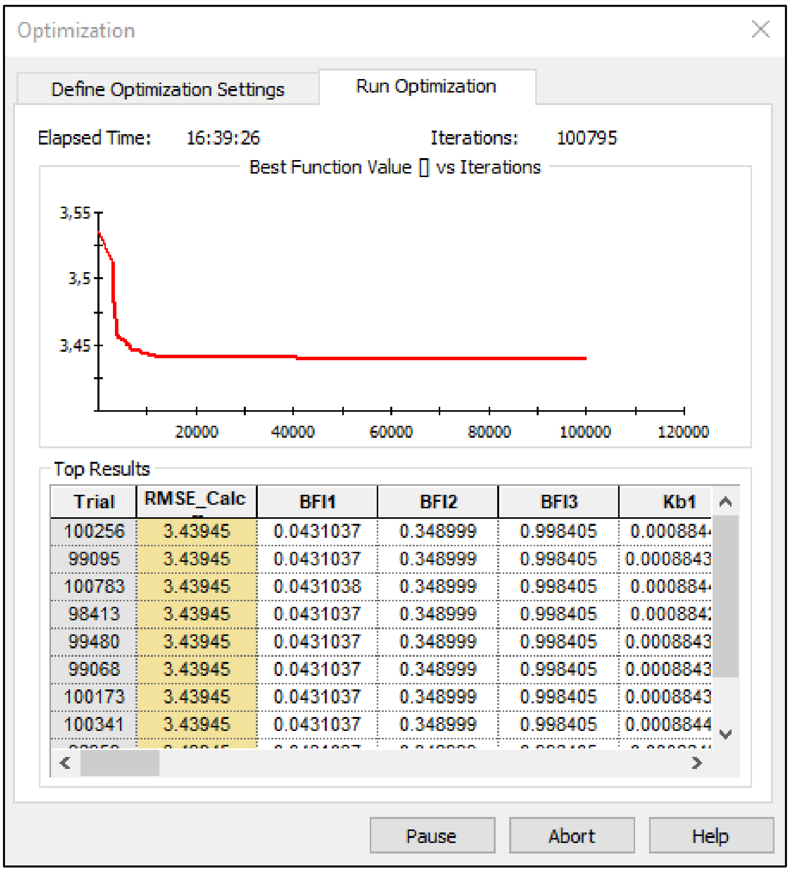
4.1 Research Question 1

This first RO was to hydrologically model the catchment of the Zaaihoek Dam.

The AWBM was utilised to account for the incoming surface and base flow components, which were considered as part of the overall Zaaihoek Dam water balance. This daily time step water balance took account of the various in- and outflows, with the predicted compared to the measured flow rates.

The mismatched rainfall and flow data for the Zaaihoek catchment area limited the available dataset which was available for modelling. This is deemed to be as a result of the patched nature of the available rainfall data and, to a greater degree, the poor quality of measured data at the weir immediately downstream of the Zaaihoek Dam (Smithers et al., 2007). Boughton (2007) found that short data sets, namely two to five years, generally give acceptable flow rate predictions but that longer data sets, typically at least ten years, give more accurate estimates.

The initial modelling runs resulted in extremely poor correlations with the observed data. This was typically due to errors in the model which were systematically worked through and rectified. An optimisation process was undertaken once the obvious errors had been rectified. This process focussed on the parameters which were deemed to be the most uncertain or the ones to which the model was understood to be the most sensitive. The ranges for these selected optimisation parameters were set to suitable values and the model was optimised, by minimisation of the RMSE, was then run. A typical optimisation run progress update is included as Figure 4.1.



Elapsed Time: 16:39:26 Iterations: 100795

Top Results

Trial	RMSE_Calc	BFI1	BFI2	BFI3	Kb1
100256	3.43945	0.0431037	0.348999	0.998405	0.000884
99095	3.43945	0.0431037	0.348999	0.998405	0.0008843
100783	3.43945	0.0431038	0.348999	0.998405	0.000884
98413	3.43945	0.0431037	0.348999	0.998405	0.000884
99480	3.43945	0.0431037	0.348999	0.998405	0.0008843
99068	3.43945	0.0431037	0.348999	0.998405	0.0008843
100173	3.43945	0.0431037	0.348999	0.998405	0.0008843
100341	3.43945	0.0431037	0.348999	0.998405	0.0008844

Figure 4.1 Typical RMSE optimisation run showing how the selected variables are adjusted to minimise the RMSE

The RMSE optimisation approach discussed in the previous chapter resulted in a R^2 correlation of 0.448 when compared with the chosen observed data. The PCSWMM results were similarly compared to the observed flow data and a R^2 correlation of 0.366 was obtained when compared with the chosen observed data. These correlation coefficients are too low to provide confidence in the modelling results according to Boughton (2006) as the value should be at least 0.6.

The calibrated AWBM and PCSWMM input parameters are presented in Table 4.1 and Table 4.2 respectively and full- and truncated times series results are presented in Figure 4.2 and Figure 4.3 respectively to allow a comparison between the rainfall and the predicted flow rates. It should be noted that the rainfall indicated is the daily sum of the rainfall from the three rain gauges, i.e. the total system rainfall for the whole catchment. The summation of catchment rainfall depths is deemed to be an appropriate inclusion on the graphs as the sub-catchments have approximately equal areas and hence there the total does not need to be a weighted total, especially considering the runoff is the sum of the sub-catchment runoff rates, i.e. system flow for the whole catchment.

Table 4.1 Comparison of AWBM input and calibrated parameters

Parameter	Units	Start value	Optimised value
BFI1		0	N/A*
BFI2			
BFI3		0.658	~0
BFI4			0.534
BFI5			0.192
BFI6			0.824
Kb1		0.309	~1
Kb2			0.971
Kb3			0.162
Kb4			~0
Kb5			0.963
Kb6			~0
Ks1		0.869	~1
Ks2			0.660
Ks3			~0
Ks4			~1
Ks5			0.054
Ks6			~1
C1L	mm	12.4	297.6
C1M			299.6
C1U			17.0
C2L	mm	126	11.2
C2M			123.7
C2U			110.9
C3L	mm	252.0	299.6
C3M			130.4
C3U			15.7
Zaaihoek Dam starting volume	m^3	55,365,000	4,673
Diameter of orifice pipe	m	1.2	1.2
Discharge coefficient (Cd)		0.67	~1
Martin's Dam starting volume	m^3	167,323	29,744
Wakkerstroom Vlei retention time	days	19	38

**Excluded from optimisation runs due to the exclusion of the baseflow component for the Wakkerstroom Vlei.*

Table 4.2 Calibrated PCSWMM variables

Parameter		Units	Initial value	Calibrated sub-catchment values		
				Upper	Middle	Lower
Depression storage	Impervious	mm	1	1	1	1
	Pervious		2	1.5	2	2.5
Percentage impervious		%	2	13.8	12.0	6.1
Zero impervious			25	100	100	100
Manning's roughness	Impervious		0.01	0.01	0.01	0.01
	Pervious		0.5	0.5	0.5	0.5
	Natural channels		0.05	0.05	0.05	0.05

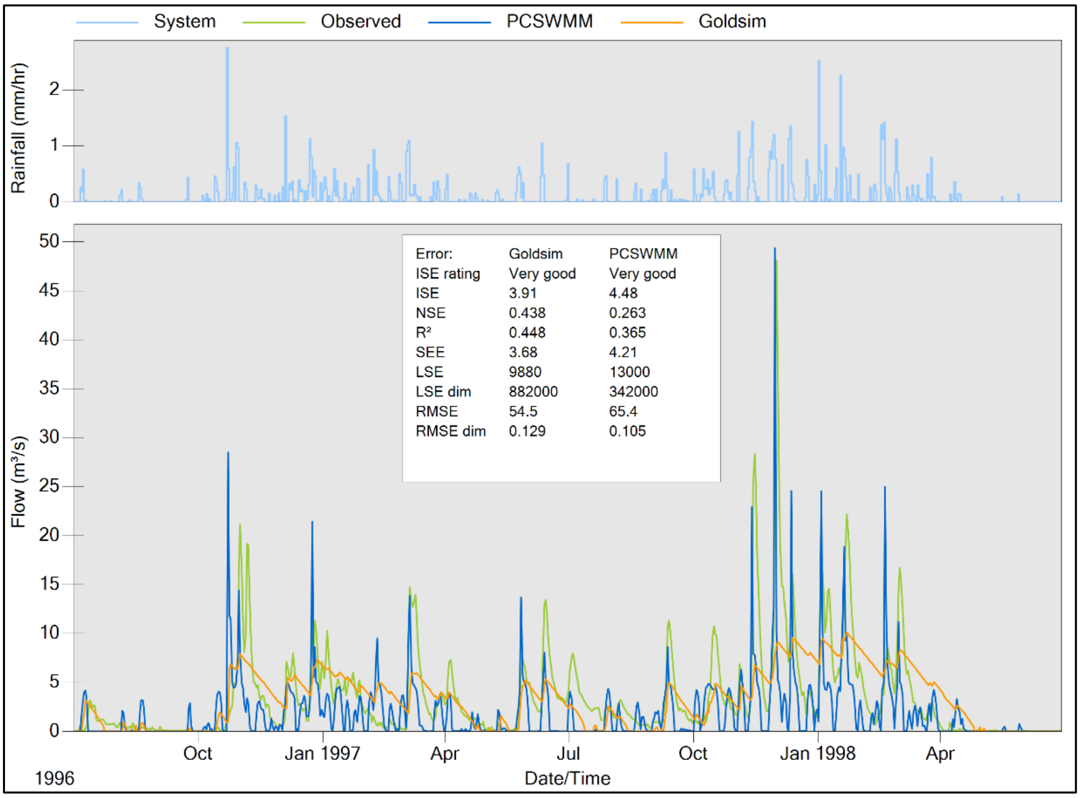


Figure 4.2 Comparison of observed and predicted flow rates with rainfall

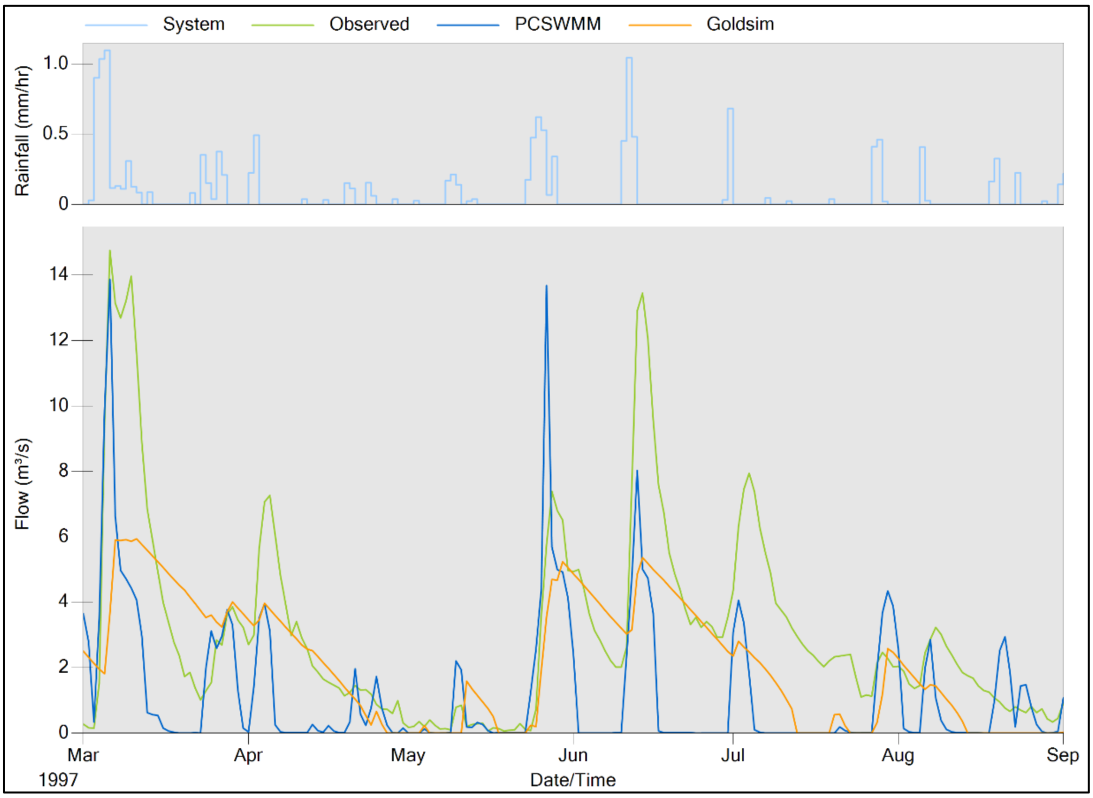


Figure 4.3 Comparison of observed and predicted flow rates with rainfall - 6 month zoomed in period

When comparing the AWBM and PCSWMM results, the following general observations are made:

- The Goldsim AWBM provided better baseflow correlations than the PCSWMM results.
- The PCSWMM results provided a better fit for the peak flows than the AWBM.

The peaks in the observed flow data appear to closely approximate the peaks in the observed rainfall data, which gives support to the selection of this period of data for the modelling. The amplitude of peaks in the Goldsim AWBM results poorly approximate the observed flow data, but the frequencies of the peaks do correspond. Conversely, the amplitude of the peaks predicted by the PCSWMM seem to match relatively well, while the frequencies of the peaks similarly match. The magnitude of the Goldsim AWBM peaks during low flows correspond better with the observed data than the similar low flows for the

PCSWMM results, although the AWBM results do seem to slightly overestimate the lower flows.

This underestimation of the larger flow events has been noted as a limitation of the model by the developer of the AWBM (Boughton, 2004). The fact that PCSWMM has a better match to the observed peak flow rates than the Goldsim AWBM results in terms of mimicking the graph, but a poorer overall R^2 correlation value (0.365 compared to 0.448), reinforces the assertion that extreme events skew the calibration of rainfall runoff models (Boughton, 2006).

A weakness in generating daily evaporation input data from monthly evaporation data is that equal evaporation occurs every day of the month, regardless of whether or not it rains that day. While this is not expected to significantly lower the correlation between the predicted and observed data, it does negatively impact upon the results but is still deemed to be an appropriate approximation for this modelling.

Some of the simplifying assumptions made during this research, such as modelling of the orifice outlet pipes from the Zaaihoek Dam as a single pipe, potentially limit the accuracy of the model but the assumptions were necessary in light of not being able to obtain more consistent and reliable data.

4.1.1 AWBM

The AWBM within Goldsim was able to account for both the surface and baseflow components of the incoming streams and it is believed that better calibration of the model would have been possible with better quality input data. Comments on the calibrated parameters have been included as follows:

- **BFI**: The baseflow indices included for BFI1 and BFI2 are for the catchment feeding the Wakkerstroom Vlei. Due to the presence of the dolerite outcrops highlighted by Joubert and Ellery (2013) which prevent groundwater flows from entering the Vlei, these baseflow contributions were set to zero. BFI3 parameter optimised to result in negligible groundwater contributions to the Zaaihoek Dam, although this is counterintuitive as there are no known dolerite outcrops within the BFI3 region to prevent groundwater reaching the Dam. The low to high range of BFI values for the Slang River catchment do not allow conclusive statements to be made around the influence of groundwater on the overall flow contributions for this river catchment.

- **Kb**: The baseflow recession constant has a default value of 0.309 within the AWBM. The calibration results ranged from ~0 to ~1 which makes it appear that the calibration, understandably, focussed more on mathematical calibration rather than calibration to achieve realistic parameter values. It would have been advantageous to physically calibrate this parameter with site specific data using the streamflow records (Klaassen and Pilgrim, 1975) if such flow data existed.
- **Ks**: Similar to the baseflow recession constant, the surface water recession had its calibrated values range between ~0 and ~1 even though the default value was 0.869. Like the baseflow recession constant, it is felt that the mathematical calibration took preference over the realistic calibration and this parameter could also be physically calibrated within the catchment using the streamflow records (Klaassen and Pilgrim, 1975) if such flow data existed.
- **C1**: The first surface storage capacity was expected to be close to 12 mm but the calibration got this value closer to 300 mm for the lower and middle catchments while the upper catchment result of 17 mm indicated relatively good agreement with the specified starting value. The large values for C1L and C1M indicate that these catchments appear to be more sensitive to larger rainfall events as the lower rainfall depths would effectively get excluded with the high C1 surface storage capacities.
- **C2**: This second surface storage capacity was initially calculated to be 126 mm and the C2M catchment is in very close agreement with this value as the calibration value was ~124 mm. C2U reached an optimised value of ~111 mm which is also relatively close to the starting value. C2L value of just over 11 mm is lower than expected and places greater reliance on smaller storm events, although this large

discrepancy between expected and optimised values could partially be mathematically compensating for the large depth reached during the calibration of C1L.

- **C3**: The third surface storage capacity was expected to be 252 mm based on literature (Boughton, 2010). C3L was only slightly higher (~300 mm) than this value and hence probably reasonable, but C3M and C3U are ~130 mm and ~16 mm respectively and hence much lower than the anticipated value. This could again be due to the model mathematically compensating for some of the higher storage capacity values in the other catchments.
- **Zaaihoek Dam starting volume**: It was assumed that the starting volume would be 30% of the capacity due to the modelling starting in the middle of the dry season. This result of 4,673 m^3 is far lower than expected as it equates to less than 0.003% of the total capacity and it is likely by this point in the stage capacity of the actual dam that the water would have negligible depth, probably appear to effectively be dry and almost unable to yield even the ecological flow reserve. This value is consequently not seen as reasonable as the modelling only started in the middle of a dry season during a fairly normal hydrological year.
- **Diameter of orifice pipe**: The possibility of multiple pipes ranging between 400 mm and 1200 mm diameter without any information on the operational rule of these pipes resulted in a single 1200 mm pipe being selected as the starting point with an upper limit of 1200 mm specified for the optimisation. It can be concluded that since the optimisation kept the diameter at the upper limit that a single pipe is probably inadequate to match the observed flows, especially during higher flow periods.
- **Discharge coefficient**: A commonly accepted factor of 0.67 was specified as the starting value for the optimisation. However, the optimisation concluded that the value should be close to unity. This result further reinforces the belief that a single 1200 mm pipe was not adequate to model the ecological reserve flows, especially

the high flows, from the Zaaihoek Dam as the coefficient was facilitating more water out through the pipe instead of allowing for realistic energy losses.

- **Martin’s Dam starting volume**: It was assumed that the starting volume would be 30% of the capacity due to the modelling starting in the middle of the dry season. This result of 29,744 m^3 is lower than expected as it equates to just over ~14% of the total capacity.
- **Wakkerstroom Vlei retention time**: the duration was found to be 38 days as part of the calibration process, which compares favourably with the nutrient data (Sanderson, 2018). The nutrient data showed that the shapes of the nitrate curves at the inlet to the Vlei and at the end are between 34 and 39 days when only looking at the large trough in the data, and roughly 40 days (±13 days) when other troughs and peaks are compared. While this manual analysis of the nutrient data is not necessarily accurate, especially given the patchy nature of the data, it does add some credibility to the predicted retention time.

4.1.2 PCSWMM

Although PCSWMM has the ability to model rural catchments, it was developed for urban catchments (Kumar et al., 2006).

Clilverd *et al.* (2016) found that PCSWMM was sensitive to the roughness coefficient but this was not evident in the calibration of the developed model. The Manning’s roughness parameters were included within the calibration set of variables, but only negligible modifications were recommended by the SRTC to the extent that these parameters were left unmodified.

The length of the weir outlet from the Vlei was initially set to be equal to the width of the Vlei, although the calibration of the model resulted in the weir length being equivalent to roughly two thirds of the Vlei width. This is probably a reasonable conclusion given how tortuous the outlet of the Vlei appears to be while narrowing to the outlet channels as highlighted on Figure 4.4.

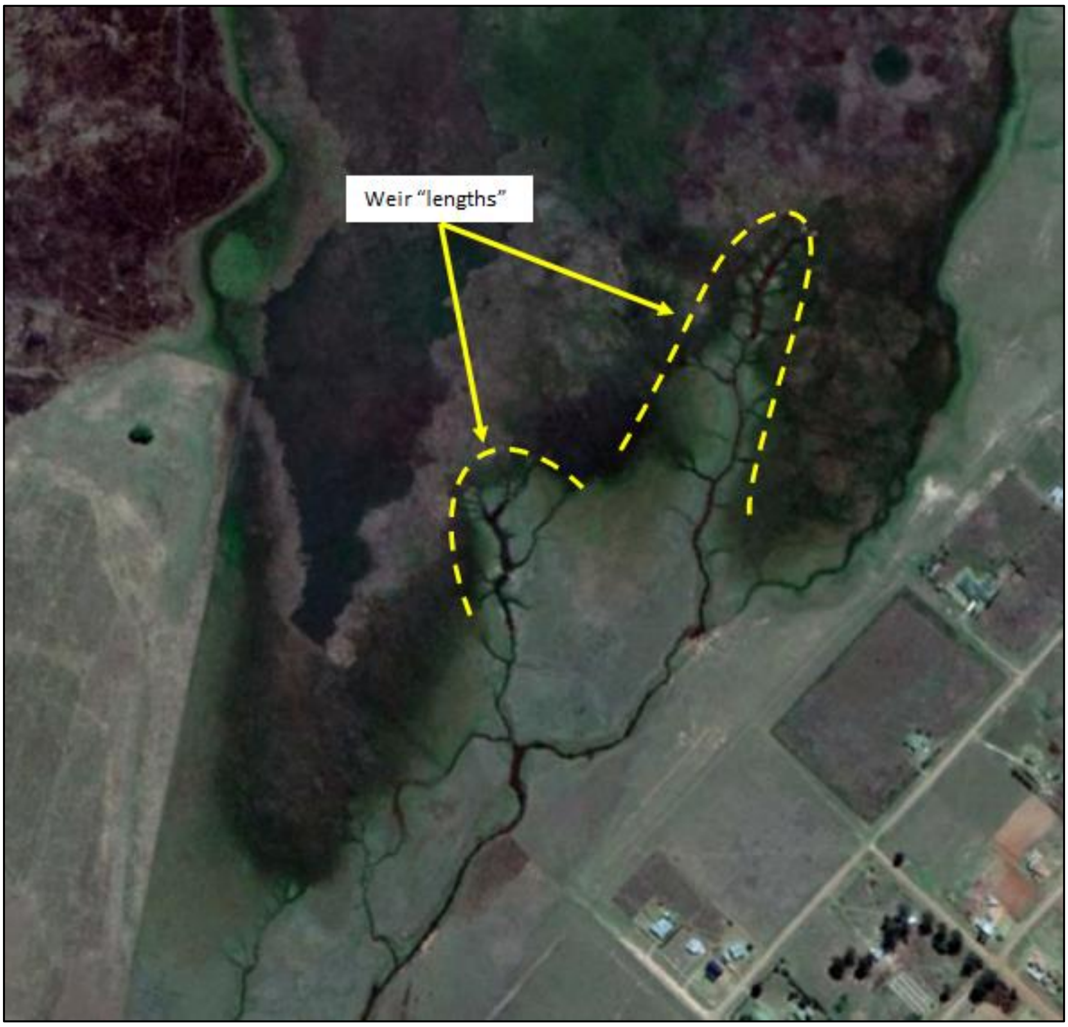


Figure 4.4 Approximated Vlei outlet weir lengths (Background image from Google (2020))

Conversely to the AWBM modelling, the calibration of the diameter of the orifice leaving the Zaaihoek Dam reduced the pipe diameter and discharge coefficient to 741 mm and 0.485 respectively.

The depression storage for the pervious catchment portions decreased slightly from 2 mm to 1.5 mm for the upper catchment, stayed the same for the middle catchment and increased slightly for the lower catchment. This is to be expected that the steeper sub-catchments will have less depression storage than flatter sub-catchments, although it was expected that the range would be closer to 4 mm to account for the tall grasses and shrubs which are present in the sub-catchments.

An unexpected larger change during the calibration tuning process was the increase in the percentage of impervious catchment in each sub-catchment. The upper, middle and lower sub-catchments increased from 2% to 13.8%, 12% and 6.1% respectively. Furthermore, the model calibrated that the whole portion of this impervious area has zero depression storage and hence reports almost immediately as runoff.

The only infiltration parameter which the calibration tuning adjusted was the saturated hydraulic conductivity. It was reduced from ~30 mm/hr to ~15 mm/hr. This was considered to be one of the ways in which the model increased the runoff to better match the peaks.

4.2 Research Question 2

This research sought to inform the work undertaken by the APES by hydrologically modelling the retention time of the Wakkerstroom Vlei. This RO utilised the results of the hydrological modelling of the Zaaihoek Dam catchment (first RO).

The overall hydrological model was setup with the Wakkerstroom Vlei as a separate modelling piece and hence minimal additional work was required to extract the relevant predictive model portion for the Vlei out of the whole model. As this portion of the model does not have observed data associated with it, it was not possible to calibrate the predictive model. The Vlei was hydrologically modelled using both the AWBM and PCSWMM and the results with the system rainfall are presented below as Figure 4.5 to allow comparisons between the predicted results from the two different models.

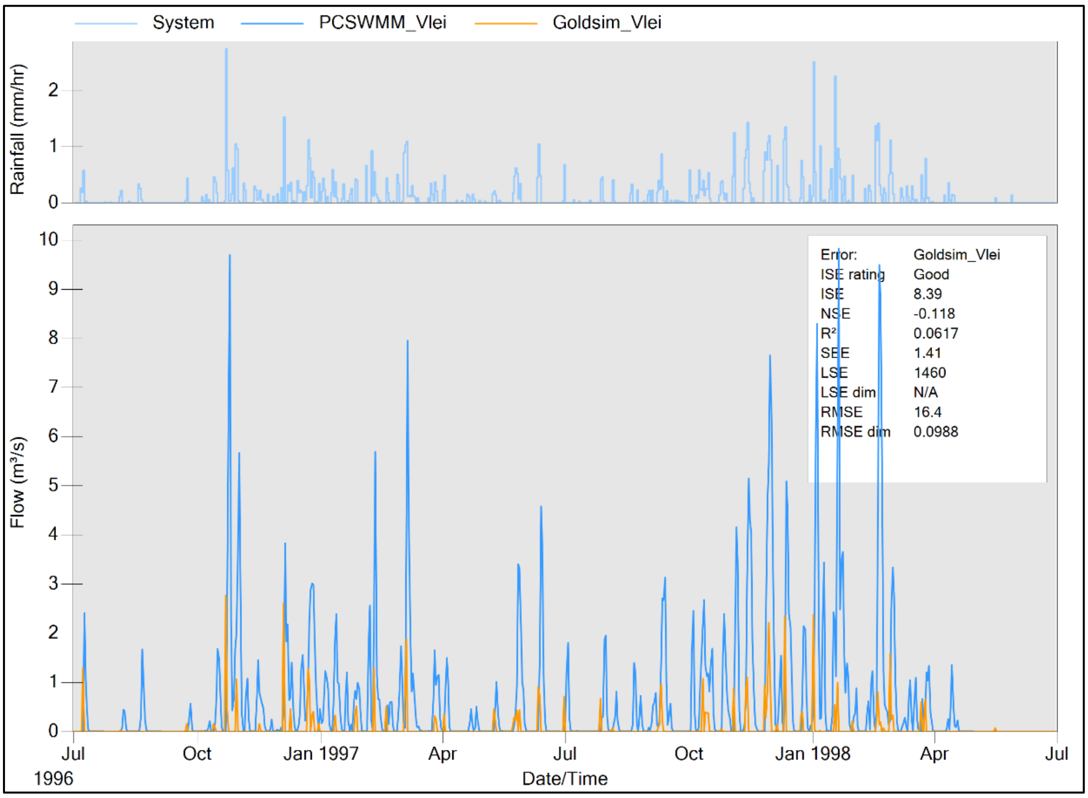


Figure 4.5 Comparison of predicted Wakkerstroom Vlei outflows for PCSWMM and Goldsim

The R^2 correlation between the predicted flow rates is only 0.062 and this indicates a poor correlation between the outputs from both models, although it is worth highlighting based on discussions for the overall catchment that each model has its own relative strengths with regards to high and low flows and hence a single comparison between them does not necessarily mean that the models are only correct for the pieces they are in agreement. The shape of the predicted rates typically follows the system rainfall, as to be expected. It can further be seen that the PCSWMM peak flow rates are generally three to four times the rates predicted by the AWBM.

4.3 Research Question 3

The intention was to create a quantitative biochemical model for nitrogen removal/ assimilation by building on the hydrological model developed as part of the second RO. However, it was necessary to make a number of simplifying assumptions to allow a qualitative model to be developed.

It was not possible to undertake quantitative nutrient modelling due to the sporadic nature of the available observed nutrient data. The relevant modelling principles were incorporated into the Goldsim AWBM by using the CTM to allow an indication of how the modelling of nitrogen would have been undertaken if more comprehensive data were available. This was done by assigning probability distributions for each set of supplied nitrate data points (Sanderson, 2018) and attempting to get the extended Goldsim model to calibrate accordingly.

The input distribution concentrations were based on the supplied data set. The various flows include the incoming river quality, sewage inflow and Wakkerstroom Vlei outflow concentrations are presented in Figure 4.6

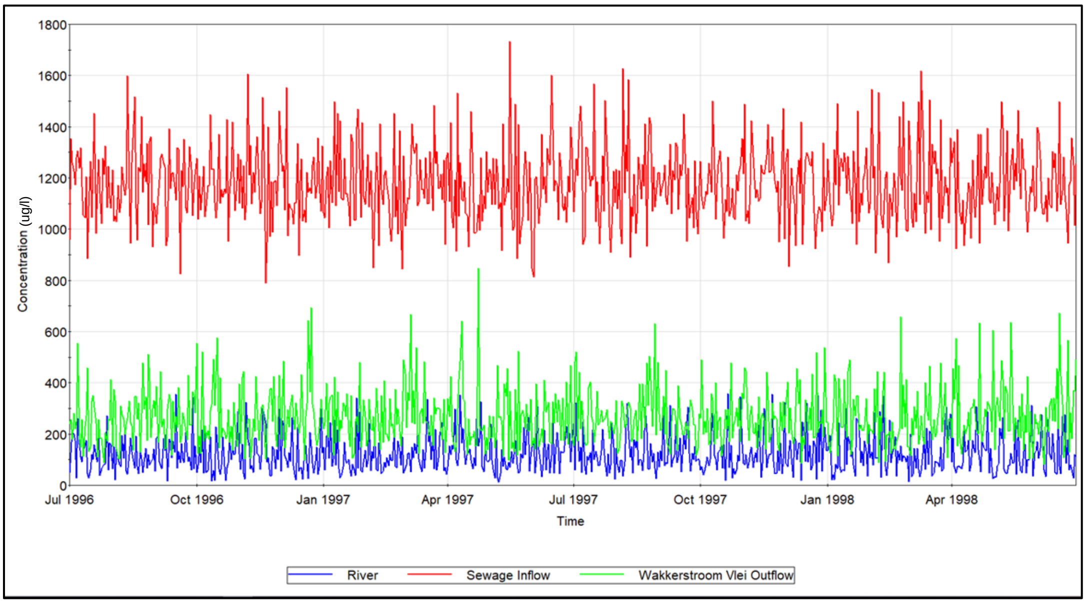


Figure 4.6 Nitrate input rates into Goldsim model

However, the numerous data gaps and simplifying assumptions made it difficult to achieve a working model that generates reasonable results, even when the same RMSE approach, as utilised during the hydrological model, was incorporated.

It was expected to see trends in the data set indicating varying uptake and transfer rates in the nutrient modelling results, as the rate at which nutrients, specifically nitrogen and phosphorous, are taken up in wetlands is influenced by seasonal changes in vegetation

(Khan and Shah, 2010). This ability to view the uptake rates was limited due to the simplistic nature of the model. The modelled results are presented in Figure 4.7.

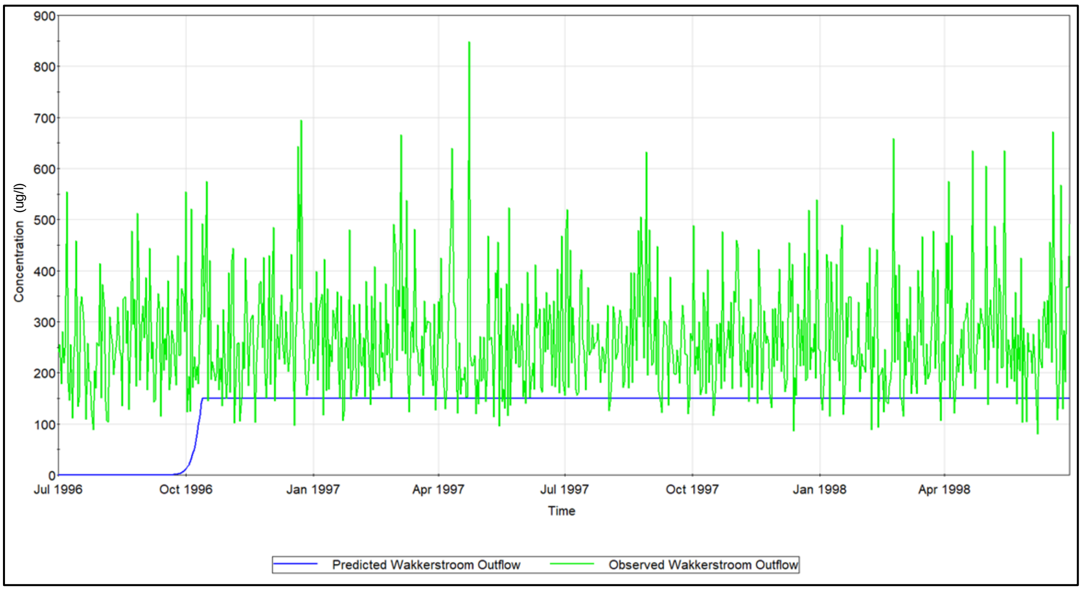


Figure 4.7 CTM results

The results are considered to be unrealistic as the modelled outflow reaches an equilibrium concentration and then stays perfectly constant even though the supplied outflow data indicates variability in the outflow nitrate concentrations.

5 CONCLUSIONS AND RECOMMENDATIONS

The AWBM and PCSWMM results both predicted flow peaks at the correct frequency when compared to observed flow data, however the peaks of the AWBM were generally of a lower amplitude than the observed data which was expected (Boughton, 2004). The amplitude of the PCSWMM peaks matched the observed data fairly well.

Due to the better correlation compared to PCSWMM, it is recommended to utilise the AWBM to support decision making purposes even though the correlation value of 0.448 is below the commonly accepted threshold value of 0.6, although some additional calibration would be required.

The baseflow and surface water recession constants could be physically calibrated within the catchment using the streamflow records (Klaassen and Pilgrim, 1975) and so it would be advantageous for additional flow monitoring stations to be installed to assist with the calibration of these parameters.

As with the majority of research studies, additional better quality data would assist in better calibration of the models. This data should include daily rainfall, evaporation and climate data as well as daily flow rates at gauging stations. The flow gauges should ideally be sited at least one per sub-catchment, with the rain gauges similarly being sited in each catchment.

A flow gauge before and after the Wakkerstroom Vlei would facilitate calibration of the predictive flow model for the Vlei.

While obtaining additional water quality data for the polluted water emanating from the sewage plant would assist with modelling the flow of nutrients, the first priority should be to stop the pollution source.

The developed nitrogen model is not considered to be useful to others due to the number of simplifications and assumptions made while setting it up. However, additional nutrient data, with the sampling frequency being on a daily time scale as far as possible, would assist in developing a more robust data set to inform the nitrogen assimilation capacity of the Vlei. The overlapping of the nutrient and rainfall data sets would also be advantageous.

The stage capacity relationships of the Zaaihoek and Martin’s Dams were developed utilising the available survey data but bathymetric surveys of these storage facilities, as well as for the Wakkerstroom Vlei would improve the accuracy of the depth-volumetric relationship.

It is strongly suspected that the weir downstream of the Zaaihoek Dam may require calibration for larger flow events due to the mismatch between the observed spillway and total weir flow rates. Development of a weir rating curve for this hydraulic structure would also assist similar modelling in the catchment.

Obtaining an understanding of the operational rule of the orifice pipes which control the ecological reserve would allow the models to be extended to take account of the additional operating considerations and complexities.

6 REFERENCES

Acreman, M. and Holden, J. (2013), “How wetlands affect floods”, *Wetlands*, Springer, Vol. 33 No. 5, pp. 773–786.

Acreman, M.C. and Miller, F. (2006), “Hydrological impact assessment of wetlands”, *Proceedings of the ISGWAS Conference on Groundwater Sustainability, Spain*, pp. 225–255.

Arega, F. (2013), “Hydrodynamic modeling and characterizing of Lagrangian flows in the West Scott Creek wetlands system, South Carolina”, *Journal of Hydro-Environment Research*, Elsevier, Vol. 7 No. 1, pp. 50–60.

Arsenault, R., Brissette, F. and Martel, J.-L. (2018), “The hazards of split-sample validation in hydrological model calibration”, *Journal of Hydrology*, Elsevier, Vol. 566, pp. 346–362.

Baldwin, D.S., Mitchell, A.M. and Rees, G. (2001), “Nitrogen cycling in Australian wetlands—a synthesis”, *Nitrogen Workshop 2000*, p. 100.

Bales, R.C. (2015), “HYDROLOGY, FLOODS AND DROUGHTS | Overview”, in North, G.R., Pyle, J. and Zhang, F.B.T.-E. of A.S. (Second E. (Eds.), , Academic Press, Oxford, pp. 180–184.

Beven, K.J. (2006), “Rainfall-runoff modeling: Introduction”, *Encyclopedia of Hydrological Sciences*, Wiley Online Library.

Boughton, W. (2006), “Calibrations of a daily rainfall-runoff model with poor quality data”, *Environmental Modelling & Software*, Elsevier, Vol. 21 No. 8, pp. 1114–1128.

Boughton, W.C. (1987), “Evaluating partial areas of watershed runoff”, *Journal of Irrigation and Drainage Engineering*, American Society of Civil Engineers, Vol. 113 No. 3, pp. 356–366.

Boughton, W.C. (2004), “The Australian water balance model”, *Environmental Modelling & Software*, Elsevier, Vol. 19 No. 10, pp. 943–956.

Boughton, W.C. (2007), “Effect of data length on rainfall--runoff modelling”, *Environmental Modelling & Software*, Elsevier, Vol. 22 No. 3, pp. 406–413.

Boughton, W.C. (2010), *Rainfall-Runoff Modelling with the AWBM*, Engineers Media, available at: https://books.google.co.za/books?id=_drIZwEACAAJ.

Broekhuizen, I., Muthanna, T.M., Leonhardt, G. and Viklander, M. (2019), “Urban drainage models for green areas: Structural differences and their effects on simulated runoff”, *Journal of Hydrology X*, Elsevier, Vol. 5, p. 100044.

Brown, P.W., Monfils, M.J. and Fredrickson, L.H. (2009), “Wetland ecology and Management for Birds and Mammals”, Elsevier.

Bullock, A. and Acreman, M. (2003), “The role of wetlands in the hydrological cycle”, *Hydrology and Earth System Sciences Discussions*, Vol. 7 No. 3, pp. 358–389.

Chapman, T.G. (2003), “Estimation of evaporation in rainfall-runoff models”, *Proceedings MODSIM 2003 International Congress on Modelling and Simulation*, Vol. 1, pp. 148–153.

Charbonneau, C. and Bradford, A. (2016), “Wetland Modeling in PCSWMM: Exploring Options to Define Wetland Features and Incorporate Groundwater Exchanges”, *Journal of Water Management Modeling*, Computational Hydraulics Int.(CHI).

Cheng, S.-T., Hwang, G.-W., Chen, C.-P., Hou, W.-S. and Hsieh, H.-L. (2012), “An integrated modeling approach to evaluate the performance of an oxygen enhancement device in the Hwajiang wetland, Taiwan”, *Ecological Engineering*, Elsevier, Vol. 42, pp. 244–248.

Chow, V. Te, Maidment, D.R. and Mays, L.W. (1988), “Applied hydrology”, *Water Resources Handbook; McGraw-Hill: New York, NY, USA*.

von Christierson, B., Nieuwenhoven, L.A., Butts, M., Hansen, F.T., Jensen, J.K. and Poulsen, J.B. (2015), “Modelling surface water, groundwater and nitrate processes in a restored riparian wetland”, *FEFLOW Conference*, pp. 21–25.

Clilverd, H.M., Thompson, J.R., Heppell, C.M., Sayer, C.D. and Axmacher, J.C. (2016), “Coupled hydrological/hydraulic modelling of river restoration impacts and floodplain hydrodynamics”, *River Research and Applications*, Wiley Online Library, Vol. 32 No. 9, pp. 1927–1948.

Van Dam, A.A., Dardona, A., Kelderman, P. and Kansiime, F. (2007), “A simulation model for nitrogen retention in a papyrus wetland near Lake Victoria, Uganda (East Africa)”, *Wetlands Ecology and Management*, Springer, Vol. 15 No. 6, pp. 469–480.

Davidson, N.C. (2014), “How much wetland has the world lost? Long-term and recent trends in global wetland area”, *Marine and Freshwater Research*, CSIRO, Vol. 65 No. 10, pp. 934–941.

Department of Water and Sanitation. (2017), “Guidelines to regulate activities/developments affecting wetlands”, Pretoria.

Department of Water and Sanitation. (2019), “Hydrological Services - Surface Water (Data, Dams, Floods and Flows)”, available at: http://www.dwa.gov.za/Hydrology/ (accessed 6 February 2019).

Devi, G.K., Ganasri, B.P. and Dwarakish, G.S. (2015), “A review on hydrological models”, *Aquatic Procedia*, Elsevier, Vol. 4, pp. 1001–1007.

Dingman, S.L. (2015), *Physical Hydrology*, Waveland press.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J. and Duncan, A.R. (1997), “The timing and duration of the Karoo igneous event, southern Gondwana”, *Journal of Geophysical Research: Solid Earth*, Wiley Online Library, Vol. 102 No. B8, pp. 18127–18138.

Ellery, W., Grenfell, M., Grenfell, S., Kotze, D., McCarthy, T.S., Tooth, S., Grundling, P.L., et al. (2011), “WET-origins: controls on the distribution and dynamics of wetlands in South Africa.”, *WRC Report*, Water Research Commission, No. 334/09.

Emmett, W.W. (1970), *The Hydraulics of Overland Flow on Hillslopes*, Vol. 662, US Government Printing Office.

Escobar, E.C., Bondad, R.G.M. and Glorioso, A.U. (2015), “Predicting the daily streamflow of ungauged Eastern Dampalit [Los Baños, Laguna, Philippines] subwatershed by using lumped conceptual rainfall-runoff model”, available at: http://agris.fao.org/agris-search/search.do?recordID=PH2017000215.

Fennessy, M.S., Jacobs, A.D. and Kentula, M.E. (2004), *Review of Rapid Methods for Assessing Wetland Condition*.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., et al. (2004), “Nitrogen cycles: past, present, and future”, *Biogeochemistry*, Springer, Vol. 70 No. 2, pp. 153–226.

Golden, H.E., Lane, C.R., Amatya, D.M., Bandilla, K.W., Kiperwas, H.R., Knightes, C.D. and Ssegane, H. (2014), "Hydrologic connectivity between geographically isolated wetlands and surface water systems: A review of select modeling methods", *Environmental Modelling & Software*, Elsevier, Vol. 53, pp. 190–206.

Goldsim. (2018), *Goldsim User's Guide*, Version 12.

Google. (2020), "Google Earth", Accessed 27 and 28 February 2020.

Gopal, B. (1991), "Wetland (mis) management by keeping people out: two examples from India", *Landscape and Urban Planning*, Elsevier, Vol. 20 No. 1–3, pp. 53–59.

Grayson, R.B., Moore, I.D. and Mcmahon, T.A. (1992), "Physically based hydrologic modeling: 1. A terrain-based model for investigative purposes", *Water Resources Research*, Wiley Online Library, Vol. 28 No. 10, pp. 2639–2658.

Griffiths, L.N. and Mitsch, W.J. (2017), "Removal of nutrients from urban stormwater runoff by storm-pulsed and seasonally pulsed created wetlands in the subtropics", *Ecological Engineering*, Elsevier, Vol. 108, pp. 414–424.

Hafezparast, M. and Fatemi, E. (2013), "A Conceptual Rainfall-Runoff Model Using the Auto Calibrated NAM Models in the Sarisoo River", *Journal of Waste Water Treatment & Analysis*, Vol. 04, available at:https://doi.org/10.4172/2157-7587.1000148.

Heneker, T.M. (2002), *An Improved Engineering Design Flood Estimation Technique: Removing the Need to Estimate Initial Loss*, University of Adelaide, Department of Civil and Environmental Engineering.

Ind, M. (2014), "Hydrology and sediment modelling in a South Pacific environment", *Hydrology and Water Resources Symposium 2014*, p. 285.

"IOL news website". (2018), , available at: https://www.iol.co.za/saturday-star/residents-of-wakkerstroom-call-for-municipal-water-pipeline-project-to-be-put-on-hold-18510744 (accessed 16 December 2019).

Jajarmizadeh, M., Harun, S. and Salarpour, M. (2012), "A review on theoretical consideration and types of models in hydrology", *Journal of Environmental Science and Technology*, Vol. 5 No. 5, pp. 249–261.

James, W., Rossman, L.E. and James, W. (2010), *User’s Guide to SWMM5*, 13th ed., CHI Press.

Joubert, R. and Ellery, W.N. (2013), “Controls on the formation of Wakkerstroom Vlei, Mpumalanga province, South Africa”, *African Journal of Aquatic Science*, Taylor & Francis, Vol. 38 No. 2, pp. 135–151.

Kansiime, F., Saunders, M.J. and Loiselle, S.A. (2007), “Functioning and dynamics of wetland vegetation of Lake Victoria: an overview”, *Wetlands Ecology and Management*, Springer, Vol. 15 No. 6, pp. 443–451.

Kazezyilmaz-Alhan, C.M., Medina Jr, M.A. and Richardson, C.J. (2007), “A wetland hydrology and water quality model incorporating surface water/groundwater interactions”, *Water Resources Research*, Wiley Online Library, Vol. 43 No. 4.

Kelly, C.A., Rudd, J.W.M. and Schindler, D.W. (1990), “Acidification by nitric acid—future considerations”, *Water, Air, and Soil Pollution*, Springer, Vol. 50 No. 1–2, pp. 49–61.

Khan, M.A. and Shah, M.A. (2010), “Studies on biomass changes and nutrient lock-up efficiency in a Kashmir Himalayan wetland ecosystem, India”, *Journal of Ecology and the Natural Environment*, Vol. 2 No. 8, pp. 147–153.

Kiesel, J., Schmalz, B., Brown, G.L. and Fohrer, N. (2013), “Application of a hydrological-hydraulic modelling cascade in lowlands for investigating water and sediment fluxes in catchment, channel and reach”, *Journal of Hydrology and Hydromechanics*, Versita, Vol. 61 No. 4, pp. 334–346.

Kim, S.M., Benham, B.L., Brannan, K.M., Zeckoski, R.W. and Doherty, J. (2007), “Comparison of hydrologic calibration of HSPF using automatic and manual methods”, *Water Resources Research*, Wiley Online Library, Vol. 43 No. 1.

Kirpich, Z.P. (1940), “Time of concentration of small agricultural watersheds”, *Civil Engineering*, Vol. 10 No. 6, p. 362.

Klaassen, B. and Pilgrim, D.H. (1975), “Hydrograph recession constants for New South Wales stream. The Institute of Engineers, Australia”, *Civil Engineering Transactions*, pp. 43–49.

Kumar, S., Kaushal, D.R. and Gosain, A.K. (2006), “Assessment of Stormwater Drainage

Network to Mitigate Urban Flooding Using GIS Compatible PCSWMM Model", *Journal of Environmental Engineering*.

Kunz, R.P. (2004), "Daily Rainfall Data Extraction Utility: User Manual v 1.0", *Institute for Commercial Forestry Research, Pietermaritzburg, RSA*.

Lee, C., Fletcher, T.D. and Sun, G. (2009), "Nitrogen removal in constructed wetland systems", *Engineering in Life Sciences*, Wiley Online Library, Vol. 9 No. 1, pp. 11–22.

Li, L., Lambert, M.F., Maier, H.R., Partington, D. and Simmons, C.T. (2015), "Assessment of the internal dynamics of the Australian Water Balance Model under different calibration regimes", *Environmental Modelling & Software*, Elsevier, Vol. 66, pp. 57–68.

Li, Y., Zhang, Q. and Yao, J. (2015), "Investigation of residence and travel times in a large floodplain lake with complex lake-river interactions: Poyang Lake (China)", *Water*, Multidisciplinary Digital Publishing Institute, Vol. 7 No. 5, pp. 1991–2012.

Low, R., Farr, G., Clarke, D. and Mould, D. (2016), *Hydrological Assessment and Monitoring of Wetlands*, edited by Finlayson C. et al., Springer, Dordrecht.

Madsen, H. (2000), "Automatic calibration of a conceptual rainfall--runoff model using multiple objectives", *Journal of Hydrology*, Elsevier, Vol. 235 No. 3–4, pp. 276–288.

Makungo, R., Odiyo, J.O., Ndiritu, J.G. and Mwaka, B. (2010), "Rainfall–runoff modelling approach for ungauged catchments: A case study of Nzhelele River sub-quaternary catchment", *Physics and Chemistry of the Earth, Parts A/B/C*, Vol. 35 No. 13, pp. 596–607.

Mansell, R.S., Bloom, S.A. and Sun, G. (2000), "A model for wetland hydrology: description and validation", *Soil Science*, LWW, Vol. 165 No. 5, pp. 384–397.

Marshall, S.J.B.T.-R.M. in E.S. and E.S. (2013), "Hydrology", Elsevier, available at:https://doi.org/https://doi.org/10.1016/B978-0-12-409548-9.05356-2.

Mayo, A.W. and Bigambo, T. (2005), "Nitrogen transformation in horizontal subsurface flow constructed wetlands I: Model development", *Physics and Chemistry of the Earth, Parts A/B/C*, Elsevier, Vol. 30 No. 11–16, pp. 658–667.

Midgeley, D.C., Pitman, W.V. and Middleton, B.J. (1994), *Surface Water Resources of*

South Africa, 1990, First edit., Water Research Commission.

Moffat, A.S. (1998), “Global nitrogen overload problem grows critical”, *Science*, American Association for the Advancement of Science, Vol. 279 No. 5353, pp. 988–989.

Mohamed, Y.A., Bastiaanssen, W.G.M., Savenije, H.H.G., den Hurk, B. and Finlayson, C.M. (2012), “Wetland versus open water evaporation: An analysis and literature review”, *Physics and Chemistry of the Earth, Parts A/B/C*, Elsevier, Vol. 47, pp. 114–121.

Moradkhani, H. and Sorooshian, S. (2009), “General review of rainfall-runoff modeling: model calibration, data assimilation, and uncertainty analysis”, *Hydrological Modelling and the Water Cycle*, Springer, pp. 1–24.

Perrelli, M. and Irvine, K. (2013), “Planning Level Modeling of E. Coli Levels in a Suburban Watershed Using PCSWMM”, *Pragmatic Modeling of Urban Water Systems, Monograph*, Vol. 21, pp. 423–435.

Price, E.P.F., Spyreas, G. and Matthews, J.W. (2018), “Biotic homogenization of regional wetland plant communities within short time-scales in the presence of an aggressive invader”, *Journal of Ecology*, Wiley Online Library, Vol. 106 No. 3, pp. 1180–1190.

Ramsar, I. (1971), “Convention on Wetlands of International Importance, Especially as Waterfowl Habitat”, *Ramsar (Iran)*, Vol. 2.

Rogers, K.H. (1995), “Riparian wetlands”, *Wetlands of South Africa*, Department of Environmental Affairs and Tourism Pretoria, pp. 41–52.

Sanderson, P. (2018), *The Role of a Natural Wetland in the Removal of Nutrients and Coliform Contaminants in the Wakkerstroom Area, Mpumalanga*, University of the Witwatersrand.

Saunders, D.L. and Kalff, J. (2001), “Nitrogen retention in wetlands, lakes and rivers”, *Hydrobiologia*, Springer, Vol. 443 No. 1–3, pp. 205–212.

Scholes, B. (2018), “Presentation on the Wakkerstroom Vlei at the Wakkerstroom Bird Club AGM, 3 February 2018”, (Unpublished).

Scholz, M. and Lee, B. (2005), “Constructed wetlands: a review”, *International Journal of Environmental Studies*, Taylor & Francis, Vol. 62 No. 4, pp. 421–447.

Şen, Z. (2015), “Chapter 1 - Water Science Basic Information”, in Şen, Z.B.T.-P. and A.H. (Ed.), , Elsevier, Oxford, pp. 1–41.

Senarath, S.U.S., Ogden, F.L., Downer, C.W. and Sharif, H.O. (2000), “On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models”, *Water Resources Research*, Wiley Online Library, Vol. 36 No. 6, pp. 1495–1510.

Shanbhag, A.B. and Borges, S.D. (2008), “Influence of innate wetland characteristics on site selection by wintering waterbirds in tropical freshwater wetlands”, *Proceedings of Taal2007: The 12th World Lake Conference*, Vol. 110, p. 115.

Sharifi, F., Safarpoor, S., Ayubzadeh, S.A. and others. (2004), “Evaluation of AWBM 2002 Simulation Model in 6 Iranian Representative Catchments”, *In Natural Resources*.

Shi, Y., Eissenstat, D.M., He, Y. and Davis, K.J. (2018), “Using a spatially-distributed hydrologic biogeochemistry model with a nitrogen transport module to study the spatial variation of carbon processes in a Critical Zone Observatory”, *Ecological Modelling*, Elsevier, Vol. 380, pp. 8–21.

Smithers, J.C., Chetty, K.T., Frezghi, M.S., Knoesen, D.M. and Tewolde, M.H. (2007), “Development and assessment of a continuous simulation modelling system for design flood estimation. WRC Report No: 1318/1/07”, *Water Research Commission, Pretoria, RSA*.

South African Institution of Civil Engineers. (1989), “Zaaihoek Dam. New developments in rollcrete construction”, *Civil Engineering*, Vol. 31 No. 9, pp. 269–271.

Strand, R., Usher, B., Strachotta, C. and Jackson, J. (2010), “Integrated water balance and water quality modelling for mine closure planning at Antamina”, in Fourie, A., Tibbett, M. & Wiertz, J. (Ed.), *Mine Closure 2010: Proceedings of the Fifth International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth.

The National Water Act (Act No. 36 of 1998). (1998), *The National Water Act (Act No. 36 of 1998)*, *Government Gazette*, Republic of South Africa.

Tiner, R.W. (2009), “Wetland hydrology”, Elsevier.

Tooth, S., Brandt, D., Hancox, P.J. and McCarthy, T.S. (2004), “Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld”, *Journal of African Earth Sciences*, Elsevier, Vol. 38 No. 1, pp. 79–97.

Tooth, S., McCarthy, T.S., Hancox, P.J., Brandt, D., Buckley, K., Nortje, E. and McQuade, S. (2002), “The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa”, *South African Geographical Journal*, Taylor & Francis, Vol. 84 No. 2, pp. 226–237.

Trivisonno, F.N., Rodriguez, J.F., Riccardi, G.A., Saco, P.M. and Stenta, H. (2013), “Modelling estuarine wetlands under climate change and infrastructure pressure”, in Piantadosi, J., Anderssen, R. and Boland, J. (Eds.), , 20th International Congress On Modelling And Simulation (Modsim2013), Adelaide, Australia, pp. 2423–2429.

Tsihrintzis, V.A., John, D.L. and Tremblay, P.J. (1998), “Hydrodynamic modeling of wetlands for flood detention”, *Water Resources Management*, Springer, Vol. 12 No. 4, pp. 251–269.

United States Environmental Protection Agency. (2016), *Storm Water Management Model Reference Manual Volume I - Hydrology (Revised)*, Cincinnati, Ohio, available at: www2.epa.gov/water-research.

UNWWAP, (United Nations World Water Assessment Programme). (2003), *Water for People-Water for Life: The United Nations World Water Development Report*, Unesco Publ.

Vandenberg, J and Lauzon, N and Prakash, S and Salzsauler, K. (2011), “Use of water quality models for design and evaluation of pit lakes”, in McCullough, C.D. (Ed.), *Mine Pit Lakes: Closure and Management*, Australian Centre for Geomechanics, Perth, pp. 63–81.

Verones, F., Saner, D., Pfister, S., Baisero, D., Rondinini, C. and Hellweg, S. (2013), “Effects of Consumptive Water Use on Biodiversity in Wetlands of International Importance”, *Environmental Science & Technology*, Vol. 47 No. 21, pp. 12248–12257.

Wen, L., Macdonald, R., Morrison, T., Hameed, T., Saintilan, N. and Ling, J. (2013), “From hydrodynamic to hydrological modelling: Investigating long-term hydrological regimes of key wetlands in the Macquarie Marshes, a semi-arid lowland floodplain in Australia", *Journal of Hydrology*, Elsevier, Vol. 500, pp. 45–61.

Wester, S.J., Grimson, R., Minotti, P.G., Booij, M.J. and Brugnach, M. (2018), "Hydrodynamic modelling of a tidal delta wetland using an enhanced quasi-2D model", *Journal of Hydrology*, Elsevier, Vol. 559, pp. 315–326.

Woltemade, C.J. (2000), "Ability of restored wetlands to reduce nitrogen and phosphorus concentrations in agricultural drainage water", *Journal of Soil and Water Conservation*, Soil and Water Conservation Society, Vol. 55 No. 3, pp. 303–309.