

Assessment of Pitman Model Capabilities in Modelling Surface Water-Groundwater Interactions in the Lake Sibaya Catchment, South Africa

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By

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DECLARATION

By submitting this thesis, I acknowledge Rhodes University's plagiarism policy and affirm that all material contained herein is my original work and all external contributions are correctly acknowledged. To the best of knowledge, this thesis has never been presented in its current form for a degree elsewhere.

A handwritten signature in blue ink, appearing to read 'Phatsimo P. Ramatsabana', positioned above a horizontal line.

Phatsimo P. Ramatsabana

ABSTRACT

Difficulties arising from data scarcity, input data error or uncertainty, heterogeneous environments, lack of process understanding, and model structural uncertainty frequently constrain hydrological assessments of South African catchments. This research aimed to assess the usefulness of a “simpler” conceptual model for the conjunctive management of surface water and groundwater. The idea is that, to leverage the limited available data and information, a compromise between model complexity and data availability is required, which improves the use of models to produce reliable hydrological systems assessments. The research methodology focused on catchment-scale lake-groundwater dynamics to explore the limits of the groundwater components of the modified Pitman model (Hughes, 2004) in this type of environment, thus, determining the potential for using this model for integrated water assessments in South Africa.

The Pitman model (Pitman, 1973; Hughes, 2013) is one of the most widely accepted models regarding surface water hydrology in South Africa; however, the newly incorporated groundwater components (Hughes, 2004) have not been applied as extensively as the surface water components. There remains uncertainty regarding their capability to adequately simulate groundwater processes and accurately represent surface and groundwater interactions in some environments. The model was assessed based on how well simulated water balance variables accurately reflected available evidence and expected catchment response (objective 1). Secondly, the research identified and addressed uncertainties as regards the structure and application of the model’s groundwater interaction components (objective 2). The model was set up for the Lake Sibaya catchment, which is a predominantly groundwater-driven system and, thus, provides an important opportunity to interrogate different aspects of uncertainty in both the conceptualizing and quantifying interaction processes.

The study’s overall conclusion is that the model performed satisfactorily as it was able to simulate the lake’s water balance correctly enough such that the influences of dominating components were sensibly reflected in variations in streamflow and lake volumes. The following key findings were noted; (i) the lake volume shows a continuous decline, (ii) the lake volume decreased with increasing development (forestry and abstractions) in the lake catchment, (iii) there is significant rainfall uncertainty in the study area and the model showed high sensitivity to rainfall differences, (iv) robust conceptual knowledge of local catchment conditions was valuable for reducing some of the data related uncertainty in the study area and for producing realistic model simulations, (v) the Pitman model (Hughes, 2013) updated GW components can provide a valuable tool for modelling integrated

hydrological processes; nevertheless, when applying the model to specific environments, implicit approaches may be necessary to account for processes that are not fully represented in the model.

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Saki, you're incredible! Thanks for all the things!

Ke a leboga bagaetsho!

DEDICATION

Spha,

When it seemed all was lost, and all hope and evidence for success had long vanished, you kept going and going and going.

You are beyond your imagination.

You are beyond the uncertainty.

Even when you fail, you're not a disappointment.

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LIST OF ACRONYMS

AMSL:	Above mean sea level
CRU:	Climatic Research Unit
ET:	Evapotranspiration
GW:	Groundwater
IWRM:	Integrated Water Resource Management
PET:	Potential evapotranspiration
SC:	Sub-catchment
SW:	Surface water
TLC	Total channel length

1. INTRODUCTION

1.1. Background

Surface water (SW) and groundwater (GW) interactions bear important implications for operational water management related to providing adequate water quantity and quality, preserving biodiversity in river ecosystems, and managing environmental flows (Brunner et al., 2017; Krause et al., 2017). However, despite a general awareness of these implications, the details of how SW and GW interact as a single resource are frequently overlooked in water management in many countries, including South Africa (Parsons, 2004; Levy and Xu, 2011). As a result, water resource estimations remain highly uncertain (Parsons, 2004; Conant et al., 2019).

A key factor barring the full implementation of Integrated Water Resources Management (IWRM) objectives is the scientific uncertainty around the study of interactions (Hughes et al., 2007). Parsons (2004); Rassam et al. (2013); Tanner and Hughes (2015), Li et al. (2016), and Glenday et al. (2021) cite a need for practical water management support tools that, along with other dominant water balance components, incorporate sufficient representations of SW-GW interactions to facilitate accurate water budget estimates. Integrated hydrological models are designed to represent surface and subsurface systems in an integrated manner, thereby enhancing the prospect of complete water cycle prediction, and improving the reliability of water resource evaluations for both SW and GW assessments.

Outputs from previous studies that investigated integrated modelling approaches e.g., Tanner and Hughes, 2015; Li et al., 2016; Yang et al., 2017; Sher et al. (2022) provide an improved understanding of catchment hydrological variables and the complex feedback and interactions between them. Notwithstanding, specific gaps still exist in simulating integrated processes occurring in most interaction environments (Tanner and Hughes, 2015). Many of these gaps are linked to data scarcity issues, particularly in developing regions. Compared to case studies in developed areas, which benefit from the availability of more extensive data sets, it is difficult to apply models in developing regions due to insufficient detailed hydrogeological information for model setup and calibration (Hughes, 2004). Since interactions vary across landscapes, integrated models developed in regions where extensive studies have been undertaken frequently omit processes that may be important in other regions; as such, these models are not always appropriate for simulating different environments (Li et al., 2016). Some key processes occurring in South Africa which require further investigation include; flow in fractured rock aquifers and discrete GW contribution to base flow from these aquifers, the dominance of unsaturated zone flow (interflow) in some environments, indirect recharge and the distribution and extent of transmission losses occurring in the semi-arid landscapes covering the

majority of South Africa (Hughes et al., 2007; Kelbe and Germishuyse, 2010; Tanner and Hughes, 2015). Hydrological models are continuously being modified to account for an improved understanding of processes.

Integrated hydrological models typically fall within two categories (although these can become blurred with more recent model developments). Firstly, physically based, distributed models work towards estimating water flows using a physics-based approach, with many algorithms based on outcomes from field and laboratory experiments (Jaiswal et al., 2020). Hydrogeologists typically use this approach for groundwater-related work. This can be considered a bottom-up approach built on a foundation of individual smaller-scale processes. As understanding these small-scale processes becomes more detailed, the model algorithms can be modified to be more detailed. However, measuring these properties at smaller scales is frequently unrealistic due to resource and measurement limitations. This results in the algorithms becoming somewhat conceptual in reality, as well as parameter values somewhat empirical since calibration is then used to determine appropriate values (Glenday et al., 2021).

Secondly, the alternative approach can be considered a top-down approach (Sivapalan et al., 2003). This approach seeks to understand the overarching nature of the drainage of a basin by finding equations that approximate the outflow (often using rainfall alone). A conceptual understanding of the hydrological processes is used to identify parameters, other inputs and compartmentalised representations guided by the model performance at the catchment scale. This results in an understanding of the conceptualisations of dominant, emergent processes. A significant difference to physically based models is that the parameters and equations are often not linked to individually measurable physical properties and processes. They could represent the consolidation of multiple processes and properties that will occur together. Hence at a larger scale, the emergent properties of the modelled system are understood (Glenday et al., 2021).

Conceptual models offer many advantages, including having fewer data requirements. However, these models employ a broad-brush approach and are therefore limited in their ability to reflect the full complexity of hydrological processes (Xu, 2002; Tanner and Hughes, 2015). Generally, it has been assumed that process-based (physical) models are better suited for the task in a highly heterogeneous environment like South Africa, where a high level of spatial information is necessary for predictions (Mul et al., 2009). However, physically-based models require large data sets that are rarely available (Hughes, 2013). The central question in this dissertation addresses whether it is valuable to employ conceptual models with simplified representations instead of pursuing complex process-based simulations based on incomplete data.

1.2. Pitman model

This study focuses on the second approach and explores the feasibility and utility of the locally developed modified Pitman model (Hughes, 2004) as an appropriate method for modelling integrated water resource interactions in South Africa. The Pitman model (Pitman, 1973; Hughes, 2013) is one of the most widely accepted models regarding surface water hydrology. The model has been utilized for various surface water investigations in South Africa and the Southern African region, for both research and operational management (see, for instance, Midgley et al., 1994; Bailey and Pitman, 2005; Andersson et al., 2006; Mazvimavi et al., 2006; Tshimanga et al., 2011; Tanner and Hughes, 2013; Tumbo and Hughes, 2015; Ndzabandzaba and Hughes, 2017; Kabuya et al., 2020). However, the original Pitman model (Pitman, 1973) model contains relatively simplistic GW components therefore, it was not applicable in environments where GW processes play a significant role in the water balance (Hughes et al., 2007). The inadequate groundwater representation in the model restricted its utilization for integrated water resource management (IWRM) (Hughes et al., 2007). The modified model by Hughes (2004) is used in this work and focuses primarily on a better representation of surface water and groundwater interactions, making it applicable to more catchment conditions than the original version. Catchment processes that have been improved or added by the Hughes (2004) modification include recharge, unsaturated zone interflow processes, GW storage variations and the effects on outflow dynamics, GW outflow to downstream catchments and contributions to stream flow, GW losses to evapotranspiration (specifically in channel riparian margins), transmission losses (streamflow contributions to GW) and catchment-scale impacts of GW abstraction both near and far from the channel (Hughes et al., 2007; Tanner and Hughes, 2015). This research investigates what could be achieved with the modified Pitman model (Hughes, 2004) by testing the use of the groundwater components in the predominantly groundwater-driven environment of the Lake Sibaya catchment.

1.2. Problem framing

Increasing water scarcity in South Africa due to population growth, increased economic development and a highly variable climate have resulted in an insufficient surface water supply (Department of Water Affairs (DWA), 2013). Groundwater resource development is an increasingly important water supply option to relieve some pressure on surface water resources (Braune et al., 2014; Department of Water and Sanitation (DWS), 2016). Given the interaction between SW and GW, comprehensive solutions to assign realistic water quantity and quality thresholds for sustainable allocation of both resources are needed (DWS, 2016). Sustainable water allocation is only possible by utilising reliable data and methodologies to assess the main water balance processes, including representing SW-GW interactions (DWA, 2013; Tanner and Hughes, 2015). Unfortunately, quantitative information on the

complex aquifers in South Africa and their links to stream flow regimes (whether gaining or losing streams) is limited; as such, water evaluations in South Africa are predominantly carried out using non-integrated approaches (Parsons, 2004). Hydrological models have the potential to support comprehensive water resources evaluations; however, given the limited data available and the complex GW setting in South Africa, model outputs are often highly uncertain. Beven (2000) described eroding trust in using hydrological models and outlined an example where planning permission was denied based on the very different outputs of two physically based groundwater models.

Given the obvious difficulties of data scarcity, input data error or uncertainty, heterogeneous environments, lack of process understanding and model structural uncertainty, this project attempts to assess the usefulness of a “simpler” conceptual model for the conjunctive management of surface water and groundwater. The key questions for successfully applying the Pitman model (Hughes, 2004) are whether processes can be adequately represented at broad spatial scales to provide useful information for practical water management and whether a robust conceptual understanding can help to reduce some of the uncertainties associated with parameter estimations in a data-scarce region (Hughes et al., 2010).

1.3. Aim and objectives

Aim:

This study aims to determine the feasibility and utility of applying the conceptual-based modified Pitman model (Hughes, 2004), which is already utilized nationally for surface water purposes for estimating groundwater processes and surface water-groundwater interactions.

Objectives:

- I. Evaluate whether the modified Pitman model (Hughes, 2004) can reliably simulate the water balance of a groundwater-driven system using a robust conceptual understanding of the environment.
- II. Identify uncertainties related to the structure and application of the model’s groundwater and SW-GW interaction components in the Lake Sibaya catchment.

1.4. Research significance and scope

The modelling approach used in this research is entirely focused on the modified Pitman model (Hughes, 2004). It is not the aim to suggest that this modelling approach answers all the problems associated with the integrated development of SW and GW resources. It is not designed for more detailed modelling, such as borehole tests, mining operations etc. (Hughes et al., 2010). The project aims to assess the potential of the model to complement these approaches. One of the key reasons

for selecting the modified Pitman model (Hughes, 2004) is that it is already deployed nationally for surface water purposes. This project examines whether there is potential for the groundwater components of the model to be used for water resource assessment purposes as well. Where less detailed information is required, or where resource evaluations need to be carried out for both surface water and groundwater, could the modified Pitman model (Hughes, 2004) add value?

This study focuses on catchment-scale lake-groundwater dynamics to explore the limits of the groundwater components in this type of environment. The specific objectives of this study (section 1.3) have been designed to assess the updated groundwater components of the Pitman model (Hughes, 2004; 2013) more directly. The case study area, Lake Sibaya, is a predominantly groundwater-driven system and thus provides a significant opportunity to interrogate different aspects of uncertainty in conceptualizing and quantifying the interaction processes. In addition, the water balance of Lake Sibaya (including SW-GW interactions) has been researched in various earlier studies, allowing comparisons to be made between the Pitman model simulations and findings from previous studies that used different approaches.

The modified Pitman model (Hughes, 2004) was developed at Rhodes University's Institute for Water Research (IWR), where the current research is conducted; thus, there is immediate access to knowledge and technical assistance. The Pitman model algorithm is compatible with various modelling platforms. The Spatial and Time Series Information Modelling (SPATSIM) software, which was also developed at the IWR (Hughes and Forsyth, 2006), was used to run the model in this study. SPATSIM includes a user-friendly interface and features facilitating data input, display, manipulation, and analysis for hydrological modelling. The SPATSIM software is freely available from the IWR website, including usage guidelines on SPATSIM and models that are embedded within the main framework, including the Pitman model (<https://www.ru.ac.za/iwr/research/software/>).

1.5. Thesis structure

Following this introduction, chapter 2 of the thesis reviews SW-GW interactions and highlights their significance for practical water resources management. After that, the review looks at how various model approaches depict SW-GW interactions, concentrating on physically-based modelling approaches and conceptually-based models. The review's last section covers the application of hydrological models in South Africa, which also highlights challenges with data insufficiency and evaluates the Pitman model. In chapter 3, a description of the study area's geographic setting is presented. It looks at locality, climate, topography, hydrology, SW & GW abstractions and land cover, all of which contribute to understanding the process that influence the lake's water balance. An overview of the structure and components of the Pitman model and the accompanying wetland/lake

sub-model will be provided in the methods section (chapter 4), which will also explain the modelling approach. A summary of the data sets used in the study is provided together with full details of the process of setting up and calibrating the model for the Lake Sibaya catchment in the context of insufficient data, model structure barriers and additional uncertainties in the study area. Chapter 5 presents the modelling outputs, including lake volume, groundwater recharge, groundwater baseflow, groundwater gradient and downstream groundwater outflow. Chapter 6 discusses the study's findings concerning the established objectives and other existing data and information. The final chapter highlights the main findings of the research.

2. LITERATURE REVIEW

2.1. Introduction

Surface water (SW) and groundwater (GW) are not isolated components of the water cycle; they are closely interconnected and interact to varying degrees across different landscapes (Sophocleous, 2002). The different states of SW-GW connectivity have important implications for water quantity, quality, and ecosystem functioning (Rassam et al., 2013). Therefore, understanding, and quantifying interactions (connections or links) between SW and GW are necessary for sustainable water resources management (Rassam et al., 2013; Conant et al., 2019). Describing either of the components as a residual of the other ignores the crucial importance of interactions with the consequence of highly uncertain water resource estimations (Parsons, 2004; Conant et al., 2019). Integrated hydrological models simulate the combined SW-GW system as a continuum and, thus, can appropriately support integrated water resources assessments (Rassam et al., 2013).

Recently, improved modelling approaches for simulating interactions between SW and GW have been developed, primarily related to the representation of groundwater components (Gilfedder et al., 2012). For example, Hughes (2004; 2013) added more complex groundwater routines to an existing surface water model, the Pitman model (Pitman, 1973), to estimate groundwater contribution to baseflow in South African catchments. Similarly, Karim Sami also modified the Pitman Model to incorporate more explicit groundwater routines, which have been applied nationally in South Africa (Bailey and Pitman, 2015; Sami, 2015). Sami's modifications differ from Hughes (2004) alterations through different representations of groundwater processes. Prucha et al. (2016) applied the MIKE SHE/MIKE11, a fully integrated, physically-based model, to the Mokolo River (South Africa) catchment to quantify the dominant hydraulic and hydrologic indicators for characterizing environmental water requirements in an arid environment. MIKE-SHE now includes the option to simulate either the surface or groundwater components in a semi-distributed and more conceptual manner for regions where data scarcity is an issue (Glenday et al., 2021). Rassam et al. (2013) developed a groundwater model for the Namoi River, Australia, to demonstrate the importance of including SW-GW exchanges in water management models, particularly within the context of a predominantly gaining river. Yang et al. (2016) tested the conceptual groundwater module for the TopNet model, a national-scale hydrologic model using the Pareora catchment in New Zealand as a case study.

Notable modelling achievements notwithstanding, the full integration, extrapolation, and interpretation of SW-GW exchanges remain to be realized. Unresolved modelling issues critical for providing reliable water resource assessments include uncertainty arising from the simplified

conceptualization of complex interaction processes and limited observed data for model parameterisation and calibration (Partington et al., 2017; Kabuya et al., 2020).

2.2. Surface water and groundwater interactions

Surface water is water that resides on the surface of the earth. It is collected into various surface formations such as streams, rivers, lakes, wetlands, estuaries, and oceans. Groundwater occurs in the subsurface below the water table (saturated zone). It occupies the fractures and pores within aquifers and is differentiated from other subsurface water residing above the water table in the unsaturated area, referred to as soil water or interflow (Parsons, 2004). Figure 2.2-1 below illustrates the land surface, unsaturated zone, water table and saturated zone (Winter et al., 1998).

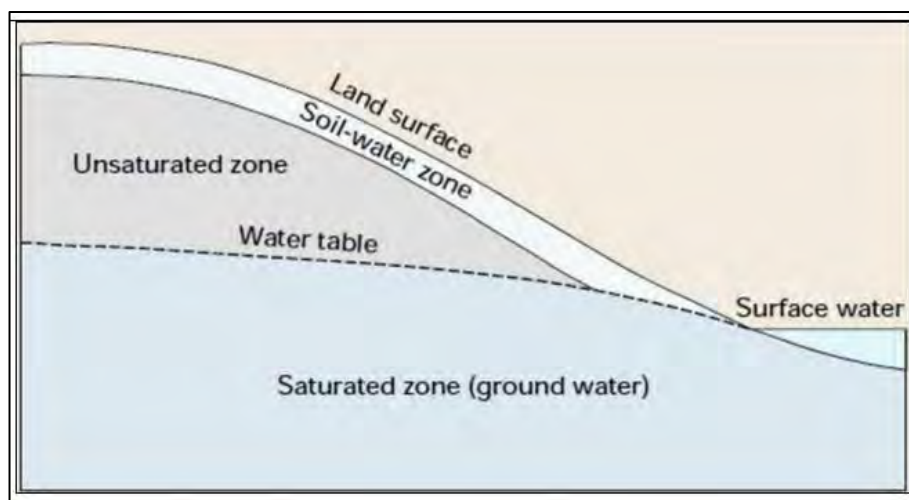


Figure 2.2-1: Illustration of the land surface, unsaturated zone, water table and saturated zone (Winter et al., 1998).

Interactions between surface water and groundwater occur in the transition zone (Biddulph, 2015). The transition zone comprises the SW-GW interface, the hyporheic zone, and the SW-GW eco-hydrological interface (Conant et al., 2019). These transition zone components aid in mixing SW and GW, resulting in the modification of water flow, biogeochemical concentrations, and ecological composition of the water moving between SW and GW (Biddulph, 2015). The approximate positions of surface water, groundwater, and the interaction interface (hyporheic zone) between them are illustrated in Figure 2.2-2.

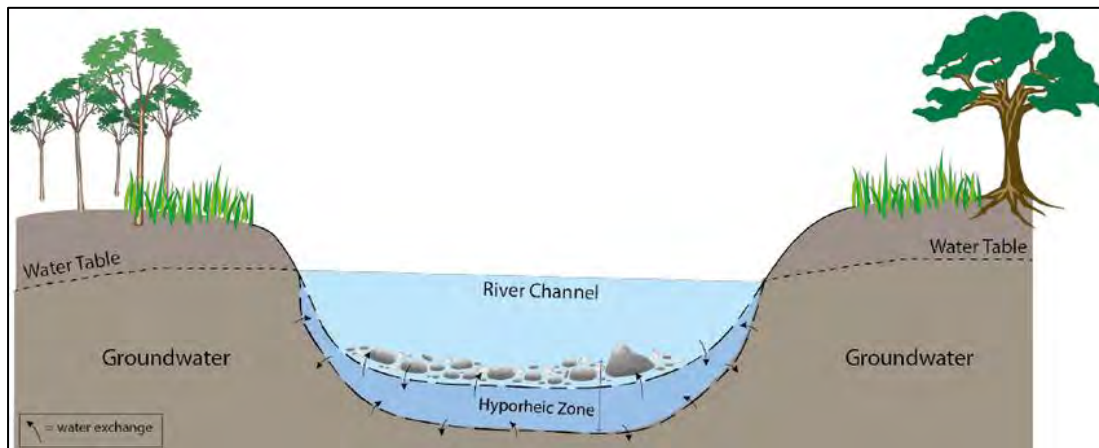


Figure 2.2-2: Cross-sectional Illustration of the approximate positions of surface water, groundwater, and the transition zone between them (Stanford and Ward, 1988).

The transition zone can vary spatially and temporally across landscapes (Biddulph, 2015), as well as different states of connection between surface water and groundwater (Bruen and Osman, 2004). The physical extent of the transition zone directly connecting the GW and SW systems determines the hydrological connection between SW and GW (Bruen and Osman, 2004; Biddulph, 2015). In addition, the physical properties of the transition zone (e.g., sediment erosion, deposition), biological characteristics, and anthropogenic alteration can contribute to enhanced or limited connectivity over time (Brunner et al., 2009). Four types of flow regimes between surface water and groundwater are recognized (Kalbus et al., 2006; Brunner et al., 2009) (Figure 2.2-3):

- I. Connected gaining stream- groundwater table is elevated higher than the streambed, causing water to move from the aquifer into the stream.
- II. Connected losing stream- the height of the water table is below the streambed level, causing water to move from the stream into the underlying aquifer.
- III. Connected intermittent stream- SW is recharged by GW in some parts of the stream and loses water to GW in other regions. In addition, the direction of the exchange flux in an intermittent stream tends to be seasonally variable.
- IV. Disconnected losing stream- similar to a connected losing stream in that the groundwater table is below the streambed; therefore, the direction of water loss is towards the aquifer. The distinguishing feature is that in a disconnected system, the stream is separated from the aquifer by an unsaturated zone.

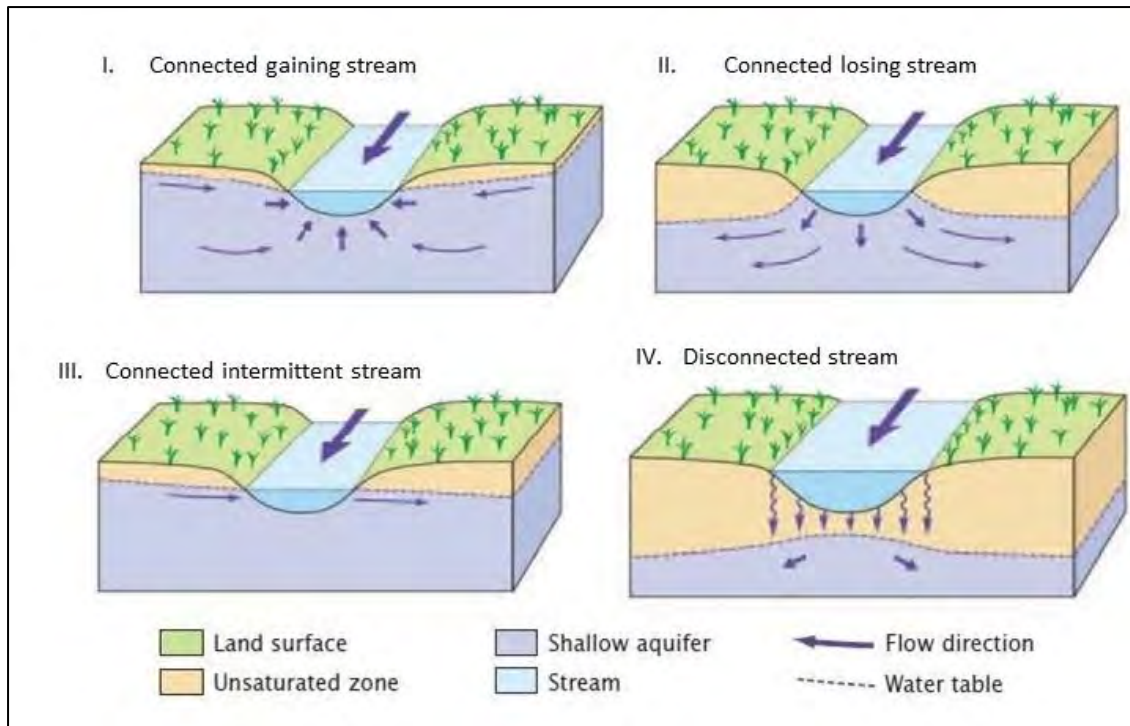


Figure 2.2-3: Illustration of the flow regimes between surface water and groundwater: (I) connected gaining stream, (II) connected losing stream, (III) connected intermittent stream and (IV) disconnected stream (modified from Winter et al., 1999 by Parsons, 2004).

2.2.1. Processes controlling surface water and groundwater interactions

The primary interaction processes making up the water balance of interconnected SW-GW systems are presented in Figure 2.2-4. Equation 2.2-1 demonstrates the impact of these processes on the water balance, providing insight into their importance and potential impact (Tanner, 2013). Understanding the behaviour of interaction processes is vital for evaluating the spatiotemporal patterns of SW-GW interactions in a given environment (Conant et al., 2019).

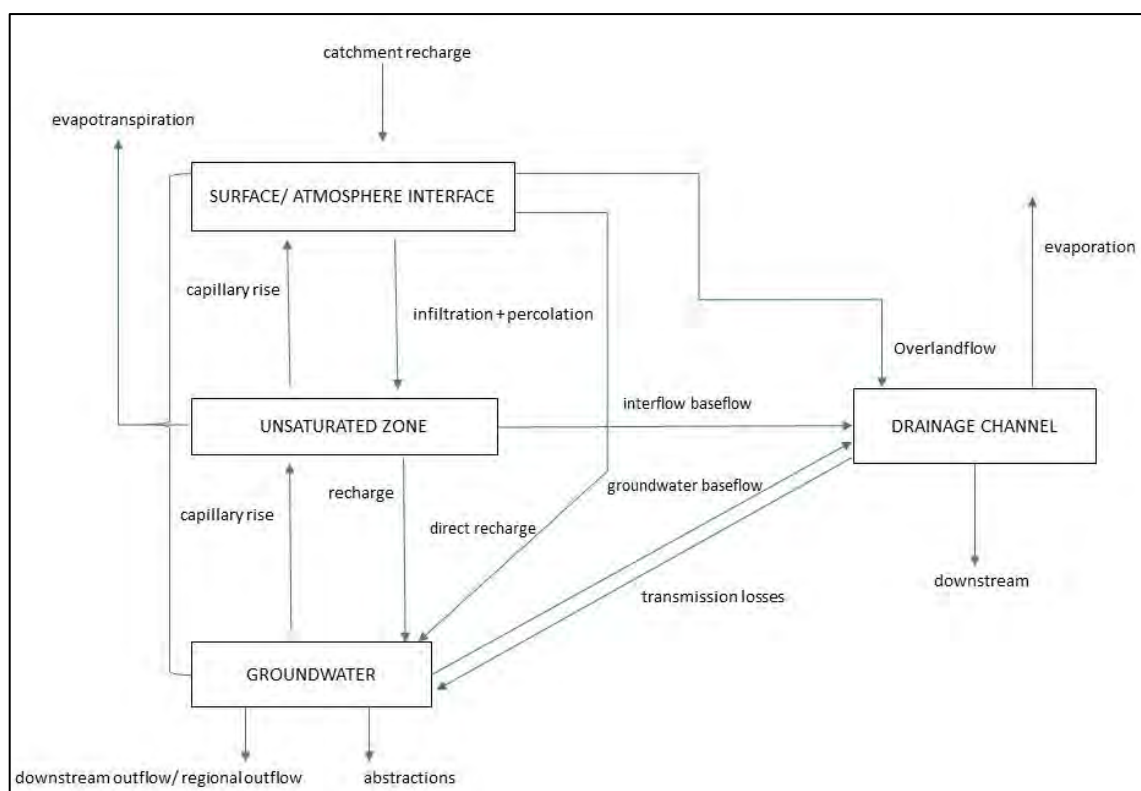


Figure 2.2-4: Basic surface water and groundwater interaction processes (modified from Tanner, 2013).

Equation 2.2-1: $R = ET - BFGW - DSGW - ABS + CL + USGW + \Delta S$

Where: R = recharge, ET = evapotranspiration, BFGW = groundwater baseflow, DSGW = downstream groundwater flow, ABS = abstractions, CL = channel or transmission losses, USGW = upstream groundwater inflow ΔS = the change in groundwater storage.

2.2.2. Implications of surface water-groundwater interactions on water resources management

In many parts of the world, concerns over the decline in the adequacy of current and future water supplies and additional uncertainties due to climate change have pushed the subject of socio-ecological systems resilience to the forefront of water policy discussions (European Commission, 2008). Until recently, these policies often presented surface water-focused assessments, while groundwater featured less prominently (Levy and Xu, 2011). However, as the hydrological sciences have progressed, this relative inattention is changing. The details of how surface water and groundwater interact as a single resource are progressively being better understood and increasingly

accounted for in water management (Fleckenstein et al., 2010). Surface water and groundwater interactions bear important implications for operational water management related to providing adequate water quantity and quality, preserving biodiversity in river ecosystems, and managing environmental flows (Brunner et al., 2017; Krause et al., 2017). Rassam et al. (2013) cite a need for water management support tools that, along with other dominant water balance components, incorporate sufficient representations of SW-GW interactions to facilitate accurate water budget estimates.

Another management challenge is human-related alterations to the natural system (Welsh et al., 2013). Developments such as water abstractions (from both SW and GW sources), dam-building and other impoundments, expansion of forestry and invasive vegetation, and structures in the built-up environment can all impact natural flows (Parsons, 2004). Expected impacts include a reduction in the overall discharge, decreased storage, and altered recharge patterns (Parsons, 2004). Once anthropogenic disturbances occur, they form part of the system and should be evaluated alongside other system components (Welsh et al., 2013). Water planners and managers are faced with difficult decisions about which land uses are sustainable, how SW-GW exchanges influence and are influenced by changes in land use and the potential impacts of climate change on land and water management. The combined effects of different catchment variables must be accounted for to reduce management uncertainties and enhance the beneficial use of both surface and groundwater resources (Rassam et al., 2013). At the same time, it is acknowledged that because many factors influence GW-SW interactions, it becomes even more challenging to assess the potential impacts of GW-SW interactions on water resources (Conant et al., 2019). For instance, interaction processes that strongly influence the water quality dynamics of a given environment may be irrelevant for water quantity assessments of that same environment (Conant et al., 2019). Therefore, the formulation of specific management questions is a critical requirement to leverage available information and correctly conceptualize SW and GW systems, quantify the dominant GW-SW interaction processes, and determine their implication on the relevant aspect of water management (Rassam et al., 2013; Conant et al., 2019).

2.3. Surface water and groundwater management in South Africa

The critical issues of water supply uncertainty and ecological sustainability that have prompted a shift in global water policy towards managing surface and groundwater as a single resource are significantly manifest in South Africa (Parsons, 2004; Levy and Xu, 2011). The South African environment is predominantly semi-arid and is ranked amongst the twenty most water-scarce countries worldwide (Braune et al., 2014). More than 60% of the major rivers in South Africa are experiencing a deficit, and

it is estimated that 98% of the available surface water supply resources are currently being used (DWA, 2013). As a result, groundwater is becoming increasingly relied on. Compared to available surface water resources, the current groundwater availability estimates point toward significant abstraction prospects (DWA, 2010; DWS, 2016). The role groundwater can play in minimizing the impact of severe water shortage is significant. Still, it highlights the need for careful management, bearing in mind that aquifers, too, have finite storage. To ensure its effective contribution, groundwater must be protected and conserved to avoid overexploitation and ongoing declines in groundwater levels over the long term (Calow et al., 2010; Kath and Dyer, 2017).

Alongside surface water management, groundwater resource planning and development in South Africa benefit from being accommodated into a well-established Integrated Water Resource Management (IWRM) policy framework (Levy and Xu, 2011). The IWRM framework encourages providing sufficient water (quality and quantity) equitably for various water-use sectors while supporting the water resource's long-term qualitative and quantitative status (Hiscock et al., 2002). A vital component of this framework is the conjunctive use of both SW and GW resources to ensure that neither resource is over-allocated (DWA, 2013; DWS, 2016).

Through the recently growing body of work exploring integrated approaches for sustainable water management in South Africa, it has emerged that the implementation of IWRM objectives is generally lacking, and SW and GW are still predominantly managed independently (Levy and Xu, 2011). One of the difficulties involved in fully integrating SW and GW into management actions is the scientific uncertainty around the study of interactions (Hughes et al., 2007). Compared to purely surface water investigations where catchment hydrological processes are readily visible, the capacity to measure and assess subsurface flow processes is limited (Parsons, 2004; Hughes et al., 2007). Groundwater fluxes that operate on various spatiotemporal scales are often not adequately considered in management decisions, despite a general awareness of their significance for water management (Parsons, 2004). The situation is further complicated because most available groundwater resources in South Africa come from fractured-bedrock aquifers (Levy and Xu, 2011). To optimize conjunctive water supply, an improved conceptualization and characterization of the main processes affecting the water balance, including representation of the interactions between surface and groundwater systems, is required (DWA, 2013; Tanner and Hughes, 2015).

2.4. Surface water and groundwater representation in water resources models

2.4.1. Classification of hydrological modelling approaches

Developing new and modifying existing models to make them more integrated has produced diverse model approaches that vary in complexity in interpreting and representing hydrological processes (Devi et al., 2015). Based on the complexity involved in process description, models can be categorized as empirical, conceptual, or physically-based (Jaiswal et al., 2020). Because spatial variabilities in model input data and catchment features significantly influence hydrological response, model classification is further expanded to include the different scales of sophistication involved in spatial resolution (Khakbaz et al., 2012). The spatial resolution classes are; lumped, semi-distributed, or distributed (Khakbaz et al., 2012). Following this, the complexity of any model structure can be explained in terms of both process description and spatial resolution (Figure 2.4-1), for example, a semi-distributed conceptual model or a distributed, physically-based model.

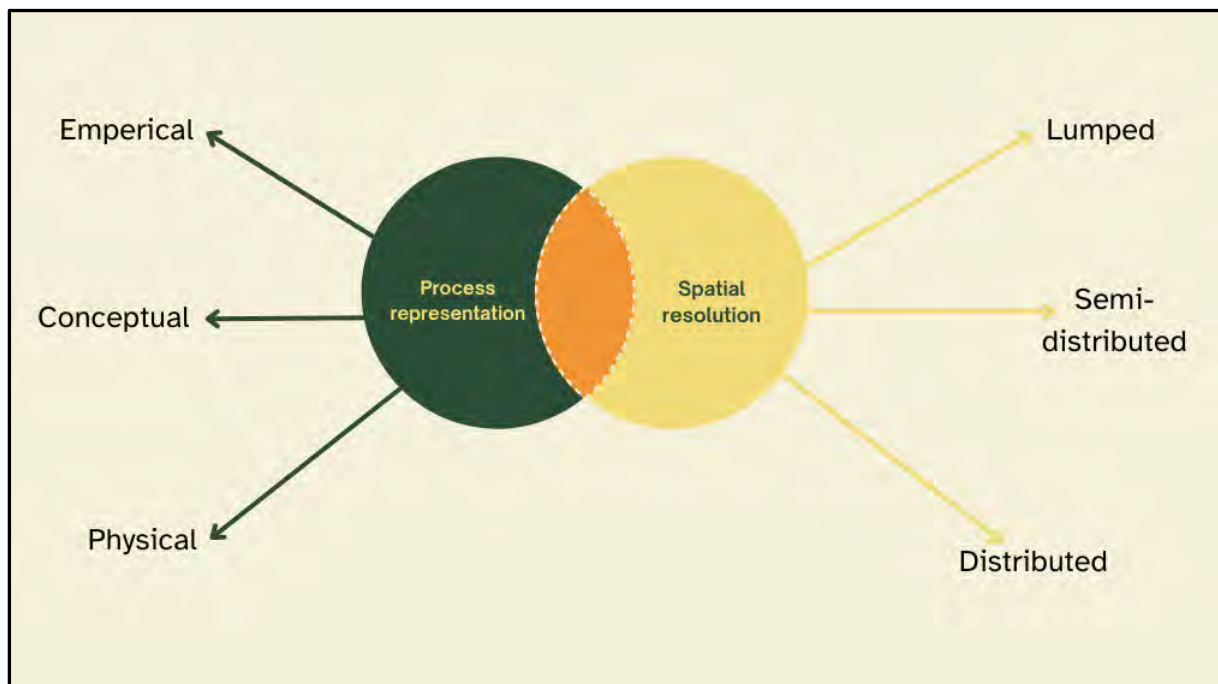


Figure 2.4-1: Hydrological model classification based on process description and spatial resolution complexity.

2.4.1.1. Process representation-based model classification

Empirical models are observation oriented; they characterise the catchment hydrological response using the available data only, without assuming any relationship between the data and the catchment characteristics and processes (Wheater et al., 1993). These models use linear mathematical equations

to describe concurrent input and output relationships between hydrological processes (Devi et al., 2015). Due to their simplicity, empirical models can be easily applied to ungauged catchments through regional analysis methods (Pechlivanidis et al., 2011). At the same time, simulations from empirical models lack precise specifications of confidence limits, which reduces assurance of their ability (Wheater, 2002). Examples of empirical models include the unit hydrograph (UH) (Sherman, 1932) as well as more advanced methods such as Artificial Neural Networks (ANN) (Lange, 1999; Dawson et al., 2006) and Data-Based Mechanistic (DBM) modelling (Young et al., 1997; Ratto et al., 2007). On the other hand, both the conceptual and physically-based modelling approaches account for physical catchment characteristics and processes (either explicitly or implicitly) (Pechlivanidis et al., 2011). Conceptual and physically-based models differ based on the level of detail involved in the model algorithms and how model parameters are quantified. Conceptual models implement semi-empirical expressions to visualise catchment components as interconnected reservoirs that can be recharged and drained by key hydrological processes perceived to be significant at the catchment scale input-output relationships (Wheater, 2002; Jaiswal et al., 2020). The complexity of conceptual models ranges from simple reservoir representations to highly complicated schematics (Wheater) (2002). Conceptual models have tolerable data requirements for parameter estimation. However, some model parameters are uncertain (not independently measurable) and require extensive calibration against observed data (Pechlivanidis et al., 2011). Examples of conceptual models include the Stanford Watershed Model IV (SWM) (Crawford and Linsley, 1966), the HBV model (Bergstrom, 1995) and the Pitman model (Pitman, 1973; Hughes, 2004).

Physical models employ a more detailed process-based approach. They describe catchment processes using complex finite difference equations and analytical expressions (Wheater et al., 1993). Representation of system components and method is deducted from measurable variables with spatial and temporal dimensions; thus, all components have direct physical interpretation (Pechlivanidis et al., 2011). Physical models have a large number of parameters requiring extensive data (e.g., topography, land cover information and soil moisture content) for describing the physical catchment characteristics (Pechlivanidis et al., 2011). Consequently, simulation of runoff response can be achieved without calibration (Beven, 2012). Physically-based models can provide a large amount of information and are generally applicable to a wide range of catchment conditions (Devi et al., 2015). However, the utilization of physical models is often restricted by data availability, quality and resolution (Devi et al., 2015). Examples of physically-based models include TOPMODEL (Kirkby and Beven, 1979; Devi et al., 2015), MIKE SHE (Refsgaard and Storm, 1995; Golmohammadi et al., 2014), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), MODFLOW (McDonald and Harbaugh, 1988; Harbaugh, 2005). Table 2.4-1 briefly compares model types based on process representation.

Table 2.4-1: Comparison between model types based on process representation (adapted from Pechlivanidis et al., 2011 and Devi et al., 2015).

Model type	Empirical model	Conceptual model	Physical-based model
Description	Data-based or black-box model	Parametric or grey box model	Mechanistic or white box model
Process representation	Concurrent input and output relation between processes based on mathematical equations.	Conceptual reservoirs are linked via semi-empirical equations with a physical basis.	Applies finite-difference or analytical equations to evaluate parameters describing physical characteristics. Involves measurable variables.
Approach	Primarily based on available data. Little consideration of catchment features and processes.	Parameters are derived from field data and calibration.	Require data about the initial state of the model and morphology of the catchment
Features	Offers high predictive power but low explanatory depth It cannot be generated to other catchments Valid within the boundary of a given domain	Few parameters, simple to setup and run Calibration requires extensive hydrological and meteorological data Calibration involves curve fitting, which makes physical interpretation difficult	Large parameter set; therefore, model set up and implementation are data intensive. Requires human expertise and robust computation capability Moderate to no calibration is required Applicable to a wide range of catchment conditions Suffer from scale-related problems
Examples	UH, ANN, DBM	SWM, HBV, Pitman model	TOPMODEL, SHE or MIKESHE model, SWAT, ACRU MODFLOW

2.4.1.2. Spatial resolution-based model classification

Catchment hydrological response is significantly affected by variabilities in rainfall and catchment features (Khakbaz et al., 2012). Previous modelling studies, including Wilson et al. (1979), Beven (1985) and Shah et al. (1996), have investigated the relationship between the spatial distributions of rainfall, catchment properties (e.g., soil type, land use, topography) and runoff generation. These studies show that accounting for precipitation variabilities over the catchment affects the simulated

volume, peak duration, and peak flow. Spatial variabilities are represented using lumped, semi-distributed and fully distributed modelling approaches (Khakbaz et al., 2012). Lumped models are the least complex of the three. They simulate the catchment as a single homogenous unit with parameters and model outputs expressing averaged values over the entire catchment area (Khakbaz et al., 2012). Lumped modelling approaches are limited in their ability to solve water resource management challenges due to their lack of spatial detail (Refsgaard, 1997). However, these models facilitate an improved general understanding of large-scale management concerns, for example, evaluating the impacts of groundwater abstraction on stream flow at the catchment scale (Tanner, 2013). Semi-distributed modelling approaches simulate the catchment response by breaking the overall catchment area into separate sub-catchments with similar characteristics (Biftu and Gan, 2001). These models offer a more detailed representation of the spatial heterogeneity of a catchment but without the accompanying additional complexity and data requirements of a fully gridded spatial resolution approach (Refsgaard, 1997). Fully distributed models are highly parameterized (Refsgaard, 1997). When utilizing a fully distributed model, the catchment is divided into many unique elements (grid squares), and modelling data are populated for each grid square (Beven, 2012). Figure 2.4-2 below illustrates the spatial resolution-based model classification.

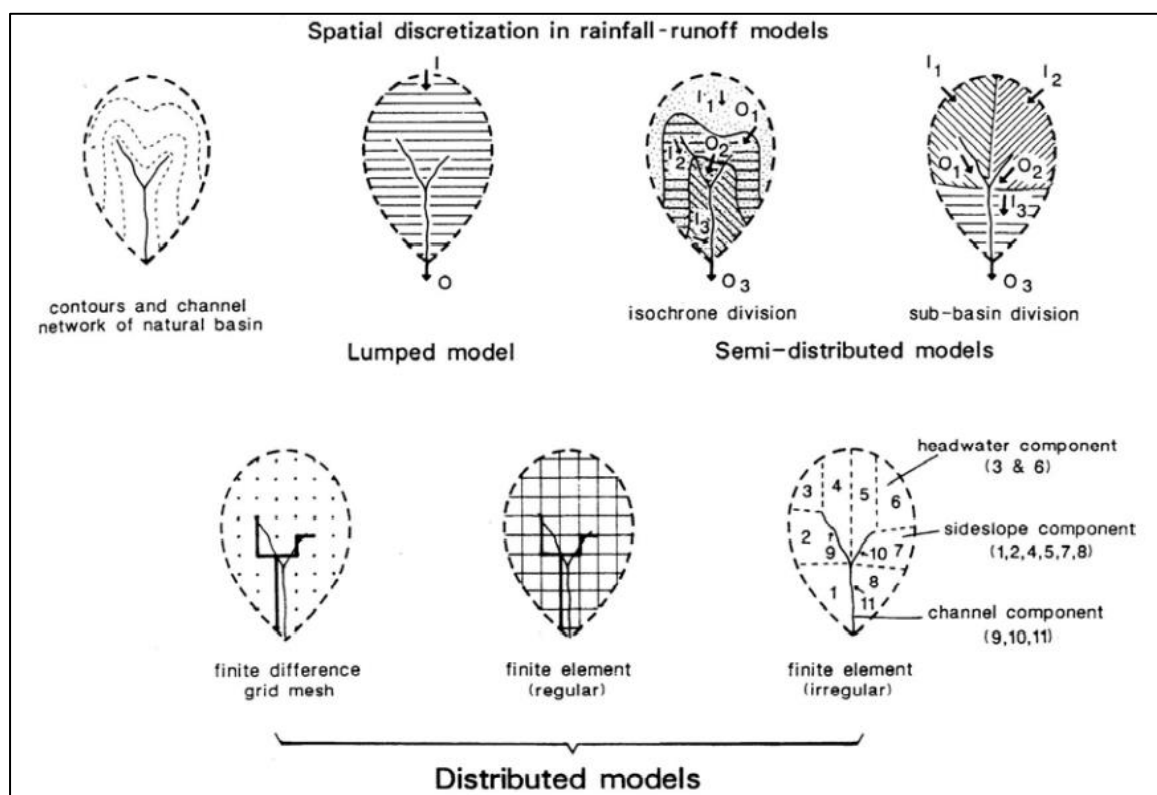


Figure 2.4-2: Illustration of the lumped, semi-distributed and fully distributed spatial resolution modelling approaches. I is input and O is output (Jones, 1997).

2.5. Development and application of hydrological models in South Africa

In South Africa, most catchments are sparsely or entirely not instrumented (Mul et al., 2009; Hughes, 2008; 2013). Consequently, the development and application of models for evaluating water resources in South Africa have generally been constrained by insufficient data to set up and calibrate models (Mul et al., 2009; Hughes, 2008; 2013). Considering the high heterogeneity inherent to the South African environment, Mul et al. (2009) stated that it is preferable to utilize physically-based models because they are most suited to capture these differences more explicitly. However, the lack of adequate long-term, good quality, spatially representative hydro-meteorological data frequently restricts the use of the more complex process-based models in favour of relatively simpler conceptual approaches (Hughes, 2013). Conceptual models with simpler structures benefit from fewer data requirements but are limited in their capacity to reflect the full complexity of hydrological processes (Xu, 2002). At the same time, a recurrent argument in the ongoing research asserts that complex modelling approaches do not necessarily provide better results as increasing model complexity introduces additional uncertainty when the required model setup and calibration data are in short supply (Beven, 2006; 2023; Hughes, 2010). A compromise between model complexity and data availability is necessary to leverage different information and correctly characterise hydrological parameter distributions, thereby enhancing the beneficial use of models to provide reliable assessments of hydrological systems (Tanner, 2013; Prucha et al., 2016).

2.5.1. The Pitman model

Among the numerous hydrological models that have been developed for research and practical water resource assessments in South Africa, the Pitman model (Pitman, 1973) is one of the most widely utilized (Middleton and Bailey, 2008). The Pitman model is a conceptual, monthly time-step model. It was developed with an acute awareness of the data scarcity issues in South Africa; as such, it has few parameters that are based on a simplified conceptualisation of catchment hydrological processes, requiring fewer data (Hughes, 2004). The main inputs to the model are rainfall and potential evapotranspiration (Pitman, 1973; Hughes, 2004). Both the original and subsequent model modifications are operated at a quaternary catchment scale (Hughes et al., 2013). However, the semi-distributed structure of the model allows for simulations to be conducted at smaller scales where sub-catchments can be modelled independently (with their own sets of parameters and input data) when needed (Hughes et al., 2013).

Applications of the earlier version of the model include Pitman (1973), Pitman et al. (1981), Bullock et al. (1990), Hughes (1997), Midgley et al. (1994) and IHP (1997). Over the years, the model has been calibrated for various catchments in South Africa and other countries in southern Africa, where hydro-meteorological data are relatively scarce (Hughes et al., 2006). Outputs generated from these studies have resulted in several subsequent modifications to the original Pitman model (Pitman, 1973) to make it more applicable to a wide range of processes occurring in the southern African region. Significant modifications include; a reservoir sub-model developed by Hughes (1992). Addition of more detailed groundwater routines for modelling surface-groundwater interactions by Hughes (2004). Hughes et al. (2010) and Kapangaziwiri et al. (2012) applied the model within an uncertainty framework. Hughes et al. (2014) developed a wetland/lake sub-model to improve simulations of large wetlands/lakes processes, including their connection with surface water. Slaughter et al. (2015) designed a sub-model for disaggregating monthly flow values to daily discharge using daily rainfall data. The latest modification by Hughes and Mazibuko (2018) focused on improving surface runoff processes by adding a saturation excess function to simulate low topography riparian areas (dambos), which are common in sub-Saharan catchments. These new versions of the model have been applied to a wide range of contrasting catchment conditions across the African continent, e.g., in the Kafue River Zambia (Mwelwa, 2004), Okavango River (Andersson et al., 2006; Mazvimavi et al., 2006; Hughes et al., 2006), Congo River (Tshimanga et al., 2011; Kabuya et al., 2020), the Great Ruaha River basin in Tanzania (Tumbo and Hughes, 2015).

Regarding the model utilization specifically in South Africa, Bailey (2007) used the Pitman model to generate natural time series for quaternary catchments covering the whole of South Africa and encompassing Lesotho and Swaziland. The data produced from this exercise are used as baseline information for a wide range of water resource assessments, most of which are surface water-focused. Regarding groundwater studies, the uptake of the model has not been significant. The integration of groundwater routines (Hughes, 2004) into the existing surface water model was met disapprovingly by the professional geohydrological community in South Africa, who have argued that the model is too simplistic and conceptual. Hughes (2004) openly acknowledged this simplification and rationalized that the level of complexity of the new components was aligned with the original design principles of the (successfully implemented) surface water model. The developers also emphasized that the model must not be seen as a replacement for existing detailed numerical approaches to GW modelling and that the two methods can be used alongside each other as they offer different types of information for water resource assessments. Tanner and Hughes (2015) further ascertain that the processes that have been incorporated into the Pitman model (Hughes, 2004) represent the key processes that occur in the heterogeneous catchment conditions found in South Africa and other regions in Southern Africa.

While detailed groundwater models are frequently used together with simple water balance spreadsheet models (where the spreadsheet models provide simplistic initial water balance calculations prior to the use of the more detailed models), the modified Pitman model aims to be a better complementary tool to this process by offering more detailed time-series analyses of the water balance components including recharge, downstream groundwater flow, soil water/interflow, evapotranspiration directly from groundwater, groundwater contribution to streamflow and indirect recharge or transmission losses.

2.6. Summary

As the hydrological sciences have progressed and our understanding of the crucial importance of surface water and groundwater interactions increased, different catchment model structures have been developed to study these processes. The differing model structures have to do with estimating parameter values and how processes are represented in spatial and temporal scales. The lack of reliable data in most catchments frequently constrains the improved technical capacity. Expanded measurement methods and hydrological observatory networks for reducing data constraints could improve modelling outcomes. Unfortunately, because of financial limitations, it is doubtful that comprehensive data sets will be available in the near future, especially in developing nations like South Africa. Thus, to make hydrological predictions in data-scarce catchments credible, it is important to consider using less detailed modelling approaches that are companionable with the limited data currently available. This study explores the use of a moderately detailed conceptual model, the modified Pitman model (Hughes, 2004), as an appropriate method for practical assessment of surface water groundwater interactions. In this context, the modelling framework deals with uncertainties related to the structure and application of the model's groundwater and SW-GW interaction components and an evaluation of the model's ability to simulate the water balance of a groundwater-driven system using a robust conceptual understanding of the environment.

3. STUDY AREA DESCRIPTION

3.1. Location

Lake Sibaya is the largest natural freshwater lake in South Africa (Meyer et al., 2001). It is situated on the vast sand-covered Maputaland Coastal Plain (MCP) along the northern part of the KwaZulu-Natal (KZN) coastline. It resides at latitudes 27°15' S to 27°25' S and longitudes 32°33' E to 32°43' E, placing it in the W70A quaternary catchment (Middleton and Bailey, 2008) approximately 180 km north of the town of Richards Bay and at least 50 km south of the Mozambique border. Lake Sibaya is one of the several lakes, swamps and lagoons that fall within the iSimangaliso Wetland Park, a UNESCO World Heritage Site (Obura et al., 2012) (Figure 3.3-1). Recent activities, such as establishing and expanding plantations around the lake, have increased the demands on this ecologically sensitive area, significantly impacting lake levels and wetlands (Weitz and Demlie, 2014; Smithers, 2017). Due to its conservation significance and position as a critical water source for rural water supply, the continued trend of declining lake levels in Lake Sibaya has prompted considerable research interest focused on various aspects of the lake, including the groundwater component.

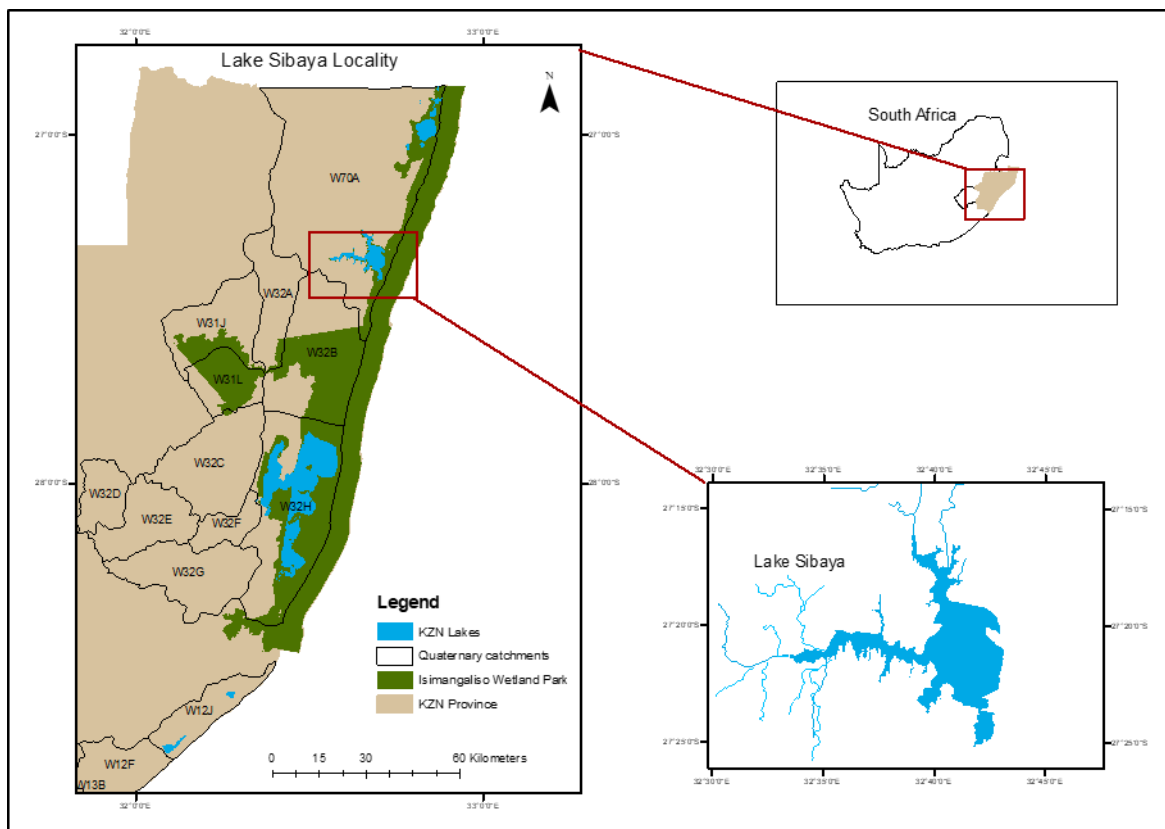


Figure 3.1-1: Locality map showing the location of Lake Sibaya within the iSimangaliso Wetland Park boundary (shapefiles from Middleton and Bailey, 2008 and Department of forestry, fisheries and the environment (DFFE), 2020).

3.2. Climate

The Lake Sibaya catchment is characterized by a humid subtropical climate (Boucher, 1975). Rainfall in the area is strongly seasonal, with summer rainfall dominating. Rainfall in the catchment is unevenly distributed and increases from inland, moving towards the coast (South African Weather Service (SAWS), 2013). The highest rainfall amounts (average of 1000 mm year⁻¹) occur in the south-eastern parts of the catchment, while an average of 900 mm year⁻¹ occurs over the lake, followed by lower quantities close to 700 mm year⁻¹ in the western parts of the lake catchment (Figure 3.2-1) (Weitz and Demlie, 2014). Estimates of average potential evaporation range between 1400–1500 mm year⁻¹ (derived using the S class pans method) and 1800–2000 mm year⁻¹ (derived using the A class pans method) (Middleton and Bailey, 2008). Mean monthly temperatures in the Lake Sibaya catchment range between 19°C (in winter) and 27°C (summer months) (Smithers et al., 2016).

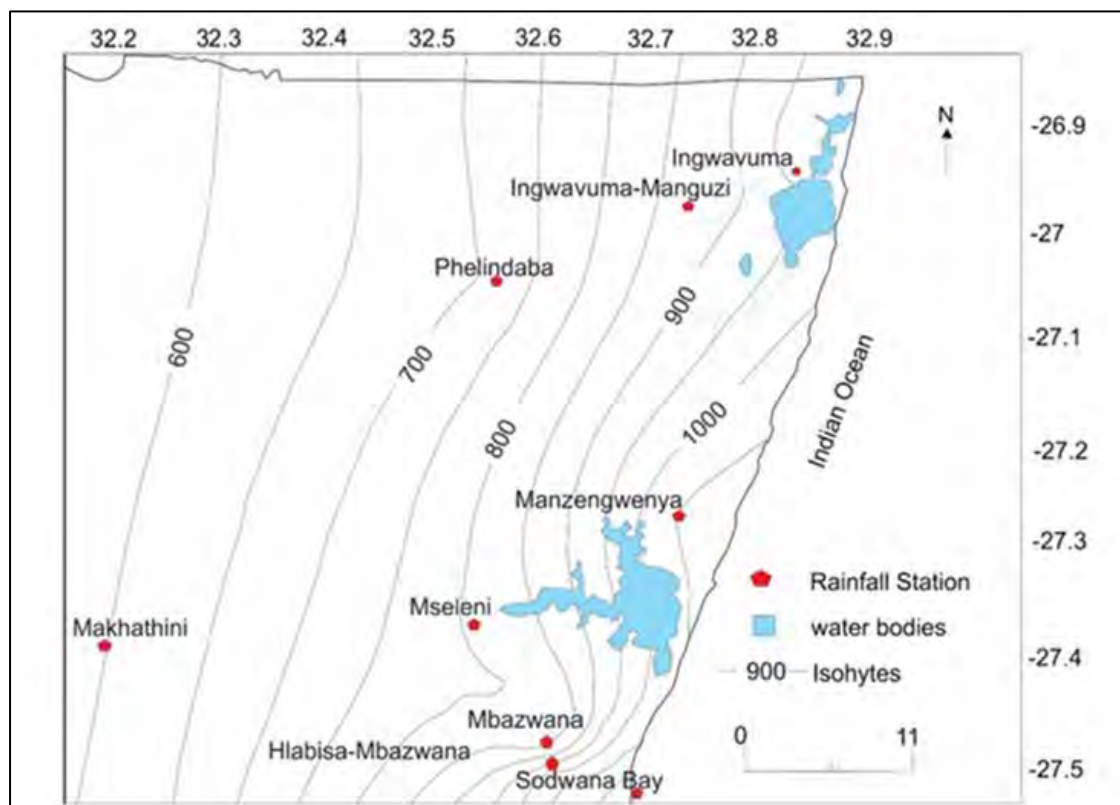


Figure 3.2-1: Spatial rainfall distribution over the Lake Sibaya catchment (mm/a). Based on data from SAWS (2013) for 23 years (1990 to 2013) (Weitz and Demlie, 2014).

3.3. Topography and Hydrology

The area surrounding Lake Sibaya has a flat topography and prominent palaeo-dune sequences that run parallel to the coastline (Figure 3.3-1) (Wright et al., 2000). The sandy substrate and flat topography limit the amount of surface runoff; as such, the lake water levels are almost entirely sustained by GW recharge (Pitman and Hutchison, 1975). However, some vital rivers feed the lake; the Mseleni River feeds the western arm, and the Kumzingwane and Velindlovu ephemeral streams serve the lake's northern arm (Figure 3.3-2) (Kelbe and Germishuys, 2010). The intimate relationship between the SW and GW systems, which derives from the catchment's sandy substrate, flat topography, and shallow water table, creates uncertainty about the exact SW and GW contributions to the lake. Meyer et al. (2001) note that the two systems are so closely connected that the lake can be considered a surface water expression of the groundwater. A palaeo-dune sequence at heights of around 170 m above mean sea level (AMSL) separates Lake Sibaya from the sea, resulting in an entirely freshwater system (Roberts et al., 2006). While there is no direct link between the lake and the sea, Miller (2001) reports that there is a connection via a palaeo-channel beneath the dunes which is an outlet point for freshwater from the lake to the sea. These findings by Miller (2001) were supported by personal communication with Nicolette Forbes, cited by Hughes and Tanner (2016), which stated that there is an upwelling of fresh water on the beach north of Sodwana Bay (eastern shore of Lake Sibaya). Weitz and Demlie (2014) used an estimate of 100 m depth (determined through Meyer et al. (2000) geophysical investigation), average permeability of 3.5 m day^{-1} (proposed by Pitman and Hutchison, 1975), a flow length of 2000 m and a head difference of 16 m to calculate that an approximate volume of $22 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ flows into the sea via the palaeo-channel, over a 20 km seepage face. This volume fluctuates depending on the lake level.

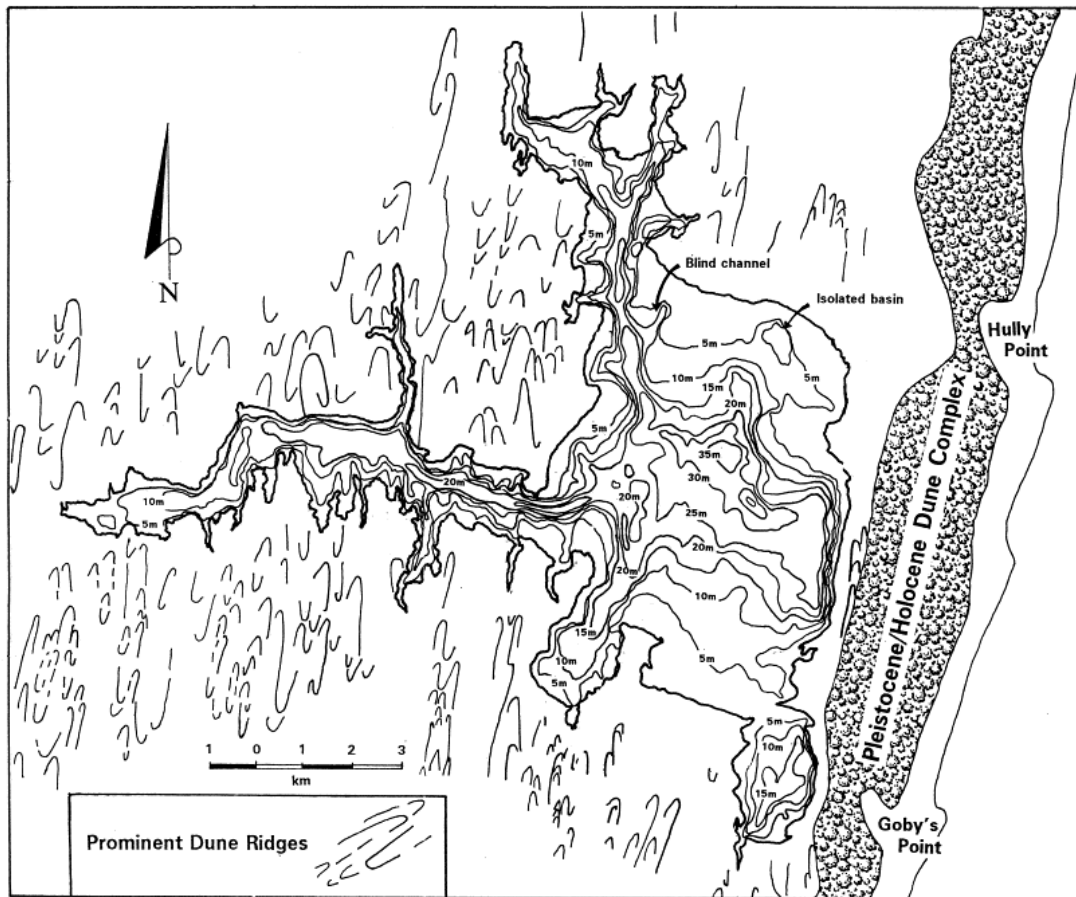


Figure 3.3-1: Lake Sibaya local geomorphology (Wright et al., 2000).

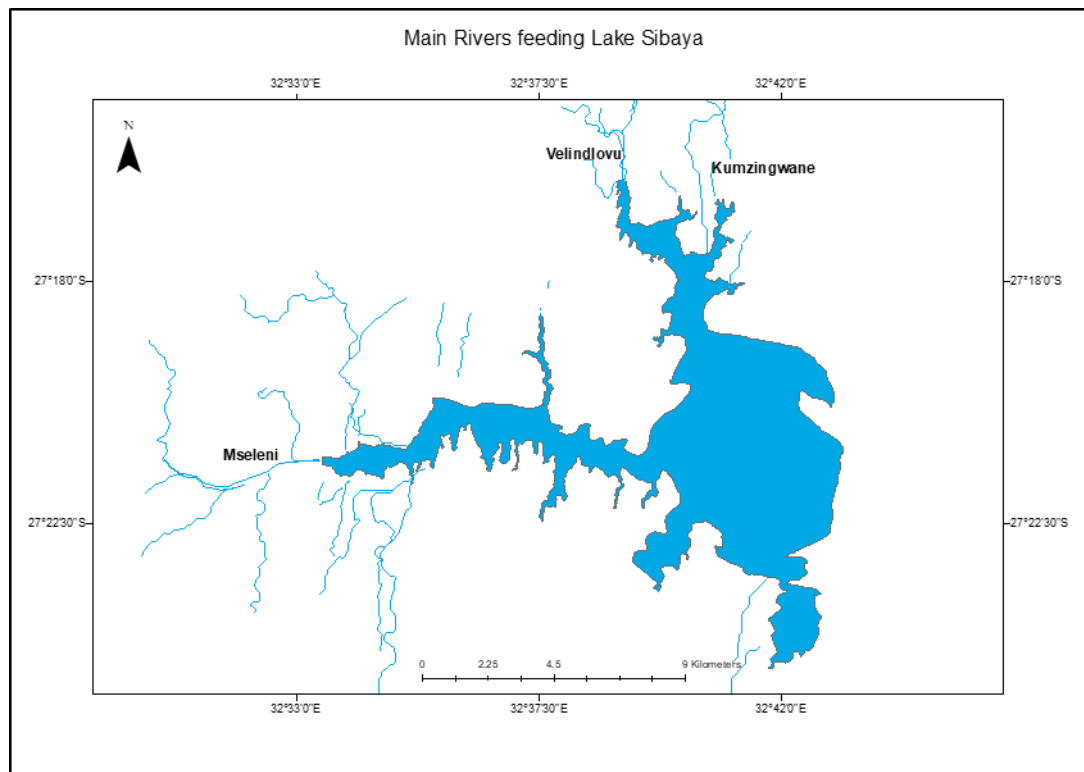


Figure 3.3-2: The main rivers feeding Lake Sibaya.

3.4. Aquifer characteristics

Across the coastal plain, the geological sequence occurs in variable sediment compositions, resulting in hydrogeological units with varying attributes (Kelbe et al., 2013). Four hydrogeological units can be identified, collectively making up South Africa's largest unconsolidated primary aquifer (Meyer, 2001; Kelbe and Germishuysen, 2010). The Zululand Group St. Lucia Formation sediments form the catchment floor. The St. Lucia Formation is characterized by very low permeability and poor borehole yield and is regarded as an aquiclude (Meyer and Godfrey, 2003). The Umkwelane/Uloa Formation is the region's most prolific aquifer (Jeffares and Green, 2012; Kelbe et al., 2013). The productivity of these formations is associated with the dissolution of channel-bearing Calcarene present in the sediments (Kelbe et al., 2013). Although high yielding, these formations are constrained in extent, occurring only in the western part of the catchment, roughly up to the middle of the central basin (Miller, 2001). The Kosi Bay and Port Durnford Formations, which lie on top of the Umkwelane and Uloa Formations, are of lesser productivity and are regarded as aquitards (Porat and Botha, 2008). The Kosi Bay and Port Durnford Formations are valued for their immense storage capacity. They are primarily a storage reservoir for the overlying Sibayi Formation, which completes the succession of hydrogeological units. The Sibayi Formation constitutes the coastal barrier dune cordon, which is over 70 m in some areas (Meyer and Godfrey, 2003). Figure 3.4-1 illustrates the succession of the different geological formations and their grouping into respective hydrostratigraphic units. The main hydraulic properties; aquifer thickness, conductivity (K), transmissivity (T) and bore-hole yields associated with the Maputaland region aquifers are summarized in Table 3.4-1.

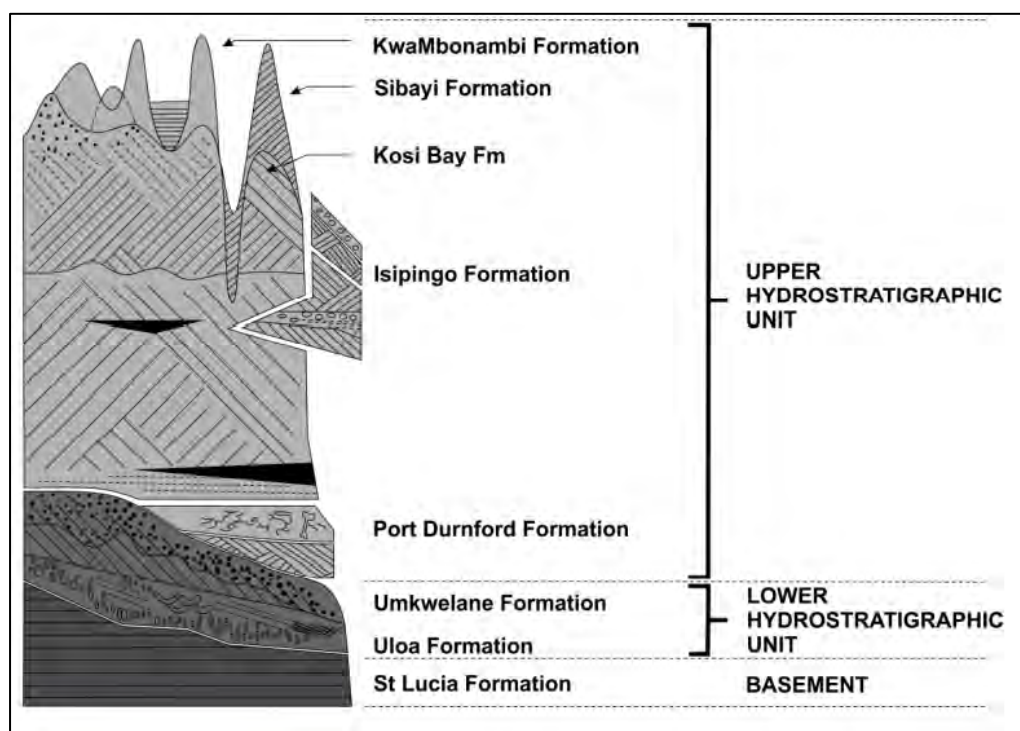


Figure 3.4-1: The Lake Sibaya catchment geological sequences classification into varying hydro-stratigraphic units (Modified from Porat and Botha, 2008 by Weitz, 2016).

Table 3.4-1: Hydraulic characteristics of the aquifer structures in the Lake Sibaya catchment Weitz and Demlie (2014; 2015) who adapted it from Meyer and Godfrey (1995) and Jeffares and Green (2012).

Aquifer name	Thickness (m)	K (m day ⁻¹)	T (m ² day ⁻¹)	Borehole yields (Ls ⁻¹)
Sibaya/KwaMbonambi	20-30*	0.87-15.6 (mean: ~5)	-	0.5-5
Kosi Bay /Port Durnford Formation	15-20*	4-5 (mean: 4.3)	-	2-10
Uloa/Umkwelane Formation	5-20	0.5-25 (mean: 4.5)	116	5-25
St Lucia Formation	900	-	-	<1

Values marked by * are based on rough approximations.

3.5. Surface and groundwater abstractions

The area surrounding Lake Sibaya, which is outside the boundary of the conservation area, has undergone significant development as a result of human settlement and land use change. Water demand in the lake catchment has increased in recent years, and the local communities utilise both surface and groundwater (Meyer and Godfrey, 2003). Lake water abstraction estimates provided by the Water Use Authorisation Registration Management System (WARMS), cited by Weitz (2016), showed an annual abstraction rate of approximately $1.825 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ in the year 1975 (measured for the Manguzi community). In 2003, measured lake water abstractions for the same community were approximately $2.128 \times 10^6 \text{ m}^3 \text{ year}^{-1}$. The WARMS water abstraction information also showed estimates of $0.496 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ for the Mbazwana community and $0.153 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ for the Mseleni community (DWA, 2014); both assessments were recorded for the year 2004. The average volume for lake abstractions in the entire catchment was roughly $2.8 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ (Weitz, 2016). The surface water abstraction information that is currently available only provides a snapshot view of the actual abstraction situation in the Lake Sibaya catchment. Information on the specific details of the rate of increase/ decrease in lake abstraction was not found, and the cited estimates are uncertain.

Groundwater in the lake catchment is commonly accessed as a secondary water source through either small to medium-scale groundwater schemes or hand-dug boreholes at the household level. Unfortunately, most of these schemes or boreholes are unmonitored, and the GW abstraction volumes are uncertain. Mark Schapers (2018) wrote an opinion piece on the falling water levels in the Maputaland Coastal Aquifer and included information on groundwater abstraction. This was based on his extensive consulting work in the region. Although there is significant unregistered GW use due to the continuing increase in the development of domestic use GW boreholes throughout the area, Schapers (2018) stated that his consulting work in the area had led him to conclude that the water use overall was significantly less than the registered volumes as most boreholes are operating at full potential. Table 3.5-1 details his findings.

Table 3.5-1: Qualified estimates of groundwater and surface water usage for human consumption (Schapers, 2018).

Description	Qty	Average use (L Day ⁻¹)	Sub Total (m ³ day ⁻¹)
Schools, clinics, small-scale agricultural projects and related government-funded water resource development	1 000	5 000	5 000
Unregistered private domestic use	10 000	650	6 500
Water supply schemes			
Enkhanyezini (groundwater and surface water)	2	400 000	800
Kwangwenase (groundwater and surface water)	15	1 000 000	15 000
Mseleni (groundwater and surface water)	6	1 000 000	6 000
Mbazwana (groundwater and surface water)	6	750 000	4 500
Other	10	100 000	1 000
Proposed interventions	10	500 000	5 000
Total (over) estimation of surface and groundwater abstraction stressing the aquifers			43 800

According to Schapers (2018), the figure of 43 800 m³ day⁻¹ is overestimated by as much as 20 000 m³ day⁻¹. The differentiation between surface water and groundwater abstraction is also unclear. These estimates (even with the reduced abstraction) are significantly higher than previous estimates. If it is assumed that the table represents all water use (lake abstraction, surface water abstraction and groundwater abstraction), then the total can be described as:

- 2.8 x 10⁶ m³ year⁻¹ (Weitz, 2016) lake abstraction
- 5.8 x 10⁶ m³ year⁻¹ (Schapers, 2018) groundwater and streamflow abstraction, although it is assumed that streamflow abstraction is minimal due to intermittent stream flows over much of the catchment.

These figures are worked out using the Schapers (2018) water use estimates (including the subtraction of 20 000 m³ day⁻¹) and subtracting the Weitz (2016) lake abstraction estimates from this volume. It is clear however, that there is significant uncertainty associated with all of these estimates as they vary considerably.

3.6. Vegetation and land cover

The Lake Sibaya catchment is classified under the Coastal Lake Zone (Mountain, 1990). The predominant land cover classes are lakes, wetlands, and vegetated dunes, while built-up areas occupy some 2% of the catchment (Ezemvelo KZN Wildlife, 2011). The natural vegetation in the area falls under three distinct biomes, the Indian Ocean Coastal Belt (IOCB) (along the coast up to 20 km inland), savanna (central and western parts) and forest (randomly distributed) (Mucina & Rutherford 2006). Over the years, plantations have replaced a large portion of the natural vegetation (Weitz & Demlie, 2014; Everson et al., 2019; Ramjeawon et al., 2020). Plantation estimates in the Maputaland Coastal Plain point to an average yearly increase of about 2.35 km² year⁻¹ in the mid-1980s to approximately 23.72 km² year⁻¹ by 2019 (Table 3.6-1) (Ramjeawon et al., 2020). The current forestry coverage in the Lake Sibaya catchment is estimated to be around 205 km² (South African National Land-Cover (SANLC), 2020).

Table 3.6-1: Maputaland Coastal Plain net area changes for plantations between measurement periods from 1986 to 2019 (Ramjeawon et al., 2020).

Period	Km ² year ⁻¹
1986-1991	2.35
1991-1996	1.51
1996-2001	8.01
2001-2006	10.84
2006-2011	-12.31
2011-2016	10.98
2016-2019	23.72
1986-2019	6.833

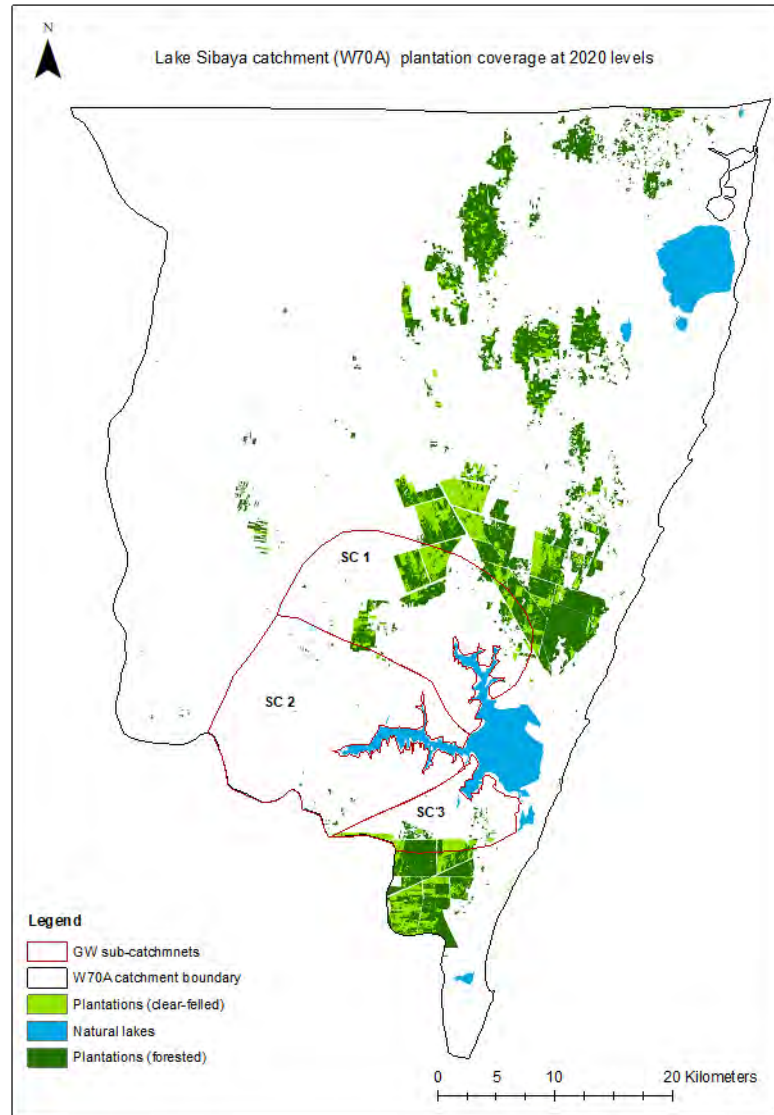


Figure 3.6-1: Plantation coverage in the Lake Sibaya catchment at 2020 levels (South African National Land-Cover (SANLC), 2020).

Plantations in the lake catchment significantly impact the lake's water balance. Plantation vegetation have a deeper rooting depth than natural vegetation, making accessing soil water and the shallow groundwater table easier (Dye and Versfeld, 2007; Brites, 2013). This access to GW is evidenced by year-round growth with marginal difference in ETa throughout wet and dry seasons, implying that plantation vegetation is accessing an alternative source of water (groundwater) for growth in addition to the primary supply of water (rainfall) (Brites, 2013; Everson et al., 2019). The use of water by plantations limits aquifer recharge by withdrawing infiltrating water in the unsaturated zone. This results in decline in GW level (direct extraction of GW from the capillary fringe above the groundwater table. Figure 3.6-2 illustrates the different sub-surface segments from which plantations can access water, including direct access to groundwater.

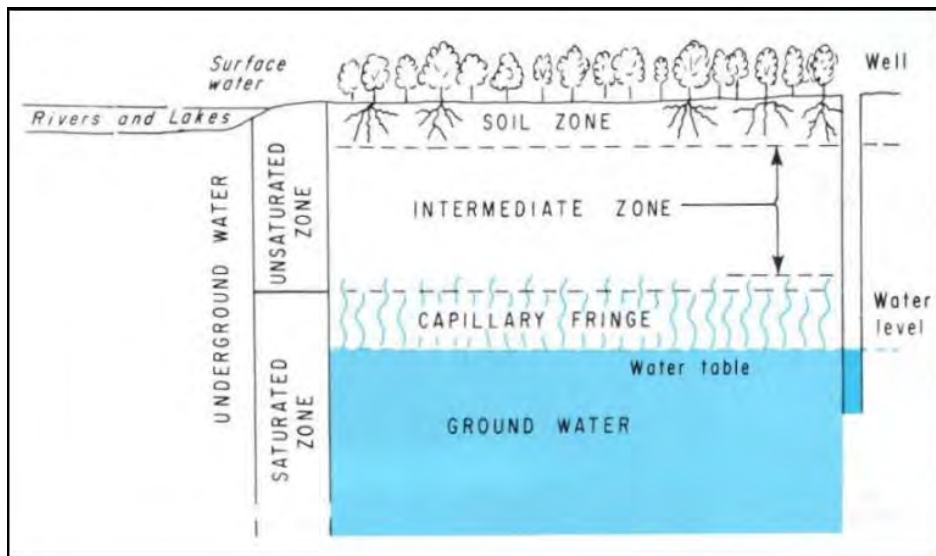


Figure 3.6-2: Illustration of the basic groundwater hydrology showing the unsaturated zone and capillary fringe where plantation vegetation access groundwater (Heath, 1983).

3.7. Bathymetry

Three bathymetric surveys have been conducted for Lake Sibaya. These include (1) a survey by the Marine Geoscience Unit of the Council for Geoscience conducted between 1992 and 1993; (2) a survey by Miller in 2001, and (3) a survey carried out by LD Muggleton for JG Afrika (Pty) Ltd in 2018. The Council for Geoscience survey was fairly limited (it included depth estimations for volumes from 725 to 818 10⁶ m³); therefore, only the Miller (2001) and Muggleton surveys are described below.

Weitz (2016) utilised the Miller (2001) data and provided the following information:

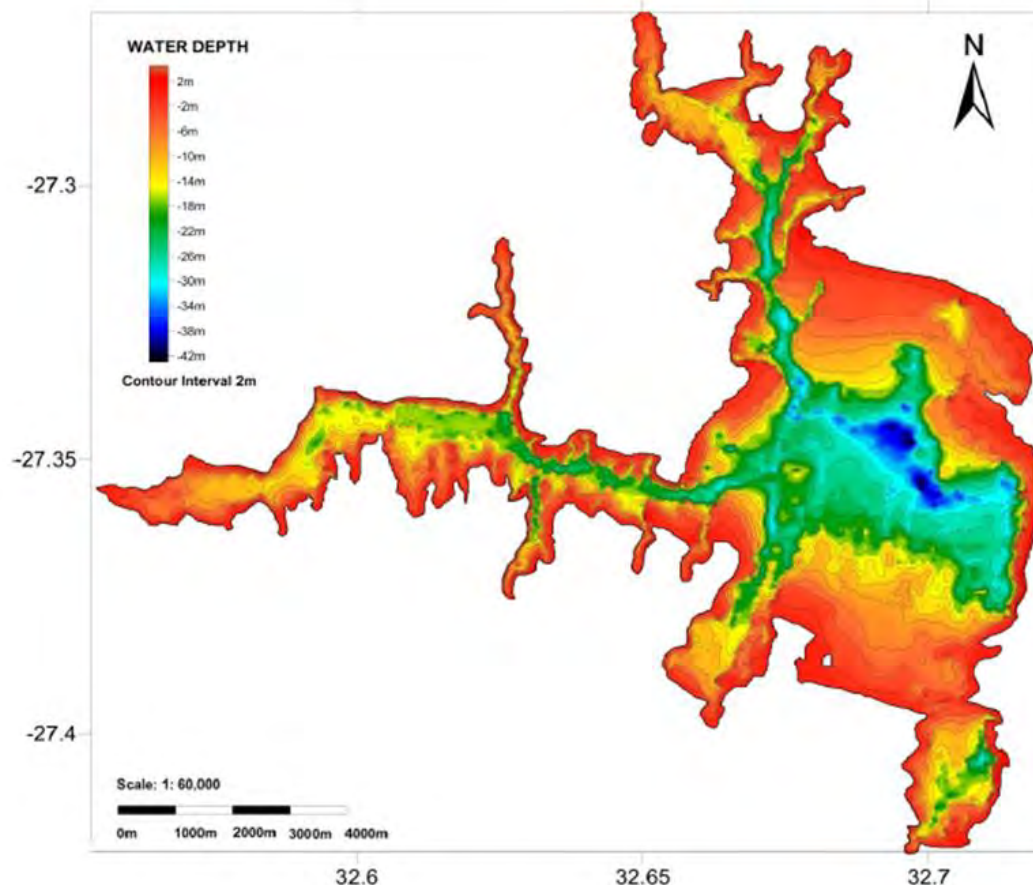


Figure 3.7-1: Lake Sibaya bathymetric map produced by Weitz (2016) using data from the survey conducted by Miller (2001).

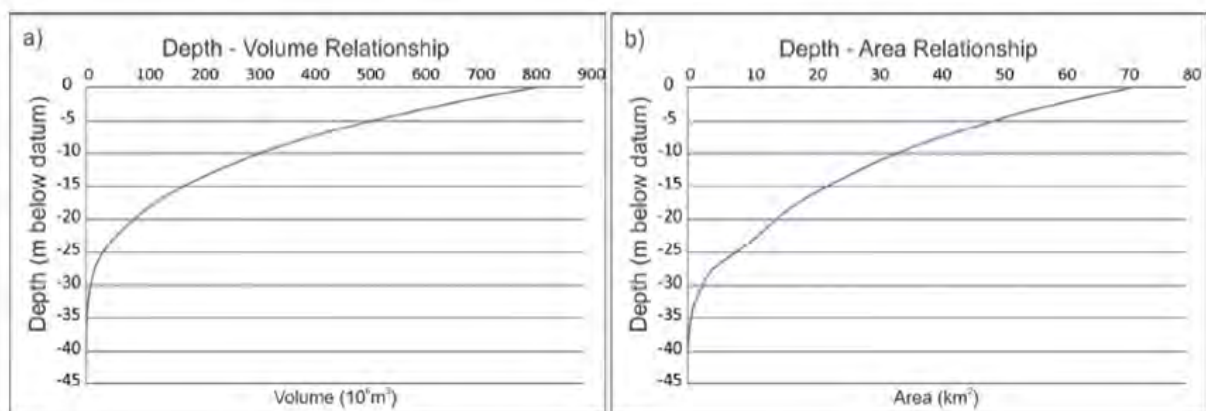


Figure 3.7-2: Depth- Area (a) and Depth-Volume (b) relationships for Lake Sibaya calculated by Weitz (2016) using the bathymetric data compiled by Miller (2001).

Table 3.7-1: Lake Sibaya depth- area- volume relationships calculated by Weitz (2016) using the bathymetric data compiled by Miller (2001).

Depth (m)	Volume (10 ⁶ m ³)	Area (km ²)
0	816	73
-4	569	52
-8	386	39
-12	252	29
-16	155	21
-20	86	14
-24	39	9
-28	14	4
-32	4	1
-36	1	0
-40	0	0

Finally, JG Africa commissioned a bathymetric survey which LD Muggleton carried out. The survey was conducted over two periods in October 2018. The first was from 8th to 19th October, and the second from 28th to 31st October 2018 Mark Schapers, (personal communication). Muggleton discovered some inconsistencies between his data and the results from the Miller (2021) survey, which he attributed to using different methods for estimating the lake's surface area. The bathymetric map produced by Muggleton is shown in Figure 3.3-3 below.

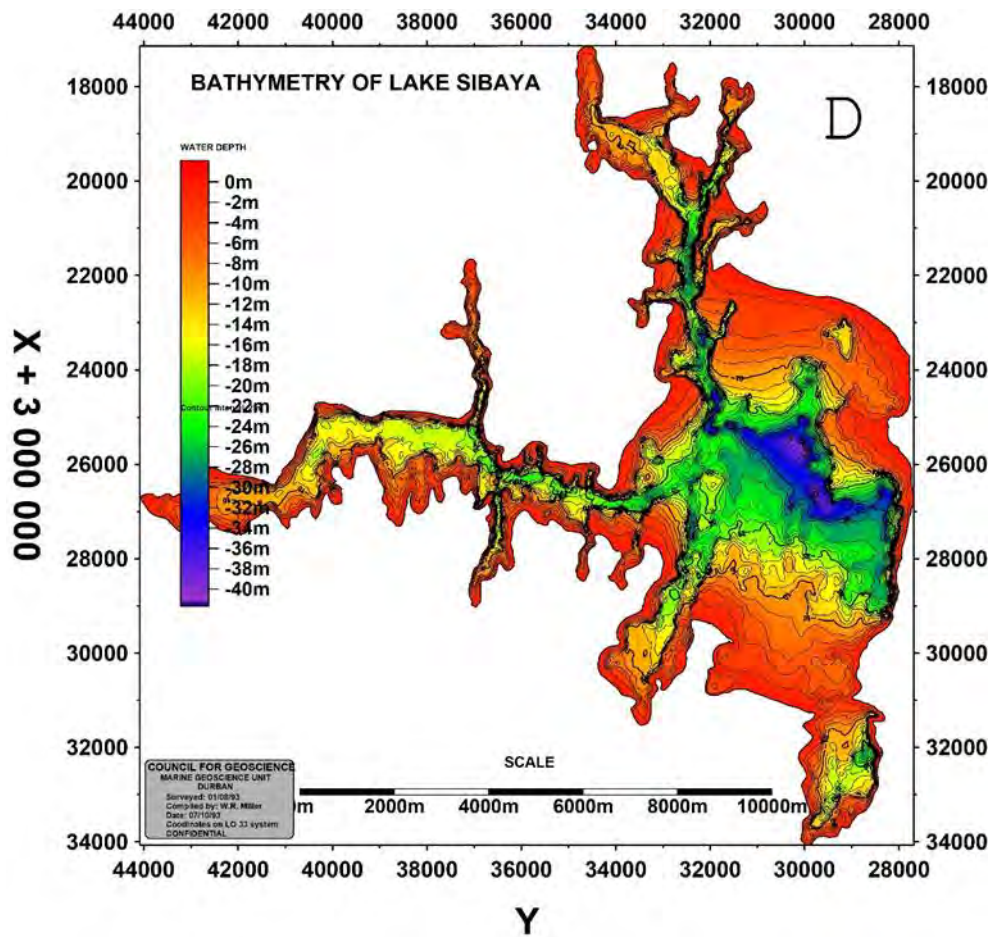


Figure 3.7-3: Lake Sibaya bathymetric map produced using data compiled by Muggleton for JG Afrika (2018).

The data reported by Miller (2001) and Muggleton's data are comparable. Although there were issues with the 2001 survey picked up in Muggleton's report, these are not significant for conceptual modelling. The data were used to define an area-volume relationship in the current research hydrological model set up for Lake Sibaya (Section 4.5.3).

4. METHODS

4.1. Model selection: Pitman model

The modified Pitman model (Hughes, 2004) was selected for this study to assess how well a moderately detailed conceptual model can characterise SW-GW interactions in a predominantly groundwater-driven system. In addition, the model simulates surface and groundwater interactions in an integrated way, ensuring the holistic water balance is accounted for. The implemented approach was motivated by the observed need to integrate SW and GW resource assessments and the understanding that in South Africa, the bulk of these assessments will likely continue to be conducted with limited data for a long time due to limited financial resources to expand monitoring networks. The Pitman model (Hughes, 2004) presents itself as a promising tool to help meet this need. The key questions for successfully applying the Pitman model (Hughes, 2004) are whether processes can be adequately represented at broad spatial scales to provide useful information for practical water management and whether a robust conceptual understanding can help to reduce some of the uncertainties associated with parameter estimations in a data-scarce region (Hughes et al., 2010).

4.2. Pitman model data requirements

The two main data inputs required to set up and drive the hydrological processes described in the Pitman model (Pitman, 1973; Hughes, 2004) are monthly time series of rainfall and potential evapotranspiration (PET). In addition, the model requires catchment parameter data that are estimated based on modelling guidelines and a conceptual understanding of the catchment conditions (Pitman, 1973; Hughes, 2004). Catchment parameter data determine how the model interprets the primary hydrological input data. Lastly, observed streamflow data are typically utilized for model calibration and validation since they are the most commonly available hydrological response data (Pitman, 1973). Additional hydrological response data, such as actual evapotranspiration, soil moisture, GW recharge, GW level, and GW baseflow, can be used to calibrate the model further when available (Hughes, 2004).

4.3. Components and parameters of the Pitman model

The conceptual structure of the modified Pitman model (Hughes, 2004) used in this study (Figure 4.3-1) illustrates the model's two main inputs: rainfall and potential evapotranspiration and their transformation into different catchment processes. The model simulates both surface and sub-surface processes, which contribute to streamflow generation, including interflow (flow in the unsaturated zone, above the water table) and groundwater (saturated zone flow) contributions to streamflow. These processes are represented by the model components and parameters (outlined in Table 4.3-1). Descriptions of the surface and groundwater components relevant to this discussion are provided

(section 4.2.2.1-3). The reader is directed to the original Pitman model manual (Pitman, 1973) and other sources documenting subsequent modifications (Hughes, 1997, Hughes, 2004; Hughes and Parsons, 2005; Hughes et al., 2006; Kapangaziwiri and Hughes, 2008 and Hughes., 2013) for detailed explanations of the model components and parameters. Table 4.3-1 below gives the Pitman model parameters, while Section 4.3.1 describes the parameters in more detail.

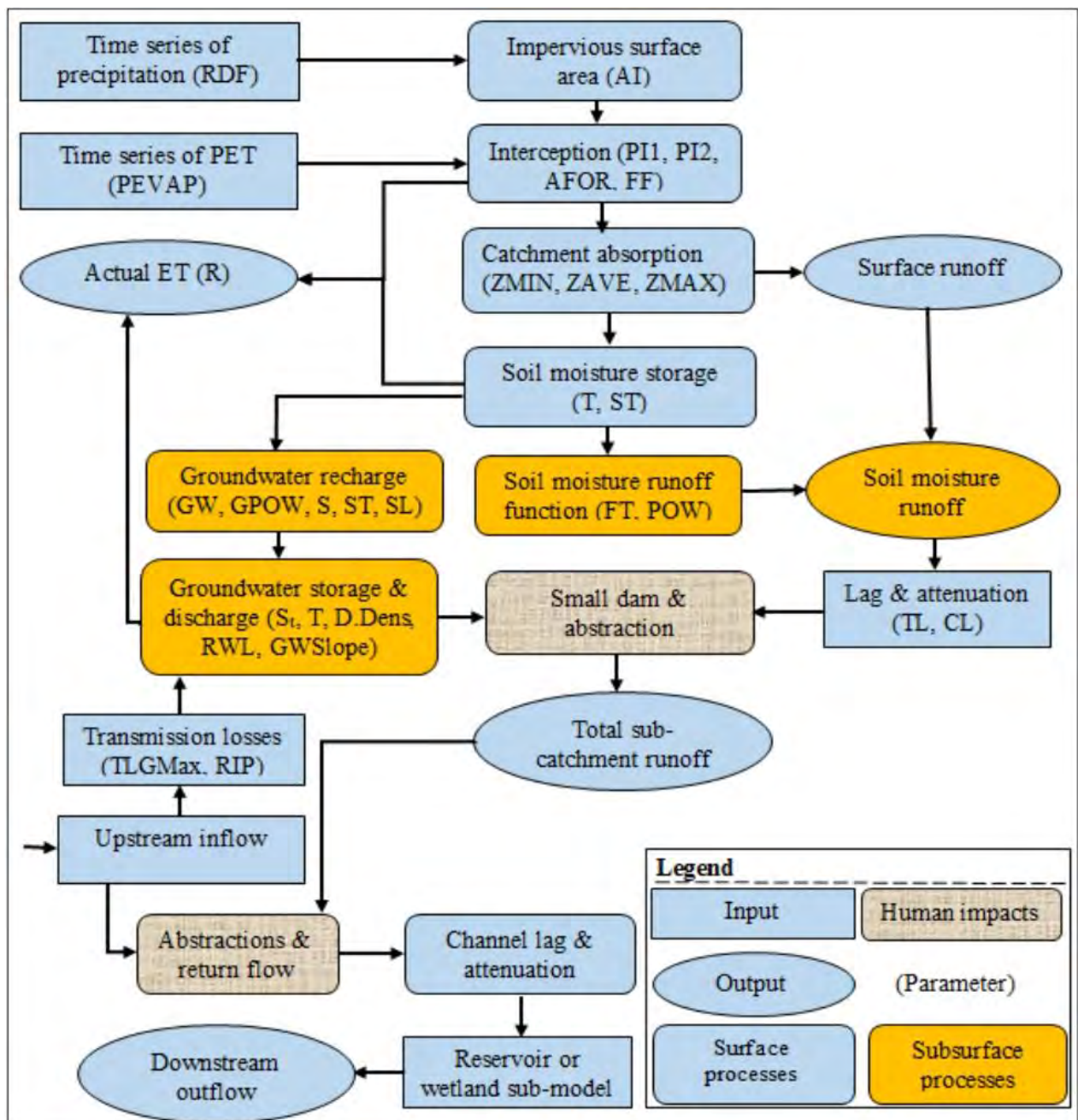


Figure 4.3-1: Structure of the modified Pitman model (modified by Mazibuko, 2016 from Hughes, 2004).

Table 4.3-1: Parameters of the modified Pitman model (Hughes et al., 2006).

Model component	Model Parameters and units	Description
NATURAL PARAMETERS		
Surface water parameters		
Precipitation distribution	RDF (N/A)	Rainfall distribution factor (default to 1.28). It controls the distribution of total monthly rainfall over four model iterations
Impervious area	AI (%)	Impervious fraction of the catchment
Interception	PI1 and PI2 (s and w) (mm)	Summer (s) and winter (w) interception storage for two vegetation types
	AFOR (%)	Catchment proportional area covered by vegetation type 2
	FF (NA)	The ratio of potential evaporation (PET) rate for vegetation type 2 relative to type 1
Potential ET	PEVAP (mm y ⁻¹)	Annual catchment potential evapotranspiration
Actual ET function	R (N/A)	Evapotranspiration-moisture storage relationship parameter
Catchment absorption	ZMIN (mm month ⁻¹)	The minimum sub- catchment absorption rate
	ZAVE (mm month ⁻¹)	Mean sub-catchment absorption rate
	ZMAX (mm month ⁻¹)	Maximum sub-catchment absorption rate
Soil moisture storage	ST (mm)	Maximum moisture storage capacity
	SL (mm)	Soil moisture below which there is no recharge
Soil moisture runoff	POW (N/A)	Power of the moisture storage equation
	FT (mm month ⁻¹)	Runoff from moisture storage at full capacity (ST)
Groundwater parameters		
GW recharge	GW (mm month ⁻¹)	Maximum groundwater recharge at full capacity (ST)
	SL mm	Soil moisture storage below which there is no GW recharge
	GPOW (N/A)	Power of moisture storage-groundwater recharge equation
GW storage & discharge	T (m ² d ⁻¹)	Groundwater transmissivity
	D.Dens (km km ⁻²)	Drainage density of the catchment
	RWL (m below surface)	Aquifer depth
	GW Slope	Regional groundwater gradient
	RIP (% slope width)	Riparian strip factor
	S (N/A)	Groundwater storativity
	TLGMax (mm month ⁻¹)	Maximum channel losses to groundwater
NON-NATURAL PARAMETERS		

Flow routing and water use		
Flow routing	TL (months)	Lag of surface and soil moisture runoff (Default of 0.25)
	CL (months)	Routing coefficient
Water use	Surface water use parameters	
	AIRR (Km ²)	Run-of-river irrigation area
	EFFECT (fraction)	Effective rainfall fraction,
	IWR (fraction)	Irrigation water return flow fraction
	RUSE (MI year ⁻¹)	Non-irrigation demand from the river
	Groundwater use parameters	
	GWA (Upper slope) (MI year ⁻¹)	Groundwater abstraction far from the channel
	GWA (Lower slope) (MI year ⁻¹)	Groundwater abstraction near the channel
	Small farm dam parameters	
	MDAM (MI)	Small dam storage capacity
	A & B (N/A)	Parameters in non-linear dam area-volume relationship
	IRRIG (Km ²)	Irrigation area from small dams
	DSTORE (MI)	Maximum storage capacity for all small dams in the sub-catchment
	DAREA (%)	The proportion of catchment above the dam

4.3.1. Pitman model surface water components

Rainfall Interception (PI1, PI2, and AFOR): The parameter PI (mm) defines the proportion of rainfall input intercepted by vegetation cover. The model adjusts to seasonal variation in vegetation cover by allocating PI values denoting two distinct vegetation types; principal vegetation (PI1) and minor vegetation (PI2). Vegetation type 1 is typically used to represent natural vegetation, while type 2 typically represents plantation forestry (although it can describe any second vegetation type). In addition, the model uses the parameter AFOR (%) to specify the coverage of vegetation type 2 in the catchment.

Evapotranspiration from moisture store parameters (PE, R, and FF): The evaporation depth is calculated based on the parameters R and FF as well as the values of the current month's potential evaporation (PE) relative to the highest potential evaporation (PEMAX) recorded for previous months. The model assumes a linear relationship between the actual evapotranspiration (ETa) from the soil moisture store (S/ST) (Figure 4.3-2). This relationship is regulated by the parameter R, which describes

the correlation between the ratio of ETa to PE and the soil moisture level. Values of R range from 0 to 1. At R = 0, ETa losses are high, regardless of decreasing PE, while a value of R = 1 implies lower ETa losses as both S/ST and PE decrease (Figure 4.3-2). The FF parameter is utilized to scale the ETa losses for a secondary vegetation type.

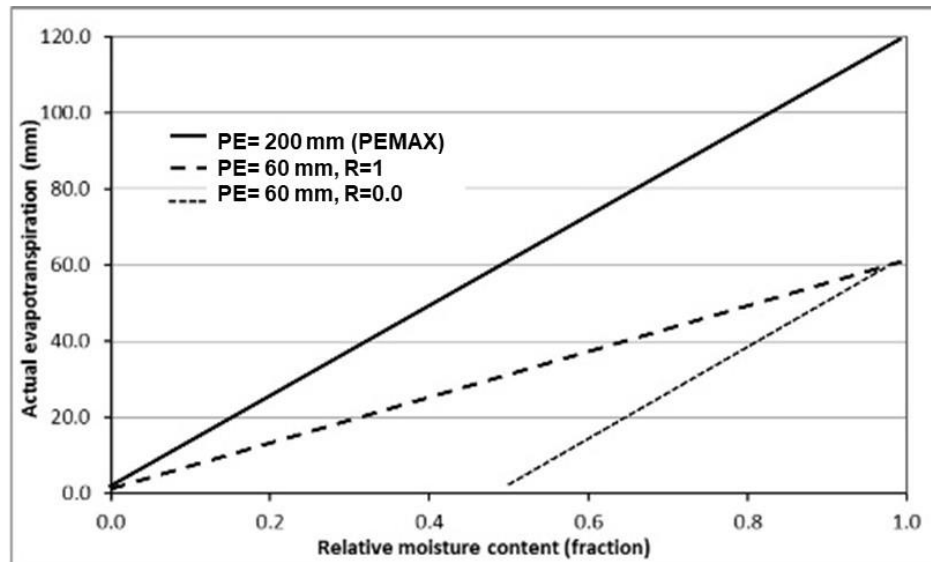


Figure 4.3-2: Illustration of the linear relationship for determining actual catchment evapotranspiration based on soil moisture (S/ST) for R = 0.0 and R = 1.0 (Hughes, 2013).

Catchment absorption and surface runoff parameters (AI, ZMIN, ZAVE, and ZMAX): The model utilizes two components to generate surface runoff (Q); (i) direct conversion of all rainfall that falls onto an impervious surface to runoff and (ii) runoff from excess infiltration. The first component is calculated as the product of the monthly rainfall and a parameter (AI) (%) representing the impervious area of the catchment. Excess infiltration runoff is calculated after the proportion of the absorbed monthly rainfall input has been worked out. Rainfall absorption in the catchment is based on an asymmetrical triangular distribution (Figure 4.3-3A) described by the ZMIN, ZAVE and ZMAX parameters (mm month^{-1}). The surface runoff generated is then estimated based on the determined infiltration rate, which is equal to the area under the cumulative rainfall input rate curve for each model iteration (Figure 4.3-3B). At rainfall input below ZMIN, the model does not generate any runoff, whereas; higher rainfalls will increasingly generate higher surface runoff volumes. Rainfall contribution greater than ZMAX causes the entire part of the distribution above ZMAX to contribute to runoff generation.

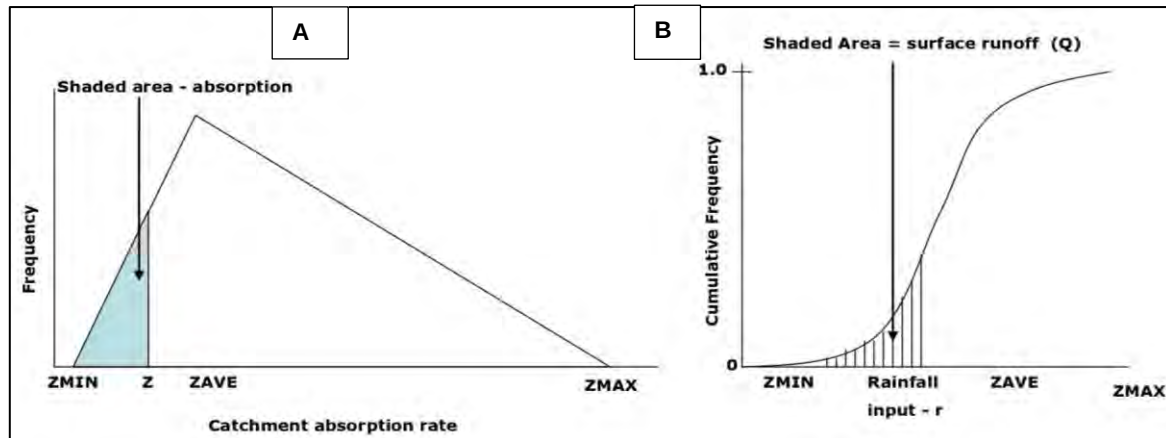


Figure 4.3-3 A/B: Illustration of the asymmetrical triangular distribution of catchment absorption rate, Z (A) and cumulative frequency curve of generated surface runoff, Q . r is the rate of rainfall input (B) (Hughes, 2013).

Soil moisture storage and runoff parameters (ST, POW, and FT): The parameter ST (mm) represents the maximum depth of soil moisture storage (S), with rainfall inputs greater than ST generating surface runoff. The soil moisture storage is characterized by both the soil moisture (ST_{soil}) and unsaturated zone (ST_{unsat}) storage above the GW table (Figure 4.3-4). Increases in S are due to infiltration, while decreases result from evapotranspiration losses, recharge to groundwater and runoff from the unsaturated zone. ST_{soil} and ST_{unsat} are estimated separately but represented in the model using a single parameter (ST) (Kapangaziwiri and Hughes, 2008). ST_{soil} is influenced by soil properties and porosity, while ST_{unsat} depends on storativity (Kapangaziwiri, 2010). Values of ST are higher for deep, well-drained soils and lower for shallower soils (Kapangaziwiri, 2010).

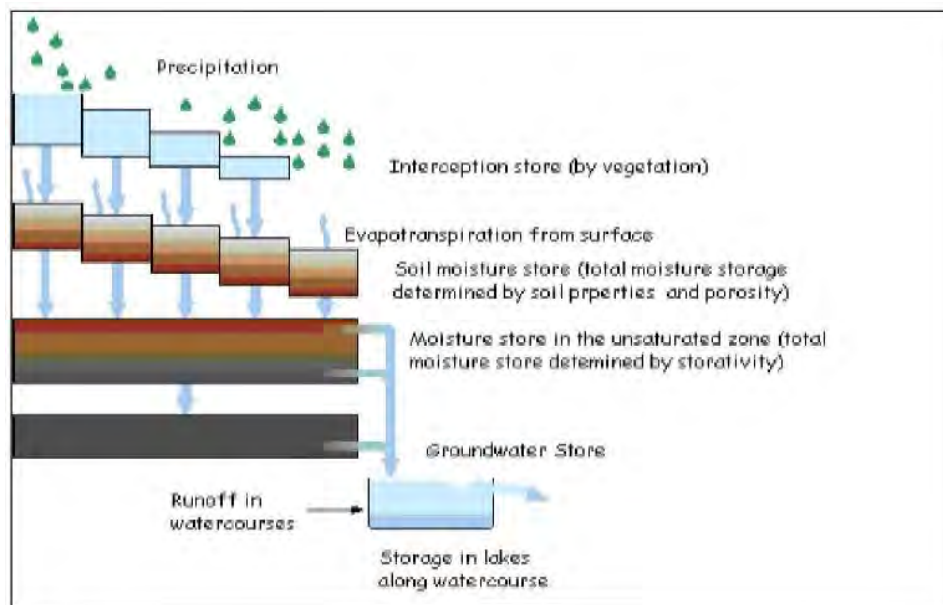


Figure 4.3-4: Conceptualization of the Pitman model moisture storage components (Kapangaziwiri, 2010).

The model estimates the amount of runoff generated from the soil moisture storage as the ratio between FT and the existing soil moisture storage level (S) using a non-linear power function expressed by the parameter POW (Figure 4.3-5). FT (mm month^{-1}) specifies the upper limit of the rate of interflow runoff at ST. The FT and POW parameters vary according to the degree of catchment wetness and the distribution and interconnectedness of drainage channels. High values of FT cause rapid runoff generation during wet conditions, while high values of POW result in rapid decreases in inflow during dry conditions.

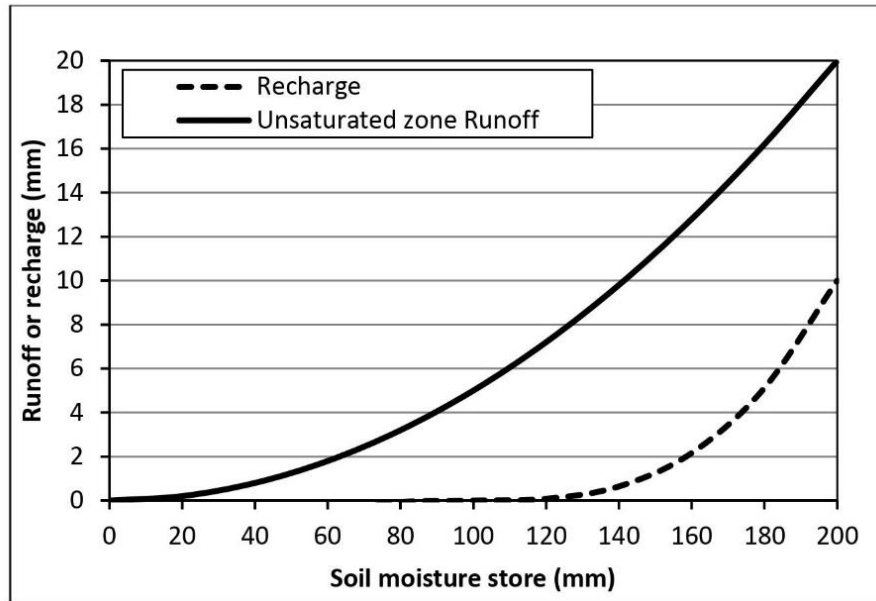


Figure 4.3-5: Illustration of the relationship between soil moisture store and runoff generation. Based on soil moisture runoff function parameters $ST=200$, $SL=0$, $FT=20$ and $POW=2$ and recharge-moisture state parameters $SL=100$, $GW=10$ and $GPOW=3$ (Hughes et al., 2007).

4.3.2. Pitman model groundwater components

Configuration of the groundwater store geometry: The Pitman model Hughes (2004) applies a simple geometry (illustrated in Figure 4.3-6) to simulate inputs and outputs into the groundwater store (Hughes, 2013). Processes in this simple geometry include GW recharge from the unsaturated zone, transmission losses to GW, and aquifer flow from upstream catchments (inputs) and outputs; evapotranspiration loss from the channel riparian zones, discharge to the river channel as groundwater baseflow and GW abstractions.

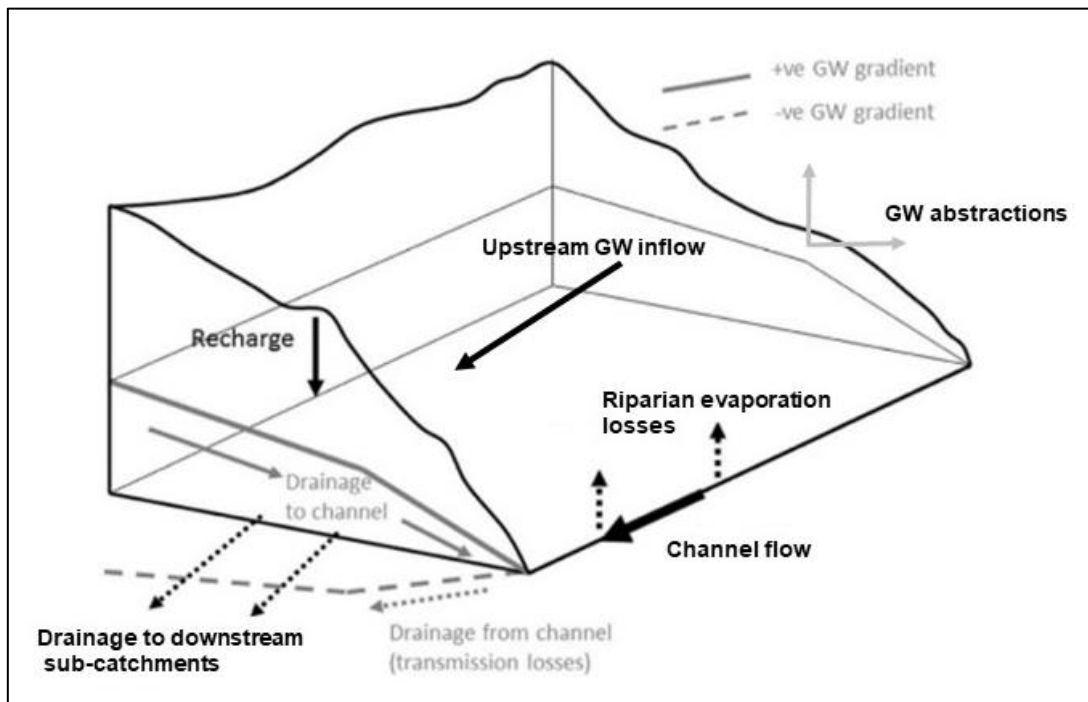


Figure 4.3-6: Illustration of the geometry of the groundwater components of the modified Pitman model (modified from Hughes, 2013).

Within the simplified GW store geometry, the catchment is conceptualised as a rectangle, and channels are represented by parallel lines bordered by drainage slopes along the lengths. The setup is such that the drainage slopes are placed between the borders of the rectangle and the outer channels (one on each side) and two slopes between every pair of the inner channels (Figure 4.3-7).

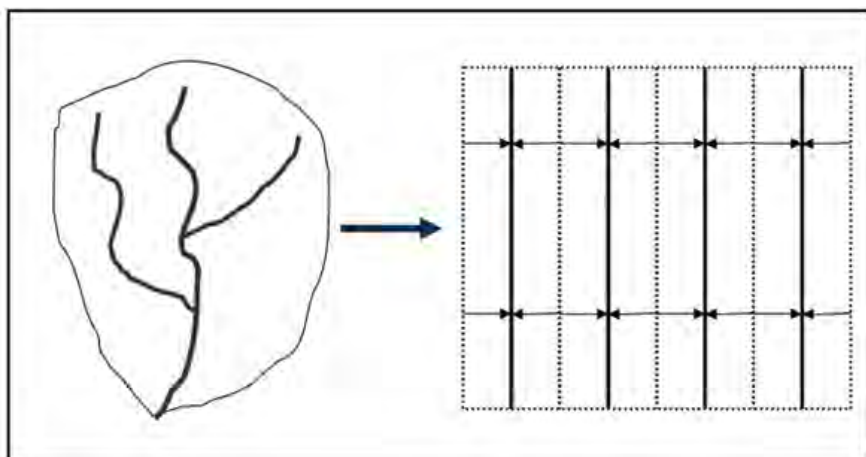


Figure 4.3-7: Conceptualization of the drainage structure in the simplified GW storage component. Solid lines represent channels, dashed lines represent drainage divides, and arrows indicate the drainage directions. This illustration has eight drainage slopes (Hughes et al., 2007).

The number, length and width of the drainage slopes are calculated using the effective drainage density parameter (D.Dens) (km km^{-2}) and basin area (km^2) (Equations 4.3-1 to 4.3-5). Generally, the effective drainage density includes only channels that are expected to receive GW discharge. Minor tributaries characterized by occasional flow incidents, such as those that generate flow only during storm events, are excluded because they are mainly recharged by surface runoff or interflow. The D.Dens parameter can be estimated from maps and a robust conceptual understanding of the catchment. The total channel length (TCL) is calculated from the following:

Equation 4.3-1: *Total channel length = Drainage density * Area*

The width and length of the catchment are related to drainage density through the following equation:

Equation 4.3-2: *Width = Length * 2.0 * Drainage density*

As previously noted, not all channels included in the TCL calculation contribute to GW discharge. The length of the channel expected to yield GW discharge is differentiated from TLC using the following equation:

Equation 4.3-3: *Length = $\sqrt{\text{Area}/(2 * (\text{Drainage density}))}$*

Subsequently, the number of contributing slope elements (NSlope) is estimated from

Equation 4.3-4: *Number of drainage slopes = 2.0 * Drainage density * Area/Length*

Lastly, the estimate of NSlope is corrected by rounding up or down to the nearest even to the number. The width of NSlope is then calculated from:

Equation 4.3-5: *Drainage width = Width/No. of drainage slopes*

The total width of each drainage slope is apportioned into a 40:60 ratio corresponding to a near-channel (down) slope and a far-channel (upper) slope. The slope gradients control water movement in the GW storage compartment by accounting for differences in the way abstractions that occur in areas bordering the channel and those that occur in remote channel areas impact GW discharge to the channel. The volume of the water added to and removed from the GW store is estimated based on the slope element widths and lengths, groundwater gradients and the storativity parameter (Equation 4.3-6). Aquifer volume is calculated from:

Equation 4.3-6: *Volume = $((\text{Drainage width})^2 * \text{Drainage length} * \text{Gradient} * \text{Storativity})/2$*

The model simulates all the GW inputs and outputs according to changes in the lateral gradient such that a positive gradient results in drainage from the GW store. In contrast, a negative gradient causes drainage from the channel as transmission loss or indirect recharge (Figure 4.3-6) (Tanner and Hughes, 2013). Water balance calculations for the slope components are completed separately. They are first performed on the near channel slope compartment (downstream point assumed to be at the same level as the channel) and then on the far slope compartment. The recharge input and downstream catchment outflow are allocated proportionately per the 40:60 ratio of the two slope components.

Groundwater Recharge (GPOW, GW, and SL): The model estimates recharge (RE) as the ratio between maximum monthly storage (ST) and the current soil moisture storage level (S) using a non-linear power function expressed by the parameter GPOW (Equation 4.3-7). This relationship is similar to calculating runoff depth from S (Figure 4.3-5). The parameter GW defines the maximum groundwater recharge volume at ST, and SL is the soil moisture limit below which no groundwater recharge occurs.

Equation 4.3-7: $RE = GW((S - SL)/(ST - SL))^{GPOW}$

Riparian losses to evapotranspiration (RSF and RWL): Evapotranspiration losses from the GW store are controlled by two parameters, the riparian strip factor (RSF) (%) and the rest water level (RWL) (m). The RSF parameter denotes the areal extent of a specified vegetation type expressed as a percentage of the total slope component width over which evapotranspiration losses are expected to occur. In many environments, evapotranspiration losses from GW occur close to the edge of the river channel through (i) direct evaporation from the surface of the channel beds and banks and/or (ii) transpiration by riparian vegetation. The average riparian strip width along a channel can be delineated using aerial photographs or Google Earth. Although the RSF parameter is typically used for riparian evaporation, further interpretation of the physical meaning of this parameter is that it represents the area of vegetation that can access GW for transpiration either from near-surface groundwater or direct interception of groundwater discharge contributions to streamflow (Kapangaziriwi, 2010). The second parameter, RWL, describes the aquifer depth below the channel at which all GW outflow processes (evapotranspiration, discharge and abstractions) cease to occur. This parameter can be estimated from aquifer depths or the median saturated thickness variable (Conrad, 2005). While this function typically represents losses from riparian areas, it can be applied to any area of a catchment where evapotranspiration occurs from groundwater. Evapotranspiration losses are calculated from the following:

Equation 4.3-8:

$$Evap. losses = Drainage width * Net Evap.* Riparian stip factor * Depletion factor$$

Where net evaporation is the difference between potential evaporation and rainfall. The GW depletion factor decreases evapotranspiration losses, reducing riparian losses as the GW gradient becomes more negative. The GW depletion factor is worked out from:

Equation 4.3-9:

$$GW \text{ depletion factor } (Gradient \text{ at } RWL - Current \text{ gradient}) / Gradient \text{ at } RWL$$

Discharge to downstream catchments: Regional GW movement can only move in a downstream direction according to the surface water catchment drainage direction. Discharge from upstream catchments to downstream catchments is estimated based on the regional groundwater gradient parameter (GW Slope) using the equation:

Equation 4.3-10:

$$Downstream \text{ outflow} = Transmissivity * Regional \text{ gradient} * Time \text{ step} * Slope \text{ width}$$

Discharge to the river channel (T, St, D.Dens, RWL, and GWSlope): Discharge from GW to the channel is calculated from estimates of the following catchment characteristics: transmissivity and storativity, drainage density, rest water level and the regional groundwater drainage slope. Transmissivity (T in $m^2 d^{-1}$) - describes the hydraulic characteristics of the catchment. It is calculated as the product of the saturated aquifer thickness and permeability. Storativity (St) represents the capacity of the aquifer to store water. Transmissivity and storativity values for South African catchments are available on the Groundwater Resources Assessment II (GRAII) database (Conrad, 2005). Drainage density (D. Dens. in $km \text{ km}^{-2}$), Rest water level (RWL in m) and Regional GW drainage slope (GWSlope in %) are as described in the preceding sections.

Transmission Losses (TLGMax): When the groundwater gradient (near channel slope compartment) drops below the level of the channel, a negative gradient occurs, causing water to move from the channel to the groundwater storage as channel transmission loss or indirect recharge. Channel transmission losses can be an important source of groundwater recharge in semi-arid and arid regions. However, there is a limited understanding of some of the more detailed mechanisms around channel transmission losses and no clear guidelines for establishing model algorithms to represent this process (Kapangaziriwi, 2010). Within the Pitman model, channel transmission losses are accounted for based on the correlation between the gradient and the current channel stream flow relative to the maximum loss parameter (TLGMax in mm).

Groundwater abstraction (GWA (Lower slope) and GWA (Upper slope): The model simulates abstractions as annual volumes with seasonal distributions. There are two abstraction parameters,

GWA (Lower slope) and GWA (Upper slope) (Ml year^{-1}), for the near (lower) and remote (upper) channel compartments. Seasonal distributions are based on the available data, and the same distribution is applied to the two slope compartments.

4.3.2.1. Summary of the groundwater components of the model

The Pitman model modifications detailed in Hughes (2004; 2013) are based on a simplified groundwater store geometry principle. To achieve this simple geometric arrangement, the model structure was designed to account for specific water balance processes, which are assumed to be of significance in the South African environment (Figure 4.3-6). In addition, the model emphasizes the importance of accounting for the different responses to abstractions in near-channel areas and those that occur in areas located far from the channel. These differences are accounted for by segmenting the channel width into the near-channel slope component (40% of the channel width) and the remote channel slope components (60% of the channel width). This modelling approach is implemented so as to avoid the complexity involved when directly simulating groundwater levels, thus, eliminating the inclusion of additional parameters that come with a direct simulation of groundwater depth (Hughes et al., 2007). The volumetric water balance of the conceptual aquifer is calculated proportionally based on the variations in the near and far channel slope components. Different gradient configurations are accounted for within the geometry of the conceptual aquifer, including positive gradients in both slope segments (Figure 4.3-8A), a positive gradient in the near-channel component and a negative gradient in the remote channel slope component (Figure 4.3-8B), a positive gradient in the far from channel segment and a negative gradient in the near-channel segment (Figure 4.3-8C) and lastly, negative gradients in both slope components (Figure 4.3-8D). The gradient setups in Figures 4.3-8B and C can only occur when there are abstractions and not under natural conditions.

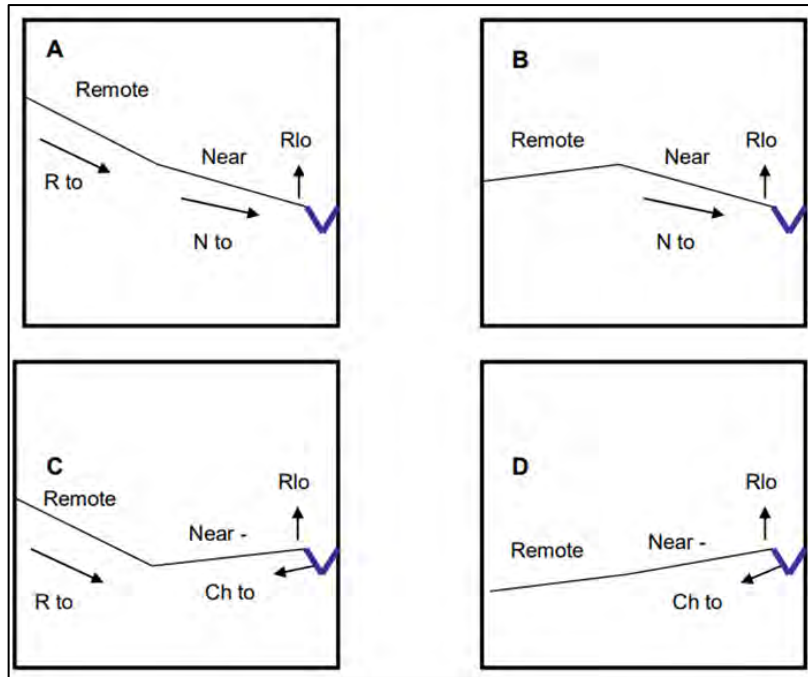


Figure 4.3-8: Illustration of the different slope configurations that can exist within the geometry of the conceptual aquifer. Ch denotes the channel, R is remote from the channel component, N is the near-channel component, and Rlo is the riparian evapotranspiration losses. The arrows show the direction of water movement (Kapangaziriwi, 2010).

Water balance calculations are performed separately for each slope component at each time interval, starting with the near-channel slope component. The model runs four iteration steps at a monthly time scale (Hughes, 2007). Each iteration step consists of the following processes:

- I. **Determination of water input into the groundwater storage** - additions to the GW storage occur as recharge from the surface component of the model, GW discharge from upstream sub-catchments and flow from the channel (transmission losses) if the near channel slope component is negative. The resultant volume of water correspondingly contributes to the two slope components, considering the storativity.
- II. **Determination of water output from the groundwater storage**- based on the slope gradients from iteration step one, water in the aquifer storage is distributed according to the various groundwater loss processes; discharge to downstream sub-catchments, riparian evapotranspiration losses (occurs in the near-channel component only), discharge to the channel (also from the near-channel component only), discharge to the near-channel component from the remote from channel component and abstractions.

- III. **Determination of the resultant groundwater storage volume-** estimated volumes of groundwater in each slope compartment are then used to determine slope gradients for the next iteration step.

4.4. Wetland/Lake sub-model

In addition to utilizing the standard modified Pitman model (Hughes, 2004), a wetland/lake sub-model detailed in Hughes et al. (2013) was used to incorporate lake processes into the modelling procedure. The sub-model (Hughes et al., 2013) was specifically designed to improve the hydrological processes in environments where large wetlands or natural lakes impact the monthly streamflow patterns. The sub-model algorithms describe the input-storage-output mechanisms between the river channel and the wetlands/lakes; however, the model structure does not include explicit wetland-groundwater exchanges, which were therefore represented implicitly in the simulations. Most sub-model parameters can be estimated from topographical analysis of the wetland/lake using simple methods such as area-volume graphs or satellite imagery. However, some parameters require detailed hydraulic data or comprehensive methods based on a robust understanding of the channel-wetland interactions. Detailed explanations of the Pitman wetland sub-model are accessible from Hughes et al. (2013). A summary of the sub-model components is provided below. Table 4.4-1 outlines and briefly describes the model parameters, followed by a summary.

Table 4.4-1: Parameters and algorithms for the wetland and lake sub-model (Hughes et al., 2013)

Model Parameters and units	Description
Code for Wetland function	Set to -99 to distinguish the wetland function from a reservoir function
MaxWA (km ²)	Maximum wetland area
RWV (m ³ * 10 ⁶)	Residual wetland storage volume below which there are no return flows to the river channel
IWV (m ³ * 10 ⁶)	Initial wetland storage volume
AVC (m ⁻¹)	Constant in the $WA = AVC * WV^{AVP}$ relationship, where WA (m ²) and WV (m ³) are the current wetland area (limited to Max WA) and volume, respectively.
AVP (N/A)	Power in the $WA=AVC * WV^{AVP}$ relationship.
QCap (m ³ * 10 ⁶)	Channel capacity below which there is no spill from the channel to the wetland.
QSF (fraction)	Channel spill factor in $SPILL = QSF * (Q - QCAP)$, where Q is the upstream flow, and SPILL is the volume added to wetland storage.
RFC (N/A)	Return flow constant in the $RFF = RFC * (WV / RWV)^{RFP}$ relationship. RFF is a fraction limited to a maximum of 0.95 and then adjusted when Q is greater

	than QCap ($RFF = RFF * QCap / Q$). The return flow volume is calculated from $RFlow = RFF * (WV - RWV)$.
RFP (N/A)	Return flow power in the $RFF = RFC * (WV / RWV)^{RFP}$ relationship.
EVAP (mm)	Annual evaporation from the wetland (distributed into monthly values using a table of calendar month percentages).
ABS ($m^3 * 10^6$)	Annual water abstractions from the wetland (distributed into monthly values using a table of calendar month percentages).
MRFF (fraction)	Maximum Return Flow Fraction If MRFF is positive & < 1.0 then $RFF = RFF_{initial} * QCAP / Q$ If MRRF MRFF is positive & > 1.0 then $RFF = RFF_{initial} + 10$ If MRRF is negative then $RFF = -RFF_{initial}$

4.4.1. Summary of wetland/lake sub-model components

- I. The wetland/lake inundation area is constrained to a maximum value MaxWA, estimated from the relationship between the current extent of the wetland/lake surface area (WA) and the volume of inundation (WV). WA and WV are related by a power function described by AVC and AVP parameters. These parameters can be set based on lake bathymetric data.
- II. Local runoff (yielded within the sub-catchment) only contributes to the portion of the wetland/lake that is not fully inundated (MaxWA - WA). The surface runoff depth is considered equal to that simulated by the main component of the hydrological model (section 4.3.1) for the wetland sub-catchment.
- III. Local rainfall volume (directly into the lake or wetland) is calculated based on the rainfall depth that falls on the portion of the wetland/lake that is submerged (WA).
- IV. Evapotranspiration losses from the wetland are estimated from monthly distributions of the potential annual evaporation (EVAP) and WA. The seasonal distribution of EVAP is based on available data and follows the same method used in the primary model (Hughes et al., 2006). This volume will vary based on the dynamic wetland area as determined in point 1 above, and losses from a lake are assumed to occur at the potential evapotranspiration rate.
- V. Inflow from the channel is estimated from the parameter QSF, representing the proportion of total upstream channel flow (Q) that exceeds the channel-threshold (QCap). Q is simulated by the other components of the surface hydrology model (section 4.3.1).
- VI. Return flows from the wetland/lake back to the river are described by a power function (RFP) relating the return flow fraction (RFF) parameter and the ratio of WV to the residual volume (RWV). Wetland/lake return flow occurs only when WV is greater than RWV. In a closed lake

system like the Lake Sibaya catchment, this function is used to represent losses via the palaeo-channel.

- VII. Abstractions from the wetland/lake are estimated from monthly distributions of the value of the annual abstraction (ABS). The water use patterns determine the seasonal distribution of ABS.
- VIII. The final computation performed by the sub-model compares the spills (to the wetland) against return flows (from the wetland) and corrects the upstream flows simulated by the primary model. The modified flows become the upstream flows into the next downstream sub-basin of the model distribution system.

4.5. Modelling approach

The research assessed the feasibility and utility of using the modified Pitman model (Hughes, 2004) to simulate water resource interactions in the Lake Sibaya catchment. This section outlines the modelling approach used to achieve this.

4.5.1. Summary of the datasets

An overview of the various data sets used in the model setup and calibration is provided in Table 2.5-1, followed by a description of the datasets.

Table 4.5-1: Details of the datasets used in the study.

Dataset	Temporal resolution	Spatial resolution	Length	Source	Reference
Rainfall	Monthly	Catchment scale localized MAP	1920-2009	WR2012 https://waterresourceswr2012.co.za/	Bailey and Pitman (2015)
	Monthly	Catchment scale localized MAP	1920-2018	Climatic Research Unit (CRU) https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.05/ge/	Harris et al. (2020)
Potential evapotranspiration	Monthly	Quaternary catchment	1920-2009	WR2012 https://waterresourceswr2012.co.za/	Bailey and Pitman (2015)
Observed lake levels	Daily	Lake	1980-2014	Department of Water and Sanitation (DWS) hydrological Services, station W7R001 https://www.dws.gov.za/Hydrology/Verified/hymain.aspx	DWS (2015)
Groundwater levels	Hourly	Borehole	SIB01A and SIB01B- 2018-2019 SIBO2 - 2018-2020	South African Environmental Observation Network (SAEON). Researchers: Paul Gordijn & Siphwe Mfeka	SAEON (2020)

Rainfall

Rainfall data was primarily acquired from the Water Resources of South Africa 2012 (WR2012) website (Bailey and Pitman, 2015), which provides climatic data and other water resource information for South Africa. The WR2012 rainfall data are derived from spatial interpolation of gauged data at the quaternary catchment scale. These data are available from 1920 to 2009 and are the longest-measured data for the study area. Additional rainfall data were obtained to extend the rainfall time series to simulate the current timeframe. This was a critical factor because, between 2001 and 2014, a significant decline in lake levels was reported (Smithers et al., 2017) and, this current study aimed to determine how the Pitman model (Hughes, 2004) would represent these changes. The additional rainfall data was sourced from Climatic Research Unit (CRU) (Harris et al., 2020). CRU rainfall data are part of a climate data set consisting of other variables, including temperature, vapour pressure, wet-day frequency and cloud cover. These data have a long and continuous record beginning in 1920,

making them suitable for hydrological modelling. They are available on a monthly time scale and a 0.5° x 0.5° grid spatial resolution (Harris et al., 2020). CRU data are derived from interpolating monthly climate anomalies acquired from a broad network of weather station observations. The utilization of as many stations as possible and integration of elevation dependence in the interpolation process maximizes the representation of spatial variability in mean climate data (New et al., 2000). The most recent version (Harris et al., 2020) interpolates data using angular-distance weighting (ADW), which adds diagnostic metadata for better accuracy and traceability. The model was setup using an integrated rainfall time series, utilizing WR2012 data from 1920 to 2009 and CRU data from 2010 to 2018. The WR2012 and CRU rainfall datasets were adjusted to represent the Lake Sibaya catchment conditions using a detailed isohyets map created by Weitz and Demlie (2014), who used gauged data from the South African Weather Service (2013).

Figure 4.5-1 compares the monthly average rainfall for Lake Sibaya based on localised WR2012 and CRU data and rainfall estimates by Weitz and Demlie (2014). The monthly rainfall distribution pattern for all three data sets is comparable, with the largest rainfall amounts occurring between January and February and the lowest rainfall occurring between July and August. A summary of additional statistics for the data is presented in Table 4.5-2.

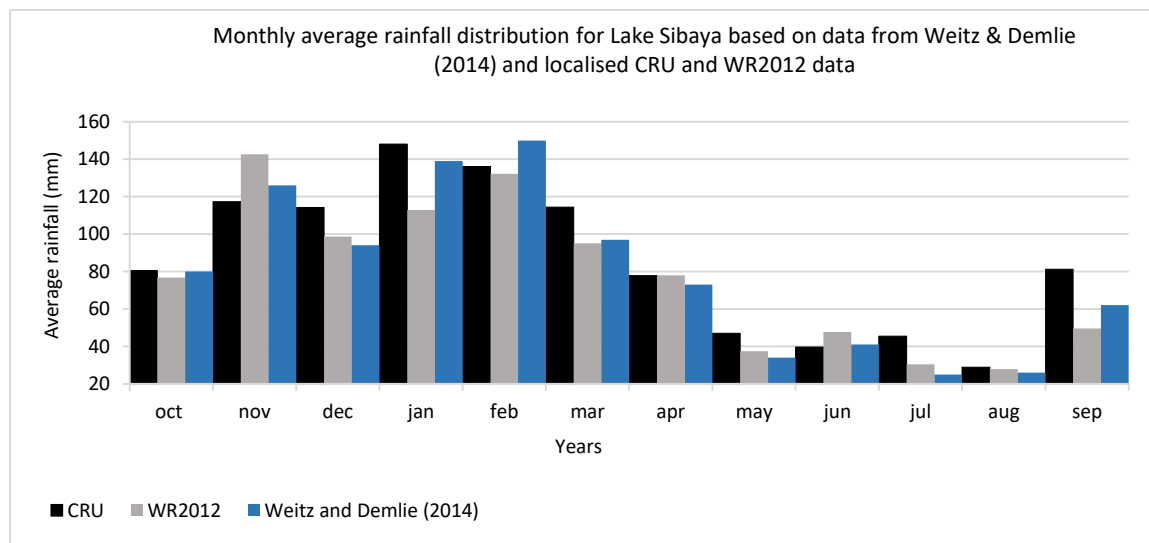


Figure 4.5-1: Comparison of monthly average rainfall for Lake Sibaya based on data from Weitz and Demlie (2014) and localised data WR2012 and CRU data. Graphs based on data from 1997 to 2014 when the Weitz and Demlie (2015) data were available. However, the WR2012 data were only available up to 2009.

Table 4.5-2: Summary statistics for Lake Sibaya rainfall data.

Statistical measure (mm)	WR2012	CRU	Weitz and Demlie (2014)
Average	77.44	85.91	78.92
Minimum value	27.80	28.90	25
Maximum value	142.68	148.05	150

The coefficient of efficiency (R^2) values obtained from correlation analysis indicated a good match between the data sets. $R^2 = 0.8324$ was obtained for WR2012 versus CRU data (Figure 4.5-2), 0.9288 for Weitz and Demlie (2014) versus WR2012 data (Figure 4.5-3) and 0.9322 for Weitz and Demlie (2014) versus CRU data (Figure 4.5-4).

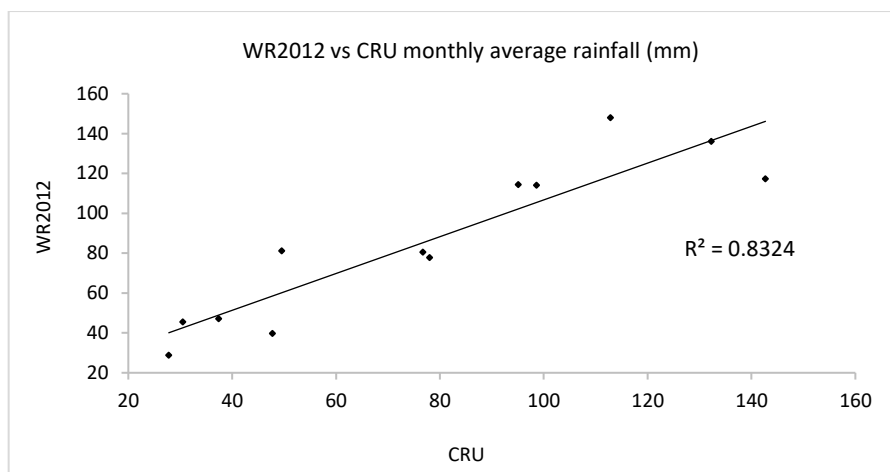


Figure 4.5-1: Scatter plot of WR2012 rainfall data versus CRU rainfall.

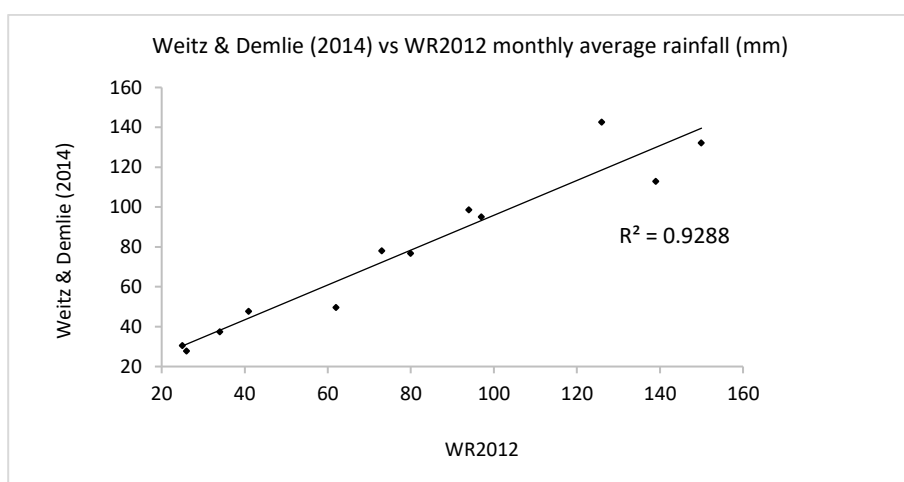


Figure 4.5-2: Scatter plot of Weitz and Demlie (2014) rainfall data versus WR2012 rainfall.

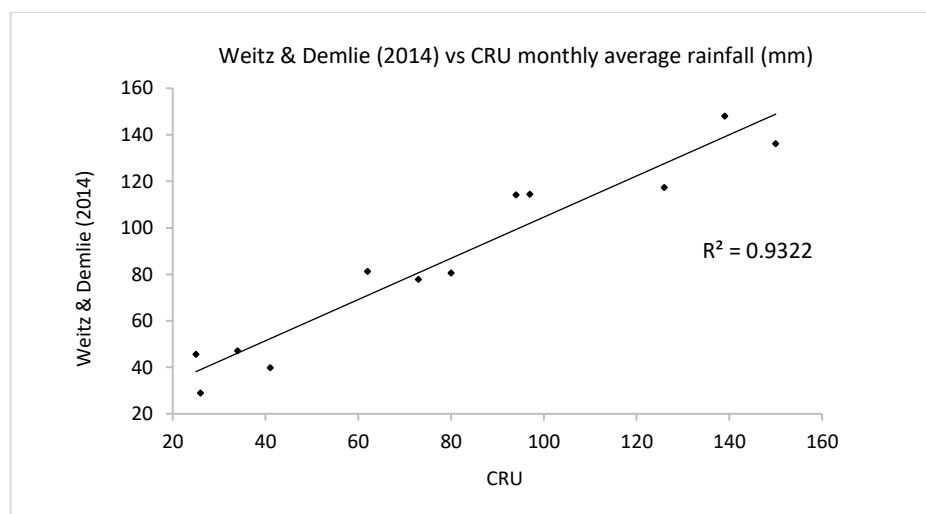


Figure 4.5-3: Scatter plot of Weitz and Demlie (2014) rainfall data versus CRU rainfall.

Potential evapotranspiration

Potential evapotranspiration data were acquired as regional mean monthly evaporation distributions from WR2012 estimates by Bailey and Pitman (2015). These data are averaged catchment values.

Observed lake levels

The model was calibrated against lake-level data from DWA (2015). These data were available for 35 years (1980-2015). The data were in meters and measured daily. For comparison with simulated lake volume, the DWS (2015) observed lake level data were converted to monthly volumes (10^6m^3).

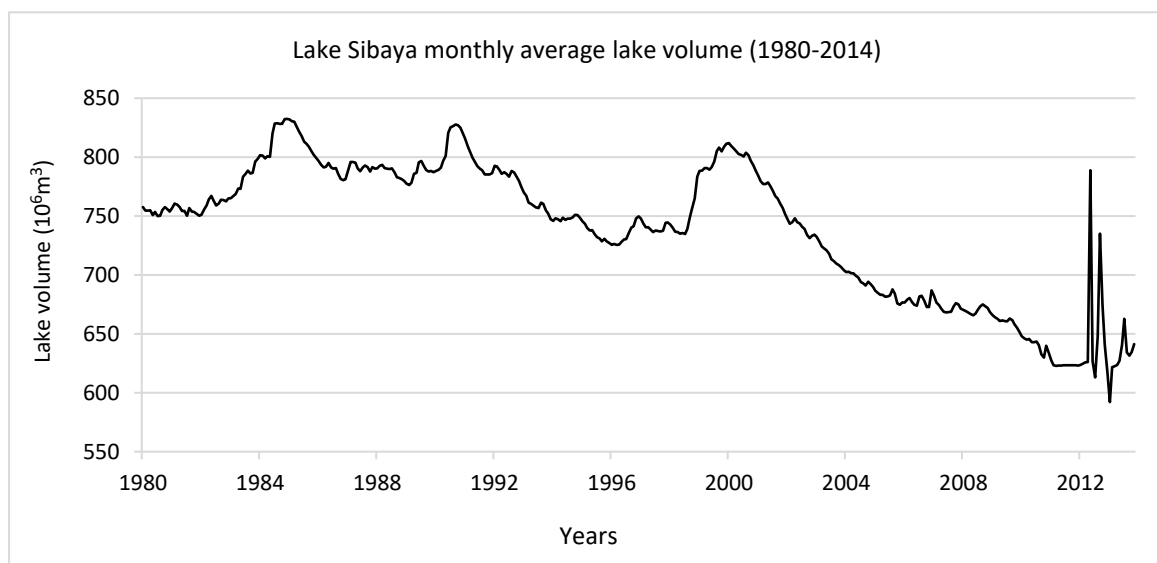


Figure 4.5-4: Lake Sibaya monthly lake volume DWS (2015).

Groundwater level

Groundwater level data were obtained from borehole data at three locations around the lake (SAEON, 2020) (Figure 4.5-6). This data was used to guide the simulation of GW gradients. These boreholes were selected because they had steady and continuous readings. SIBO1A and SIBO2 are shallow boreholes with depths of 27m and 14m, respectively. SIBO1B is a deeper borehole with a depth of 46m. The borehole data were available at an hourly time scale. In the period between 2018 and 2020, when data was available, a pattern of decreasing GW levels was observed for all boreholes. Groundwater level data comparison between the three boreholes sites is provided in Table 4.5-3.



Figure 4.5-5: Google Earth imagery showing the location of borehole sampling points (SIB01A, SIB01B and SIB02) around Lake Sibaya (Google earth images, 2022). Borehole points location acquired from SAEON Researchers; Paul Gordijn & Siphwe Mfeka.

The observed groundwater levels from the three sampling points (SB10A, SIB01B and SIB02) are shown in Figure 4.5-7 below.

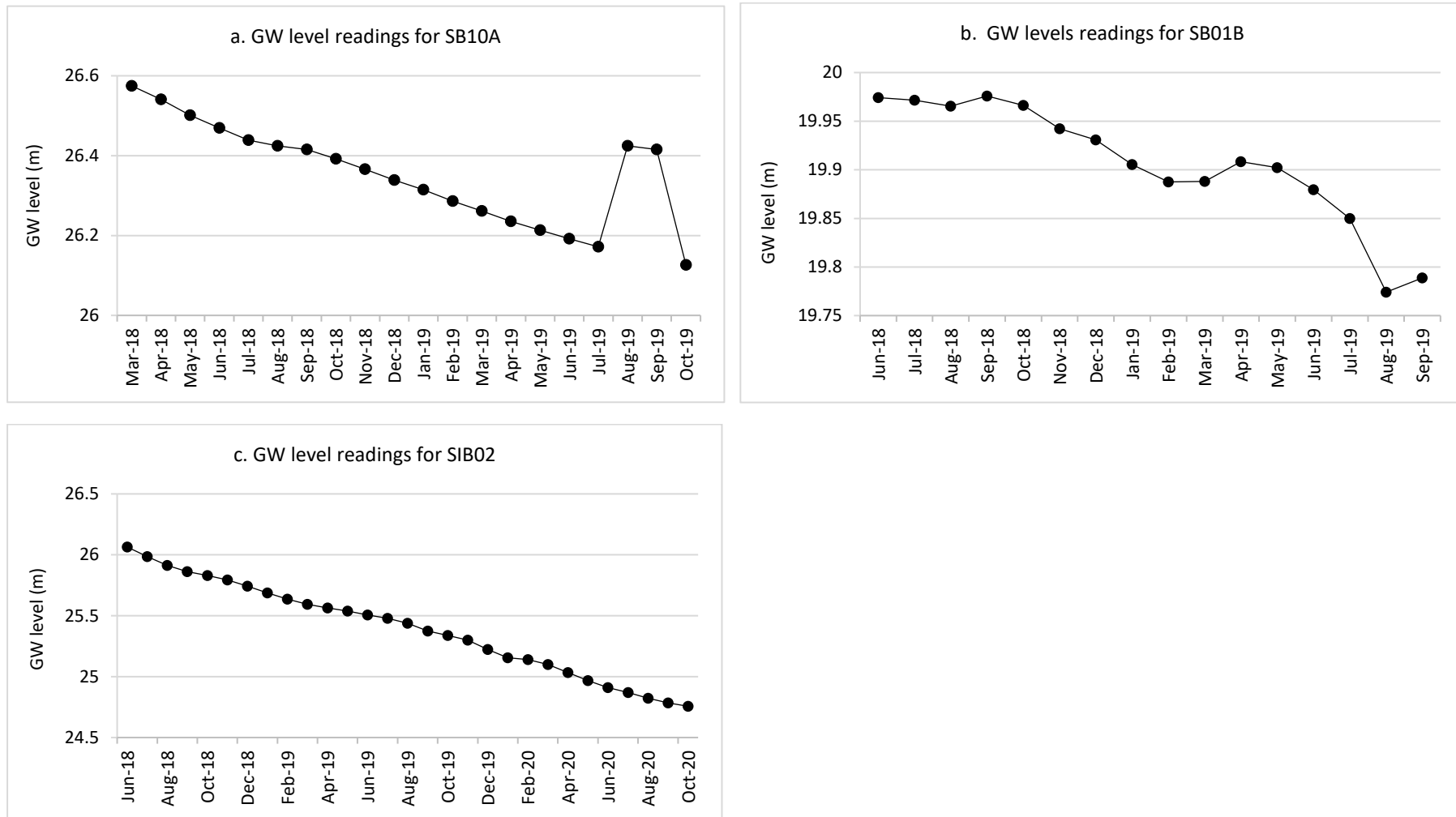


Figure 4.5-6: Groundwater levels measured from boreholes SB10A (a), SIB01B (b) and SIB02 SAEON (c) (2020).

Table 4.5-3: Summary statistics for groundwater level data from boreholes in the Lake Sibaya catchment. Borehole data acquired from SAEON (2020).

Statistical measure (m)	SIB01A (27 m)	SIB02 (14 m)	SIB01B (46 m)
Average	26.36	25.39	19.91
Minimum value	26.13	24.76	19.77
Maximum value	26.57	26.06	19.98

4.5.2. Setting up the Pitman model for the Lake Sibaya catchment

The modified Pitman model (Hughes, 2004) was set up using the SPATSIM software (Hughes and Forsyth, 2006). The model setup/ application was run using the single-run version of the model, which uses a single parameter set to simulate a hydrological response for each catchment/ sub-catchment (Hughes et al., 2010). The processes for establishing the model application involved:

- I. Creating the relevant features by loading shapefiles to display spatial data types such as points (land and interface nodes, borehole points), lines and polygons (catchment boundaries and rivers), and then
- II. Linking the features with a database of attribute data (rainfall, evapotranspiration, lake levels, and model parameters).

The lake Sibaya catchment is a predominantly GW-driven system; therefore, the model was set up based on the groundwater catchment area. This approach ensured that the dominant lake processes are represented in the modelling simulations. Due to the area's flat topography, it is difficult to obtain precise measurements of the contributing GW catchment. Existing estimates of the catchment area include 509 km² (Smithers et al., 2017) and 521 km² (Weitz and Demlie, 2014). Smithers et al. (2017) identified a surface water catchment of 509 km² and a groundwater-contributing area to the lake at approximately 569 km². An estimate of 530 km² worked out by Hughes and Tanner (2016) based on the North West University (NWU, 2014) groundwater flow distribution map was used in the current model setup. A semi-distributed approach was followed to improve the representation of catchment heterogeneity, whereby the groundwater catchment was divided into three sub-catchments (SCs) or nodes. These sub-catchments correspond to the three main rivers in the lake catchment; Mseleni tributary (perennial) (sub-catchment 2), the Velindlovu and Kumzingwane rivers (non-perennial) (sub-catchment 1) as well as the South Western arm of the lake, which receives groundwater inflow (sub-catchments 3) (Figure 4.5-8) (Sue van Rensburg, personal communication).

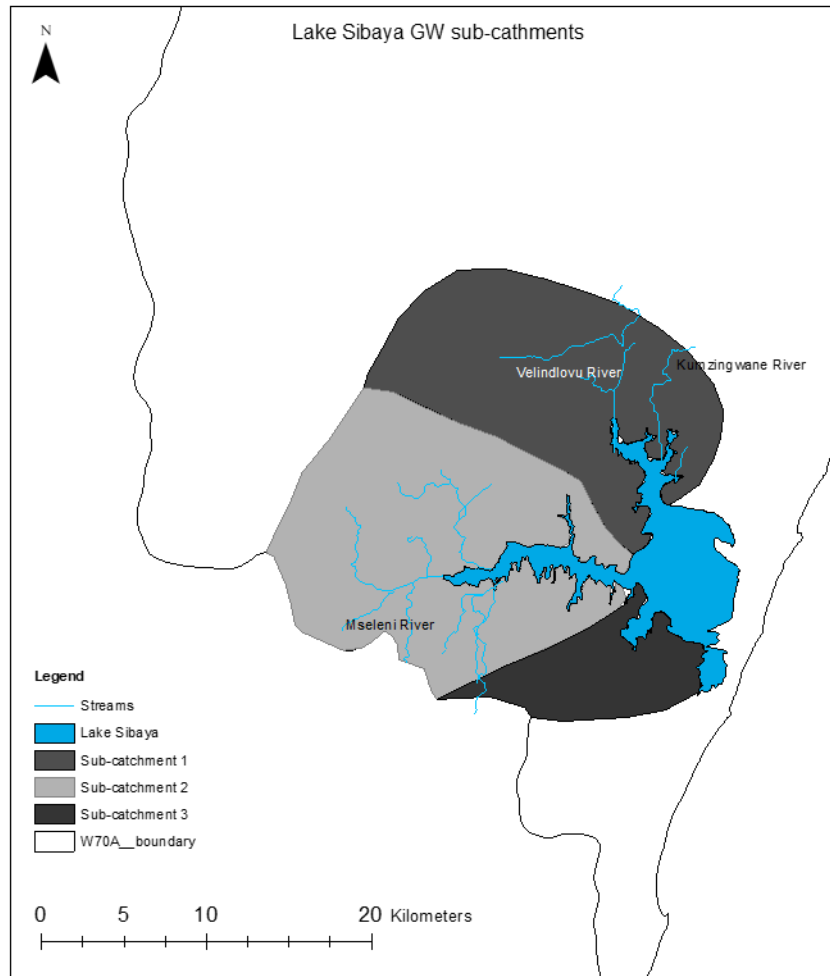


Figure 4.5-7: Illustration of the groundwater sub-catchments and corresponding rivers feeding the lake.

Each sub-catchment was characterized by its rainfall, evapotranspiration and catchment parameter data. Figure 4.5-9 illustrates the mean annual precipitation for the sub-catchments. The graphs are based on integrated data (1920-2018), and they show an increasing rainfall gradient moving from the western part of the catchment (SC 2) to the south eastern part (SC 3). The displayed rainfall pattern is similar to what was established by other researchers, Weitz and Demlie (2014), for this catchment. A summary of the rainfall series data statistics is provided in Table 4.5-4.

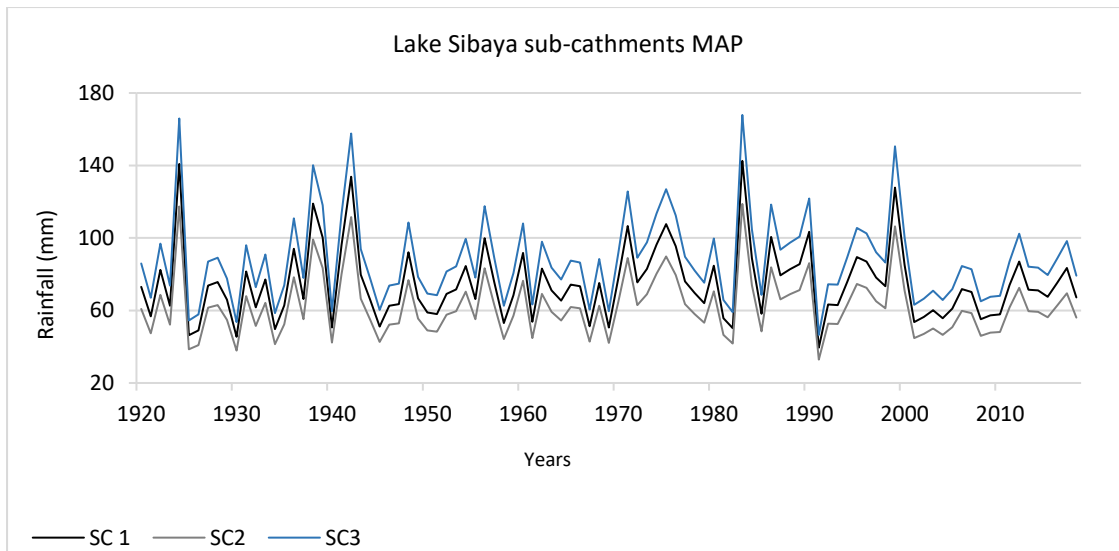


Figure 4.5-8: Lake Sibaya sub-catchments mean annual precipitation based on WR2012 and CRU integrated rainfall time series.

Table 4.5-4: Summary statistics for the sub-catchments' rainfall time series.

Statistical measure (mm)	SC 1	SC 2	SC 3
Average	74.80	62.33	88.10
Minimum value	39.49	32.91	46.51
Maximum value	142.55	118.79	167.90

4.5.3. Pitman model representation of the main water balance components occurring in the Lake Sibaya catchment

This research focused on resolving some uncertainties in representing the SW-GW interaction water balance at the catchment scale. Processes that contribute significantly to the lake were identified based on a general understanding of the fundamental processes involved in a hydrological system and a conceptual understanding of the Lake Sibaya catchment. Table 4.5-5 summarizes the key water balance components of the Lake Sibaya catchment and the ability of the Pitman model to represent them.

Table 4.5-5: Dominant processes in the Lake Sibaya catchment and the ability of the Pitman model to represent them.

Process	Simulated
Precipitation onto the lake	Yes
Surface runoff into the lake	Yes
Channel flow into the lake	Yes
Direct groundwater outflow (seepage) into the lake	No
Lake outflow to the sea through a palaeo-channel	Not explicitly
Abstractions I. from the river II. from the lake III. from groundwater	Yes Yes Yes
Evapotranspiration I. directly from the lake surface II. from groundwater by vegetation	Yes Yes
Land cover change	No

The processes listed in Table 4.5-5 were simulated according to the model algorithms described in Section 4.3. Explanations are provided below for processes that required additional external calculations of variables.

- I. **Evapotranspiration directly from the lake surface:** The model uses the surface area-volume relationship to determine the area of the lake that can contribute to evapotranspiration losses. The surface area-volume relationship (Figure 4.5-13) for Lake Sibaya was defined using information from the bathymetric survey by Miller (2001) and the survey by Muggleton (see Section 3.7).

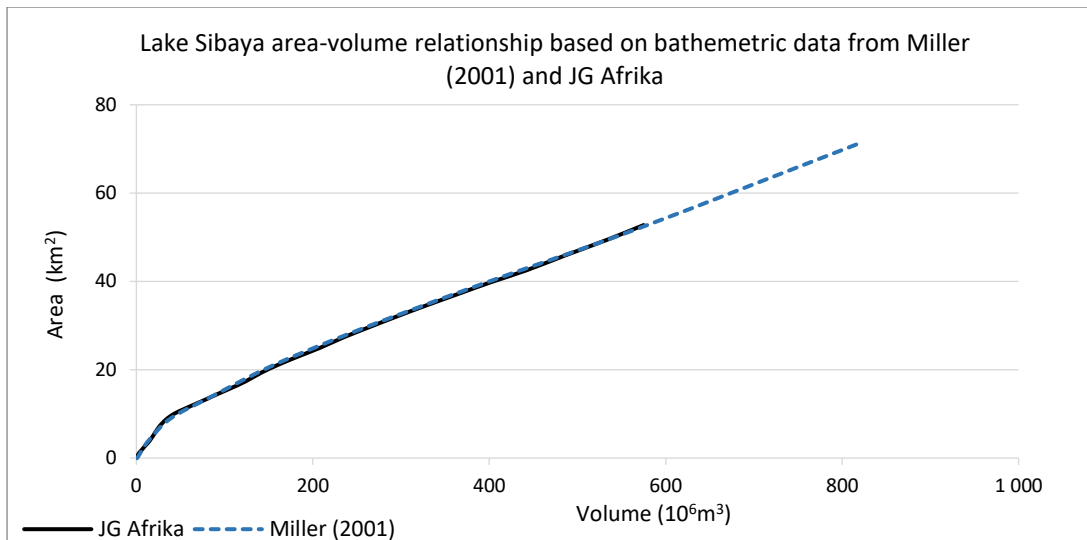


Figure 4.5-9: Lake Sibaya area-volume relationship calculated using the bathymetric data compiled by Miller (2001) and JG Afrika.

- II. **Evapotranspiration from groundwater by vegetation:** This process is detailed in Section 4.3.2. The Pitman Model calculates ET from the groundwater store for the riparian zone of the sub-catchment but does not output this. The model's algorithm for the process (Hughes, 2004) was re-applied outside the software. The RIP parameter specifies the catchment area where vegetation can access GW. The amount of water lost to ET from the GW store is a function of the riparian zone area, the evaporative demand minus rainfall (both input), and the groundwater storage (hence gradient). Due to the study area's shallow groundwater level, there are wetland areas where vegetation does access groundwater. These areas do not always fall within a riparian zone, but this function can be simply applied to the catchment as a whole. Although the function was conceptualised for riparian areas, it applies to a percentage of the entire sub-catchment, so it is applicable outside riparian areas.

Table 4.5-6 below shows the figures used in the calculations for the Riparian area (or vegetated area with access to groundwater) for the catchment. The equations behind the values below are given in Section 4.3.2. These calculations relate to the model variables rather than the actual physical catchment values (for example, channel width and length are those within the model, calculated using model parameters).

Table 4.5-6: Riparian area calculations.

Natural											
Sub-catchment	Catchment area	Drainage density	Total channel length	Total channel width	Forestry area	Forestry area	Riparian area including wetlands	Total riparian/ access to GW area	Riparian width (in model)	Riparian width (in model)	RIP parameter
	km ²		km	km	%	km ²	km ²	km ²	m	km	%
1	213	0.40	85.20	68.16	0.00	0.00	42.60	42.60	500.00	0.50	0.01
2	255	0.40	102.00	81.60	0.00	0.00	51.00	51.00	500.00	0.50	0.01
3	62	0.40	24.80	19.84	0.00	0.00	12.40	12.40	500.00	0.50	0.03
1980											
Sub-catchment	Catchment area	Drainage density	Total channel length	Total channel width	Forestry area	Forestry area	Riparian area including wetlands	Total riparian/ access to GW area	Riparian width (in model)	Riparian width (in model)	RIP parameter
	km ²		km	km	%	km ²	km ²	km ²	m	km	%
1	213	0.40	85.20	68.16	7.50	15.98	42.60	58.58	687.50	0.69	0.01
2	255	0.40	102.00	81.60	0.30	0.77	51.00	51.77	507.50	0.51	0.01
3	62	0.40	24.80	19.84	15.60	9.67	12.40	22.07	890.00	0.89	0.04
2005											
Sub-catchment	Catchment area	Drainage density	Total channel length	Total channel width	Forestry area	Forestry area	Riparian area including wetlands	Total riparian/ access to GW area	Riparian width (in model)	Riparian width (in model)	RIP parameter
	km ²		km	km	%	km ²	km ²	km ²	m	km	%
1	213	0.40	85.20	68.16	20.30	43.24	42.60	85.84	1007.50	1.01	0.01
2	255	0.40	102.00	81.60	0.30	0.77	51.00	51.77	507.50	0.51	0.01
3	62	0.40	24.80	19.84	15.60	9.67	12.40	22.07	890.00	0.89	0.04
2011											
Sub-catchment	Catchment area	Drainage density	Total channel length	Total channel width	Forestry area	Forestry area	Riparian area including wetlands	Total riparian/ access to GW area	Riparian width (in model)	Riparian width (in model)	RIP parameter
	km ²		km	km	%	km ²	km ²	km ²	m	km	%
1	213	0.40	85.20	68.16	22.20	47.29	42.60	89.89	1055.00	1.06	0.02
2	255	0.40	102.00	81.60	3.00	7.65	51.00	58.65	575.00	0.58	0.01
3	62	0.40	24.80	19.84	42.60	26.41	12.40	38.81	1565.00	1.57	0.08
2021											
Sub-catchment	Catchment area	Drainage density	Total channel length	Total channel width	Forestry area	Forestry area	Riparian area including wetlands	Total riparian/ access to GW area	Riparian width (in model)	Riparian width (in model)	RIP parameter
	km ²		km	km	%	km ²	km ²	km ²	m	km	%
1	213	0.40	85.20	68.16	27.00	57.51	42.60	100.11	1175.00	1.18	0.02
2	255	0.40	102.00	81.60	12.00	30.60	51.00	81.60	800.00	0.80	0.01
3	62	0.40	24.80	19.84	44.00	27.28	12.40	39.68	1600.00	1.60	0.08

NB: Riparian width, in this particular case, refers to the area of the catchment where vegetation (both natural and plantation forestry) can access groundwater.

Given the shallow groundwater level and the number of wetlands in the catchment, the natural riparian area was assumed to be 20% of the catchment. Although this is a significant simplification, the estimate was based on an average of areas identified as wetland or riparian, mapped through

Google earth. The natural riparian area was summed with the area of forestry in the catchment, as all plantation forestry was assumed to have access to groundwater. The model function specifically designed to represent increased water use by plantation forestry focuses on the surface water and vadose zone. It uses an ET multiplier parameter assigned to a portion of the catchment. While this function was designed to represent the increased water use by alien vegetation, it can be used for any cover type with different water use characteristics than the dominant vegetation type described in the model. The parameter scales up canopy interception and ET from the soil in as much as water is available. A parameter (% AFOR) specifies the percentage of the catchment area that is covered by forestry, and a second parameter (FF) sets the ET ratio of the forestry area compared to that of the rest of the vegetation. Typically, this factor is set to 1.4 for plantation forestry, but given the primary sandy aquifer and shallow groundwater table, this factor was increased to 1.6 in this environment (Hughes and Tanner, 2016).

- III. Abstraction from groundwater and the lake:** The Pitman model represents run-of-river abstraction, groundwater abstraction, and lake abstraction. Information on lake abstraction was obtained from Weitz (2016). There is no information on any run of river abstraction; therefore, this was deemed insignificant. While available literature does mention groundwater abstraction occurring in the catchment, there was minimal information on quantities or distribution. The differentiation between surface water and groundwater abstraction is also unclear. Thus, only lake abstraction was represented in the model.

4.5.3.1. Uncertainties in the representation of processes

The Hughes (2004) model modifications were designed to represent large-scale SW-GW interactions. As a result, compared to the complex realities of groundwater movement, many of the model representations are relatively simple (Hughes et al., 2007; Tanner, 2013). Therefore, it is expected that the simplified conceptualization of groundwater components will not be appropriate for all environments. For instance, the model does not explicitly represent some dominant processes in the Lake Sibaya catchment (Table 4.5-3). There are, however, implicit ways to describe these processes, which this research utilised where necessary.

Lake outflow to the sea: Return flows from the lake back to the river are described by a power function (RFP) in the wetland/lake sub-model. The RFP parameter represents the relation between the return flow fraction (RFF) parameter and the ratio of the volume of inundation (WV) to the residual wetland

volume (RWV). Lake outflow occurs only when WV is greater than RWV. This was the function used to represent outflow via the palaeo-channel.

Direct groundwater outflow (seepage) into the lake: Direct groundwater outflow into the lake is a key process supporting Lake Sibaya, but the wetland/lake sub-model (Hughes et al., 2013) structure does not include wetland-groundwater exchanges because the algorithms assume relatively simple water exchanges between the river channel and the wetland. Therefore, an implicit approach (Hughes and Tanner, 2016) was followed to simulate groundwater contribution to the lake. The approach included setting up interface sub-catchment nodes (dummy nodes), whose primary function was to receive groundwater seepage from the detailed sub-catchment nodes and convert that volume to groundwater baseflow. The converted GW baseflow was then added to the river channel and contributed to the lake as stream flow (lake-surface water exchange process explicitly represented in the model). Figure 4.5-10 shows the placement of the detailed and dummy sub-catchment nodes in the model setup, while Figure 4.5-11 illustrates a breakdown of the implicit process employed.

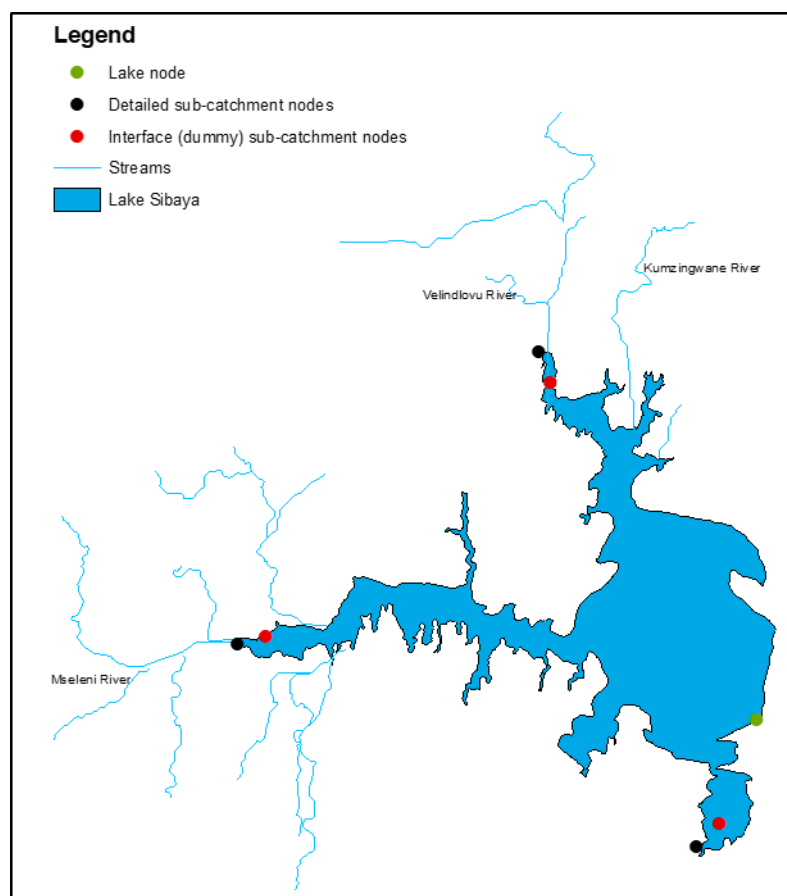


Figure 4.5-10: Illustration of the placement of the detailed and interface sub-catchment nodes in the model setup.

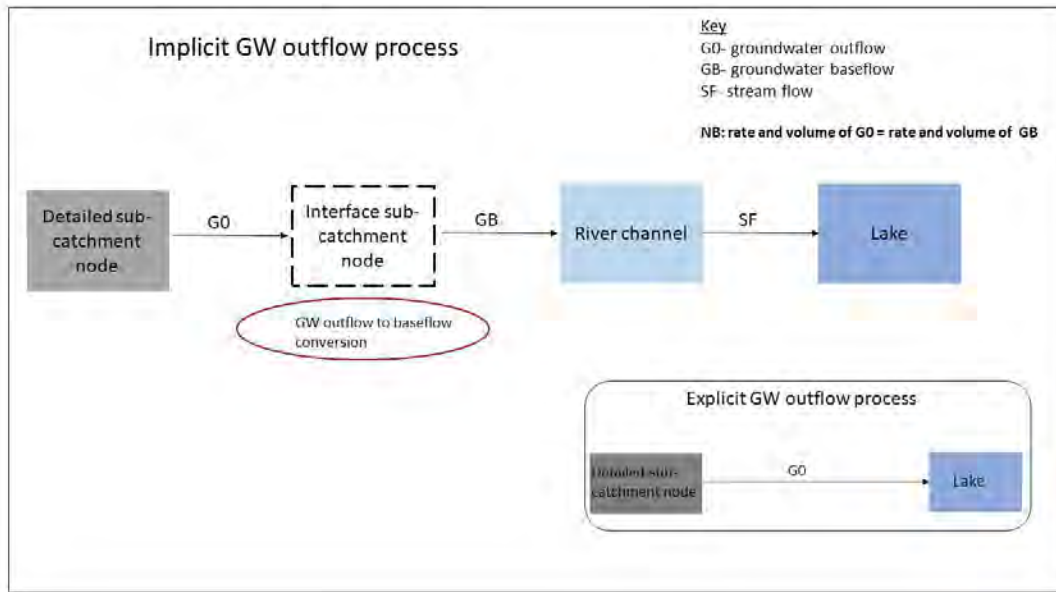


Figure 4.5-11: Breakdown of the implicit approach used to simulate groundwater outflow (seepage) in the Lake Sibaya catchment.

The shape and dimensions of the dummy sub-catchment nodes were designed according to the dimensions of the actual (detailed) node and the lake boundary receiving groundwater baseflow. The groundwater seepage process is controlled by the aquifer transmissivity ($\text{m}^2 \text{ day}^{-1}$), GW gradient (GWslope) and the catchment outlet width, which is calculated from the catchment area and drainage density (Section 4.3.2). The dummy nodes are not characterized by any additional attribute data (rainfall and evapotranspiration) such that the volume of GW outflow from the detailed sub-catchment nodes is the exact volume of water added to the lake. Table 4.5-7 shows a volume comparison between groundwater outflow from the detailed nodes and groundwater baseflow from the interface nodes. The equal volumes of these components indicate that the model set up for implicit representation of the groundwater seepage produced the intended outcome of ensuring that the correct volume of groundwater outflow contribution from upstream nodes moves into the lake.

Table 4.5-7: Comparison between groundwater outflow volume from upstream node and baseflow volume from interface node. Comparison based on model outputs for the natural scenario.

Sub-catchment	Average GW outflow ($10^6\text{m}^3\text{month}^{-1}$) from detailed sub-catchment node	Average routed baseflow ($10^6\text{m}^3\text{month}^{-1}$) sub-catchment node
1 (213 km ²)	2.035	2.035
2 (255 km ²)	1.985	1.985
3 (62 km ²)	0.642	0.642
Total	4.662	4.662

4.5.4. Integrating changing development conditions into the model setup

When temporal changes occur in the catchment to the degree that their impact on the stream flow is significant, these changes must be accounted for in the modelling process. Simulations that omit these adjustments do not accurately match the observed data across the full-time series. This consideration was essential for the Lake Sibaya case study because the lake catchment has undergone significant development over time in land use change (forestry plantations) and water abstractions (Everson et al., 2019; Smithers et al., 2017). However, the Pitman model algorithm (Hughes, 2013) does not represent changing development conditions during a model run. Integration of these development changes was achieved by working out calculations externally and modifying the relevant model parameters.

Five-time stamps (development scenarios) were studied; natural, 1980, 2005, 2011 and 2020. The increasing forestry and water use over time (Table 4.5-8) were integrated into each simulation according to the timeline given in Table 4.5-9. The model setups for the different development scenarios were run with the same input data, with only the parameters affecting forestry and abstractions modified between scenarios. The model setups were run separately for each scenario.

The dominant changing land use includes exotic plantation forestry, which consists predominantly of Eucalyptus (51%) and Pine plantations (34%), while 15% of the plantation is clear-felled (Ezemvelo KZN Wildlife, 2011). There is significant uncertainty regarding the exact timeline of plantation forestry increase, but based on the time stamps of land use change (scenarios), changes in forestry were integrated into each simulation according to the timeline given in Table 4.5-9.

Table 4.5-8: Time periods simulated with different parameters representing anthropogenic impacts.

Simulation time stamp	Lake abstraction (10 ⁶ m ³)	Forestry (% of catchment area)
Natural	0.0	0.0
1980	1.825	5.0*
2005	2.8	10.1
2011	2.8	15.4
2020	2.8	21.8

*This is an inferred value as we do not have information on how much forestry was planted before 2000.

Table 4.5-9: Details of the integration of forestry and water use into the simulations.

Years	Integration details
1920 to 1960	No forestry (0%)
1960 to 1975	Linear increase in forestry from 0% to 5%
1975 to 1989	Forestry constant at 5%
1989 to 2000	Linear increase in forestry from 5% to 10.1%
2000 to 2006	Forestry constant at 10.1%
2007 to 2011	Linear increase in forestry from 10.1 to 15.4%
2011 to 2005	Forestry constant at 15.4%
2005 to 2020	Linear increase in forestry to 21.8%

The information available for this study did not include detailed data on when and how much forestry was planted; the above timeline is based on the datasets described below, as well as some knowledge regarding forestry in this region (Ramjeawon et al., 2020). While it is not an exact timeline, the approximate timeline is still useful to analyse the impacts of the changing forestry coverage on lake levels. The data sets include the 2011 KwaZulu-Natal land-cover dataset (Ezemvelo KZN Wildlife and GeoTerraImage, 2013). The land cover dataset has been derived from 2011 SPOT5 multispectral single date imagery. In addition, coverages with forestry areas dated 2000, 2006 and 2011 were obtained from iSimangaliso Wetland Park, and these were used to confirm the information from Ezemvelo KZN Wildlife and to assist in the integration of the forestry data over time. These additional coverages only covered portions of the study area. Lastly, the South African National Land-Cover (SANLC), 2020) was used for the latest land cover information.

Table 4.5-10 outlines the parameters representing changing forestry and water use in the catchment. The model parameter Area of Veg2 controls the amount of forestry in the catchment. The Riparian Strip Factor (RSF) parameter represents the percentage area of the catchment from which evapotranspiration losses occur directly from GW. Based on the understanding that the rooting depth of plantation vegetation facilitates access to the water below the GW table, the RSF parameter essentially represents direct GW losses from plantations. There may be other natural vegetation/ wetlands around the margins which can utilise GW; the value of the RSF parameter also accounts for these. The annual abstractions parameter controls the volume of water abstracted from the lake. Annual abstractions were modified in the wetland/lake sub-model.

Table 4.5-10: Parameters used to represent changing forestry and water use for the selected modelling scenarios.

Forestry and abstraction model parameters	Sub-catchment 1	Sub-catchment 1	Sub-catchment 1
natural			
Area of Veg2 AFOR (%)	0	0	0
Riparian strip factor (%)	3.030	3.020	3.090
Annual abstractions	0	0	0
1980			
Area of Veg2 AFOR (%)	7.50	0.30	15.60
Riparian strip factor (%)	3.310	3.030	5.060
Annual abstractions from lake (10 ⁶ m ³)	1.825	1.825	1.825
2005			
Area of Veg2 AFOR (%)	20.3	0.3	15.6
Riparian strip factor (%)	3.760	3.010	5.030
Annual abstractions from lake (10 ⁶ m ³)	2.8	2.8	2.8
2011			
Area of Veg2 AFOR (%)	22.2	3	42.6
Riparian strip factor (%)	3.860	3.110	8.440
Annual abstractions from lake (10 ⁶ m ³)	2.8	2.8	2.8
2020			
Area of Veg2 AFOR (%)	27	12	44
Riparian strip factor (%)	3.850	3.250	8.370
Annual abstractions from lake (10 ⁶ m ³)	2.8	2.8	2.8

4.5.6. Model calibration

Due to a lack of observed streamflow data and short time series of GW data, the model setup was primarily calibrated using observed lake levels from the Department of Water Affairs (DWA, 2013). Observed lake-level data were available for 34 years (1980-2014). The calibration process was further supported by background knowledge of the Lake Sibaya catchment and findings from previous studies, which helped ensure that the model setup was as sensible as possible, given this evidence. The key catchment characteristics which guided the calibration are explained below:

- I. Surface flow characteristics of the main rivers contributing to the lake. Mseleni, the largest stream, is a perennial system, but Velindlovu and Kumzingwane are non-perennial. Due to a lack of monitoring stations in the river system, it is unclear how much each river contributes to the lake.
- II. Recharge simulations were compared against estimates from previous studies (Table 4.5-9) to ensure that the model simulations were reasonable.

Table 4.5-11: Maputaland coastal plain recharge estimations calculated by Weitz and Demlie (2015) based on catchment physical properties and data from published maps.

Source/ methods	Recharge (mm year ⁻¹)	Recharge (% MAP)
Chloride mass balance (CMB) Weitz and Demlie (2015) catchment MAP = 1012 mm year ⁻¹	126	12.5
Published maps catchment MAP = 936 mm year ⁻¹		
Vegter (1995)	65	6.9
ACRU (Schulze, 1989)	90	9.6
GW harvest Potential (Baron et al., 1996)	100	10.7
Soil/ vegetation information (Kirchner et al., 1991; Bredenkamp et al., 1995)	97.2	10.4
Geology information Kirchner et al., 1991; Bredenkamp et al., 1995)	104.6	11.2
GW resources of South Africa (WRC, 1995)	110	11.8
Average	94.5	10.1

NB: The soil/vegetation and geology recharge estimations are based on expert options and equations proposed by Kirchner et al. (1991) and Bredenkamp et al. (1995).

- III. There are four main aquifer units in the Lake Sibaya catchment (Kelbe et al., 2013); however, the model can only represent one. The model setup was based on the Umkwelane/Uloa Formation, as this is the main aquifer that contributes to the lake (Jeffares and Green, 2012; Kelbe et al., 2013). The estimated transmissivity for this aquifer is $116 \text{ m}^2 \text{ day}^{-1}$ (Table 3.4-1).
- IV. Groundwater level data from three borehole points in the lake catchment (Figure 4.5-3) indicated that groundwater levels are experiencing a decline (Figures 4.5-7 to 4.5-9).

Based on the model setup and calibration and considering the uncertainties described, the final parameters used in the Pitman model simulation for the Lake Sibaya catchment were as presented in Table 4.5-12. These parameters remained constant for all development scenarios. This table does not include parameters representing forestry and abstractions as they changed between scenarios. These are detailed in Table 4.5-10 under Section 4.5.4.

Table 4.5-12: Final calibrated parameters used in the Pitman model simulation for the Lake Sibaya catchment.

Calibrated model parameters	Sub-catchment 1	Sub-catchment 2	Sub-catchment 3
Veg2/Veg1 Pot. Evap Ratio (FF)	1.600	1.600	1.600
Minimum absorption rate (ZMIN) (mm month ⁻¹)	999	999	999
Maximum absorption rate (ZMAX) (mm month ⁻¹)	1001	1001	1001
Maximum storage capacity (ST)	900	900	900
Maximum recharge rate (GW) (mm month ⁻¹)	65	65	46
Evaporation storage coefficient - R	0.300	0.300	0.300
Power: storage recharge curve - GPOW	2.000	2.000	3.000
Drainage density (km km ⁻²)	0.400	0.400	0.400
Transmissivity (m ² day ⁻¹)	110	110	110
Storativity	0.015	0.015	0.015
Regional GW drainage slope	0.050	0.050	0.050
Rest water level (m below surface)	30	30	30
Wetland/lake sub-model parameters			
Residual wetland storage (10 ⁶ m ³)	660.000		
A in Area (m ²) = A × Volume (m ³) B	40.000		
B in Area (m ²) = A × Volume (m ³) B	0.700		
Channel capacity for spillage (10 ⁶ m ³)	0.000		
Channel spill factor (fraction)	1.000		
AA in (Return Flow = AA*(Vol/RWS) BB	0.055		
BB in (Return Flow = AA*(Vol/RWS) BB	0.050		
Annual evaporation (mm)	1500.000		

5. RESULTS

5.1. Introduction

As part of the model setup and calibration, the time series of the groundwater balance components were evaluated, as well as the lake volume to ensure a simulation as representative as possible was achieved. Taking account of a variety of water balance components results in higher reliability of outputs due to equifinality issues and to ensure the model outputs are in line with the conceptual understanding of processes occurring in the catchment. The evaluated time series included lake volume, groundwater recharge, groundwater baseflow, groundwater gradient (part representative of groundwater level) and downstream groundwater outflow. Observed data or previous modelling estimates were not always available for this evaluation; therefore, the assessment included other local information, such as the frequency of flow of the lake's tributaries (Mseleni is a perennial river, while Kumzingwane and Velindlovu are intermittent rivers) for example. This information ensured that the model simulations were as realistic as possible based on our knowledge of the system. Balancing a sensible water balance simulation, with the simulated lake volume was a challenge but a key focus of the modelling approach.

As discussed in the previous chapter, some of the representations in the model were implicit due to model structural barriers. Below is a brief overview of these issues and the key setup aspects of the model.

5.1.1. Summary of the implicit representation of direct groundwater seepage into the lake:

The streamflow (consisting of both overland flow and groundwater baseflow) and the groundwater outflow (or direct seepage into the lake) simulated by the Pitman model were both added to the groundwater interface nodes. The width of the groundwater interface nodes was set to equal the lake's perimeter that is thought to receive groundwater outflow (or seepage). These nodes then converted the groundwater outflow from the upstream nodes or sub-catchments into streamflow (via the groundwater baseflow process), resulting in surface runoff, groundwater baseflow and groundwater outflow being added to the lake volume. The groundwater interface nodes do not simulate any other processes, so the volume of water added to the groundwater interface node is the same volume of water added to the lake. This method needs to be followed as the lake sub-model in its current format does not include groundwater seepage into the lake as one of its functions (described in more detail in Section 4.5.3.1).

5.1.2. Summary of implicit representation of non-stationarity associated with land use change in the model:

The model was run with input data (rainfall) from 1920 to 2018. The development scenarios (natural, 1980, 2005, 2011 and 2020 land covers) represent various time stamps reflecting the assumed changing forestry coverage and abstractions from the lake. The catchment outputs from all three tributary catchments were time integrated to represent the changing land cover. This integrated catchment output was added to the lake as input to obtain one time series of lake volume, including the evolution of the change in land uses. There were, however, significant uncertainties associated with the timeline of land use change and with the evolution of water use in the catchment, which impacted the simulation results. The significant non-stationarity in this catchment was therefore successfully represented in the model but calculations external to the model needed to be performed.

5.1.3. Summary of groundwater system representation:

There are four main aquifers (Table 5.1-1) which are generally saturated from the Cretaceous interface to the shallow water table. However, of those four aquifers, the Uloa Formation is considered the principal aquifer regarding water use and contribution to the lake. Since the model simulates a single aquifer, the descriptions of the specific aquifer characteristics through the parameter values have focused on the Uloa aquifer characteristics. The transmissivity value used in the model ($110 \text{ m}^2 \text{ day}^{-1}$) aligns with the estimate of transmissivity for the Uloa Formation given in Table 3.4-1 ($116 \text{ m}^2 \text{ day}^{-1}$). The estimates of transmissivity values for the aquifers above the Uloa Formation are around $30 \text{ m}^2 \text{ day}^{-1}$.

The model simulation results for the Lake Sibaya catchment are provided below.

5.2. Lake volumes

5.2.1. Lake volumes under changing development conditions

Figure 5.2.-1 shows the observed lake volume versus the integrated lake volume simulation together with rainfall time series on a secondary axis to aid in visualizing the observations with regards to the reasons for the increasing or decreasing lake volumes. Figure 5.2-2 shows the lake volumes simulated separately for the development scenarios.

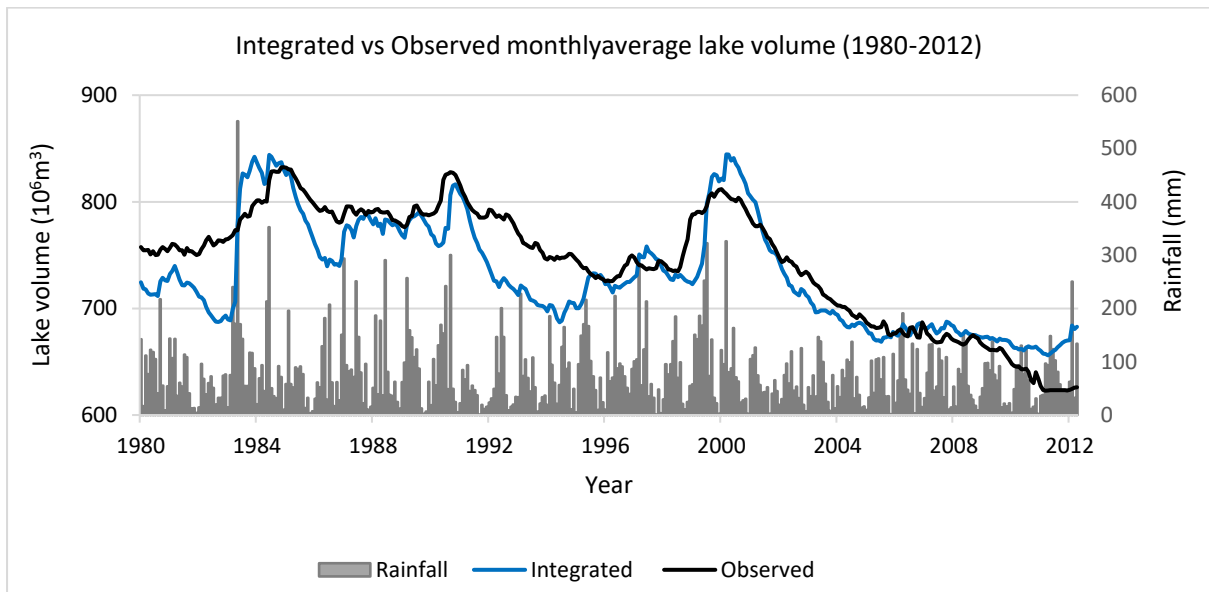


Figure 5.2-1: Lake volume for integrated simulation vs observed data (observed lake level was converted to a volume using bathymetric information, in order to directly compare to model simulated lake volume).

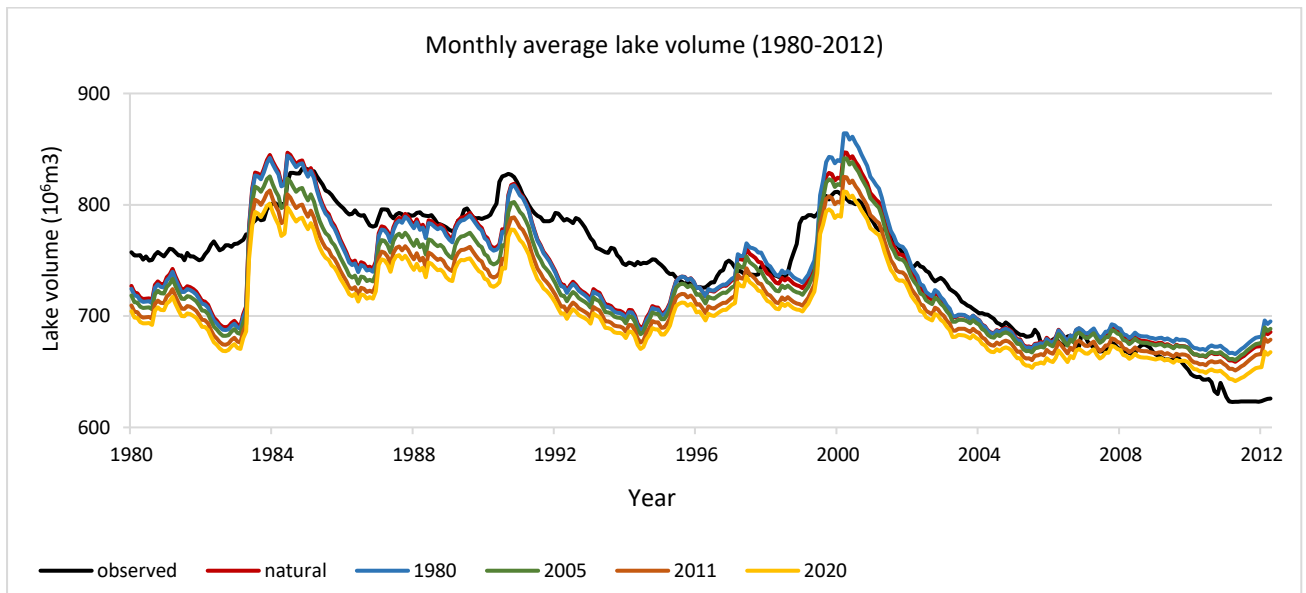


Figure 5.2-2: Simulated Lake volume for different development scenarios compared to observed lake volume.

Table 5.2-1: Comparison statistics for lake volume simulations under changing development conditions.

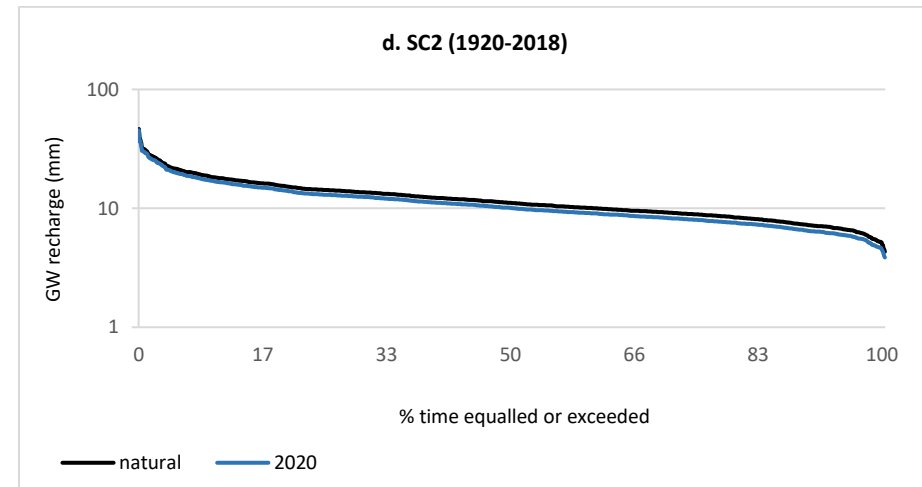
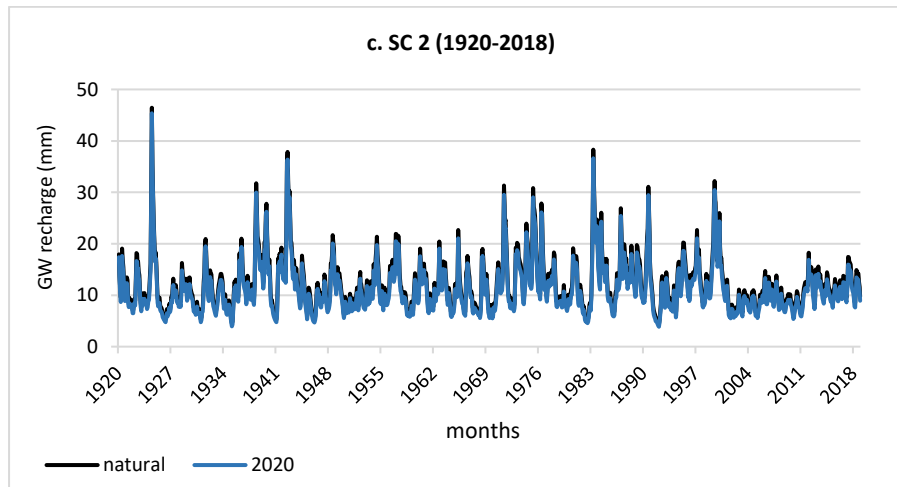
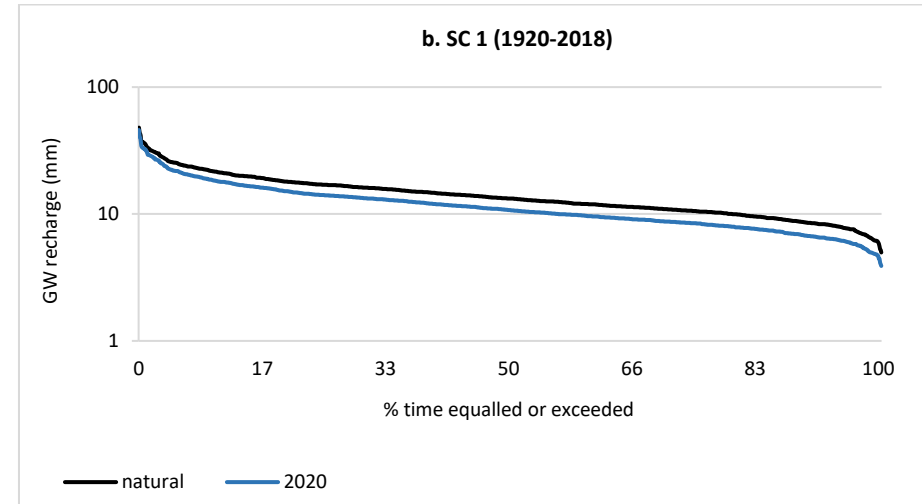
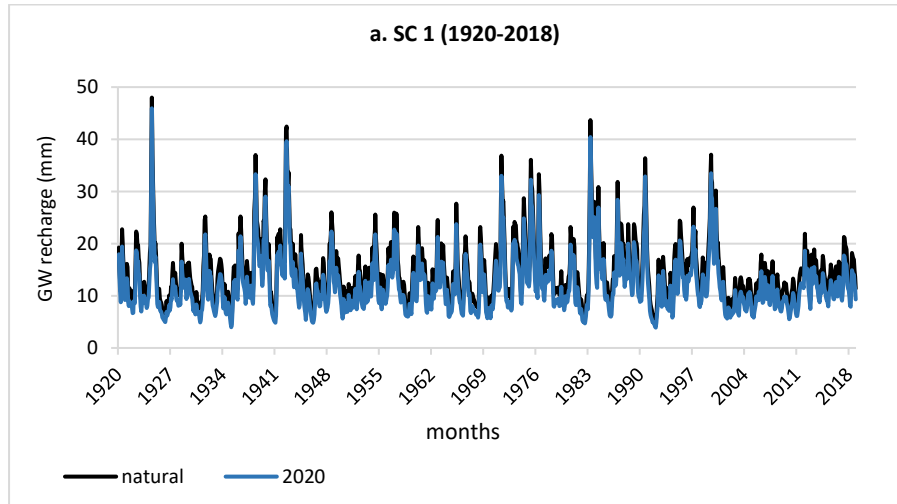
Development scenario	Observed	Natural	1980	2005	2011	2020
Forestry coverage (% of total catchment area)		-	7.50	20.3	22.2	27.0
Lake abstractions (10^6m^3)		0	1.825	2.8	2.8	2.8
Volume statistics (10^6m^3)						
Average	743.93	734.57	735.86	726.56	716.63	709.03
Minimum	622.84	658.97	665.87	660.48	651.16	641.62
Maximum	832.42	847.13	864.21	841.69	825.12	811.99

The results for lake volume modelled under various development scenarios show declining lake volumes from the earliest time period (natural scenario) down to the most recent (2020), indicating that lake volume decreased as forestry and lake abstractions increased in the lake catchment (Figure 5.2-1). These results are consistent with the research output from an analysis of land cover changes in the Maputaland Coastal Plain undertaken by Ramjeawon et al. (2020) which revealed that increasing forestry and decreasing rainfall resulted in a decrease in the number of surface water bodies and wetlands in the region. Smithers et al. (2017) simulated a decrease of about 1.4 m in lake levels due to increasing forestry between 1959 and 2014. In the same study, Smithers et al. (2017) established that abstractions had an insignificant impact on the lake levels compared to forestry. The results show a similar pattern of lake volume variation between the observed and simulated lake volumes (Figure 5.2-1 and Figure 5.2-2). Both the observed and simulated data displayed decreasing lake volumes starting around 2001. The findings are consistent with the available local information, which shows that the lake catchment experienced below-average rainfall from 2001 to 2012 due to a decade-long regional drought (Taylor, 2013; Smithers, 2015). Overall, the model captured the dominant volume dynamics, although there are periods that are poorly matched. Given the uncertainty with the non-stationarity timeline, this is perhaps not unexpected.

The following analyses for groundwater recharge, groundwater baseflow, groundwater gradient and groundwater baseflow are only focusing on the natural and 2020 development scenarios to showcase the two extremes in the study area so that the impact of changing forestry coverage and lake abstractions can be emphasized.

5.3. Groundwater recharge

The simulated recharge for two scenarios (natural and most recent – 2020) are shown in Figure 5.3-1 below for all three sub-catchments.



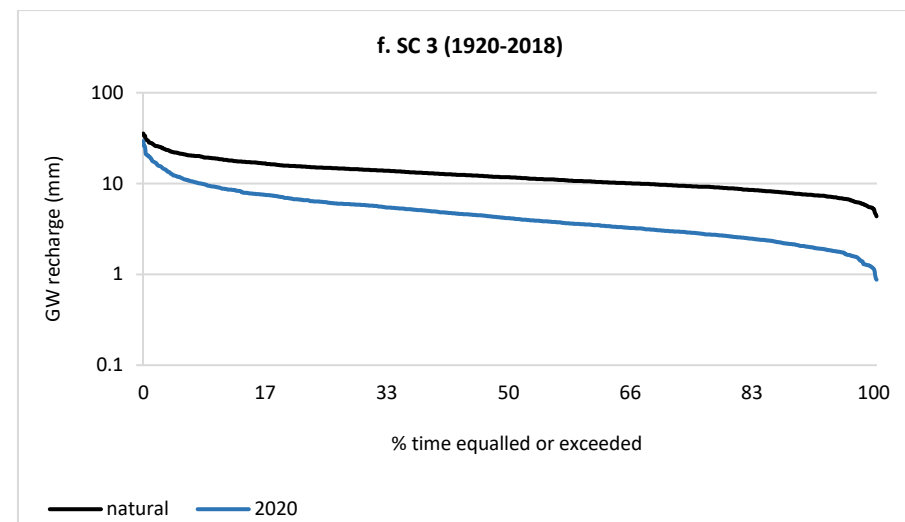
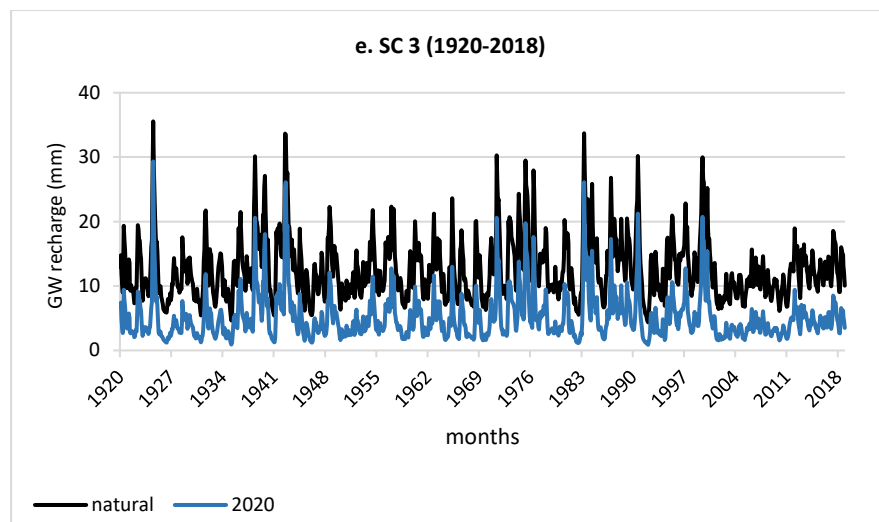


Figure 5.3-1: Hydrographs (a, c, e) and flow duration curves (c, d, f) showing simulated monthly average groundwater recharge under natural conditions, and under 2020 forestry conditions in sub-catchments 1, 2 and 3. Flow duration curves plotted on a semi- logarithmic scale.

Table 5.3-1: Simulated average GW recharge depth for each development scenario.

Development scenario	Natural	1980	2005	2011	2020
Forestry coverage (% of total catchment area)	-	7.50	20.3	22.2	27.0
Lake abstractions (10^6m^3)	0	1.825	2.8	2.8	2.8
Average GW recharge depth (mm month^{-1})					
SC1	14.47	13.83	12.55	12.38	11.97
SC2	12.23	12.21	12.20	11.96	11.17
SC3	12.60	11.51	11.34	5.18	5.11

The results show a dynamic GW recharge time series that responds quickly to rainfall and a pattern of decreasing GW recharge with increasing forestry and abstractions in all three sub-catchments (SCs) (Figures 5.3-1 a, c and e). The combined simulated average recharge from the three sub-catchments was calculated to be $157.2 \text{ mm year}^{-1}$ (17 % of the catchment MAP of $944.4 \text{ mm year}^{-1}$) under natural conditions and $113.04 \text{ mm year}^{-1}$ (12 % MAP) under the 2020 forestry and lake abstraction conditions.

Weitz (2016) worked out an average recharge estimate of 126 mm year^{-1} (13 % of the catchment MAP of $1012 \text{ mm year}^{-1}$) using the chloride mass balance method. Weitz (2016) findings were verified against calculations based on information from Vegter (1995), Schulze (1989), Baron et al. (1996), Kirchner et al. (1991), Bredenkamp et al. (1995) and WRC (1995), yielded an estimate of 95 mm year^{-1} (10 % of the catchment MAP = 936 mm year^{-1}).

The effects of the reduced rainfall due to the 2001 drought are evidenced in the significantly reduced recharge. For example, for Sub-catchment 1, simulated average recharge from 1980 to 2000 was $15.90 \text{ mm month}^{-1}$, and from 2000 to 2019, the simulated average recharge was $13.37 \text{ mm month}^{-1}$. Due to the primary aquifer and shallow groundwater levels, a fairly quick response in recharge due to reduced rainfall is expected, so the simulated pattern of reduced recharge is representative. The flow duration curves of recharge for the three sub-catchments highlight the substantial impact on recharge from the plantation forestry in the sub-catchments (SC 3 is covered by 44% forestry and shows a significant reduction in recharge as a result). This is mainly due to increased transpiration from the unsaturated zone, leading to reduced unsaturated zone water to percolate to the saturated zone as recharge.

5.4. Groundwater baseflow

The simulated groundwater baseflow for two scenarios (natural and most recent – 2020) are shown in Figure 5.4-1 below for two sub-catchments (there was no groundwater baseflow simulated in SC 3 due to its small size and limited river system).

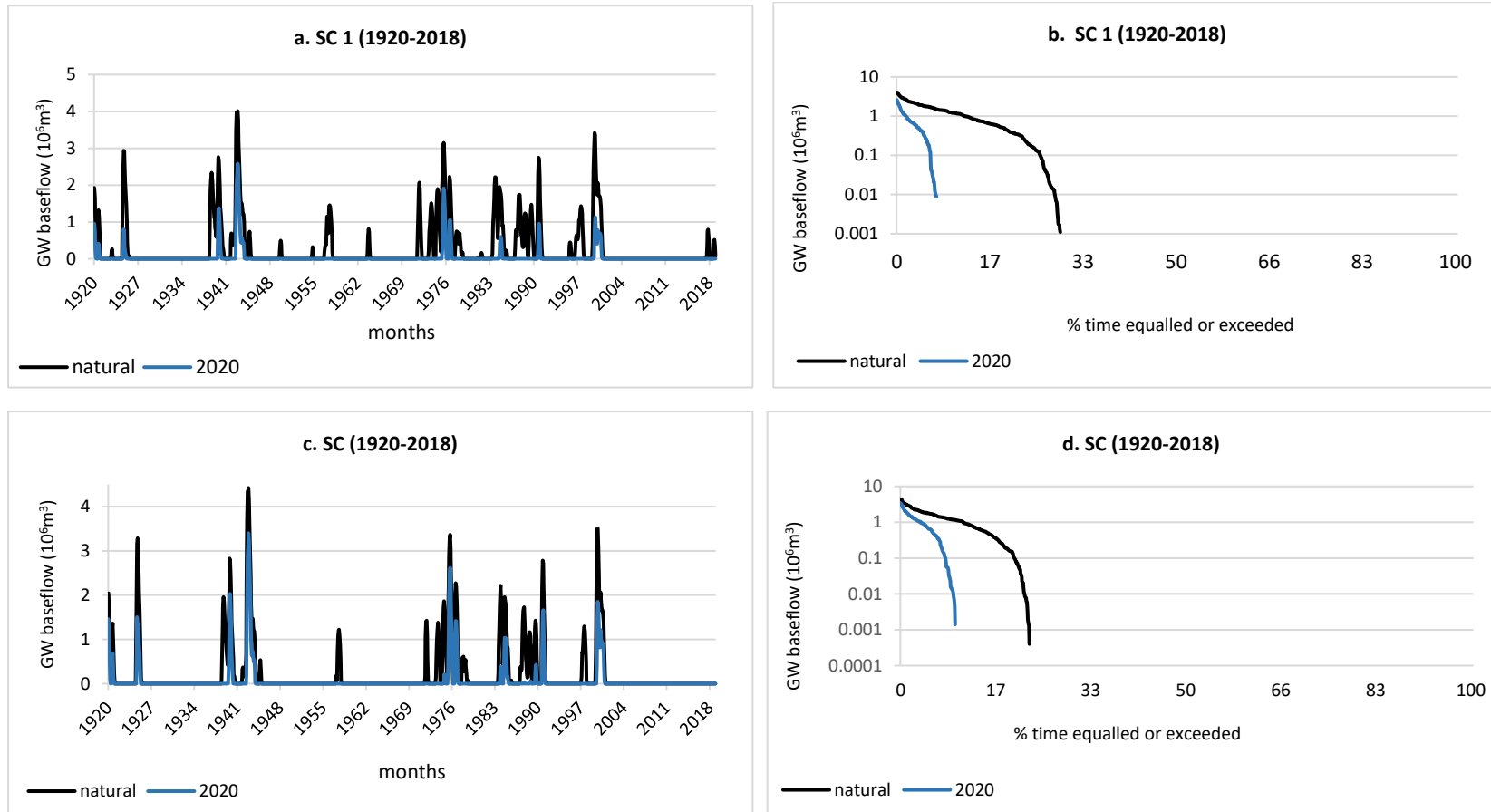


Figure 5.4-1: Hydrographs (a, c) and flow duration curves (c, d) showing simulated monthly average groundwater baseflow under natural conditions and under 2020 forestry and lake abstraction conditions in sub-catchments 1 and 2. Flow duration curves plotted on a semi- logarithmic scale.

Table 5.4-1: Simulated average GW baseflow for each development scenario.

Development scenario	Natural	1980	2005	2011	2020
Forestry coverage (% of total catchment area)	-	7.50	20.3	22.2	27.0
Lake abstractions (10^6m^3)	0	1.825	2.8	2.8	2.8
Average GW baseflow depth ($10^6\text{m}^3 \text{ month}^{-1}$)					
SC1	0.29	0.21	0.07	0.05	0.05
SC2	0.25	0.19	0.17	0.14	0.08

The results show a significant decrease in groundwater baseflow volume from the natural to the 2020 scenario in both sub-catchments 1 and 2. This indicates that GW baseflow reduced as forestry and abstractions increased in the catchment (Figure 5.4-1 a; c, Table 5.4-1).

For the entire modelling duration, groundwater baseflow in sub-catchment 1 occurred approximately 26% of the time under the natural conditions and 7% under the 2020 forestry and abstraction conditions (Figure 5.4-1 b; d). In sub-catchment 2, groundwater baseflow was generated approximately 21% of the time under the natural scenario and 9 % for the 2020 scenario (Figure 5.4-1 b; d). The reduction of groundwater levels due to increased water use of forestry is expected to be the main reason for the decrease in GW baseflow in the sub-catchments. Due to the small size of sub-catchment 3, no baseflow is generated; hence, exclusion from the comparisons.

Given the difference in the two river systems (one is more constantly flowing than the other), there should have been a larger difference in the groundwater baseflow in terms of frequency of occurrence. It was however found that in order to achieve this (through parameter adjustment), other elements of the model became unrealistic.

5.5. Groundwater gradient

The groundwater gradient in the Pitman model is broadly representative of groundwater level in a catchment. The reasoning behind representing groundwater as a gradient in the Pitman model is that the model is typically applied over a large catchment area (quaternary catchment scale), and due to normal variation in groundwater levels over a catchment, this level is expected to vary considerably at that scale. Therefore, the groundwater gradient aims to broadly represent groundwater level at a large spatial scale. Figure 5.5-1 below highlights the significant impact on the groundwater gradient by plantation forestry for the lake sub-catchments. The gradient becomes more dynamic and variable as the groundwater use increases, linked to a drier unsaturated zone which increases the non-linearity and volume of recharge, in addition to direct transpiration from the shallow groundwater by the deep-

rooted plantation trees. The statistics of the changes in groundwater gradient are provided in Table 5.5-1.

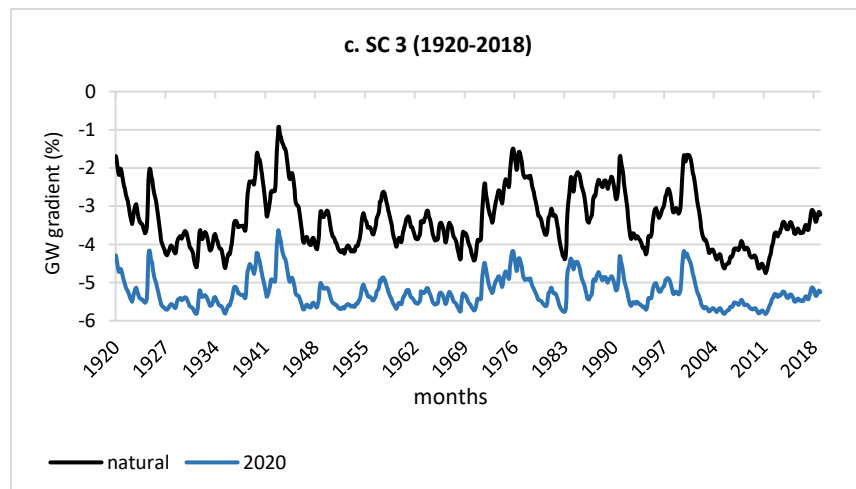
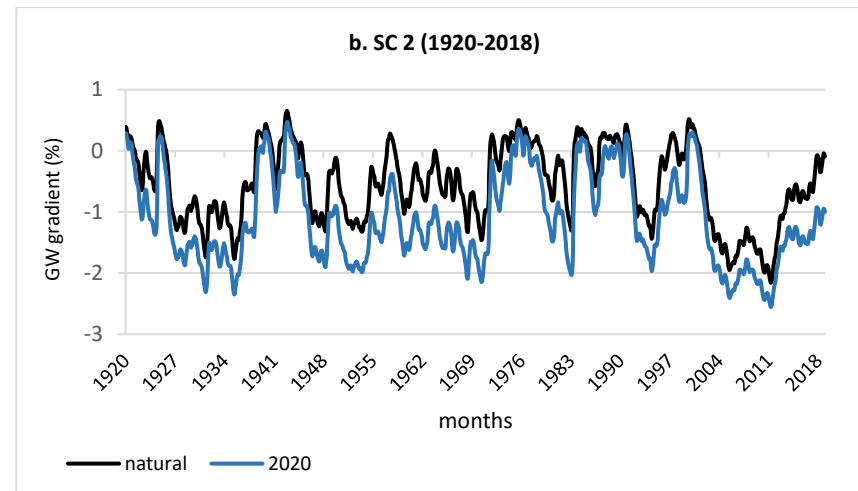
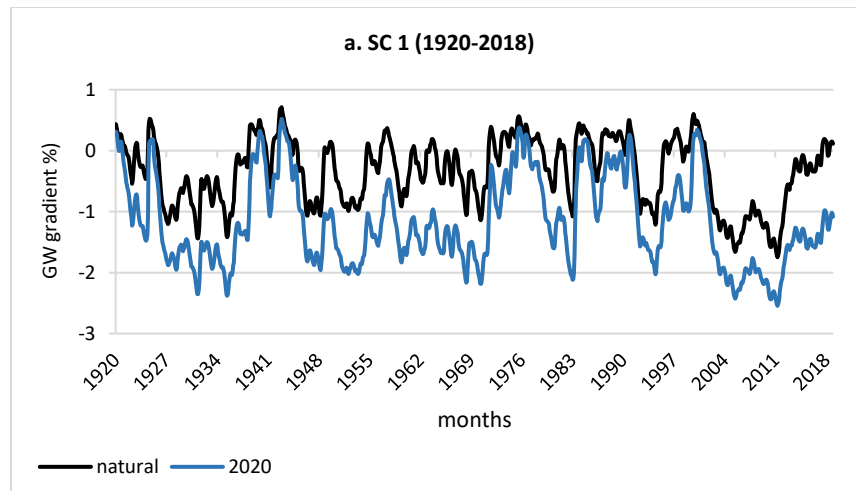


Figure 5.5-1: Hydrographs (a, b, c) showing simulated monthly average groundwater gradient under natural conditions and under 2020 forestry and lake abstraction conditions in sub-catchments 1, 2 and 3.

Table 5.5-1: Simulated average GW gradient for each development scenario.

Development scenario	Natural	1980	2005	2011	2020
Forestry coverage (% of total catchment area)	-	7.50	20.3	22.2	27.0
Lake abstractions (10^6m^3)	0	1.825	2.8	2.8	2.8
Average GW gradient ($10^6\text{m}^3 \text{ month}^{-1}$)					
SC1	-0.34	-0.48	-1.26	-1.36	-1.17
SC2	-0.56	-0.69	-0.87	-1.02	-1.11
SC3	-3.35	-3.44	-4.63	-6.99	-5.26

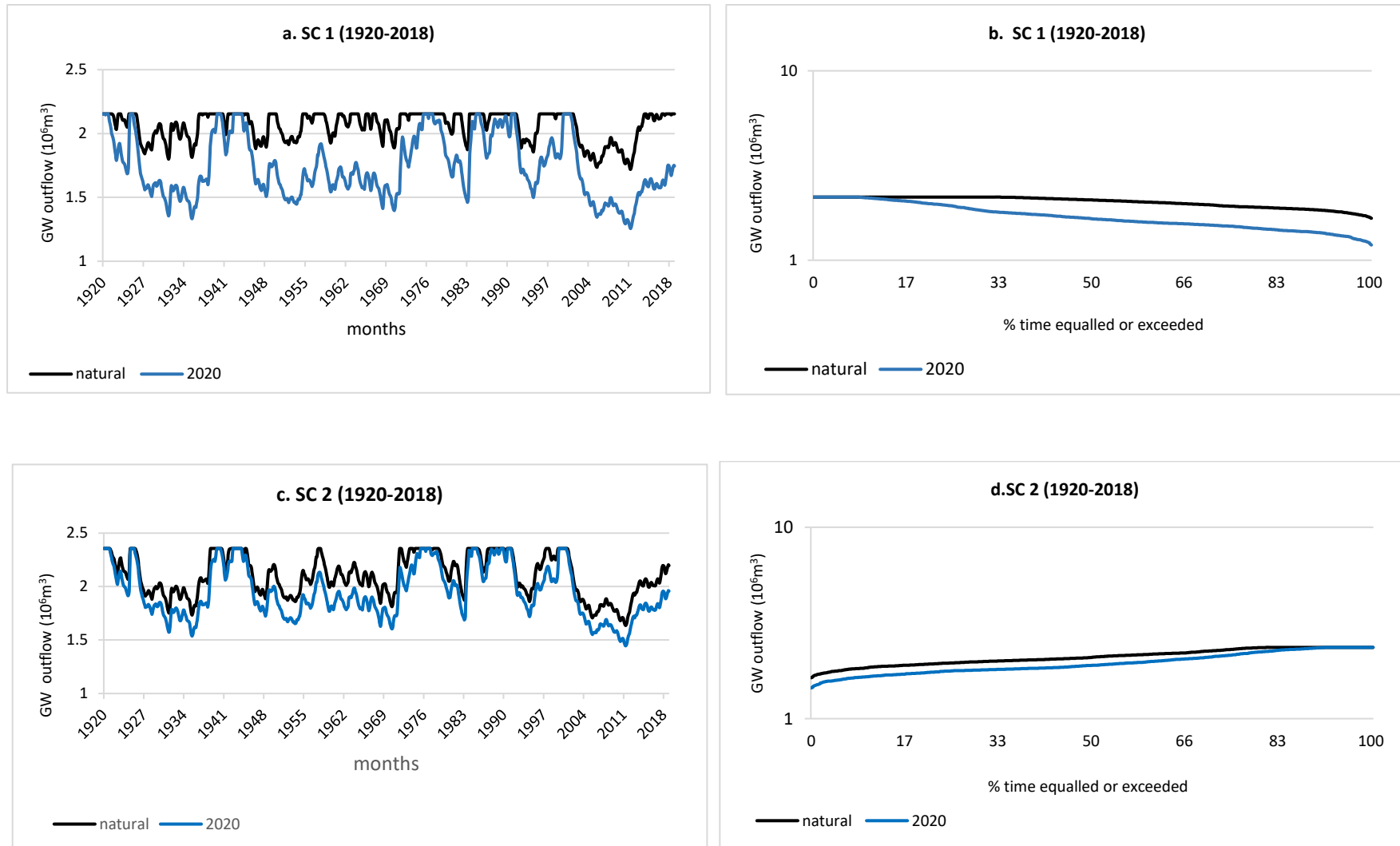
The results for sub-catchment one show mostly negative average gradients for all scenarios throughout the simulation. Bearing in mind that these figures are monthly averages, they do not reflect that the gradient is positive at points.

Figure 5.5-1: b shows the groundwater gradient for sub-catchment 2, which shows a similar increase in variability with increased plantation forestry, although at a lesser scale due to fewer plantations located in this sub-catchment compared to SC 1. Similarly, to SC 1, the results for SC 2 depict primarily negative average gradients for all scenarios throughout the simulation, with a lesser incidence of positive gradients. Consequently, baseflow generation in this catchment is limited (GW baseflow occurs only when the GW gradient is positive).

The results for sub-catchment 3 Figure 5.5-1: c show a slightly different variability. The dynamics remain similar between scenarios, and the slope percentage has changed more consistently. The groundwater gradients for this sub-catchment are negative for all scenarios throughout the simulation period and the difference between scenarios is high due to the high proportion of plantation forestry in the sub-catchment in the 2020 scenario. Consequently, this catchment has no baseflow generation since GW baseflow occurs only when the GW gradient is positive.

5.6. Groundwater outflow (seepage into the lake)

The simulated groundwater outflow for two scenarios (natural and most recent – 2020) are shown in Figure 5.6-1 below for all three sub-catchments.



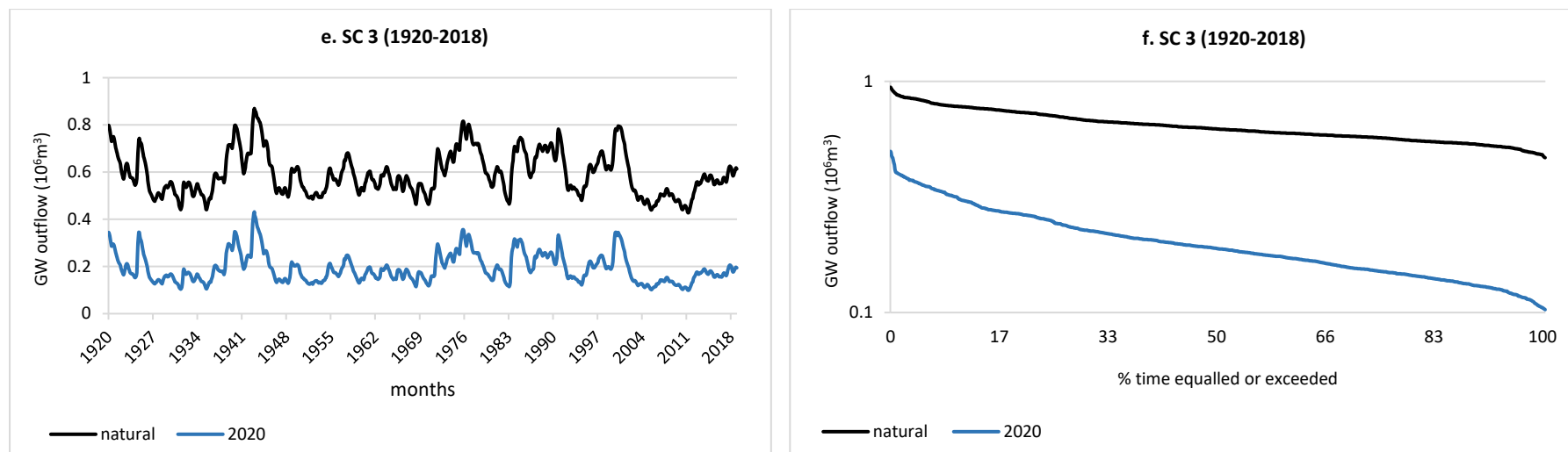


Figure 5.6-1: Hydrographs (a, c, e) and flow duration curves (c, d, f) showing simulated monthly average groundwater outflow under natural conditions and under 2020 forestry and lake abstraction conditions in sub-catchments 1, 2 and 3. Flow duration curves plotted on a semi- logarithmic scale.

Table 5.6-1: Simulated average GW outflow for each development scenario.

Development scenario	Natural	1980	2005	2011	2020
Forestry coverage (% of total catchment area)	-	7.50	20.3	22.2	27.0
Lake abstractions (10^6m^3)	0	1.825	2.8	2.8	2.8
Average GW baseflow outflow ($10^6\text{m}^3 \text{ month}^{-1}$)					
SC1	2.03	1.95	1.79	1.77	1.71
SC2	2.10	2.08	2.10	2.06	1.95
SC3	0.64	0.54	0.53	0.21	0.21

Analysis of groundwater outflow in sub-catchment 1 shows dynamic groundwater outflow interrupted by brief periods of constant outflow (Figure 5.6-1: a). Groundwater outflow in the sub-catchment decreases from the natural to 2020 scenario. Groundwater outflow occurs at a maximum of $2.2 \times 10^6\text{m}^3$ in this catchment and is constant at this point. This is the point at which the groundwater gradient is positive.

Similarly, to sub-catchment 1, the simulations for groundwater outflow in sub-catchment 2 show variable groundwater outflow interrupted by transitory periods of sustained outflow (Figure 5.6-1: c) at the point at which the groundwater gradient is positive. Similarly, to the other sub-catchments, groundwater outflow in the sub-catchment decreases from the natural scenario to the 2020 scenario. Compared to sub-catchment 1 (Figure 5.6-1: a), the periods of sustained flow in sub-catchment 2 are slightly more extended (longer periods where the groundwater gradient is positive), and there is a larger GW outflow volume (Table 5.6-1). This is linked to the larger size of the sub-catchment.

The simulations for groundwater outflow in sub-catchment 3 (Figure 5.6-1: c) show non-constant groundwater outflow through the entire simulation period, linked to groundwater gradient always being negative and no baseflow occurring. Groundwater outflow is occurring consistently; however, the rate of occurrence is just variable when the groundwater gradient is negative.

To illustrate the relationship between groundwater gradient (level), groundwater baseflow and groundwater outflow (seepage) in the model, the three time series have been included for sub-catchment 1 in Figure 5.6-2 below.

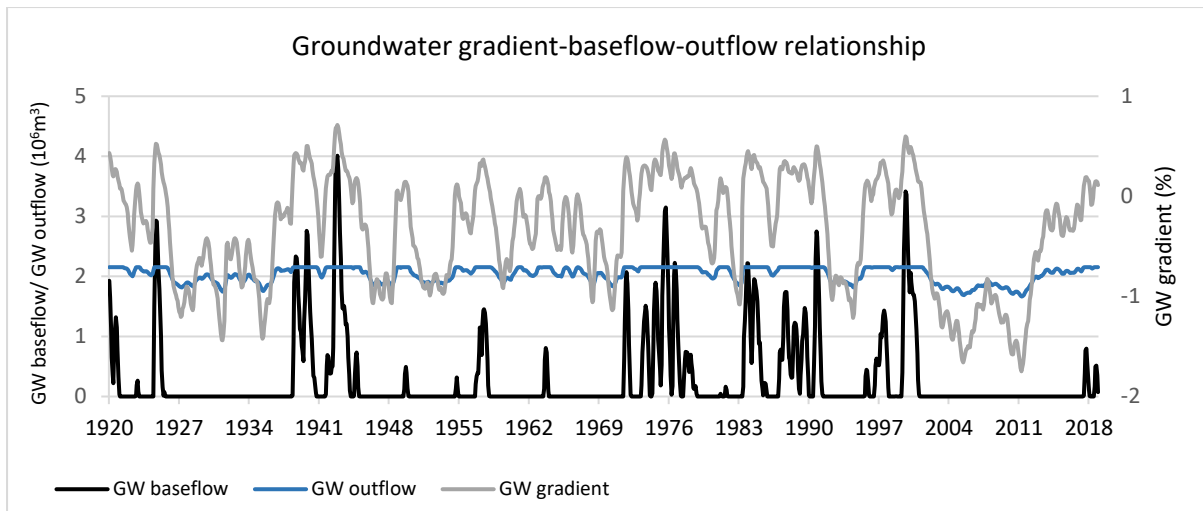


Figure 5.6-2: Relationship between GW gradient, GW baseflow and GW outflow in the model.

When the GW gradient is positive, GW outflow becomes consistent and non-varying, while negative GW gradients correspond to variable GW outflow. At the point at which GW outflow becomes stable ($2.2 \times 10^6 \text{m}^3$ in this instance), groundwater baseflow is initiated.

5.7. Lake volume- groundwater components relationship

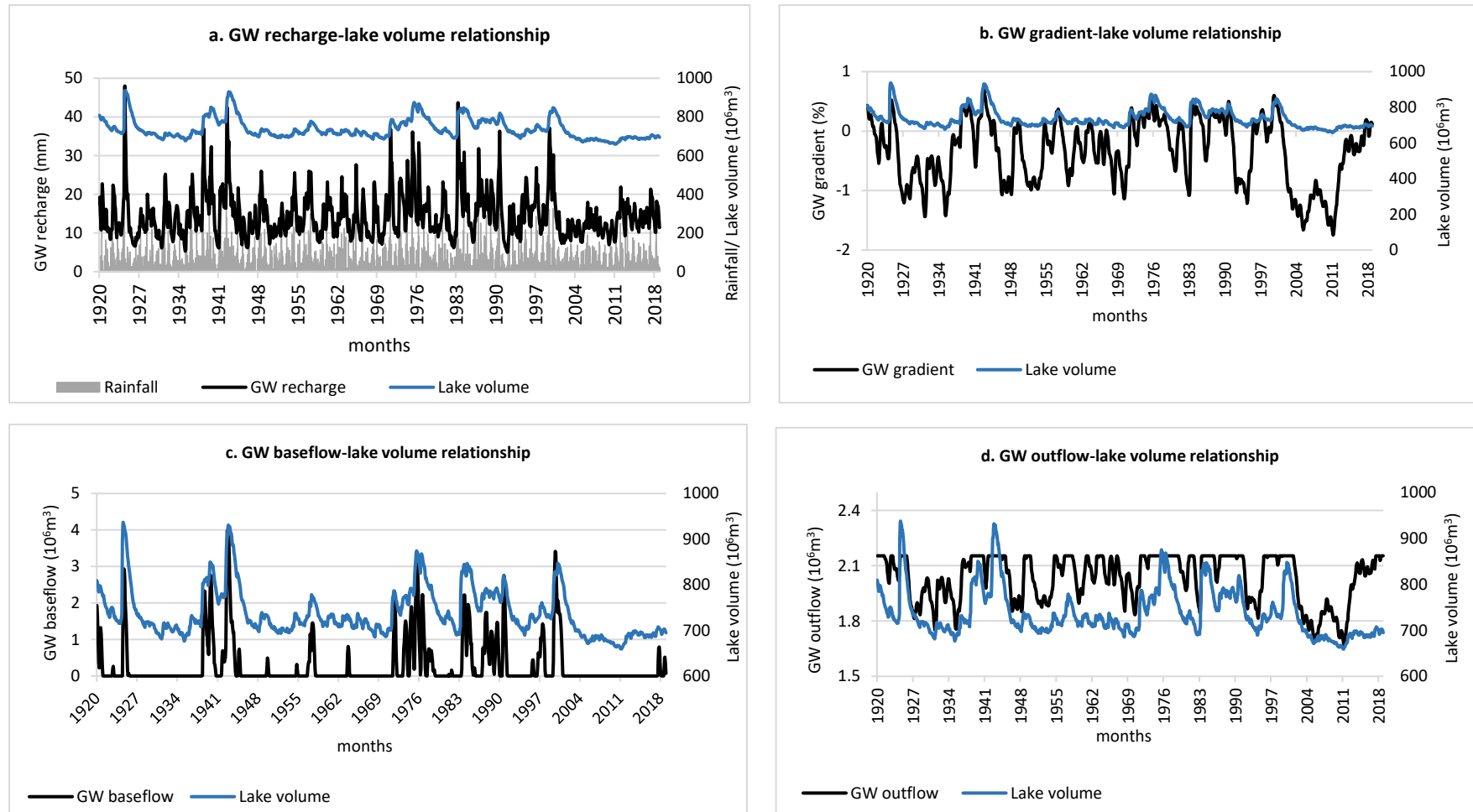


Figure 5.7-1: Lake volume and groundwater dynamics in the Lake Sibaya catchment.

The model and its various water balance components respond relatively quickly to higher rainfall input, and in this environment, it is appropriate given the shallow groundwater levels and primary aquifers. Periods of higher rainfall result in increased recharge (Figure 5.7-1: a). This, in addition to surface runoff, results in higher lake levels. Lake levels are positively correlated to GW gradient in the model; positive gradients coincide with high lake volumes, while negative gradients correspond to lower lake volume (Figure 5.7-1: b). The positive gradient drives the baseflow process (Figure 5.7-1: c), resulting in increased groundwater outflows. (Figure 5.7-1: d).

5.8. Overall Water Balance Comparison

5.8.1. Lake water balance

The water balance of Lake Sibaya was estimated by determining the various inflow and outflow components of overall lake storage. The lake is recharged by rainfall, streamflow (including surface runoff and groundwater baseflow) and groundwater outflow into the lake, while reductions include evaporation from the lake surface, and lake outflow to the sea via a palaeo-channel and lake abstractions. The essential water balance components of Lake Sibaya are depicted in Figure 5.8-1 and outlined in Table 5.8-1. The major water balance components of Lake Sibaya are expressed according to the equation adapted from Pitman and Hutchison (1975) as follows:

Equation 5.8-1: $PPT + SF + GW_{out} - ET - L_{out} - A = \Delta S$

Where PPT refers to precipitation on to the lake surface, SF is streamflow into the lake, GW_{out} is groundwater outflow into the lake, ET is evaporation from the lake surface, L_{out} is the lake outflow to the sea, A is abstractions from the lake and ΔS is change in storage.

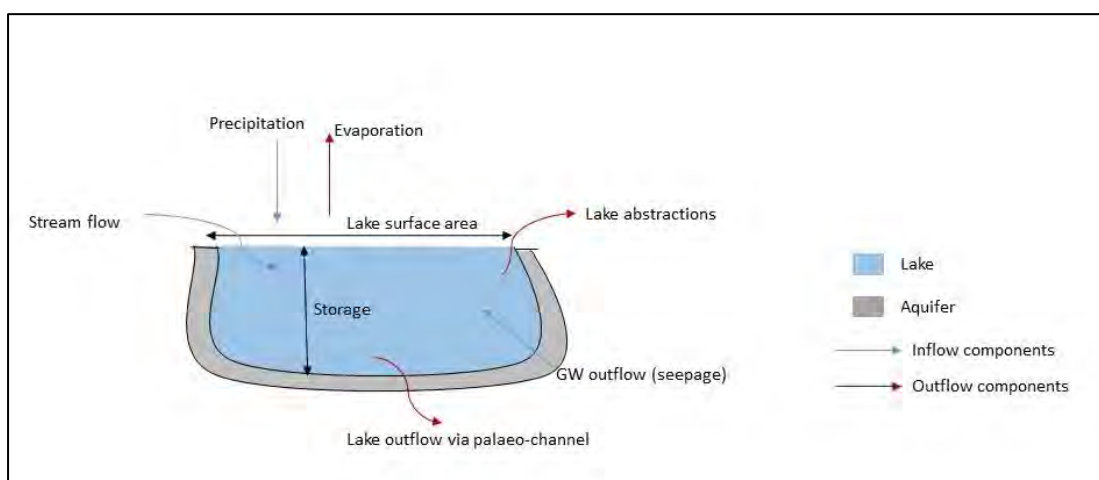


Figure 5.8-1: Conceptualization of the of the lake volumetric water balance component

Table 5.8-1: Simulated major water balance components of Lake Sibaya up to the year 2020 ($10^6 \times \text{m}^3 \text{ year}^{-1}$) (based on 1920 to 2020 simulation length).

Water balance component	Natural scenario ($10^6 \times \text{m}^3 \text{ year}^{-1}$)	2020 scenario ($10^6 \times \text{m}^3 \text{ year}^{-1}$)
Streamflow into the lake (including baseflow)	33.16	20.71
Groundwater inflow (seepage) into the lake	55.94	46.19
Net lake evaporation (accounting for precipitation)	36.12	34.60
Lake outflow to the sea	55.75	32.57
Change in storage	-2.77	-0.27

Table 5.8-2: Comparison of Pitman model simulated annual water balance components for the Lake Sibaya catchment with those produced by Weitz and Demlie (2015).

Year	% of forest	Pitman	W&D (2015)	Pitman	W&D (2015)	Pitman	W&D (2015)
		Precipitation*		Streamflow inflow		Groundwater inflow	
2001/2002	10.1	46.36	30.8	7.52	21.9	58.98	88.0
2005/2006	10.1	47.03	41.8	5.09	30.8	42.72	55.3
2011/2012	15.4	55.7	61.1	9.12	39.3	37.0	31.3
		Net Evaporation		Lake outflow		Change in storage	
2001/2002	10.1	55.06	85.4	72.10	22.08	-32.1	-33.2
2005/2006	10.1	43.84	90.3	7.60	22.08	-3.63	-15.5
2011/2012	15.4	33.3	86.3	1.0	22.08	11.8	-23.3

Note: All values are reported as 10^6 m^3 . *Not included in calculations of change in storage since it is accounted for in net evaporation.

Previous studies which simulated lake outflow to the sea include Pitman and Hutchison (1975), Meyer and Godfrey (2003), NWU (2014) and Weitz and Demlie (2015). Pitman and Hutchison (1975) calculated a lake outflow ranging between $1 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ and $4 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ or $1 \times 10^5 \text{ m}^3 \text{ year}^{-1}$ and 4×10^5 per kilometre of coastline (seepage channel approximate length of 10km and depth of

25m). Meyer and Godfrey (2003) worked out an outflow value of approximately $3 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ per kilometre of coastline (assumed total coastline length coastline of 100km). Weitz (2016) calculated Lake Outflow of $23 \times 10^6 \text{ m}^3 \text{ year}^{-1}$ through 12 km seepage length. The Pitman model lake outflow varied considerably according to lake volume. While variability is expected due to porous sands in the region, this value for all studies is highly uncertain due to a lack of any measured data.

Weitz and Demlie (2015) calculated surface runoff from the lake catchment using runoff coefficients determined using the rational formula reported in Tripathi and Singh (1993) with a final runoff coefficient calculated at 0.13. This worked out at $32.9 \times 10^3 \text{ m}^3 \text{ year}^{-1}$ (9% MAP) which was greater than the estimate given by Jeffares and Green (pers. comm.) of 2 to 3 % MAP. The current model simulated surface runoff at an average of $20.71 \times 10^3 \text{ m}^3 \text{ year}^{-1}$ (2% MAP) under 2020 conditions.

Overall, the water balance compared well in some instances and was quite different from existing studies in other instances. Again, it is difficult to identify which study is most reliable given that they are all based on models set up with scarce data.

6. DISCUSSION

6.1. Introduction

The research aimed to determine the feasibility and utility of applying the conceptual-based modified Pitman model (Hughes, 2004), which is extensively utilized nationally for surface water purposes and less commonly for estimating groundwater processes and surface water-groundwater interactions. The model was assessed based on how well simulated water balance variables accurately reflected available evidence and expected catchment response (objective 1). Secondly, the study identified and addressed uncertainties regarding the structure and application of the model's groundwater interaction components (objective 2). The model was set up and calibrated for the Lake Sibaya catchment, which is a primarily groundwater-driven environment.

To reiterate, this case study was not a typical application of the Pitman modelling tool from a scale perspective, as well as from a groundwater perspective. This project aimed to test the limits of the Pitman model to assess whether it adds value to groundwater-focused modelling exercises. The model is a conceptual model and will never replace a numerical groundwater model. Still, in light of the data and time intensity of running a numerical model, it is anticipated that the Pitman model could add value, even if it is only focused on exploring a system's major water balance components prior to more detailed water balance modelling. A time series of the major water balance components and the data analysis options in the model could be helpful for a first-stage investigation.

It is acknowledged that the data used as inputs and to inform and evaluate the model structure and parameterization had short-comings. It may not be the most accurate data currently available, given ongoing research, improvements in remote sensing products, etc. However, the focus of the exercise was testing the model structure when aiming to represent the catchment in a reliable manner. It was assumed that the datasets obtained for the analysis provided a reasonable description of the catchments and climate conditions, and also represent the types of datasets modellers would typically have access to.

The sub-delineation of the case study catchment area in sub-catchments was guided by the various ephemeral river systems contributing to the lake. They vary in their consistency of flow; hence it was anticipated that these should be represented separately to align with the conceptual understanding of the catchment. This is a relatively easy function within the Pitman model and means the set-up process of including a greater number of sub-catchments is easy and not time-consuming (unlike many other models).

6.2. Assessment of the modelling approach

6.2.1. Positive outcomes regarding the setup and use of the modified Pitman model (Hughes, 2004)

- I. The model simulates the water balance in an integrated way; thereby, no variable is treated as a residual.
- II. There are a variety of analysis options in TSOFT (Hughes and Forsyth, 2006), which is a data analysis interface built into the SPATSM database.
- III. Modelled outputs are generated as time series, making it easier to monitor hydrological response under various climatic and changing catchment conditions.
- IV. The model generates outputs for most system variables, for example, recharge, downstream GW flow, interflow contribution to the river, and GW contribution to the river. Depending on the availability of observed data, the model set-up can be calibrated against any of the variables rather than just streamflow data.
- V. The Pitman model (Hughes, 2004) was designed to be used in data-scarce environments; therefore, it does not require large data sets or even a comparable amount of time to set up (compared to physically-based models). However, calibrating both SW and GW variables and achieving balance in that regard can be laborious (something that is probably true of all integrated models).
- VI. Although the model is typically designed to be applied at quaternary catchments, it has flexibility in that it can be set up at smaller spatial scales, such as in the current application (the main restriction on spatial scale is the monthly time step which would become unhelpful at very small scales).
- VII. The model successfully represented the lake volume changes compared with the observed lake levels.

6.2.2. Limitations regarding the setup and use of the modified Pitman model (Hughes, 2004)

- I. GW gradient representation did not reflect the gradual lowering of the GW table that was expected due to the large scale at which the model is usually applied. The large scale of the model means that GW level depths will be highly variable at the catchment scale, so the GW level is represented as a gradient, which is intended to be an average GW level over the entire catchment. It is not really accurate to compare GW gradient simulations with point measurements of groundwater level. In addition, each scenario represents a snapshot in time,

and when comparing all the groundwater levels together from all the scenarios, there is a distinct lowering of the GW table. This is, however, due to anthropogenic influences a similar trend to the lowering lake levels in any of the scenarios was not reflected in the GW gradient simulations.

- II. The structure of the wetland/lake sub-model does not include direct movement of GW into the lake; therefore, this process had to be represented implicitly.
- III. The simplified representation of aquifers, whereby the aquifer characteristics were averaged or based on one principal aquifer, reduces the accuracy of the GW simulations.
- IV. The inability of the model to represent changing land use meant the model was less able to be applied in a non-stationary environment. This is fairly common among hydrological models but was a significant hindrance in this case study.
- V. The simple evapotranspiration function in terms of plantation forestry, which includes the separation of the evapotranspiration process from the unsaturated zone and from groundwater, meant that this representation was highly uncertain.

6.3. Study area uncertainties

One of the significant challenges in setting up and calibrating the model application for the Lake Sibaya catchment was a lack of reliable and comprehensive data. The following data uncertainties were encountered:

- I. Rainfall uncertainties were highlighted by different simulations using WR2012 and CRU data. The rainfall in this region is variable and the model is highly sensitive to rainfall data. Since rainfall is the primary input to the model the quality of the data is likely to have a large impact on the accuracy of the model simulations.
- II. Limited information on observed lake levels and GW levels made the calibration process difficult.
- III. Forestry and water use integration was based on an approximate timeline due to a lack of specific information on the timing and amount of forestry planted. Calculations external to the model needed to be performed to construct a timeline of lake volume reflecting changing forestry and water use.
- IV. Although the system is largely a primary aquifer, there are hydrogeological complexities related to the linkages and extents of the various aquifers.

- V. Outflow from the lake via the palaeo-channel is highly uncertain due to a lack of data on that process.

6.4. Modelling outcomes

The modelling outcomes are discussed in relation to the research objectives.

6.4.1. Objective 1

Evaluate whether the modified Pitman model (Hughes, 2004) can reliably simulate the water balance of a groundwater-driven system using a robust conceptual understanding of the environment.

When assessed against the available data and understanding of the catchment conditions, the overall indication is that the model was able to adequately represent the major water balance components of the Lake Sibaya catchment. This suggestion is evidenced by the following;

- I. An overall trend of decreasing lake volume with increasing forestry and abstractions in the lake catchment. Previous studies, e.g., Smithers (2017), had similar findings.
- II. The direct relationship between lake volume and GW outflow into the lake whereby periods of sustained high GW outflow coincided with larger lake volume while lower GW outflows corresponded with decreased lake volume. These results reinforced the understanding of the lake being a predominately GW-driven system.
- III. GW recharge simulation of $157.2 \text{ mm year}^{-1}$ (17 % of the catchment MAP of $944.4 \text{ mm year}^{-1}$) under natural conditions and $113.04 \text{ mm year}^{-1}$ (12 % MAP) under the 2020 forestry and lake abstraction conditions were comparable to the Weitz (2016) estimate of 126 mm year^{-1} (13 % MAP).
- IV. Groundwater baseflow simulations showed groundwater baseflow flux moving into the rivers was significantly impacted by the water used by plantation forestry. This was the expected response as deep-rooted plantation forestry present in the catchment are able to utilise water both in the unsaturated zone and directly from groundwater (Brites, 2013; Everson et al., 2019).

6.4.2. Objective 2

Identify uncertainties related to the structure and application of the model's groundwater interaction components in the Lake Sibaya catchment.

The identified model structural and application uncertainties included the inability to explicitly represent GW outflow in a closed system and direct lake-groundwater exchanges (section 4.5.3.1). These uncertainties were resolved by:

- I. Applying a model approach that equates to a similar process in reality. E.g., representation of palaeo-channel outflow via the lake spill, which is a surface water process.
- II. Baseflow conversion by applying an implicit approach (for GW direct groundwater outflow into the lake). Table 4.5-7 shows comparable volumes between GW outflow from the upstream nodes and GW baseflow from the interface nodes suggesting that the upstream GW contribution was correctly converted to baseflow.
- III. Adjusting the relevant parameter values where there was a scale incompatibility between measured values and model algorithms.

Glenday et al. (2021) compared five different models from a structural perspective and identified the following generic model approach lessons which are valid for this modelling exercise:

- I. Compromise in modelling is unavoidable. Therefore, it is essential to establish clear objectives at the outset and continually revisit them as the modelling progresses. The level of compromise will vary. Typically, compromises may be necessary due to issues arising from process representation, physical constraints of implementing a model, and processing simulations.
- II. A robust conceptual understanding of the catchment is needed to ensure realistic model simulations.
- III. Usually, a model will not generate outputs for all catchment fluxes at the relevant spatial scales. It is up to the modeller to determine which model outputs are key. This decision must be advised by a combination of the modelling exercise objectives, conceptual understanding of the catchment, and the available data.
- IV. External mapping of the model structure can be helpful when comparing the surface and subsurface flow connections that are feasible in the model to the conceptual understanding of the catchment. This is crucial when modelling individual units or sub-catchments because these distinctions affect how the model represents processes, allocates input data, and connects flows.
- V. Additionally, externally mapping out the model's processes predictions helps adjust parameter values, including parameters with direct physical meaning. A more realistic simulation can be achieved by considering alternative process interpretations rather than relying solely on exact field measurements or literature values.

7. CONCLUSION

7.1. Key findings

The investigation arrived at the following key findings:

- I. Lake Sibaya's volume fluctuates in response to varying inputs (rainfall, surface runoff and groundwater outflow into the lake) and outputs (evaporation from the Lake Surface, Lake outflow and abstractions).
- II. Groundwater outflow simulations support previous findings that show GW largely sustains the lake.
- III. The overall decline observed in lake volumes.
- IV. The lake volume decreases with increasing development (forestry and abstractions) in the lake catchment.
- V. The presence of forestry in the lake catchment reduces the volume of baseflow moving into the rivers.
- VI. Rainfall uncertainty in the study area is significant.
- VII. Knowledge of local catchment conditions is valuable for producing realistic model simulations.
- VIII. The updated GW and SW-GW interaction components of the model were able to model the GW-driven environment of the Lake Sibaya catchment satisfactorily.

7.2. Overall conclusion

In its assessment of the modified Pitman model (Hughes, 2004) to determine its applicability for estimating groundwater processes and surface water-groundwater interactions, the research concludes that the model was applied successfully to the Lake Sibaya case study. Given the encounters with inadequate data and the model structure uncertainty, the lake's water balance was simulated correctly enough such that the main water balance components' influences were sensibly reflected in streamflow and lake volume variations. The research demonstrated that the modified Pitman model (Hughes, 2004) can be reliable for estimating SW-GW interactions, particularly in data-scarce catchments. The implicit methods employed to resolve the model structural uncertainties helped to make the model simulations as realistic as possible, based on a conceptual understanding of the catchment conditions. However, familiarity and experience with the model had a significant role in the effectiveness of these strategies. This represents a limitation to the study, it may be challenging for modellers who are less familiar with the Pitman model to replicate this success, especially for catchment processes that were not dealt with in this study but may be important in other case studies.

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