HYDROLOGICAL CHARACTERISATION OF WETLANDS: UNDERSTANDING WETLANDS-CATCHMENT LINKAGES

Nompumelelo Pretty Mandlazi

A thesis submitted in partial fulfilment of the requirements for the Degree of Magister Scientiae in the Department of Earth Science, University of Western Cape.

Supervisor: Prof D. Mazvimavi
Co-supervisors Dr E. Kapangaziwiri
Dr. JM Mwenge Kahinda

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KEYWORDS

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Wetland-catchment linkage
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ABSTRACT

This study explores the hydrological processes of selected wetlands in four different catchments in South Africa (the Nuwejaars River in the Western Cape which has the Elandsdrift-Wiesdrift wetland; the Mohlapetsi river in the lower Olifants river in Limpopo where the GaMampa wetland is located; the Usuthu River in Mpumalanga which has the Bonnie Brook wetlands; and the UMgeni River in KwaZulu Natal with the Lions river wetlands). The representation of wetlands processes in the Pitman and Agricultural Catchments Research Unit (ACRU) - commonly used hydrological models in Southern Africa – is also evaluated. In the Nuwejaars river catchment, hydrological processes were monitored for over a year, while literature and available conceptual frameworks were used in the other catchments. The Pitman and ACRU models were used to represent the main process and to determine how wetlands influence catchment-scale processes.

Current understanding of the hydrology of Elandsdrift-Wiesdrift floodplain suggests that the floodplain is dominated by precipitation, overland flow from the catchment area of the floodplain, evapotranspiration, and surface flow from the left sides of the floodplain to the Nuwejaars River. In the Mohlapetsi River catchment the GaMampa wetland is dominated by local rainfall falling directly onto the wetland, surface runoff from the valley sides, and spring flow at the bottom of the surrounding hills occasioned by recharge on the hills, evapotranspiration and lateral flow between the wetland to the river. The Bonnie Brook and Lion's river catchment are valley bottom floodplains dominated by evapotranspiration, precipitation, overland flow, overbank flooding, groundwater discharge and groundwater recharge.

Hydrological modelling of wetlands in the four basins yielded reasonable success (Nash Sutcliffe (NSE) ranged from 0.510 to 0.75 with less than 15% percentage of different between observed and selected mean values (PBIAS). Most characteristics of the observed flows for the four catchments were satisfactorily simulated. The overall results from both models indicate that the models can reasonably represent hydrological processes of wetlands, though there is need to improve the routines in both models. Therefore, further studies that will focus on parameter estimation and improving the current wetland modules of both models are recommended.

DECLARATION

I declare that ***Hydrological Characterisation of wetlands: understanding wetlands-catchment linkages*** is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name.. Date..................................

Signed..

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Philippians 4:6-7*: "Do not worry about anything, but in everything by prayer and supplication with thanksgiving let your requests be made known to God and the peace of God, which surpasses all understanding, will guard your hearts and your minds in Christ Jesus".*

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1 INTRODUCTION

1.1 BACKGROUND

Wetlands are unique, complex hydrological systems that occur within a wide range of climatic and topographic conditions. They are defined as "land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water and which, in normal circumstances, supports or would support vegetation typically adapted to saturated soil" (Collins, 2005). The term "wetlands" encompasses ecosystems of different shapes and sizes (such as fens, bogs, swamps, floodplains), which occur within a wide range of environmental conditions, normally under different topographic, geologic and climatic conditions.

The general functions of wetlands are shown in Figure 1.1. They influence both the quality and quantity of water since they retain nutrients (Saunders and Kalff, 2001), store water (Cole, 2006), improve water quality (Schulz and Peall, 2001; Verhoeven *et al.*, 2006), mitigate flooding (Ming *et al.*, 2007), recharge groundwater (Winter, 1999) and control flooding and erosion (Gedan *et al.*, 2011). Wetlands provide a habitat for aquatic species, thus conserving the biodiversity, and are used for water supply and tourism and recreation (Collins, 2005). There have been discussions on the hydrological role of wetlands and impacts on stream flow. The general hydrological role that wetland plays on stream flow is delay and reduce flood peaks, therefore augmenting low flow (Bullock and Acreman, 2003; Cai *et al.*, 2012; Acreman and Holden, 2013 and McCartney *et al.*, 2013). However, because wetlands occur within a wide range of environments, and in different topographic, geological, and climatic conditions, the above mentioned role on stream flow may not be true for all wetlands. There are also cases reported in the literature with wetlands increasing floods and reducing low flow (Bullock and Acreman, 2003). It is therefore important to carefully investigate the influence of each wetland on the hydrological regime of a stream.

In order to characterise the hydrology of wetlands, numerous methods are often used. This includes the use of isotopes as tracers, hydro-chemical characterisation and hydrological models. The use of isotopes to investigate groundwater flow paths and directions in wetlands has become popular in recent years (Clay *et al.*, 2004; Nyarko *et al.*, 2010; Mekiso, 2011; Hoy, 2012 and Riddell *et al.*, 2013). These studies indicate that isotopes are successful in determining the source of water in wetlands sources. The use of hydro-chemistry in characterising wetlands has also gained momentum in recent years (Adam *et al.*, 2001; Jeen *et al.*, 2001 and Taak and Singh, 2014).

In order to improve the understanding of the hydrological role of wetlands, hydrological models play a significant role, and a catchment-scale hydrological modelling approach that can be used to understand the linkages that exist between wetlands and their catchment is required. However, there are still deficiencies in the representation of wetland processes in hydrological models due to the lack of reliable data for verification of the models.

In South Africa, the number of studies that have characterised wetland hydrology has also increased over the years (e.g. Sarron, 2005; McCartney, 2006; McCartney *et al.*, 2006; Kogelbauer, 2010; Masiyandima *et al.*, 2011; Mekiso, 2011; le Roux, 2011; Riddell, 2011; Riddell *et al.*, 2013; Grundling *et al.*, 2013 and Grundling *et al.*, 2014). However, these studies are limited to specific areas (mostly focusing on the GaMampa and Craigieburn wetlands, and Mfabeni Peatland) and therefore general application in models is a challenge.

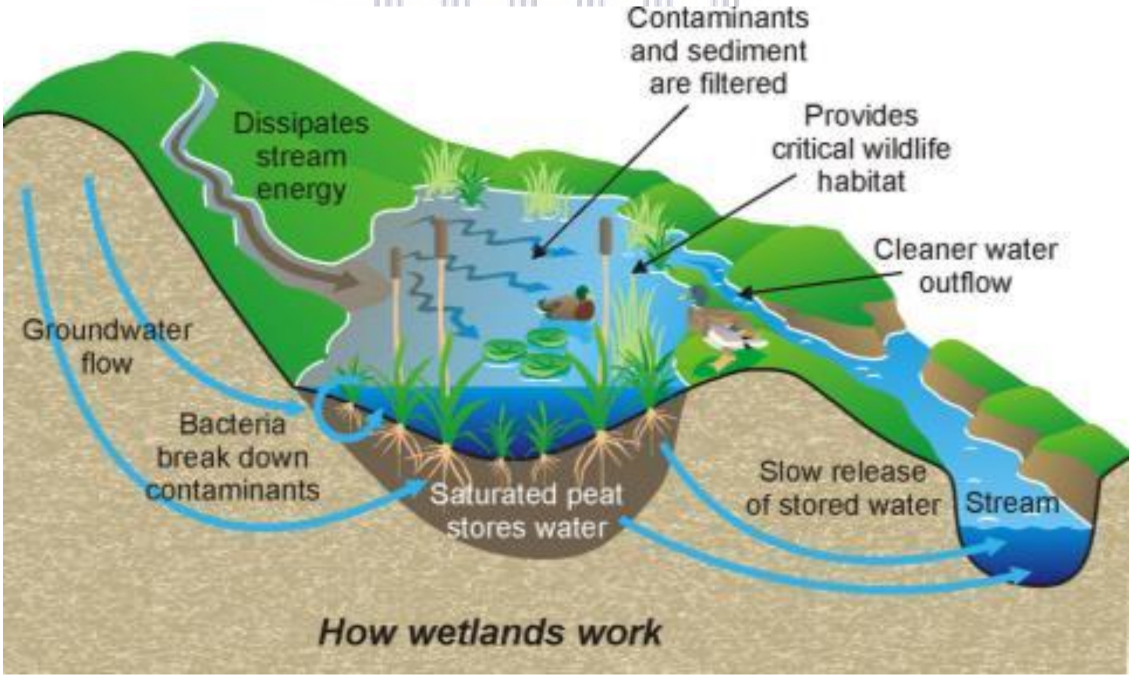


Figure 1.1. Illustrations of functions of wetlands, including the dissipation of incoming stream energy (important during high flow times), breaking down contaminants, and filtering sediments and excess nutrients. (Source: http://awwatersheds.org/category/watershed-word-of-the-week/).

1.2 PROBLEM STATEMENT

The nature of the wetland and the quantity of water available within it is determined by the hydrology of the catchment in which that wetland is located. A wetland in a catchment is impacted by hydrological processes occurring upstream while the wetland impacts downstream hydrological processes. Therefore there are dynamic hydrological interlinkages between the wetland and the catchment. However, knowledge of the linkage between wetlands and their catchment is limited. This is because wetlands are often treated as separate entities and their hydrology is often investigated as an isolated landscape feature, with hydrological interaction between them and their catchment ignored (Mitsch and Gosselink, 2000). Across many hydrological studies on wetlands, more focus has been on the hydrological processes of wetlands or the sources of water that sustain the wetland or the interaction of groundwater and surface water in wetlands. However, studies that characterise the interaction between the hydrological processes of wetlands and catchment scale hydrological processes are limited. Field monitoring of hydrological processes in wetlands is limited and this presents challenges to studies of their interactions. As a result, simulation models are used to better understand and represent this relationship between wetlands and their catchments.

The development of tools that accurately represent natural processes occurring in basin, including wetlands processes, is important for comprehensive and sustainable water resources management. Hydrological models can be used to establish the effects of flood attenuation, determine the contribution of wetlands to sustaining and reducing down river flows, the interaction between surface water and groundwater and influences on the rate of contamination. Therefore, it is important that these processes are accurately represented in hydrological models. However, due to the geomorphological differences of the landscape, wetlands are difficult hydrological systems to model and accurately represented. Recently, different hydrological models have been developed to simulate the hydrological processes of wetland (Maltby and Barker, 2009), while efforts have been made configuring existing hydrological models to incorporate wetlands processes (e.g. in the ACRU (Agricultural Catchments Research Unit) (Schulze, 1987; 1995; Smithers, 1991 and Smithers and Schulze, 1993) and Pitman (Pitman, 1973; Hughes *et al.*, 2006) models. However, despite the efforts made, very few hydrological models can explicitly simulate the hydrological pathways and processes in wetlands (Maltby and Barker, 2009).

Due to the importance of wetlands processes, functions and impacts on the hydrological regime of a catchment, wetlands constitute a good target of study in terms of the hydrological linkage that exist between wetlands and other hydrological processes in the catchment. Even though studies and investigation of these factors have been done, there are few and limited to specific regions (Tockner and Stanford 2002; Gray *et al.*, 2012; Hughes *et al.*, 2013).

1.3 RESEARCH QUESTIONS

This study seeks to provide answers to the following questions:

What are the hydrological linkages that exist between wetlands and their catchments?

This question seeks to address the hydrological linkage between wetlands and their catchments. Firstly, the main hydrological processes of the selected wetlands within four different physiographic catchments will be determined.

How does channelled and un-channelled valley bottom, riparian and non-riparian ponds impacts on stream flow?

This question aims to address the hydrological impact that the selected wetlands have within their catchment. Through monitoring of surface water inflows and outflows from/and to the wetland, groundwater levels, hydro-chemistry and tracers analysis that will be carried out, the study will be able to determine the kind of impact that the wetlands have on stream flow (whether they reduces or increases stream flow, recharges the groundwater system or vice versa.

What tools can be used to understand the relationship between the wetlands and the catchments in which they exist, and to predict the impacts of these wetlands?

This question seeks to address the application of hydrological models in wetlands in order to simulate the link that exists between wetlands and their catchment and/or the hydrological impacts of wetlands to catchment hydrology. The aim is to use hydrological models currently used in South Africa to represent the hydrological processes of wetlands for flow estimation and/or prediction. This study has chosen both the Pitman and ACRU models since they are used extensively in South Africa for water resources assessment.

1.4 OBJECTIVES

The main aim of this study is to investigate the hydrological link between wetlands and their catchment. The study also intends to assess the best way of predicting the impact or influence of wetlands in the chosen sub-basins. The specific objectives for the study are:

- To describe the main hydrological processes of selected wetlands in different physiographic settings.
- To assess the impact of channelled and un-channelled valley bottom, riparian and non-riparian ponds on sub-basin hydrological responses.

1.5 THESIS STRUCTURE

To fully understand wetlands; the basic concepts, hydrological processes, functions and impacts to the hydrological regime of their catchment are reviewed in chapter two. Chapter three describes the four catchments which this study focuses on. Hydrological models have generally been used to inform decision making in water resources management and, in recent years, existing hydrological models have been configured to incorporate wetlands processes. Chapter four describes the hydrological models used in this study. Chapter five presents the methods used to achieve the objectives of this study, while chapter six presents the results and discussion. Chapter seven presents the conclusions and recommendations from the study.

2 LITERATURE REVIEW

This chapter presents a review of literature in the context of wetlands hydrological processes and hydrological modelling of wetlands in general. It reviews wetlands definitions, criterion for wetland delineation, hydrological processes of wetlands and hydrological modelling of the processes and wetlands functions.

2.1 DEFINITION OF WETLAND

Wetlands are unique, complex hydrological systems that occur within a wide range of climatic and topographic conditions. The term "wetlands" covers a wide range of ecosystems occurring within different conditions. As a result, wetlands are difficult to define and delineate. The definition of wetlands has been subjected to a number of debates due to the complex nature of wetlands, and the scientific literature contains several definitions of wetlands as well as systems for their classification. These are summarised in Turner (1999) and Mitsch and Gosselink (2007). Cowardin (1982) states that the problem with the definition of wetlands has direct impact on their classification and inventories, and further states that this problem results from the lack of adequate data, various concepts to the limit of wetlands and conflicting ideas amongst the public on how to better use the resource. Definitions are important for wetlands classification and inventories used for sustainable use and proper management of wetlands as resources (Dugan, 1990). The lack of an acceptable definition of wetlands leads to the exclusion of wetlands which require important conservation (Adam, 1992), misuse of classification systems and erroneous conclusions drawn from wetland inventories.

2.2 CRITERION FOR WETLAND DELINEATION

Even though there is no universal definition for wetlands, three basic criteria have been adopted for the identification and characterisation of wetlands:

i) the presence of wetland water;
ii) hydric soils, and
iii) vegetation made of hydrophytic plants.

Water availability is often regarded as the most important factor because both hydrophytes and hydric soils depend on water (Mitsch and Gosselink, 1993). However, studies have indicated that water availability alone is often not enough to accurately identify the boundaries of wetlands (Tiner, 1991; DWAF, 2004; Collins, 2005). Direct methods of soil morphology and vegetation are then used.

2.2.1 Wetlands hydrology

For any area to be regarded as a wetland, it must be inundated by water for some time in a year, seasonally or permanently (Collins, 2005). The hydrological regime of wetland (i.e. water depth, flow patterns, frequency and duration and seasonality of inundation) is a major factor responsible for the function, composition and structure of wetlands. Hydrological processes of wetlands influence the regime of a wetland since input and output from the different processes differ in quantity and timing (Brinson, 1993 and Goslee *et al.*, 1997). Hydrological processes may become more variable, may increase or decrease in magnitude and may peak at times of the year when flow would naturally be at its lowest (Reid and Brooks, 2000). These changes to the hydrological processes of wetland conditions have direct consequences to the timing, magnitude and duration of water received by wetland, which can result in significant, lasting changes to the nature and function of the wetland.

2.2.2 Wetland vegetation

Wetlands vary in types; there are flood plains which contain water within the soil particles as soil moisture; and estuaries where the water table is at the surface. The impact and/or influence that hydrological processes have on each wetlands differs. Hughes *et al.* (1998) described the hydrological regime of estuaries as complicated and highly dependent on rainfall, seasonal variations in evapotranspiration, extreme tidal or flood events, and variations in regional groundwater flow. While Mitsch and Gosselink (1993) described the hydrological regime of floodplain wetlands as being strongly controlled by surface water and groundwater.

Hydrophytes are plants that grow and survive in saturated soil conditions, and their influence on hydrological processes of wetlands is well recognised. Evapotranspiration is one of the most important wetlands process that is largely influenced by hydrophytes in many wetlands (Pauliukonis and Schneider, 2001), which may account for up to 100 % of annual water losses in other wetlands (Souch *et al.*, 1998). Moisture is continuously available in wetlands for plants to transpire and for evaporation demands (Allen, 1998). A number of studies have argued that evapotranspiration in wetlands is higher compared to evapotranspiration of agricultural or forest land due to high wetness and dense vegetation in wetlands (Kampf *et al.*, 2005; and Acreman *et al.*, 2007).

Interception from rainfall is another hydrological process of wetlands that is influenced by hydrophytes (Tsai *et al.*, 2007). Wetlands are normally densely vegetated and hydrophytes plants have larger leaves thus intercepting more precipitation compared to normal plants. Such intercepted water may later be evaporated (Renault *et al.*, 2000).

2.2.3 Hydric soils

Understanding the hydrological processes of wetlands and how they interact with catchment scale processes requires an understanding of wetland soils. Wetland hydric soils have been described as the most important component because of their function in regulating hydrological functions (Bardgett *et al.*, 2001). Riddell (2011) in characterising the hydrology of the Craigieburn wetland showed that the hydrology of the wetland is largely controlled by the presence of both horizontal and vertical clay aquicludes within a hydraulically conductive sandy matrix.

The soil partitions precipitation into infiltration, evaporation, surface runoff, interflow and deep groundwater percolation. The above mentioned processes are greatly influenced by the physical structure (i.e. texture type) of the soil. Wetland soils are divided into mineral and organic soils (Mitsch and Gosselink, 2015), where the later are saturated with water for longer periods, with higher concentration of clay and lower concentration of organic carbon; while mineral soils have low clay content and higher organic carbon. As a result of the high content of organic matter and clay in wetlands there is high water retention (Reddy *et al.*, 2000). The presence of water within wetlands soil is indicated by morphological features such as mottles and gleying (Collins, 2005). Gleyed soils indicate slow downward movement of water through a permeable soil horizon into unsaturated subsoil where a deep water table may occur (Beven and Germann, 1982). Mottling indicates the reduction of iron and manganese oxides and are indicative of annual water flow patterns. Temporary or seasonal wetlands have a higher concentration of mottles while permanent wetlands have fewer mottles (Collins, 2005).

2.3 CLASSIFICATION OF WETLANDS

Classification is a process of systematic arrangement where wetlands with similar elements are put into a single group that is distinctly different from other groups (Zoltia and Vitt, 1995). Wetland classifications and inventories are important tools for the understanding, conserving and sustainable use of wetlands and are used for decision making, identifying gaps and providing uniform terms that can be universally applied (Cowardin *et al.*, 1979).

Wetlands can be classified by vegetation, topography and soils, or on the basis of their hydrological processes (Brinson, 1993). At regional scales, Brinson (1993) suggests that bedrock composition, geomorphic history and soil characteristics strongly influence wetland processes and they can be used for classification, whereas at a local scale, he suggests water table data as the most effective way to develop a wetland classification since this method isolates water as the key driver. Maltby and Barker (2009) thus highlight the importance of understanding hydrological characteristics in wetland classification and inventories.

The classification of wetlands using hydrological processes is however complicated by many factors (Scott and Jones, 1995) as there is close influence by processes operating at the larger catchment scale. Thus, classifying wetlands based on hydrology entails that catchment scale processes should also be taken into consideration (Scott and Jones, 1995). Moreover, the seasonality of hydrological processes, uncertainties associated with estimating hydrological parameters and problems with heterogeneity further complicate such classification (Hunt *et al.*, 1998). Riddell *et al.* (2013) state that hydrological studies of wetlands that have been conducted within the southern African region are constrained by the heterogeneous geomorphic template of the landscape, which shows that each wetland seems to be operating in a different way; thus, challenging the development of classification systems.

Cowardin *et al.* (1979) developed a classification of wetlands and deepwater habitats. Under this system, wetlands are of two basic types: coastal (tidal or estuarine wetlands) and inland (non-tidal, freshwater, or palustrine wetlands). The Ramsar Convention also developed a classification system based on Cowardin *et al.* (1979) principles. The systems classify wetlands as being marine, estuarine, lacustrine, and riverine or palustrine. Man-made wetlands are also included in the Ramsar system.

2.4 WETLAND DELINEATION

Furthermore, because the inundation of wetlands is controlled by climatic variables such as precipitation and temperature, wetlands are either temporary, seasonally or permanent inundated. The lack of adequate and reliable data on the hydrological processes of wetlands that can be used to define wetlands boundaries has also been highlighted as a challenge in wetland delineation (Jones, 2002). Thus, the hydrological condition referred to in the criterion and definition is so that it supports the hydrophytes vegetation and wet soils (Tiner, 1989). As a result of the above challenges, delineation using hydrological processes can result in other wetland and/or boundary of wetlands being missed (Tiner, 1989). Despite the limits in delineation using hydrological processes, these are still used to verify whether or not an area is a wetland.

2.5 TERMS USED AND TYPE OF WETLANDS

A number of terms are commonly used in literature to describe different type of wetlands (Mitsch and Gosselink, 2015). The term *dambo* defines "valley grassland which is seasonally inundated and is distinguished by its characteristics grass and sedges vegetation" (Matiza and Chabwela, 1992). Dambos are similar to *vleis*, which are seasonal wetland and there are mostly found in Southern Africa, i.e. South Africa, Zambia and Zimbabwe (Riddell *et al.*, 2013). Marshes are wetlands dominated by herbaceous plants, with their stems occurring above the water surface. Marshes can either be deep or shallow (Collins, 2005). In the Gulf coast region of the southern United States, marshes are referred to as Bayou. Swamps are often covered with woody plants (Mitsch and Gosselink, 2000). Slough is an elongated swamp or shallow lake system, while a morass refers to a tract of low lying swampy wetland. Peatland is any wetland that accumulates partially decayed plant matter due to incomplete decomposition, and is similar to a mire, where peat formation is still active. A peatland is also called a muskeg. Different terms are used to describe peat forming wetlands, including fens, which are peatland dominated by herbaceous plants and bogs also dominated by herbaceous plants but of different chemistry. A bog is also referred to as quagmire. Depending on regional perceptions and field of research, these terms may often not mean the same thing in different regions.

2.6 ECOLOGICAL ROLE OF WETLANDS

In the past three decades, there has been growing interest in ecological functions provided by wetlands. These functions and values of wetlands to the ecology are well documented (Kotze *et al.*, 2005; McCartney *et al.*, 2005; and Mitsch and Gosselink 2015). In southern African rural communities, wetlands are significant resources (Masiyandima *et al.*, 2006) that are used for grazing, cultivation, irrigation, domestic uses, recreation purposes, traditional medicinal plants and job creations (Kotze *et al.*, 2005). They also provide a habitat for fauna and flora species (Kotze *et al.*, 2005); hence wetlands are important for maintaining aquatic ecosystem biodiversity (Mitsch and Gosselink, 2007; and Zhang *et al.*, 2010). Some birds and fish are dependent on wetlands for habitat. The ability of wetlands to store water and releasing it slowly during the dry season serves an important function to downstream users, and are thus used as important water sources (McCartney *et al.*, 2013). Also, wetlands enhance the quality of water as they act as filters that trap pollutants (Kotze, 2000).

2.7 THE MAIN HYDROLOGICAL PROCESSES OF WETLANDS

Wetlands are formed and sustained by hydrological processes driven by climate, geology, and landscape setting (Acreman and Miller, 2004; Acreman *et al.*, 2007; and Mitsh, Gosselink, 2007, McCartney *et al.*, 2010 and Schook and Cooper, 2014). Hydrological processes influence the biological/geo-chemical cycle, structure and functions of the wetland, soil salinity, microbial activities within the soil, availability of nutrients etc. (Feng *et al.*, 2013). The importance of each process varies from wetland to wetland. Understanding these processes is essential (Mitsch and Gosselink, 2000), especially in understanding the hydrological linkage between wetlands and the catchments in which they occur.

Processes that occur in wetlands are hydrologically linked to the wider catchment processes. Surface water and/or groundwater upstream and/or downstream of a wetland influences the hydrological processes of the wetland. Substantial efforts have been made to investigate the hydrological processes that govern most wetlands (Hayashi *et al.*, 1998; LaBaugh *et al.*, 1998; Zhang and Mitsch, 2005; Mekiso, 2011 and Feng *et al.*, 2013). In recent years, there has been growth in knowledge and research on wetlands hydrological processes (Acreman *et al.*, 2007). However, very little effort has been put in understanding the hydrological link that exists between wetlands and the basins in which they occur.

Devito *et al.* (1997) have investigated the hydrological linkage that exists between wetlands and landscapes, with a strong focus on how the linkage regulates wetlands biogeochemistry and the source-sink function of the wetland. Devito *et al.* (1997) showed how hydrological processes occurring in wetlands are controlled by catchment and regional hydrogeology and how wetland processes are linked to their uplands.

2.7.1 Precipitation

Precipitation serves as a primary and major source of water in wetland water balance (Bedford, 1996). In most wetlands, it is regarded as the driving force of the water budget (e.g. Feng *et al.*, 2013; and Riddell *et al.*, 2013). It serves as a direct water source to wetlands and also recharges indirect sources such as surface water and groundwater sources (Maltby and Barker, 2009). Interception, surface runoff, infiltration, groundwater recharge, water levels fluctuations and inundation all depend on precipitation. For any of these processes to occur, it must rain first. Indirect precipitation contributes significant amount of water to wetlands. However, Maltby and Barker, (2009) state that precipitation that falls in non-wetland area is subjected to evaporation losses, losses from depression and soil moisture storage along pathways to the wetland, thus direct precipitation end up being the main source of water in other wetlands. The significance of direct precipitation in wetland water budget varies from wetland to wetland and depends on the area of the wetland (Perrow and Davy, 2002). The majority of wetlands within South Africa have smaller surface areas, less than 1% of total catchment area, implying minimal contribution of direct precipitation (Maltby and Barker, 2009). Precipitation is easily measured with rain gauges.

2.7.2 Evapotranspiration

Evapotranspiration is regarded as the major water flux through which water is lost in most wetlands (Bullock and Acreman, 2003, Sanchez-Carrillo *et al.*, 2004 and Chaubey and Ward, 2006), and influences water level fluctuations, areal extent of water coverage and inundation duration. There has been a great interest in studies that cover evapotranspiration of wetlands since it impacts on water availability and subsequent use (e.g. Abtew, 1996; Souch *et al.*, 1998; Jacobs *et al.*, 2002; Drexlex *et al.*, 2004 and Sanderson and Cooper, 2008). Some of these studies have treated evapotranspiration as a single component (e.g. Sanderson and Cooper, 2008), while others have focused on differentiating between transpiration rates of particular wetland plants and evaporation demands of open water areas to determine the overall consumptive use (e.g. Campbell and Williamson, 1997; Sanchez-Carrillo *et al.*, 2004 and Mohamed *et al.*, 2012). There has also been debate on whether evapotranspiration of vegetated wetlands differs from that of open water wetland types (Gilman, 2002), but it is still not clear whether evapotranspiration of vegetated wetland is higher or lower than that of open water bodies (Andersen, 2003). Several attempts to estimate transpiration and evaporation rates from vegetation and open water have provided contradicting and, sometimes, confusing results (Sanchez-Carrillo *et al.*, 2004). This is caused by uncertainties in methods used and inadequate descriptions of the evapotranspiration components actually measured or estimated. Evapotranspiration is not limited to moist areas only (Sanchez-Carrillo *et al.*, 2004) but decreases with decreasing areas of open water in wetlands.

The type of vegetation plays a major role in evapotranspiration. Acreman *et al.* (2003) state that reed beds have high evapotranspiration rates compared to grass because of their leafy area. Orang *et al.* (2009) reported high percentages of evapotranspiration of wetlands compared to irrigated crops in San Joaquin-Sacramento river delta, while Jacobs *et al.* (2002) reported a total evapotranspiration of 249 mm a^{-1}, exceeding the total precipitation of 179 mm a^{-1}, from maiden cane, weed, and dog fennel in the prairie wetland. Studies of evapotranspiration are still limited to specific types of wetlands and vegetation only (Gilman, 2002). However, due to the diversity of wetlands and the complex nature of wetlands surface characteristics, quantifying evapotranspiration rates in wetlands still remains a challenge. While, various methods have been developed to estimate evapotranspiration in wetlands (Praveen *et al.*, 2011), most of the methods used, like the Penman-Monteith equation, require a substantial amount of meteorological data, often not available for many wetlands. Despite an increase in the number of studies that use remote sensing to determine evapotranspiration in wetlands, it is challenging to use this method because wetlands are not unified by a common land cover type and are highly dynamic in ways that substantially alter their reflectance and energy backscattering properties (Gibson *et al.*, 2013; Gallant, 2015).

2.7.3 Interception

Interception is the amount of precipitation that does not reach the soil surfaces because it has been caught by plants leaf surfaces. Interception is often regarded as another component of evaporation since most of the water that is intercepted by plants is later evaporated (Yaseef *et al.*, 2009; Klaassen, 2001). Hill (2007) states that interception plays a significant role in the water balance of wetlands; especially those dominated by vertical processes. Despite its significant role, many hydrological studies ignore interception (Savenije, 2004). Furthermore, Savenije (2004) argues that often interception is limited to the amount of water captured by leaf surfaces while it also includes interception by a soil wet ‘crust’ occurring on the same day as a rain event. The amount of water intercepted by plants depends on the intensity and duration of rainfall. Low-intensity, short-duration rainfall yields large quantities of interception (Eamus *et al.*, 2006). The type of vegetation, leaf area index, vegetation heights, wind speed and energy also influence the amount of water intercepted by vegetation. Studies of interception in wetlands have focused on different types of wetlands vegetation (e.g. Liorens *et al.*, 1997, Calder and Dye, 2001; Savenije, 2004; and Mitsch and Gosselink, 2008). Mitsch and Gosselink (2008) have stated that about 8% to 35% of precipitation is intercepted by forests. Calder and Dye (2001) reported that interception by forests (pines) is higher than that of shorter crops (grassland). Liorens *et al.*, (1997) reported a 24% of interception loss by *pinus* forest located in a Mediterranean mountain. Savenije (2004) reported interception loss of 4-5 mm/day by crops and isolated trees in the Mupfure catchment in Zimbabwe. Helmschrot (2006) indicated that forest plantations in wetlands of the Mooi and Weatherly catchments will reduce water availability significantly as a result of higher interception. Bulcock and Jewitt (2012) who modelled interception in commercial forest catchments of South Africa indicated that canopy and litter interception can account for as much as 26.6% and 13.4 % of gross precipitation.

2.7.4 Surface and groundwater interaction in wetlands

Groundwater and surface water have been described to be interdependent (Winter, 1999), thus these two components cannot be isolated (Sophocleous, 2002). Groundwater and surface water play a significant role in the water balance of a wetland. Groundwater or surface water can serve as a primary source of water in some wetlands while other wetlands are dependant in both surface water and groundwater. Surface water enters a wetland through channel flow, overland flow and base flow, while hydrological exchange between wetlands and groundwater occurs through groundwater recharge from wetlands, groundwater discharge to wetlands and through flow (Figure 2.1) (Kasenow, 2001).

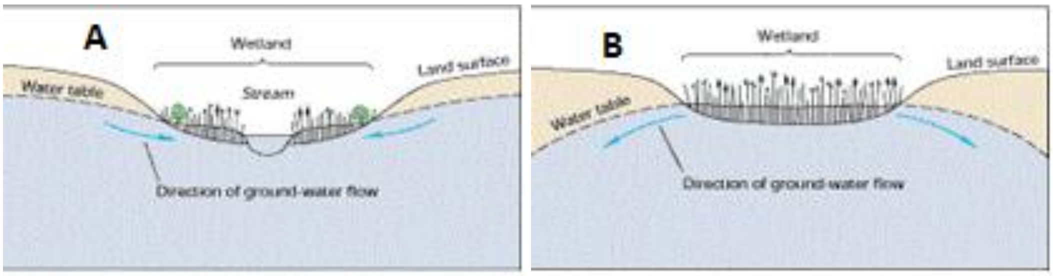


Figure 2.1. Hydrological exchanges processes between wetlands and groundwater. A illustrates groundwater contributing to a wetland; B illustrates the wetland contributing to groundwater (https://pubs.usgs.gov/sbin:/usr/sbin:/bin:/usr/bin).

Understanding wetland hydrology requires an understanding of the interaction between surface water and groundwater as this interaction creates an important link between wetlands and their basin (Schot and Winter, 2006). It sustains the base flow component (Hayashi and Rossenberry, 2002), influences runoff production (Devito *et al.*, 1996) and influences water chemistry (Kazezyilmaz-Alhan, 2011) in a basin. Thus, groundwater-surface water interaction plays an important role in spatial and temporal availability of surface and groundwater within a basin (Schot and Winter, 2006) and studies have highlighted the importance of this interaction (Hunt *et al.*, 2006; Schot and Winter, 2006; and Van der Kamp and Hayishi, 1998).

Since surface-ground water interaction plays a major role in ecological and hydrological functions of wetlands (Garth *et al.*, 2015), it is important to understand this interaction in order to deal with water quality issues, over-exploitation of groundwater and flood and droughts mitigation in catchment management. The role and proportion of surface-ground water interaction in wetlands and the interaction between the wetland and the groundwater is determined by the position of the wetland within the groundwater flow subsystem, the soil settings and aquifer characteristics of the wetland. Wetlands may develop in low topographical areas were groundwater discharges into the wetland or they may develop in high topographic areas where they may recharge groundwater (Schot and Winter, 2006). Devito *et al.* (1996) reported a relatively uniform elevation in the position of water table and surface water for wetlands which are recharged by groundwater in a 21.1 ha catchment (e.g. swamps and fens). Groundwater and surface water are often regarded as a single resource because groundwater is almost always connected to surface water (Hayashi and Rossenberry, 2002 and Winter *et al.*, 1998). As a result of the hydrological importance of their interconnectedness, there has been an increasing attention given to this complex interaction in wetlands (Devito *et al.*, 1996). Winter *et al.* (1998) reported that riverine and coastal wetlands are complicated by periodic water level changes, while Anibas *et al.* (2012) reported that the interaction of groundwater and surface water is complicated by aquifer heterogeneity. Siegel (1988) stated that groundwater-surface water in wetlands is complicated by multiple groundwater flow systems conform. Studies that have characterised the interaction of surface water and groundwater in wetlands are limited to specific region (e.g. the Sand river catchment in Mpumalanga in South Africa (Riddell *et al.*, 2013), South Central Ontario in the United States of America (USA) (Devito and Hill, 1997), Biebrza river basin in Poland (Anibas *et al.*, 2012) and the Trout Lake Watershed in northern Wisconsin in the USA (Hunt *et al.,* 2006). McEwan *et al.* (2006) reviewed the current knowledge of groundwater-surface water interaction in arid/semi-arid wetlands, and results indicated that the interaction between surface water and groundwater is dynamic, complex and often extends beyond the surface water boundary. Khisa *et al.* (2012) studied the interaction between surface water and groundwater in papyrus wetlands, in the Nyambo river basin and their results indicated that the soil moisture content is influenced by groundwater exfiltration, rainfall, river overtopping and back water effects. Liu and Mou (2014) in reviewing the interaction between surface water and groundwater in coastal wetlands reported that the interaction control salinity and the hydrological regime in wetlands. Liu and Mou (2014) further emphasise the importance hydrological models in groundwater-surface water interaction of coastal wetlands. Since surface water and groundwater are a single resource, the chemical composition of one cannot be separated from the other (Winter *et al.*, 1998). The hydrochemical analysis of groundwater has been used to understand and characterise this interaction. Bekele and Ndlovu (2014) investigated the groundwater-surface water relationship of the Kosi bay lakes in the north eastern coast of South Africa where the results of the study indicated a strong connection between them within the lake. Garth *et al.* (2015) investigated the interaction of surface water and groundwater at a wetlands system in Milledgeville using heat tracers and the results indicated the interaction in some parts of the wetland while there was disconnect in others.

Wetlands which are controlled by groundwater-surface water interaction are often complex and thus require complex hydrological models to understand them (Acreman and Mounford, 2009). However, there are generally few hydrological models that incorporate the interaction of groundwater and surface water in wetlands (Butts *et al.*, 2014 and

Kazezyilmaz-Alhan *et al.*, 2007). Thus, there is still a need of more sophisticated hydrological models that explicitly account for groundwater surface water interaction in wetlands. Kazezyilmaz-Alhan (2011) also stressed the importance of incorporating the role of groundwater-surface water interaction in wetlands into hydrological models. However the complex nature of wetland flow system and the interaction between groundwater and surface water makes the hydrological modelling of wetlands a difficult task (Acreman and Miller, 2007 and Chauvelon *et al.*, 2003).

Different methods are used to quantify both surface and groundwater. Channelized flow in wetlands can be easily determined using stream gauges or area-velocity method. Groundwater input and outputs estimates in wetlands require large amount of data on subsurface geometry, lithology and hydraulic head (Dobbs, 2010). Piezometer and wells are installed and monitored for longer periods to determine and quantify groundwater movement. Hence groundwater flow estimates are considered to be complex (O'Driscoll and Parizek, 2003).

2.8 HYDROLOGICAL FUNCTIONS OF WETLANDS

The hydrological functions of wetlands are well documented (Adamus and Stockwell, 1983; Bullock and Acreman, 2003 and Hooijer, 2003). Wetlands serve important functions to the hydrology of their basins and can influence both the quality and quantity of water since they retain nutrients (Saunders and Kalff, 2001), store water (Cole, 2006), improve water quality (Schulz and Peall, 2001; Verhoeven *et al.*, 2006), attenuate floods (Ming *et al.*, 2007), recharge groundwater (Winter, 1999) and control erosion (Gedan *et al.*, 2011). Since most wetlands occur in valleys that are poorly drained, they provide significant potential storage (Demissie *et al.*, 1993). Wetlands which are adjacent to streams soak and absorb runoff during the wet season, when surface runoff is typically higher. By absorbing and storing runoff from adjacent areas, wetlands delay the amount of runoff that reaches stream channels, thus reducing the magnitude of flood peaks. The delay and reduction of flood peaks and flow velocities provide wetlands an opportunity to trap sediments and immobilise nutrients thus purifying the water. During the dry season, when runoff in streams drops, adjacent wetlands discharge runoff to streams, thus augmenting stream flow. The term "wetland" encompasses a variety of ecosystems that varies in size and shape (e.g. floodplain, swamps, fens etc.), and as such the function of one type of wetland tends to be generalised to all type and such may not be true. Bullock and Acreman (2003) contend therefore that it is difficult to make definitive statements regarding the role of various types of wetlands in runoff production or storm water detention. The role of each wetland is controlled to a large extent by its landscape position within a basin and topography. The hydrological role of a wetland located on the upstream most parts of the catchment will have a small catchment area contributing to it, thus minor impact to the hydrology of the basin compared to a wetland located on the downstream most of the catchment which will have a larger catchment area contributing to it. Acreman and Holden (2013) define the landscape position as wetlands upstream in areas of flood generation and/or wetlands downstream in lowland areas adjacent to rivers in floods. Spence *et al.* (2011) presented an example of a downstream most fen wetland in Boreal stream, Canada, were the hydrological functions of the wetland were investigated and that the wetland transmits stream flow from the higher parts to lower parts of the catchment.

In studying the hydrological function of depression wetlands in the northern prairie, Van der Kamp and Hayashi (1998) reported that the wetlands function as both groundwater recharge and discharge areas. USGS (1996) reported that lacustrine wetlands store floodwater by spreading it over a large flat area. Brinson *et al.* (1995) investigated the hydrological function of riverine wetlands in Gulf coastal plains, Glaciated northeast, Southwest, Rocky Mountains, Olympic peninsula and Puget Sound and that these store subsurface, moderate groundwater flow and discharge, dissipate energy, and store surface water. In investigating the impact of urbanisation on coastal wetlands and structure, Lee *et al.* (2006) contested that while the literature has reported many functions of coastal wetlands, very few of the reported functions have been demonstrated or observed. However, not all riverine wetlands associated with lakes or non-riparian wetlands perform these functions.

The size and shape of a wetland influences its hydrological functioning. Cia *et al.* (2012) in evaluating ecosystem flow regulating functions in the Zambezi river basin reported a decrease in flood flow and an increase in low flow from a floodplain wetland. McCartney *et al.* (2013) studied few regulating functions of floodplains, headwater wetlands and miambo wetlands in the Zambezi river basin, including floodplains which were studied by Cia *et al.* (2012) and the results from their study revealed that different wetland types tend to affect flow differently, with floodplains decreasing flood flow and increasing low flow, headwaters wetlands increase flood flow and decreases low flow and miambo forest decrease both floods flows and low flow. In comparing scientific evidence amongst hydrological functions and wetlands types, Bullock and Acreman (2003) concluded that floodplain wetlands generally reduce or delay flood peaks. Ladouche and Weng (2005) in an assessment of the role of surface and groundwater in the hydrological functioning of the Rochefort agricultural marsh indicated that the marsh is a groundwater discharging zone. Yao *et al.* (2014) investigated changes in stream peak flow and regulation in Naoli river watershed as a result of Naoli marsh loss and concluded that peak flows are increased as the wetlands area is decreased and stream flow regulatory function is decreased as the wetland diminishes. Feng *et al.* (2013) reported that the Zhalong wetlands in northern China, which are 90% dominated by marshes, show free exchanges of waters between channels and surrounding wetlands when the water level is high. Quinton *et al.* (2003) investigated the connectivity and storage functions of channel fens and flat bogs and the results indicated that runoff increases as the cover of channel fens increase and decreases with an increase in that of bogs. McCartney *et al.* (2011) who investigated the hydrology and ecosystem provision of the GaMampa wetland in South Africa indicated that the wetland contributes to dry season flow of the Mohlapetsi river.

Different studies have reported contradicting statements about previously widely accepted knowledge (Bullock and Acreman, 2003). Several publications in literature regard Malaysian peat swamp in Sarawak catchment as sponge with very large pores and highly absorptive (UNDP, 2006). However, Hooijer (2003) opposed that the assumption that peat swamps act like a sponge is not hydrologically accurate, given that a sponge releases as much water as possible while peat swamps limit water release. Hooijer (2003) further stated that the slow response to rainfall in peat swamps is due to slow release from open water storage along the channels. Bullock (1992), Bullock and McCartney (1996), and Maltby and Barker (2009) have also challenged the perception that *dambos*, which are common in most Southern African rivers, act as a “sponge” storing water that is used to maintain downstream flow during the dry season. Bullock (1992); Bullock and McCartney (1996); von der Heyden and New (2003); Maltby and Barker (2009); Maltby and Barker (2009); McCartney *et al.* (2013); and Riddell *et al.* (2013) have all agreed that most water that is stored in dambos is lost through evapotranspiration. Bullock and McCartney (1996), further content that dambos’ contributions to river flow account for as little as 2% during the dry season. Also, the perception that headwater wetlands attenuate floods has been challenged. Riddell *et al.* (2013), in characterising the water budget of a rehabilitated headwater wetland system, showed that the dominant component of flows comes from event water, which contradicts the perception that headwater wetlands attenuate floods.

Through flow regulation, wetlands do not only play a role in the hydrology of a basin, but also to the human population living downstream (McCartney *et al.*, 2013). They serve as potential solutions to integrated water resources issues i.e. flood risk, water supply etc. (Maltby and Barker, 2009). However, the degree to which each wetland functions differs (Rogers *et al.*, 2009; and Hooijer, 2003). Furthermore, some wetlands functions may be beneficial to the hydrology of their wider basins while others might not. The Usangu wetland in Tanzania is an example of a wetland were there has been a tremendous reduction of downstream flow. However, the reduction of downstream flow often results from extensive water use upstream and not from the wetland itself (Kashaigili *et al.*, 2006). Some wetlands such as the dambo wetlands in Chambishi catchment in Zambia (Von der Heyden and New, 2003) may increase flood flows during the wet season posing a flooding threat downstream. Grundling *et al*. (2015) stated that the Mfabeni mire in KwaZulu Natal contributed a small fraction to downstream flow throughout the year.

2.9 THE USE OF HYDROCHEMISTRY TO INVESTIGATE HYDROLOGICAL PROCESSES OF WETLANDS

Hydrological tracers are used to characterise the hydrology of a basin. Common hydrological tracers include hydro chemicals, dyes, salts and isotopes. The use of these tracers to investigate hydrological processes in wetlands has increased in recent years. Deuterium and oxygen are the most common isotope tracers that have been used successfully in previous studies to investigate the hydrological processes of wetlands. Mekiso and Ochieng (2014) used Deuterium and oxygen to characterise different water dynamics within the Mohlapetsi river catchment in South Africa. Riddell *et al*. (2013) also used Deuterium and Oxygen for hydrograph separation in the Manalana wetland in South Africa. Dissolved silica is another hydrological tracer that has been successfully used to investigate runoff processes, flow path ways and to separate different runoff components. Wenninger *et al*. (2010) used dissolved Silica to identify the hydrological processes in a semi-arid headwater catchment in the Eastern Cape Province of South Africa. Huth *et al*. (2004) also used dissolved silica for hydrograph separation in three high resolution catchments in Sierra.

2.10 SUMMARY OF CHAPTER

Due to the complex nature of wetlands, their definition has been subject to a number of debates. This research has reviewed definitions which are widely used, and national definitions used within South Africa. The three criteria used as indicators of wetlands have also been outlined. In the past, wetlands were generally considered to have little fundamental value. However, this perception has been changed over time. Recently, there has been an increase in the number of studies on wetlands and some have highlighted the importance of wetlands to the ecology. The review has shown that tracers such as hydrochemistry are important tools for hydrological investigations in wetlands. This is true for characterising groundwater flow paths and directions and determining the sources of water that sustain wetlands. The review has also indicated the importance of the main hydrological processes in sustaining the functions of wetlands. Moreover, the impacts of different wetlands to the hydrological regime of their basins are still not well understood, and the generalisation of functions to all wetland does not hold true.

3 DESCRIPTION OF CASE STUDY CATCHMENTS

This section describes the four selected catchments used in the study. This includes the geographic location, climate, topography, geology, soils and land use types. The selected wetlands within the four catchments are also described.

3.1 INTRODUCTION

To evaluate the applicability of both the Pitman and ACRU models in a wide range of wetlands, it was important that the study be applied to wetlands with different climatic and physiographic settings. Therefore four sites were chosen for the study. These are the Elandsdrift-Wiesdrift wetland in the Nuwejaars River catchment in the Western Cape, the GaMampa wetland in the Mohlapetsi river catchment in the lower Olifants river in Limpopo, the Bonnie Brook river catchment wetlands in the Usuthu River in Mpumalanga and Lion's river catchment wetlands in the UMgeni river in KwaZulu Natal (Figure 3.1). The selected wetlands have different climatic and physiographic characteristics.

The application of the models in more than one wetland will provide validation in the ability of both wetland modules of Pitman and ACRU models to provide outputs relevant to wetland hydrological processes.

The Nuwejaars catchment was selected as one of case study catchments for hydrological modelling of wetlands because of its diversity. The catchment has diverse wetlands formed under different varying geomorphological conditions. The catchment has been instrumented with hydrological apparatus to collect data that will contribute to the hydrological processes of the floodplain and to the hydrology of wetlands in the Nuwejaars catchment.

The Mohlapetsi catchment was selected because it has been the subject of previous research projects, and therefore the hydrological processes of the GaMampa wetland have been investigated and hydrological data that could be used for hydrological modelling has been collected as is available.

The Bonnie Brook river catchment and the Lion's river catchment were selected because the catchments have observed stream flow data from gauging stations located at the outlets of the quaternary catchments in which they are found and other hydro-climate data such as rainfall that is required for hydrological modelling are also available. However, the hydrological processes of the wetlands in these catchments have not been monitored or studied. Therefore the study explores basins which are gauged, partially gauged and ungauged.

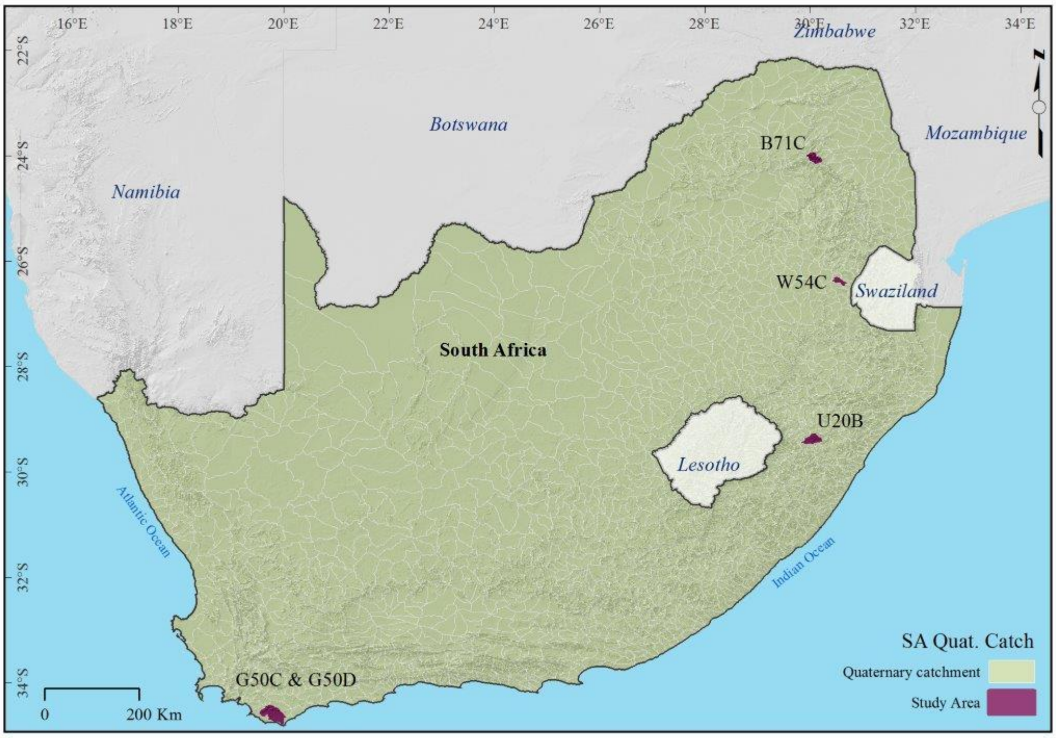


Figure 3.1. The quaternary catchments in which the wetlands used in this study are located.

3.1.1 The Nuwejaars catchment location, topography, geology, land use and climate

The Nuwejaars river catchment (Figure 3.2) is a sub-basin in the Breede-Gouritz Water Management Area. The catchment is located on the southernmost part of South Africa and comprises quaternary catchments G50B and G50C, with an area of 760 km^2. The Nuwejaars River is an ephemeral stream that receives high flows during the wet winter season between May and August and low flows in summer between October and April. The river originates in the Bredarsdorp mountains north of Elim and flows into the Soetendalsvlei, which flows out as Heuningnes river. It meander as it moves from its upper reaches to the downstream and between Elandsdrift and Wiesdrift, then forms a floodplain wetland with an average elevation of eleven (11) meters above sea level.

The climate of the Nuwejaars river catchment is classified as Mediterranean characterised with hot dry summers and cold wet winters. Annual average rainfall for the catchment ranges between 400 mm a^{-1} to 500 mm a^{-1}. Annual evaporation is about 1445 mm a^{-1} (Middleton and Bailey, 2008), with a mean annual temperature for the catchment of 17^{θ} C, the lowest of which occurs in winter and high temperature in summer.

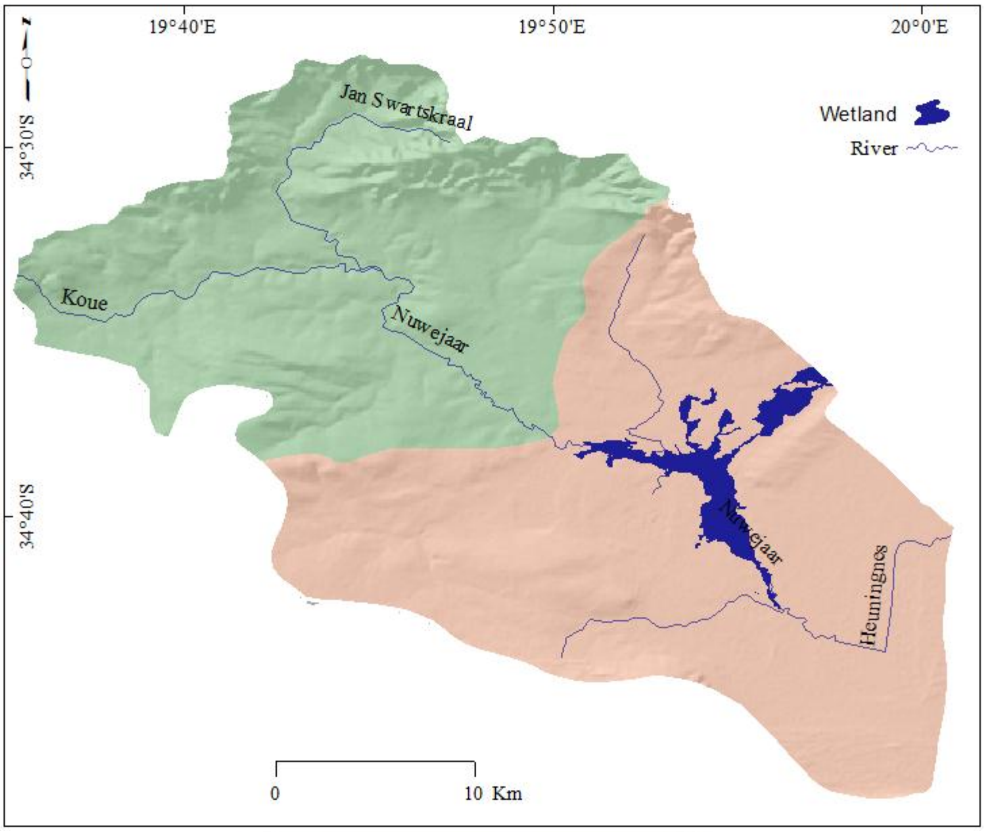


Figure 3.2. The Nuwejaars River catchment showing the location of the Elandsdrift-Wiesdrift floodplain and the rivers of the catchment.

The topography of the Nuwejaars river catchment comprises of a gentle rolling lowland landscape. The upper part of the catchment is mountainous with peaks while the topography of the lower reaches is gentle. The geology of the Nuwejaars river catchment is shown in Figure 3.3. The catchment is characterised with geology of the Table Mountain group, comprising of shale, limestone, granite and sandstones.

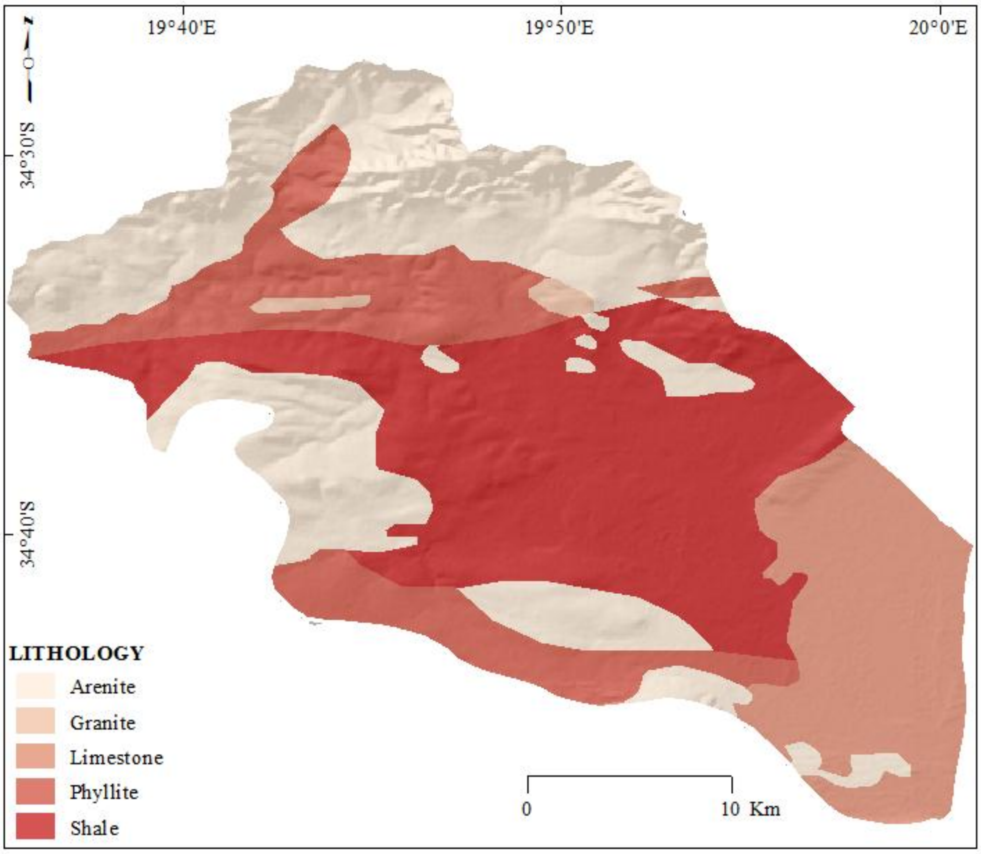


Figure 3.3. The geology of the Nuwejaars catchment.

The catchment area feeding the Nuwejaars river is predominantly cultivated land and shrub land, covering an area of approximately 35% and 40 % respectively (Figure 3.4). Much of farming activities in the catchment is commercial. About 13% of the catchment is covered by water bodies, with a small percentage of less than 10% covered by natural grassland and forest. Settlements make about 2% of the catchment.

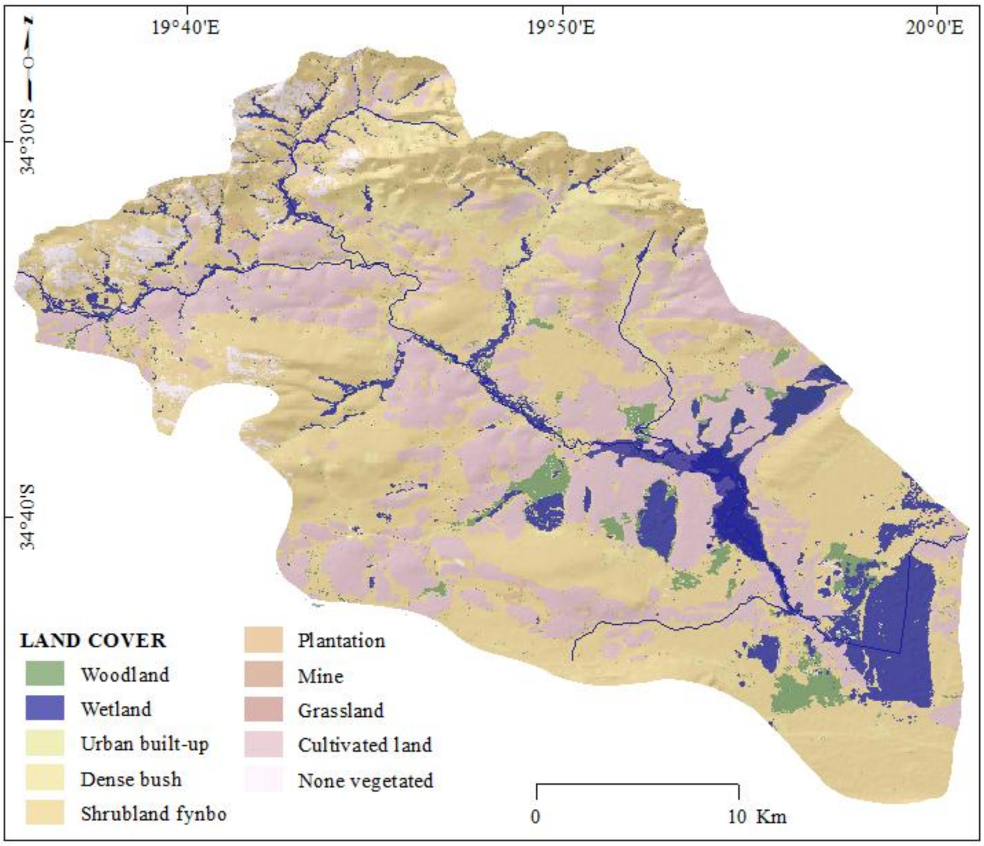


Figure 3.4. Land cover of the Nuwejaars River (National Land Cover, 2013/14).

The Elandsdrift-Wiesdrift floodplain wetland is located just before the Soetendalsvlei, between $19^0$52’ and $19^0$55’ E and $34^0$35’ and $34^0$35’S. This palustrine floodplain covers an area of approximately 6.7 km^2 (Jones *et al.*, 2000), which is the area between Elandsdrift bridge and Wiesdrift bridge. This floodplain lies in the shale debris, with low potential groundwater storage but allows for groundwater movement (Figure 3.2) and has an elevation that ranges from 5 to 20 meters above sea level.

The floodplain and its boundaries is heavily flanked with restiod reeds grass from the *Phragmites mauritianus* group (Figure 3.5), with a small percentage of grassland. The area surrounding the floodplain is characterised by farms (Figure 3.6), which are used for growing pasture for sheep and cattle grazing. Wheat and canola are the main crops that are grown within the farms. Within the floodplain catchment, there are no stream flow-reducing activities (i.e. trees plantation, alien species or dam).

The mean annual precipitation for the local catchment derived from two stations (Moddervlei and Visserdrift) closer to the wetland measured during the study ranged from 467 mm a^{-1} to 558 mm a^{-1} for 2015.

Figure 3.5. Typical restiod reed grass in the Elandsdrift-Wiesdrift floodplain.

Figure 3.6. Google earth image showing land use within the area of the Elandsdrift-Wiesdrift floodplain.

3.1.2 The Mohlapetsi catchment location, topography, geology and land use

The Mohlapetsi river catchment (quaternary catchment B71C) (Figure 3.7) falls within the Olifants basin, covering an area of 263 km^2. The Mohlapetsi river is located in the Lebowa homesteads in the Capricorn District and in the middle part of the Limpopo. The river originates from the Wolkberg mountains and flows until its confluence with the Olifants river (Masiyandima *et al.*, 2004). It is perennial, with peak flows during October to February period and low flows during May to September period. The upper parts of the catchment have an altitude of 2050 meters above sea level, while reaches have an altitude of 760 meters above sea level (Mekiso, 2011).

The uplands area receives an annual precipitation that exceeds 1000 mm a^{-1}and the lower reaches are typically 500-600 mm a^{-1}, giving a mean annual rainfall of 771 mm a^{-1}. Precipitation in the catchment occurs in summer between October and April. Evapotranspiration derived from the Penman-Monteith equation within the catchment is estimated to be 1428 mm a^{-1} (McCartney *et al.*, 2006).

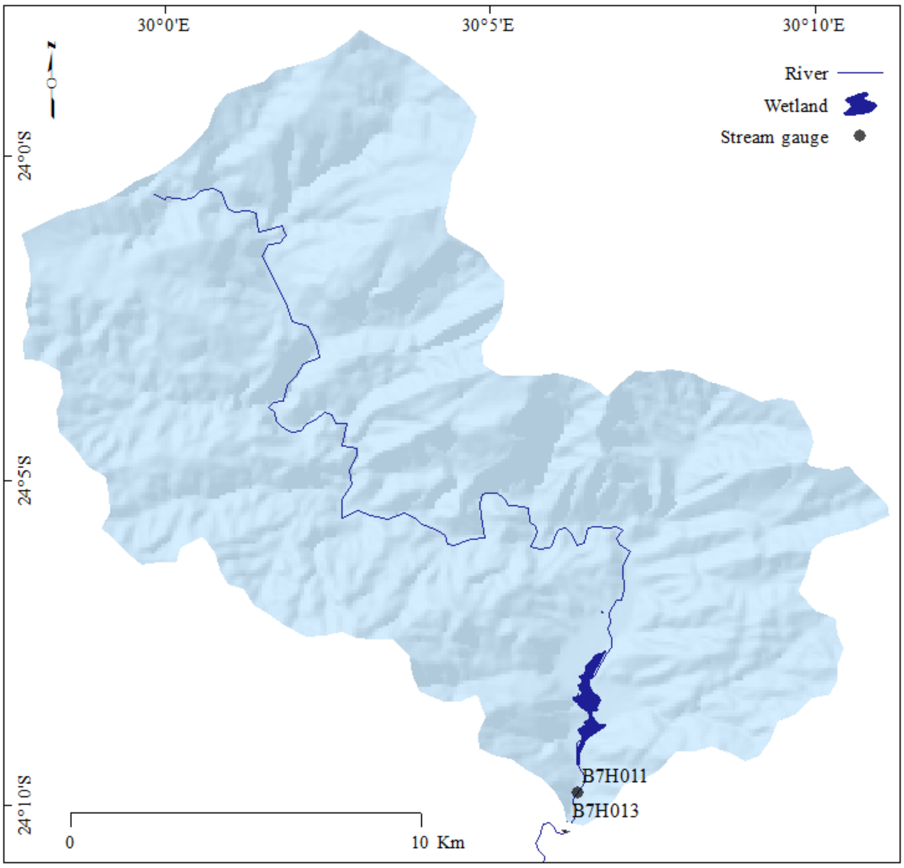


Figure 3.7. The location of the GaMampa wetland and the Mohlapetsi River.

Within the mountains, the catchment is dominated by bushveld forests while cultivated land is evident on the lowland areas (Figure 3.8). The catchment lies on a dolomite with high groundwater storage, quartzite and shale (Figure 3.9).

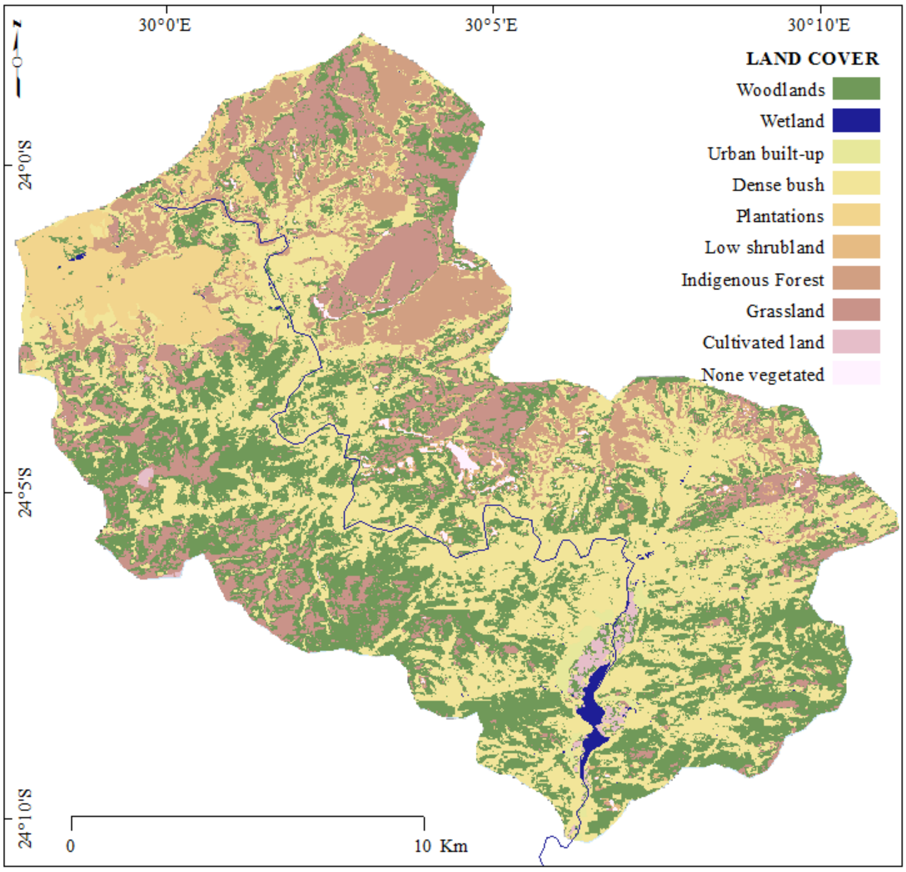


Figure 3.8. The Mohlapetsi river catchment showing the land cover (National Land Cover, 2013/14).

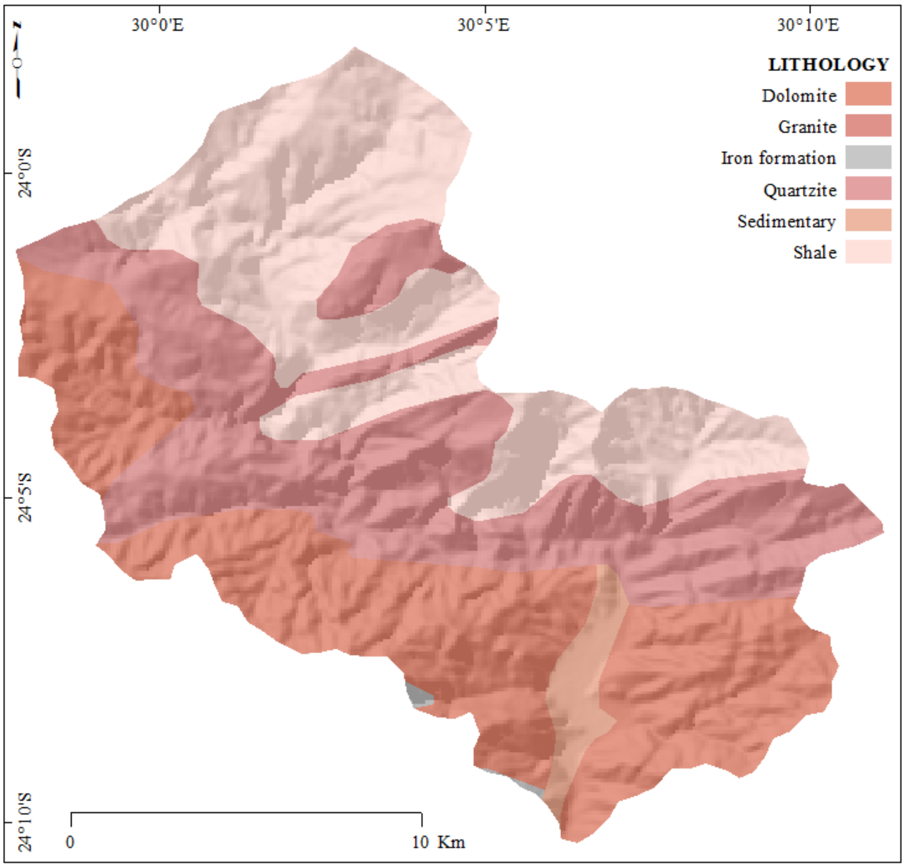


Figure 3.9. The geology of the Mohlapetsi river catchment.

The GaMampa wetland, a permanently inundated valley bottom floodplain occurs downstream of the Mohlapetsi river between coordinates $30^0$0’ and $30^0$10’E and $24^0$0’ and $24^0$10’S. The floodplain is formed in the channelled valley bottom section of the Mohlapetsi river. The floodplain is a palustrine and covers an area of approximately 1 km^2 extending 4 to 5 km on both sides of the river, with the width that ranging from 10 to 100 m (Mai, 2010).

The population of people around the wetland is largely rural communities, with an estimated population of 2580 (McCartney *et al.*, 2010). The wetland provides domestic water use to five villages within the wetland area (McCartney *et al.*, 2010) and is also used for crop production (mainly maize). Within the wetland boundary, reed beds are predominant.

The wetland site is characterized by seasonal rainfall and experiences frequent drought and floods (Mekiso, 2011). Mean annual rainfall in the valley bottom, where the wetland is located, is typically 500-600 mm a^{-1} (Mekiso, 2011).

The wetland is situated on a sedimentary sandstone rock, which allows for groundwater movement through fractures and joints.

3.1.3 The Bonnie Brook river catchment

The Bonnie Brook river catchment (quaternary catchment W54C) (Figure 3.10) is a sub basin in the Usuthu-Inkomati Water Management Area. The river, located in Lothair, north of Ermelo in Mpumalanga, forms part of the upper Usuthu river and covers an area of 107 km^2. It is perennial, with high flows occurring between October and March and low flows between April and September. The river originates in the Ermelo mountains and flows until it confluences with the Usuthu river.

Climate is humid, with seasonal rainfall mostly occurring in summer. The mean annual rainfall for the catchment ranges from 1500 mm a^{-1} within mountainous areas to 600 mm a^{-1} in lowlands. Annual evaporation is about 1400 mm a^{-1} (Middleton and Bailey, 2008), with a mean annual temperature of 22 ^{0} C, the lowest of which occurs in winter and high temperature in summer.

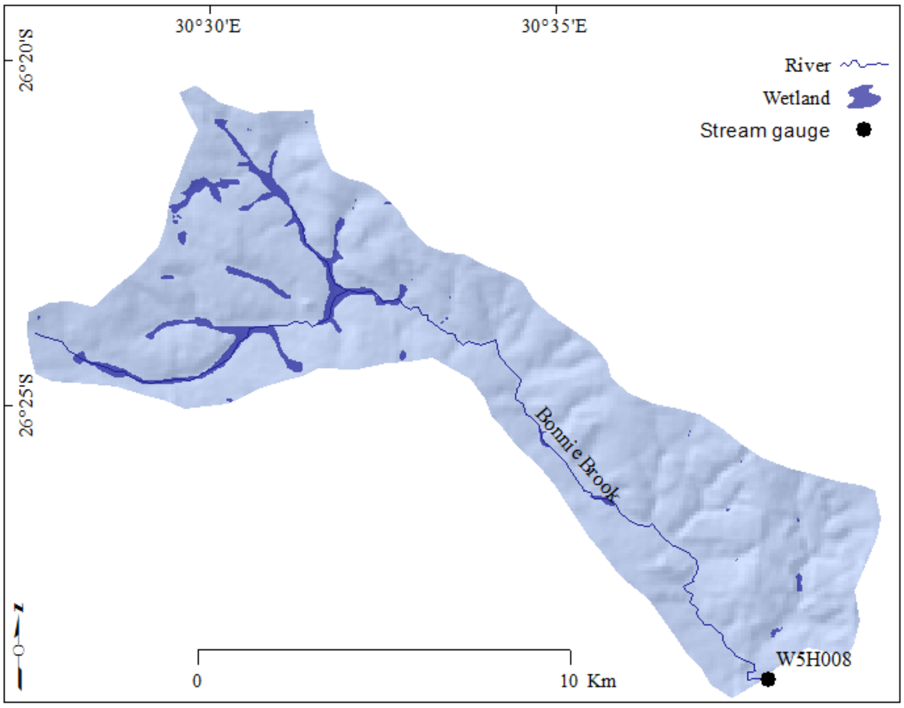


Figure 3.10. The Bonnie Brook river catchment showing the location of the different wetlands, rivers and stream gauge.

Land use (Figure 3.11), is dominated by plantations and forestry, specifically timber (Beuster and Clarke, 2008). Livestock farming of sheep, cattle and goat are also important activities in the catchment (Beuster and Clarke, 2008).

The average altitude of the catchment is approximately 1720 meters above sea level, with the geology dominated by quartzite rock which underlies the river (Figure 3.12). The rest of the catchment is characterised by arenite and tillite, which are also sandstone and gabbro.

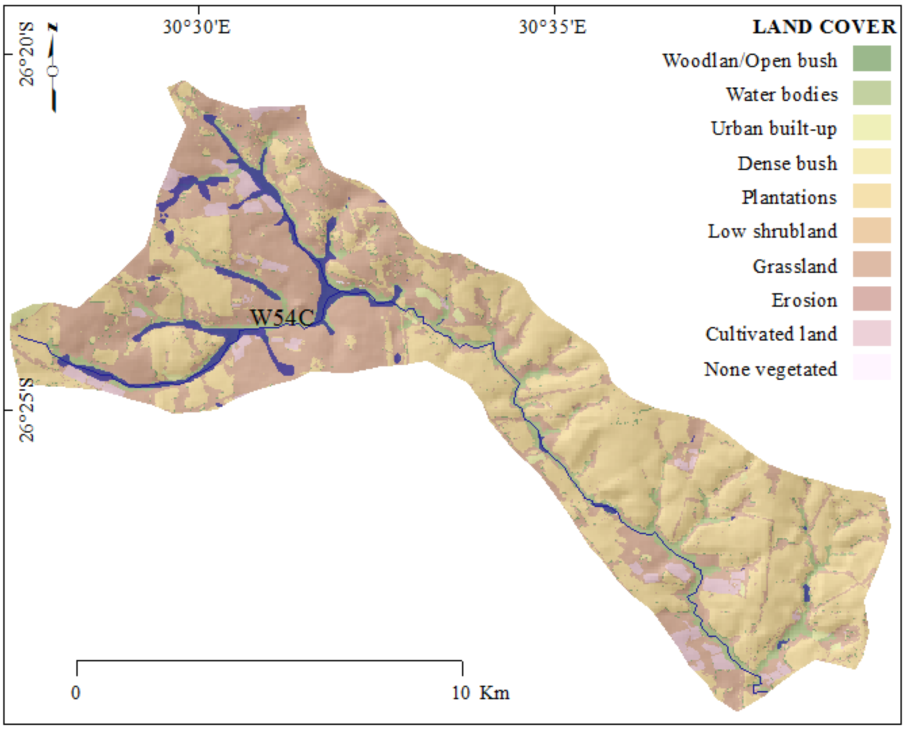


Figure 3.11. Land cover types occurring in Bonnie Brook river catchment.

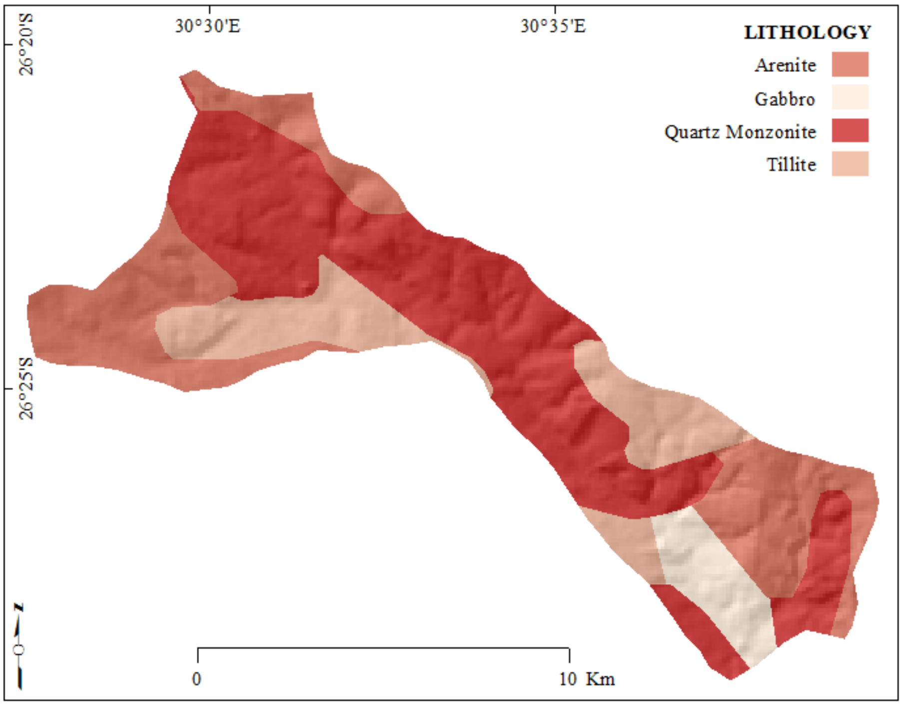


Figure 3.12. The geology of the Bonnie Brook river catchment.

The Bonnie brook wetland occurs upstream of the Bonnie brook river between coordinates $30^0$25’ and $30^0$35’E and $26^0$20’ and $26^0$25’S. The wetland, a floodplain, covers an area of approximately 4.2 km^2. The boundary of the wetland is characterised by grassland with a small percentage of cultivated land. An urban built-up area is in close proximity of the wetlands. The small community around the built up area depends on the farms situated around the wetland.

The wetland lies on a quartzite, which is sandstone and allow for groundwater movement.

3.1.4 The Lions river catchment

The Lion’s river catchment (quaternary catchment U20B) (Figure 3.13) is a sub-basin in the uMgeni Water Management Area. The catchment, located between Lidgeton and Hawick in the uppermost part of the UMgeni river basin, covers an area of 353 km^2. There are two tributaries within the river, the Mpofana river, and the Ndiza river.

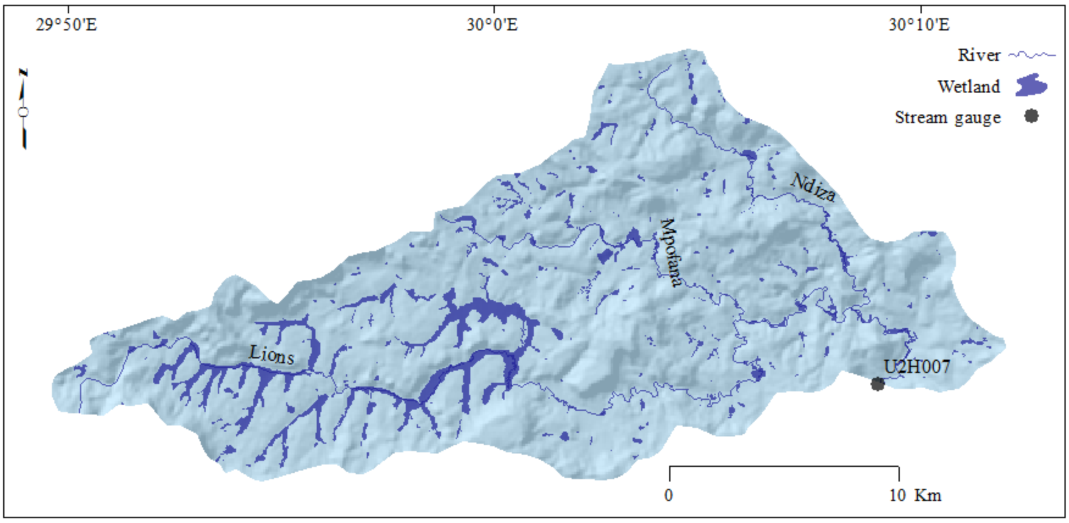


Figure 3.13. The Lion's river catchment showing the rivers, wetlands and location of the flow gauging station.

Rainfall occurs in summer (between October and March) with an annual mean ranging from 870 to 1040 mm a^{-1}. Evaporation in the catchment ranges from 1567 to 1737 mm a^{-1}. Temperature is highly variable in the catchment due to the variability of altitude. In winter, the mean annual temperature is 14ºC while the mean maximum temperature in summer can be as high as 35°C. Crop cultivation and plantations dominate land uses in the catchment (Figure 3.14).

The upper parts of the catchment have an altitude of approximately 1200 meters above sea level, while reaches have an altitude of approximately 560 meters above sea level (Mekiso, 2011). The geology of the catchment is mainly shale, mudstones and dolerite, and mudstones (Figure 3.15). Mudstone has a low permeability and transmissivity. The upstream of the catchment is characterised by dolerite, while the downstream has shale, mudstone and dolerite.

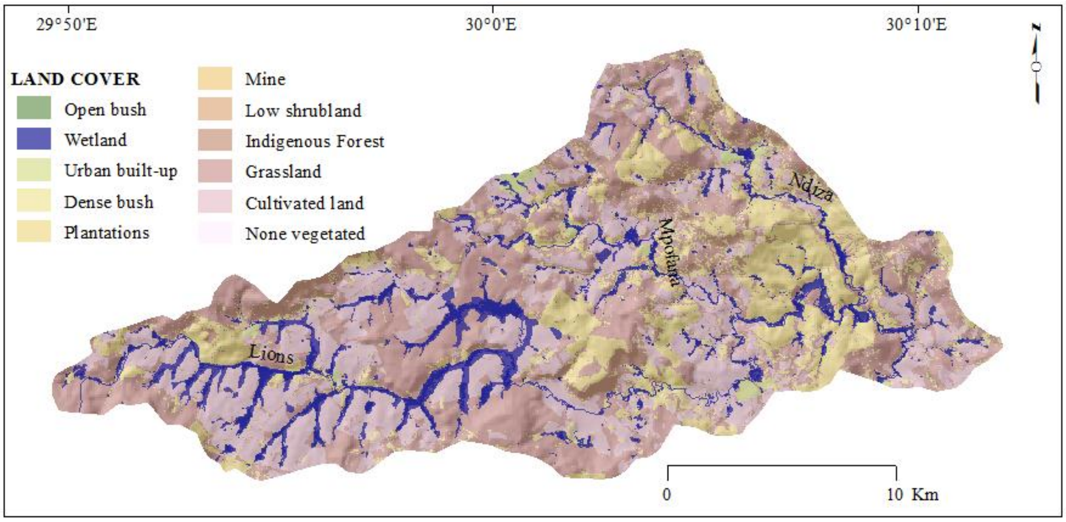


Figure 3.14. Land cover for the Lion's river catchment.

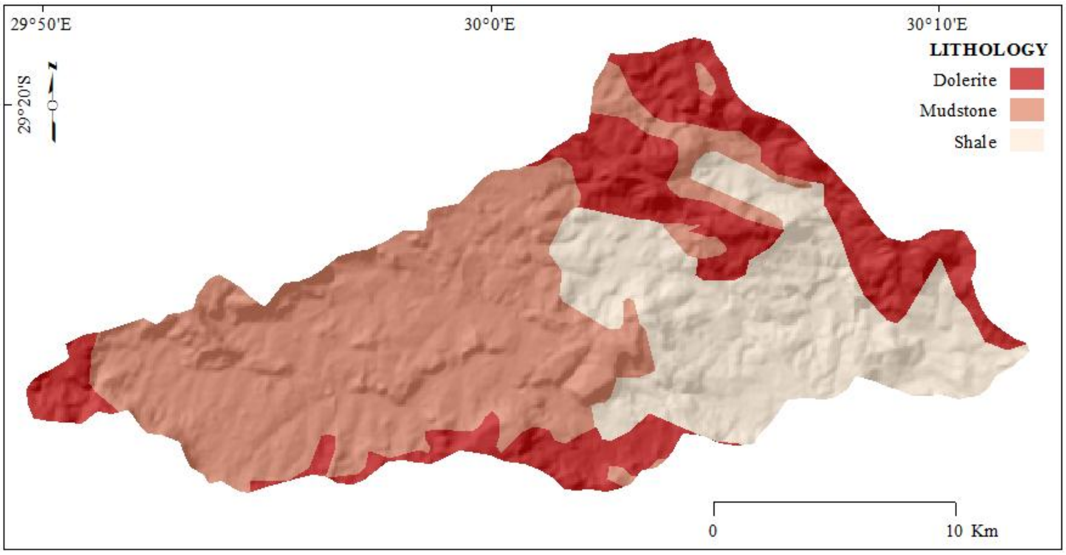


Figure 3.15. The geology of the Lion's river catchment.

Wetlands within the Lions river catchment occur within the riparian areas of the main channel and the two tributaries. The wetlands are floodplains, and cover a total area of approximately 22.5 km^2. The floodplains lie on a shale, mudstone and delorite, with mudstone dominating the geology with low groundwater permeability.

4 MODELLING OF WETLANDS IN SOUTH AFRICA

This section describes the general approach used in the application of the Pitman and ACRU models in the four selected catchments. This includes the description of the general structure of the models and the parameters used by the models. The wetland modules of both models, which include approaches and relationships that are used to represent wetlands processes in the models, are also presented.

4.1 HYDROLOGICAL MODELLING

It has been more than four decades since the beginning of hydrological modelling of basin hydrology in South Africa (Hughes, 2004). Since then, the number of hydrological models used to quantify hydrological processes has substantially increased. Thus, more work is recently focused on improving existing hydrological models currently used rather than developing new ones (Hughes *et al.*, 2006). The number of studies focused on validating the effectiveness of model structure applied in Southern African conditions has substantially increased (Ndiritu, 2009; Tanner; and Hughes, 2013). However, Hughes, (2004c) highlighted the challenges of incorporating and improving new sub-components. Hydrological modelling involves conceptualising the understating of hydrological processes and their interaction and developing mathematical models. As a result of the fact that variables, parameters and processes assumed in catchments are based on physical characteristics of basin. The Pitman and ACRU models have been developed within the Southern African region to cater for semi-arid hydrological processes. The models have been used as basis for water resources management within the region, (Pitman (surface water resources of south Africa in 1990 (Midgley *et al*., 1994) in 2005 (Middleton and Bailey, 2008) and in 2012 (Bailey, 2012)), and ACRU n 2004 (Schulze and Pike, 2004)). Therefore the two models were used in this study.

4.2 THE PITMAN MODEL

The Pitman model is a monthly time step, conceptual hydrological model. The model consist of storages (interception, soil moisture and groundwater) linked by functions representing the dominant hydrological processes within a basin (Hughes *et al.*, 2006). The model was developed in 1973 by W.V. Pitman with various versions and upgrades such as WRSM90, WRSM2000, and SPATSIM (Pitman, 1973; Middleton and Bailey, 2009; Hughes *et al.*, 2006). The core design and equations are still the same. Figure 4.1 is a flow diagram of the Pitman model. SPATSIM is an integrated data management and modelling software package developed at the Institute for Water Research (IWR), Rhodes University (Hughes *et al.*, 2002). The SPATSIM-version is a semi-distributed implementation of the Pitman model, with each sub-basin modelled with independent input data and parameters (Hughes *et al.*, 2006).

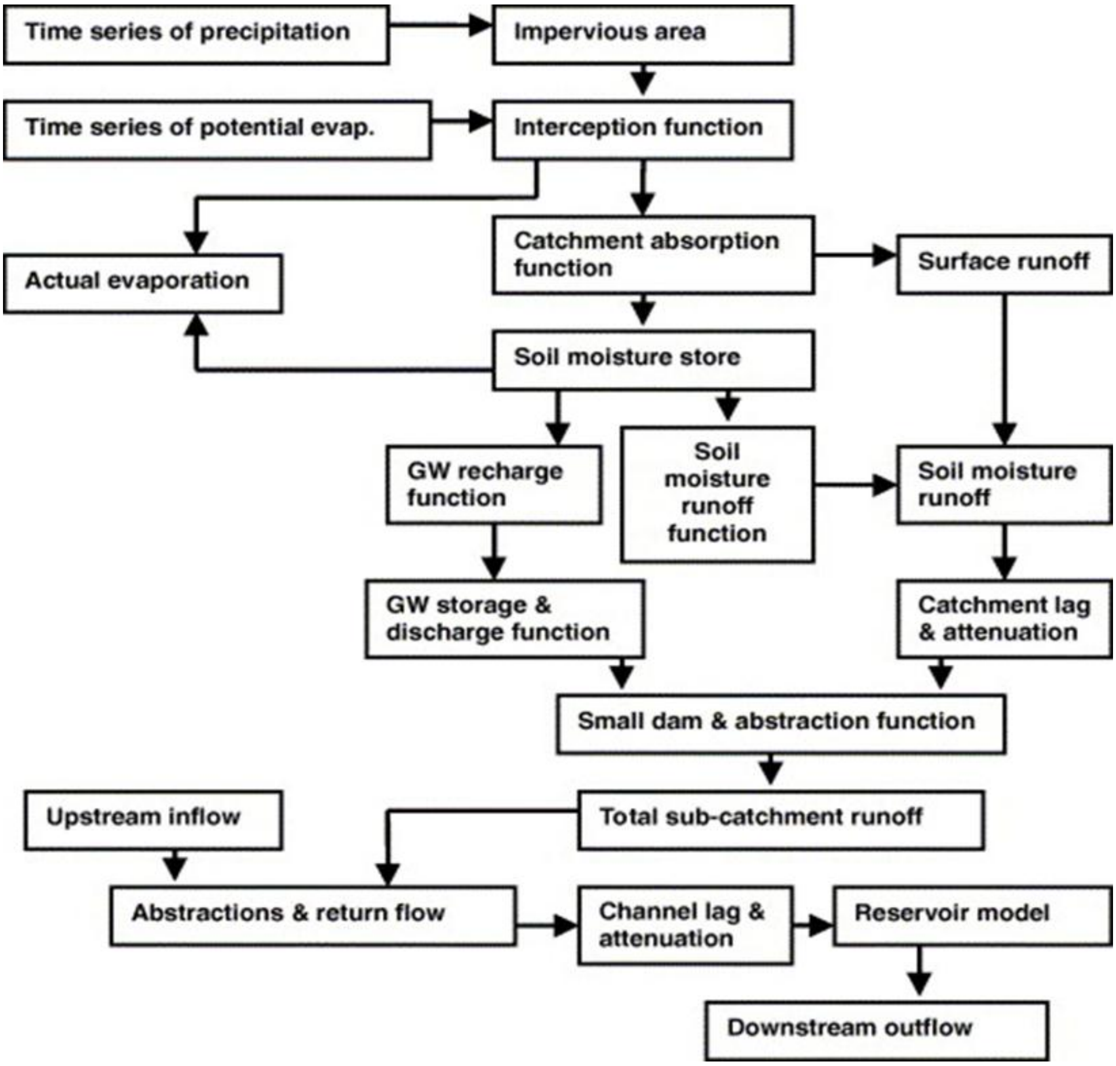


Figure 4.1. Flow diagram of the main components of the Pitman model (Hughes *et al.*, 2006).

The Pitman model explicitly accounts for interception, soil moisture and groundwater storages. While parameterisation has been based on calibration, recent developments are that the parameters can be estimated using basin physical characteristics based on relationships between physical hydrological processes and the parameters (Kapangaziwiri and Hughes, 2008; Kapangaziwiri *et al.*, 2012). To simulate hydrological processes, the Pitman model requires catchment area, catchment rainfall, and monthly potential evaporation. Optional input data include abstractions and irrigation water use. Processes simulated by the model include stream flow, channel losses, soil moisture storages and other catchment hydrological processes.

The model is used as a basis for water resources assessment in South Africa (Midgley *et al.*, 1994). Recently, a wetland module that assumes a water balance approach to simulate wetland processes was added to the model where a dummy dam was assumed whenever wetlands were encountered (Mwelwa, 2004). The parameters of the model are briefly explained in Table 4.1. The following paragraphs explain the main processes (and their parameters) simulated by the Pitman model.

Table 4.1. A list of the parameters of the Pitman model including those of the reservoir water balance model (Hughes *et al.*, 2006).

Parameter	Unit	Parameter description
RDF	-	Controls the distribution of total monthly rainfall over four model iterations
AI	Fraction	Impervious fraction of sub-basin
PI1 and PI2	Mm	Interception storage for two vegetation types
AFOR	%	% area of sub-basin under vegetation type 2
FF	-	Ratio of potential evaporation rate for Veg2 relative to Veg1
PEVAP	Mm	Annual sub-basin evaporation
ZMIN	mm month^{-1}	Minimum sub-basin absorption rate
ZAVE	mm month^{-1}	Mean sub-basin absorption rate
ZMAX	mm month^{-1}	Maximum sub-basin absorption rate
ST	Mm	Maximum moisture storage capacity
SL	Mm	Minimum moisture storage below which no GW recharge occurs
POW	-	Power of the moisture storage- runoff equation
FT	mm month^{-1}	Runoff from moisture storage at full capacity (ST)
GPOW	-	Power of the moisture storage-GW recharge equation
GW	mm month^{-1}	Maximum ground water recharge at full capacity, ST
R	-	Evaporation-moisture storage relationship parameter
TL	Months	Lag of surface and soil moisture runoff
CL	Months	Channel routing coefficient
DDENS	-	Drainage density
T	m^2 d^{-1}	Ground water transmissivity
S	-	Ground water storativity
GWSlope	%	Initial ground water gradient
AIRR	km^2	Irrigation area
IWR	Fraction	Irrigation water return flow fraction
EffRf	Fraction	Effective rainfall fraction
NIrrDm	Ml yr^{-1}	Non-irrigation demand from the river
MAXDAM	Ml	Small dam storage capacity
DAREA	%	Percentage of sub-basin above dams
A, B	-	Parameters in non-linear dam area-volume relationship

Parameter	Unit	Parameter description
IrrAreaDmd	km^2	Irrigation area from small dams
CAP	Mm^3	Reservoir capacity
DEAD	%	Dead storage
INIT	%	Initial storage
A, B	-	Parameters in non-linear dam area-volume relationship
RES 1–5	%	Reserve supply levels (percentage of full capacity)
ABS	Mm^3	Annual abstraction volume
COMP	Mm^3	Annual compensation flow volume

4.2.1 Interception

The amount of rainfall intercepted by vegetation canopy is accounted for in the Pitman model through parameter PI which represents the interception storage with a seasonal variation. Interception is included in the Pitman model using the following relationship:

$$I = X^{*}(1 - e^{yP}) \qquad \text{Equation 4.1}$$

Where: I is the total interception loss per months [], P is the total monthly precipitation [], x and y are the constants.

Parameter PI1 and PI2 represent two different vegetation types in a basin while parameter AFOR represents the size of the basin which is covered by vegetation types and FF has been introduced to the model to account for evaporation of the dominant vegetation types.

4.2.2 Catchment absorption (infiltration)

The infiltration capacity is the amount of water absorbed by the soil surfaces in response to rainfall. This process depends mainly on the soil and vegetation type (Kapangaziwiri and Hughes, 2008). The Pitman model takes into account of the catchment absorption rate of rainfall that is partitioned in to infiltration and surface runoff through parameters AI, ZMIN, ZAVE and ZMAX. The parameter AI represents the proportion of a sub-basin which is impermeable, while the parameters ZMIN, ZAVE and ZMAX represent the absorption rates of a catchment which is represented by a triangular distribution. Rain falling at low intensities (less than ZMIN) allows for all the water to be absorbed thus low generation of runoff while high intensity rainfall (greater than ZMAX) results in all the water contributing to runoff generation.

4.2.3 Soil moisture accounting and runoff generation

Soil moisture refers to the proportion of water held by the soil particles. In the Pitman model, soil moisture is accounted for by parameters ST, FT, POW and GW. ST is the maximum soil moisture storage of the soil (i.e. soil is saturated). Water within soil moisture store is lost through evaporation, lateral movement contributing to runoff and recharge to groundwater (Kapangaziwiri and Hughes, 2008). FT represents the runoff rate at maximum soil moisture storage (i.e. at ST). The relationship between moisture storage and interflow in a catchment is described by parameter POW, which is the power of the moisture storage–runoff equation. An increase in POW will result in an increase in runoff generation. Groundwater is recharged through losses from the soil moisture storage through percolation. The parameter GW refers to the maximum amount of groundwater recharge at maximum soil moisture storage (ST).These parameters are controlled by two non-linear equations:

$$SQ = \mathrm{FT} * (S/ST)^{pow} \qquad \text{Equation 4.2}$$

$$SQ = \mathrm{GW} * (S - SL/ST)^{Gpow} \qquad \text{Equation 4.3}$$

Where: ST is maximum soil moisture storage (mm), S is current soil moisture storage (mm), SL is soil moisture storage (mm) below which recharge equals = 0, FT is runoff at maximum storage (mm), and GW is maximum recharge (mm) at S= ST. POW and GPOW are the powers of the relationships.

The generation of runoff through soil moisture is usually delayed or lagged (TL with the default value of 0.25 months), depending on the basin characteristics. Higher TL values imply greater delays of movement of runoff from upstream to basin outlet.

4.2.4 Parameters used to represent man-made or non-natural modifications

The model accounts for man-made modification to the hydrological regime of a basin. This includes abstractions, reservoirs, irrigation demand and return flow from irrigation. Parameter MAXDAM represents the storage capacity of small farm dams, while parameters A and B represent the parameters of the non-linear dam surface area-volume relationship. Irrigation demand parameters are AIRR and IrrAreaDmd.

4.2.5 Representation of wetlands processes in SPATSIM

Prior to the addition of the wetland module in the Pitman model, changes in parameters were used to compensate for wetland (Mwelwa, 2004). This led to simulation of hydrological processes well yet using variables/parameters which were not realistic and had little meaning. In the Kafue river basin of Zambia, the wetlands were represented by a dummy reservoir (Mwelwa, 2004). However, the results did not represent the real processes even though the approach produced good results. Thus, the wetland module was added to account for the downstream impact of wetlands and natural lakes systems (Tshimanga, 2012). The wetland module in SPATSIM is based on a simple water balance approach with water draining into and out of the wetland (Hughes *et al.*, 2013). Table 4.2 presents the wetland parameters that are used in SPATSIM.

Table 4.2. The parameters and algorithms used for the wetlands sub-model in the SPATSIM Pitman model. (-) denotes that parameter is dimensionless (Hughes *et al.*, 2013).

Parameter and Units	Description and use
MaxWA (km^2)	Maximum wetland area, permanently or temporarily flooded, accounts for local runoff entering directly in to the wetland.
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 at the start of the simulation.
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 MaxWA) and volume, respectively.
AVP	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 (-)	Channel spill factor in SPILL= QSF * (Q–QCAP), where Q is the upstream flow, and SPILL is the volume added to wetland storage. That is the proportion of flow above the channel that is assumed to spill to the wetland.
RFC (-)	Return flow constant in the following relationship: $RFF = RFC * (WV / RWV)^{RFP}$ where RFF is a Return Flow Factor that determines the amount of water that returns from the wetland to the river channel and contributes to downstream. A maximum fraction is assumed to be 0.95
RFP (-)	Return flow power in the $RFF = RFC * (WV / RWV)^{RFP}$ (wetland storage-return flow relationship) designed to account for non-linear relationships.
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).

The wetland module has been designed to work over four time steps within a month just like the main model does. This was done to avoid excessively large changes in any single component of the wetland water balance before other components are updated. A detailed description of the setup of the wetland model is found in Hughes *et al.* (2013) as is summarised here.

- The maximum area of the wetland (including area inundated periodically or permanently) is given by MaxWA. The surface areas of the wetlands are estimated using the area-volume relationship:

$$WA=AVC * WV^{AVP} \qquad \text{Equation 4.4}$$

Where: WA = Wetland Surface Area [m^2], WV = wetland volume [m^3], AVC and AVP are the constant and power in the area-volume relationship.

- Local runoff is added to the part of maximum wetland area (MaxWA) that is not inundated. The volume of rainfall is assumed to be added on the basis of the rainfall depth falling on the inundated area of the wetland (WA).
- Water is added to the wetland through:
  - Direct precipitation falling onto the wetland;
  - Surface runoff from the contributing catchment area; and
  - Surface water inflow from stream, calculated as a proportion of the total upstream channel. The inflow from the channel is calculated as a fixed proportion (QSF) of the total upstream flow.
- Water in the wetlands is lost through:
  - Potential evapotranspiration. Evapotranspiration losses from wetlands are calculated using an annual potential evaporation (PEVAP) distributed in 12 months values and the current submerged wetland area (WA).
  - Return flow from the wetlands to the stream- determines the amount of water that returns from the wetland to the river channel and contributes to downstream.The size of the flow is determined by a power function between a return flow fraction (RFF, with maximum value of 0.95) and the ratio of the current storage of the wetland (WV) to the residual (RWV), where RWV is the volume below which water is unable to flow back to the channel.
  - Abstractions from the wetland used for irrigation, domestic use and other uses. Artificial abstractions from the wetlands are calculated from an annual value,

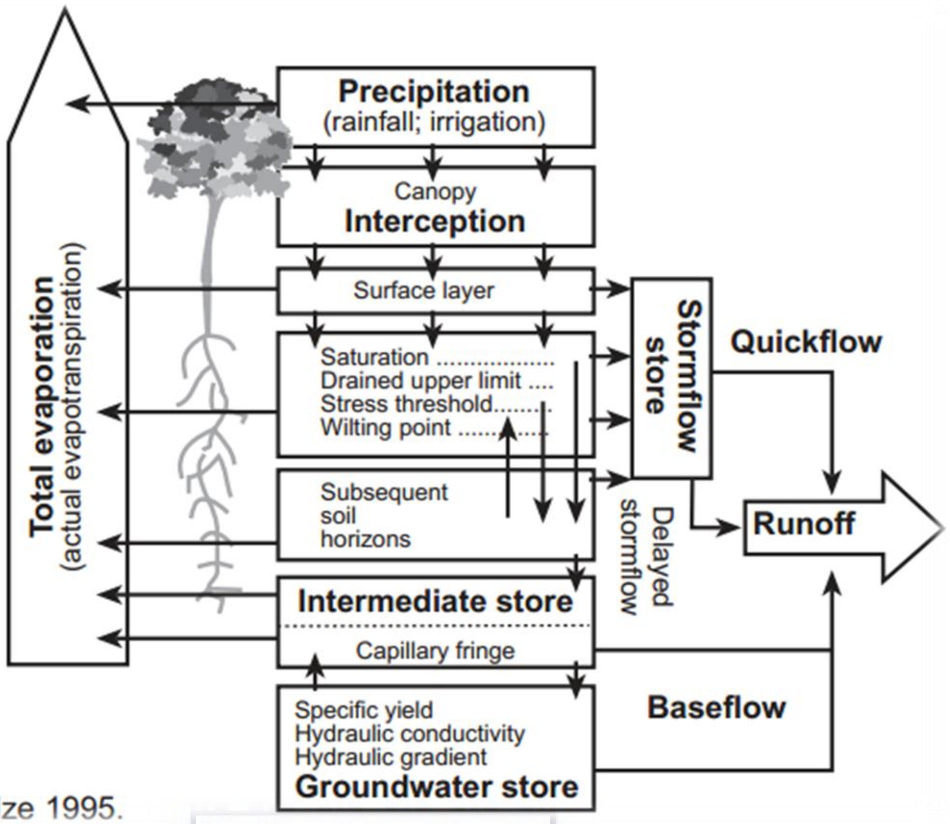
(ABS), which is distributed into twelve month values based on knowledge of abstraction patterns.

It is prudent to note that this simplified water balance approach ignores any interactions between the wetland and the groundwater component of the natural hydrology of the catchment, which in some areas could be very important and could control the wetland's hydrology. The Pitman wetland module has been successfully applied by Tshimanga (2012) in Bangweulu wetland in Zambia, the Kamalondo depression wetland in Congo River basin and Lake Tanganyika. For the Bangweulu wetland, the model was able to reproduce high flows, low flows, early seasons and recession with reasonable efficiency with coefficient of efficiency (CE) and coefficient of determination (R^2) values of 0.79 and 0.8 respectively. Hughes *et al.* (2013) report on work using the SPATSIM wetland module in the Kafue River basin, Congo River and the Okavango basin where it was applied to three sites - the linear valley bottom type of wetlands of the Okavango River, steep valley and flat floodplains of the Kafue River and the natural lakes of the Congo River.

The Maximum area of the wetland (MaxWA) can be estimated using topographic data. The residual volume of the wetlands and the empirical parameters of the non-linear relationship (AVP and AVC) can be estimated from measurable properties of the wetlands.

4.3 THE AGRICULTURAL CATCHMENTS RESEARCH UNIT (ACRU) MODEL

ACRU is an agro-hydrological model, physically-based and conceptual type designed to work on a daily time step. The model was designed to be applied to design hydrology, crop yield modelling, reservoir yield simulation, irrigation and water demand, climate change and land use and impact management and has been extensively applied in climate and hydrological studies (Kienzle, 1993; Hardcastle, 1995; Smithers *et al.*, 1997 and Warburton *et al.*, 2010). The ACRU model (Figure 4.2) uses physical characteristics of a catchment to estimate variables. It is based on a multi-layer soil water budget approach that integrates the various runoff production and water budgeting components of the surface water hydrological systems to simulate agro-hydrological outputs (Figure 4.2).



Source: Schulze 1995.

Figure 4.2. The Conceptual representation of processes of the ACRU model (Schulze, 1995).

The multi-layer soil water budget assumes that water infiltrates the topsoil, satisfies the moisture storage, and percolates to the subsoil. Groundwater recharge occurs when the maximum soil moisture storage of the subsoil has been reached. A decay function is used to release water stored in the base flow. The parameters used by the model are shown

Table 4.3. Evaporation takes place from intercepted water on the plants and from different soils horizons. The model is driven by daily climate input data (daily rainfall and minimum and maximum daily temperatures) and basin information such as soil type and hydraulic properties, land cover, altitudes (including optional input data such as relative humidity, solar radiation, evaporation and other relevant hydro-meteorological data) to simulate basin hydrological response including impact on this response from changes of land use or land cover and climate (Schulze, 2001b). Key outputs include evapotranspiration, stream flow, soil water deficit, irrigation requirements, and water use by vegetation.

Table 4.3. The parameters used by the ACRU model (Everson *et al*., 2006).

Parameter	Unit	Description
QFRESP	days	Stormflow response fraction for the sub-catchment

Parameter	Unit	Description
DEPAHO	m	Effective depth of the A horizon
DEPBHO	m	Effective depth of the B horizon
DEPINTZ	m	Effective depth of the intermediate zone
ABRESP	Fraction	Fraction of the saturated soil water to be distributed daily from the topsoil into the subsoil when the topsoil is above its drained upper limit
WP1	-	Wilting point of the A horizon
WP2	-	Wilting point of the B horizon.
FC1	-	Field capacity of the A horizon.
FC2	-	Field capacity of the B horizon.
PO1	-	Porosity of the A horizon
PO2	-	Porosity of the B horizon
COIAM	-	Coefficient of abstraction
VEGINT	m	Potential interception
FPAW	Fraction	Plant stress onset
CONST	-	Soil stress function
PSCUCO	%	Percent surface cover
EFRDEP	m	Effective root depth
ROOTA	Fraction	Root fraction for A horizon
ROOTB	Fraction	Root fraction for B horizon
CONOLA	%	Percentage of root colonisation for the A horizon
CONOL	%	Percentage of root colonisation for the B horizon
COFRU	Fraction	Coefficient of base flow

4.3.1 The ACRU wetland module

The wetland module in the ACRU model is based on a lumped approach that uses the mass balance equation (Equation 4.4) which is popular with many other hydrological modelling approaches for wetlands (Maltby and Barker 2009, and Mitsch and Gosselink 2000). The equation is represented as follows:

$$dS_W = P_g + I_S + I_{gw} - E - O_S - O_{gw} \qquad \text{Equation 4.5}$$

Where: d_{SW} = change in storage [mm]; P_g = rainfall [mm]; I_S = surface inflow [mm]; I_{gw} = groundwater inflow [mm], E = total evaporation [mm]; O_S = the surface outflow [mm] and O_{gw} = groundwater outflow [mm].

The wetland module includes inflow hydrograph attenuation, evaporation from open surfaces, transpiration from riparian vegetation, rainfall onto the wetland area, and losses to or gains from underlying aquifers and outflows from these features of wetlands. Gray *et* *al.* (2011) emphasises that the wetland module of the ACRU model was designed to account for water quantity not for water quality. The morphology of the wetlands and associated effects of increases in ponded surface areas are also accounted for. The ACRU simulates a wetland as a basin of its own, with limited boundaries. It considers a wetland area to be the land area which is frequently inundated rather than an open water body. The model also assumes that wetlands are underlain by an impervious layer (no interaction between ground and surface water), and when a large rainfall event occurs, any saturated overland flow exits the wetland catchment the same day. Rainfall will first satisfy the soil moisture storage before it exits the wetland as stream flow. When the channel capacity is exceeded, spills from the channel to the wetland occur. Water in the wetland is lost through total evaporation, stormflow discharge and base flow. The model is focused on a single channel rather than a dendritic network pattern (Helmschrot, 2006), which thus affects its applicability in some areas. The conceptualisation and flow diagram of the wetland sub-model within the ACRU model is illustrated in Figure 4.3 and Figure 4.4.

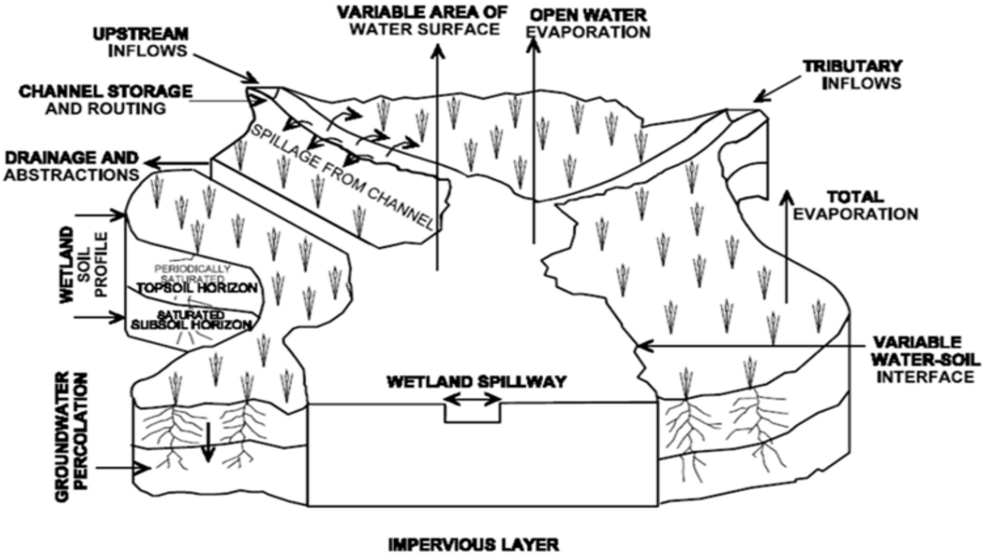


Figure 4.3. Concepts, processes and assumptions of the ACRU wetlands module (Schulze, 1987; Schulze, 2001).

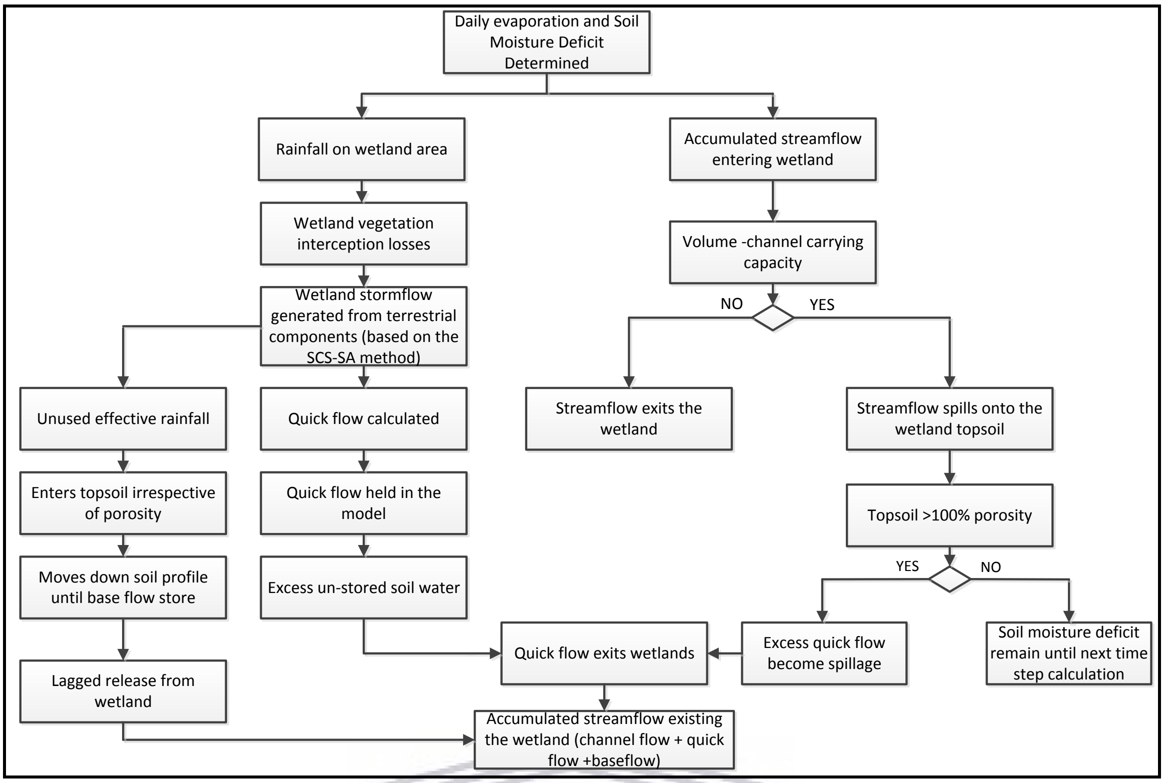


Figure 4.4. A flow diagram of the implementation of the hydrological processes in the ACRU Wetland Routines (Gray, 2011).

The ACRU model wetland module was first applied in Ntabamhlophe wetland in South Africa by Smithers (1991) to assess the hydrological impacts of upstream reservoirs. Gray *et al.* (2011) assessed the impacts of wetlands on hydrological responses within the Thukela catchment. Two types of wetland were assumed for the whole catchment (upland and riparian wetland), and all riparian wetlands of a single sub basin were lumped, while upland wetlands were assumed to feed an area that equals its own area as the ACRU model requires an upland wetland to have a feeder catchment. Results indicated that wetlands impact on flood attenuation and stream flow regulation was relatively small when assessing mean annual stream flows generated from 50 years of a historical climate dataset. Le Roux *et al.* (2011) also used the model to simulate flows of both the Craigieburn and Weatherly catchments.

4.4 SUMMARY

This chapter described the current status of representing the main hydrological processes of wetlands in hydrological models routinely used in South Africa, the Pitman and ACRU models. The models use water balance and mass balance to simulate wetland hydrological processes. Reports indicate that the models have been used in a limited number of localities where data were available, and their general applicability in many different types of wetlands is therefore still not known. This study will apply these models in chosen basins where they have not been used before.

5 METHODOLOGY

This chapter describes the general approach and steps followed to achieve the objectives of the study. The first section describes the general approaches that have been used in the study. The second section describes methods which were followed to understand the hydrological processes of the Elandsdrift-Wiesdrift. The final section describes data and parameters used, and calibration steps for modelling the impacts of wetlands in the four catchments.

5.1 THE GENERAL APPROACHES USED IN THE STUDY

5.1.1 The wetland water balance approach

A simple water balance approach is used to determine inputs and outputs of hydrological fluxes operating at a wetland scale. A water balance of a wetland depends on flow and storage processes within the wetland and the catchment within which the wetland is located in. The main processes that occurs in a wetland include precipitation, flow in surface streams, groundwater flow to and from underlying aquifers, seepage of water through the soil, and evapotranspiration losses. In this study, hydrological processes of the water balance were measured and monitored using hydrometric techniques.

5.1.2 Hydrological modelling

Reference has already been made to the use of hydrological modelling for understanding impact of wetlands on hydrological response. Chapter four has reviewed the approaches used by both the Pitman and ACRU models in representing wetlands processes in more detail. In this study, hydrological models are used to determine the impact of wetlands on streamflow.

5.2 METHODS

5.2.1 Monitoring of hydrological processes

This study was part of a larger Water Research Commission project which aims to determine hydrological processes of the ungauged Heuningnes catchment for water resources management. The first objective of the study was to establish the hydrological processes of the Elandsdrift-Wiesdrift floodplain. In order to establish this, installation of hydrological monitoring network and monitoring of hydrological processes was required. The data collected within the catchment (water levels, rainfall, Temperature, humidity, wind speed, solar radiation and soils) is of reasonable quality. Hydrological data monitored for the study is given below.

5.2.1.1 Meteorological data

The following data were recorded continuously beginning from August 2014 till 2016, using different hydrological instruments:

- Rainfall (mm) – was measured using tipping bucket rain gauges.
- Temperature (°C), humidity (%), wind speed (m/s) and solar radiation (W/m^2) – were measured in two weather stations.
- Water levels (m) – were measured using water automatic data loggers.
- Rain gauges and weather stations were installed at four stations namely Tiersfontein, Spanjaardskloof, Visserdrift, and Moddervlei, while water loggers were installed at two bridges (Elandsdrift and Wiesdrift) (Figure 5.1).

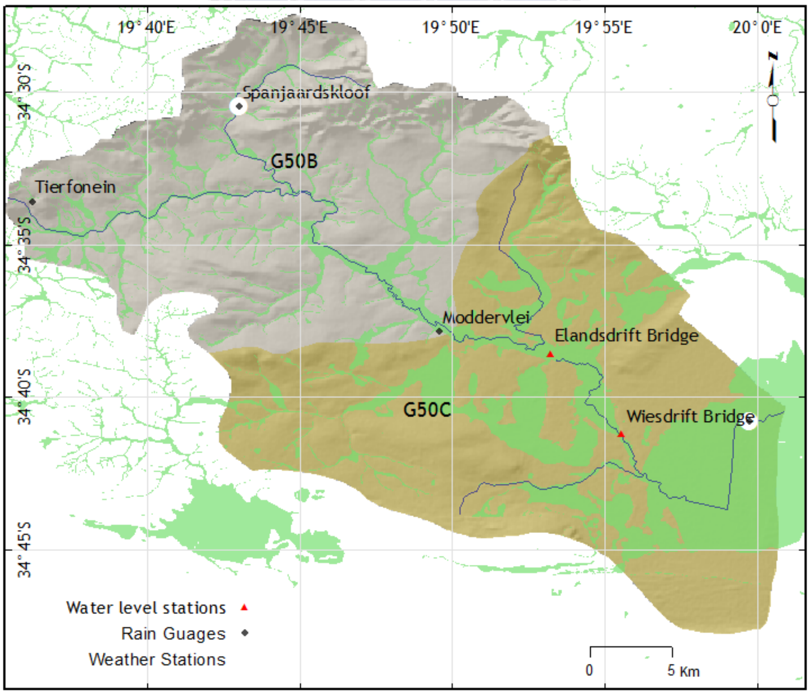


Figure 5.1. Location of the rain gauges, weather stations and river flow gauging stations in the Nuwejaars catchment.

5.2.1.2 Evapotranspiration

The meteorological data (temperature, humidity, wind speed and solar radiation) was used to estimate potential reference evapotranspiration using the Penman-Monteith equation. The Penman-Monteith equation is given below:

$$\leftthreetimes ET = \frac{\triangle\, (Rn - G) + PaCp \frac{es - ea)}{ra}}{\triangle\ + \gamma \left(1 + \frac{rs}{ra}\right)} \qquad \text{Equation 5.1}$$

Where: Rn is the net radiation [], G is the soil heat flux,[], (e_s - e_a) represents the vapour pressure deficit of the air [], c_p is the specific heat of the air [], △ represents the slope of the saturation vapour pressure temperature relationship [], g is the psychrometric constant [], and r_s and r_a are the (bulk) surface and aerodynamic resistances [], 1 is the latent heat, P_a is a unit conversion, r_s is the canopy resistance [], ra is the aerodynamic resistance [].

Development of the rating equation

In the absence of river flow data or gauge in the catchment, water level loggers were installed in the Elandsdrift Bridge to monitor water levels. River flow was also measured with a current meter at the bridge. The Nuwejaars Bridge is made out of two culverts, with a width of 2.52m on the left and 2.62 m on the right. The height of the bridge is 1.56 m. The stage-discharge relationship, which assumes that discharge (Q) passing through a section is directly proportional to the flow depth (H), was used.

The stage data recorded with the data loggers and discharge data measured using a current meter were plotted to develop a rating curve and the rating curve was used to determine the equation for Elandsdrift bridge (equation 5.2). The rating equation was developed to estimate stream flow series of the Nuwejaars River at the Elandsdrift Bridge. Using the measured water levels, the first equation was used to estimate flows which are less than 1.560 meters while the second equation was used to estimate flows that equals or are greater than 1.560m.

$$Q = \begin{cases} 1.256\ \mathrm{H}^{2.961} & \text{if H} < 1.560\text{m} \\ 18.163\mathrm{H} - 23.670 & \text{if H} \geq 1.560\text{m} \end{cases} \qquad \text{Equation 5.2}$$

Where: Q is the discharge [$m^3\ s^{-1}$]; and H is the stage [m] measured by the stage recorder.

5.2.1.3 Surveys

5.2.1.3.1 Soil survey

A detailed soil survey was conducted in the Elandsdrift-Wiesdrift floodplain to determine the physical characteristics of the soil. Soil survey was carried out at the transects given in

Figure 5.2. Soil samples were collected using augers while additional samples were obtained during drilling for piezometer installation. The piezometers were necessary to establish the flow direction of groundwater. Auguring was limited to a meter, while drilling ranged between 5 and 10 meters. Each point was sampled at different depths using stainless steel soil core rings and laboratory samples were analysed at the University of Western Cape for texture, organic content, soil moisture and bulk density.

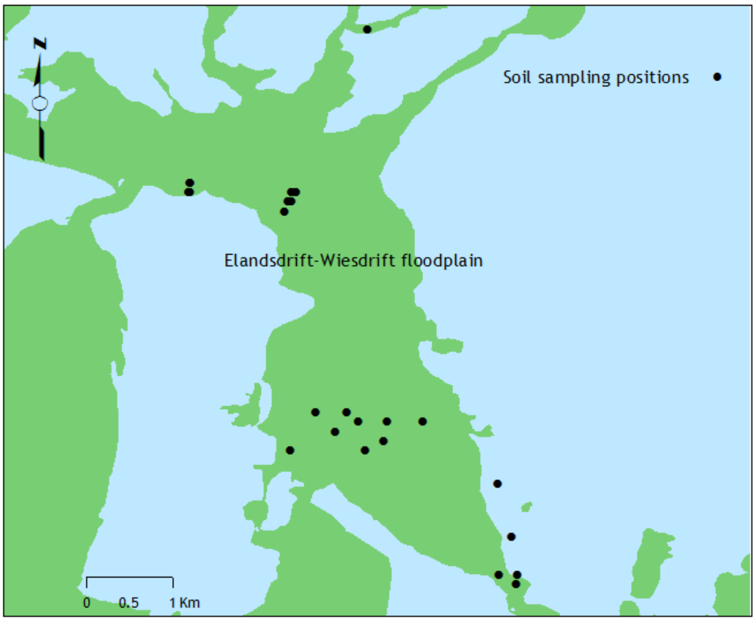


Figure 5.2. Locations within the floodplain wetland at which soils samples were collected and infiltration rates were measured (green represents the wetland and blue represent the area surrounding the wetland).

5.2.1.3.2 Measuring infiltration

Infiltration capacities were measured using an infiltrometer at selected points within the catchment. Hydraulic conductivities were then determined using the van Genguchten tables (Leij *et al.*, 1992).

5.3 HYDROLOGICAL MODELLING

The second objective was to assess the impact of channelled and un-channelled valley bottom, riparian and non-riparian wetlands on the stream flow of the whole sub-basin. The Pitman and ACRU models were configured to represent the wetland processes and assess the potential impacts on stream flow. To simulate the hydrological processes of wetlands in the four catchments, climate, soil, and land cover data are required for both the Pitman and ACRU models to generate hydrologic variables including stream flow. Climate data are required to drive the modelling process while observed runoff data are important for validation of simulated flows.

5.3.1 Rainfall data

Monthly rainfall data used in the Pitman model were obtained from the database of the 2005 water resources assessment (Middleton and Bailey, 2008). The 2012 database of water resources assessment (Bailey, 2012) was only finalised after simulations for the four catchments were made therefore the 2005 database was used for the study. This monthly dataset provides 85 years of rainfall data from October 1920 to September 2004 and the 50 years of average daily rainfall data (1950-1990) used to run the ACRU model (Schulze *et al.*, 2007). The data used are the best estimates available in the country and the quality is acceptable for water resources assessment. Daily rainfall data for the Nuwejaars catchment was measured at 4 rain gauges from August 2014 to December 2015. The modelling period was guided by the length of available rainfall and observed runoff data, and the final modelling periods are given in Table 5.1.

Table 5.1. Modelling periods used for the Pitman and ACRU models in the different catchments based on availability of rainfall and river flow data.

Catchment	**Pitman**	**ACRU**
Nuwejaars river	2015	2015
Mohlapetsi river	1971-2005	1971-1999
Bonnie Brook river	1951-2005	1951-1999
Lions river	1955-2005	1955-1999

5.3.2 Temperature data

The ACRU model uses the Hargreaves and Sanami (1985) approach to determine potential evapotranspiration based on inputs of temperature (maximum and minimum) values (Equation 5.3) in the Mohlapetsi, Bonnie brook and the Lion’s river catchments; which do not have evapotranspiration data.

$$ET_0(HS) = 0.0135.\,kRs.\,Ra\sqrt{(T_{max-}T_{min})\cdot(T_a + 17.8)} \qquad \text{Equation 5.3}$$

Where: ETo is the potential evaporation, HS indicates the estimation is Hargreaves and Sanami, Ra is the extra-terrestrial radiation [mm d^{-1}], 0.0135 is a factor for conversion from American to the International system of units and kRs is the radiation adjustment coefficient. T_{max} is the maximum daily temperature; T_{min} is the minimum temperature; Ta is the mean temperature.

Temperature data for the basins were obtained from Schulze *et al.* (2007) for the period 1950 to 1990.

5.3.3 Evaporation

The Pitman model requires the annual potential evapotranspiration (PEVAP) with average monthly distribution of evapotranspiration, these data was obtained from evapotranspiration data used for the water resources assessment by Middleton and Bailey (2008).

5.3.4 Land cover

Land cover has a significant influence on hydrological response of a catchment, specifically the interception and evapotranspiration processes. The land cover maps, National Land Cover (2013/2014) maps were used to identify the general land cover types within the catchments. The dominant land cover types for the study basins used in the simulations are described in detail in Chapter 3 and given in Figures 3.3, 3.8, 3.11 and 3.14.

5.3.5 Soil

Detailed soil information was obtained through field campaigns for the Elandsdrift-Wiesdrift floodplain. However, this information is only available for the floodplain not the entire catchment. Across the floodplain, soils are predominantly medium grained sandy loam soils and according to Middleton and Bailey (2008), the catchment is characterised by sandy loamy soil. Moreover, no such information was available for the Mohlapetsi River, Bonnie Brook and Lions river catchments, therefore soil information provided by Middleton and Bailey (2008) (and for the Mohlapetsi basins by Mekiso (2012)) was used. The ACRU model requires information related to soil texture, soil depth and initial moisture storage for the A and B horizons.

According to Middleton and Bailey (2008), the Mohlapetsi catchment has shallow soils, dominated by loamy sand to sandy loam, while the Bonnie Brook river catchment is characterised by well drained, fertile alluvium loamy sand to sandy loam soils and the Lion's catchment is characterised sandy loam to loamy sands.

5.3.6 Runoff

For the Mohlapetsi, Bonnie Brook and Lions catchments, historical observed daily flow records at the outlet of each were available and were used to guide the simulations. The records are from gauging stations of the Department of Water and Sanitation (DWS) and the data were obtained from their website at https://www.dwa.gov.za/Hydrology/hymain.aspx. For the Nuwejaars catchment, river flow was estimated from water level measurements. The general characteristics of each the gauging stations used are presented in Table 5.2.

Table 5.2. Stream gauges in the four catchments used in this study.

Station No	Catchment	Area (km^2)	Length of record	% of missing
Elandsdrift Bridge	Nuwejaars	421	2014-2016	15
B7H013	Mohlapetsi	263	1970-present	14
B7H011	Mohlapetsi	262	1963-1988	21
W5H008	Bonnie Brook	118	1951-present	3
U2H007	Lions River	358	1971-present	1

5.3.7 Model Calibration

The models were calibrated manually using visual comparison of simulated and measured time series and flow duration curves and their performance assessed quantitatively through use of statistical objective functions which are part of the models. The model evaluation statistics are Nash-Sutcliffe coefficient of efficiency (NSE), percent bias (PBIAS), and the root mean square error (RMSE). NSE expresses the total stream flow trend (water balance), PBIAS expresses the difference between the mean magnitude of simulated and observed stream flow, and RMSE expresses the average magnitude of error in the simulated and observed flow time series.

In the Pitman model, each of the objective function is extended to consider both normal values and natural logarithm-transformed values. The transformation allows a better assessment of the medium to low flows. For consistency, the recommended qualitative description of performance of the models was based on the Moriasi *et al.* (2007, Table 5.3) criteria. For instance, the regression relationship between the simulated and observed flows is deemed unsatisfactory for NSE ≤0.5 and PBIAS ≤ ±25 %. The same principles were extended to the statistics based on natural logarithm (ln)-transformed values.

Table 5.3. Recommended qualitative rating for different model performance statistics (after Moriasi *et al.*, 2007).

Performance rating	NSE	PBIAS
Very good	0.75 < NSE < 1	PBIAS < ±10
Good	0.65 < NSE < 0.75	±10 < PBIAS < ±15
Satisfactory	0.50 < NSE < 0.65	±15 < PBIAS < ±25
Unsatisfactory	NSE < 0.5	PBIAS < ±25

To assess how the model simulate wetland processes, the following was undertaken: (1) setup and calibration of the Pitman model under natural conditions using the uncertainty version without the wetland module; (2) setup and calibration of the Pitman model under natural conditions using the uncertainty version with the wetland module. The ACRU model was only setup once, with the wetland module included.

5.3.7.1 Calibration of the Pitman Model

The initial parameterisation of the model for the simulation of the hydrological processes of wetlands in the four study areas was guided by the water resources assessment database

(Middleton and Bailey, 2008) and the physical properties of the basins. The water resources assessment database (Middleton and Bailey, 2008) has regionalised parameters for all 1947 so called quaternary catchments in South Africa. These regionalised parameters were obtained through parameter mapping guided by hydrological similarities of basins (Midgley *et al.*, 1994). The parameters in Table 5.4 were used for the initial model run. Based on the understanding of runoff generation (the Hortonian overland flow which is based on the relationship between rainfall intensity and infiltration capacity of the ground surface), in basins where runoff generation is dominated by saturation excess flow instead surface runoff parameters Z_{min}, Z_{ave} and Z_{max} were not used. In basins which are not dominated by interflow, parameter (FT) was not used.

Table 5.4. Model parameters obtained from the water resources assessment database (Middleton and Bailey, 2008).

Parameters	Mohlapetsi	Nuwejaars	Bonnie Brook	Lions
Z_{min}	92	20	0	998
Z_{max}	1100	350	800	1000
ST	375	250	300	240
POW	2	2	3	3
FT	30	4	10	30
GW	3	3	3	3
R	0.50	0.50	0.50	0.50
TL	0.25	0.25	0.60	0.40
GPOW	2	3	3	3

N.B. Z_{ave} is the midpoint between Z_{min} and Z_{max}

Table 5.5. Wetland parameters values for the four study sites.

Parameters	Nuwejaars	Mohlapetsi	Bonnie Brook	Lion's
Local Catchment Area (km^2)	6.700	1.000	4.360	22.501
Residual Wetland Storage ($10^6 m^3$)	0.800	0.300	0.400	0.600
Initial storage ($10^6 m^3$)	0.850	0.300	0.400	0.650
A in Area(m2) = A * $Volume(m^3)^B$	0.600	0.250	0.350	0.500
B in Area(m2) = A * $Volume(m^3)^B$	0.650	0.200	0.300	0.550
Channel capacity for spillage ($10^6 m^3$)	0.009	0.001	0.008	0.008
Channel Spill Factor (Fraction)	0.100	0.100	0.100	0.100
AA in (Ret.Flow = $AA*(Vol/RWS)^{BB}$	0.800	0.600	0.700	0.800
BB in (Ret.Flow = $AA*(Vol/RWS)^{BB}$	0.350	0.100	0.200	0.300

Parameters	Nuwejaars	Mohlapetsi	Bonnie Brook	Lion’s
Annual Evaporation (mm)	1440	1450	1300	1300
Annual Abstraction (MCM)	0.000	0.000	0.000	0.000
AA scaling factor	0.000	0.000	0.000	0.000

5.3.7.2 Incorporation of the wetland module in the Pitman model

Wetland parameters for the Pitman model were estimated based on the physical properties of the basins. The maximum area of all the wetlands (MaxWA) was calculated from the wetland coverage (SANBI, 2011). In the absence of data for the direct quantification of the parameters in the GaMampa wetland the volume of the wetland (RWV) was calculated using the maximum soil depth and porosity from the land type data (AGIS, 2007). Parameters of the wetland’s area-capacity relationship (AVP and AVC) and the return flow (RFC and RFP) were estimated based on data taken from small dams of similar size in sub-basins closer to the wetlands. Evapotranspiration demand was obtained from water resources assessment database (Middleton and Bailey, 2008). A similar procedure was used for the wetlands in the Bonnie Brook, the Lions river and the Nuwejaars catchments.

Wetland parameters were then fixed and the parameters of the main model (Table 5.5) were then recalibrated based on the physical characteristics of the basins (Kapangaziwiri and Hughes, 2008; 2009 and Kapangaziwiri, 2012) using the following steps:

- From the initial estimated parameter values, a range of parameters sorted based on maximum and minimum values that are used to control the calibration process was developed (Table 5.6),
- 10 000 ensembles, which is the total number of ensembles of monthly flow by the model were then automatically generated, and one that gave the best fit was chosen for use in the model with the wetland module.

This approach is similar to guided automatic calibration of the Pitman model.

Table 5.6. Range of parameters used for each catchment.

Parameters	Nuwejaars		Mohlapetsi		Bonnie Brook		Lions	
	Min	Max	Min	Max	Min	Max	Min	Max
Z_{min}	10	50	50	150	10	150	998	998
Z_{max}	100	1000	700	1200	100	1000	999	999

Parameters	**Nuwejaars**		**Mohlapetsi**		**Bonnie Brook**		**Lions**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
ST	50	500	100	800	100	500	1000	1000
POW	1	4	2	3.5	0.4	5	100	1000
FT	5	100	10	55	1	50	1	5
GW	1	30	1	10	1	10	1	100
R	0.1	1.0	0.1	0.9	0.1	0.9	0.1	0.9
TL	0.2	0.8	0.2	0.8	0.2	0.9	0.1	0.9
GPOW	1	6	2	5	1	6	1	5

5.3.7.3 Calibration of the ACRU model and delineation of catchments

The four catchments were delineated into hydrological response unit (HRUs) which assumes uniform distribution of soil types, topography, altitude and land use types. The Mohlapetsi catchment was disintegrated in to 2 HRUs, the Elandsdrift-Wiesdrift floodplain into a single HRU (only the catchment area of the floodplain was modelled), the Bonnie brook in to a single HRU and the Lion's river into 3 HRUs. The HRUs were setup such that they contribute to each other in a sequence, with the upstream HRUs contributing to the downstream HRUs. For the Mohlapetsi, Nuwejaars and the Bonnie brook, only one wetland in each catchment was used for the simulation of hydrological impacts of wetlands on flow, while wetlands within the Lion's river were added together to form one wetland in each of the 6 hydrological response units.

The catchments were then populated with meteorological data, soils, land cover and streamflow data described in section 5.3.

Model parameters used for the ACRU were estimated based on the physical characteristics of the soil, land cover and streamflow of each of the basin while additional parameters are default parameters recommended for use in the ACRU model manual where data are not available. The initial sets of parameters are presented by Table 5.7.

Table 5.7. Initial parameters used in the study by the ACRU model.

Parameters	**Nuwejaars**	**Mohlapetsi**	**Bonnie Brook**	**Lion's**
QFRESP	0.0300	0.0200	0.0300	0.0200
COFRU	0.0090	0.0090	0.0090	0.0090
SMDDEP	0	0	0	0

Parameters	Nuwejaars	Mohlapetsi	Bonnie Brook	Lion’s
FOREST	0	0	0	0
FPAW	0	0	0	0
CONST	0.4	0.4	0.4	0.4
EFRDEP	0	0	0	0

The storm flow response fraction (QFRESP) was estimated based on understanding runoff generation mechanisms for the different basins. Default values of the coefficient of base flow response (COFRU) were used as initial values.

Detailed soil information for all the catchments was not available; therefore the intermediate zone parameters (WP1, WP2, PO1, PO2, FC1, FC2, DEPAWO, DEPBHO, ABRESP and BFRESP) were all not used in the study. Thus the soil texture parameter (ITEXT) and soil depth parameter (PEDDER) were used by the model to estimate the hydrological processes within the soil. The effective depth of the soil from which stormflow generation takes place (SMDDED) and the effective root depth (EFRDEP) are assumed to be zero by the model. The vegetation parameters represented in months within the model (COIAM, CAY, VEGINT, PCSUCO, CONOLA and CONOL) were estimated based on physical properties of the basin. These parameters were manually calibrated to get the best fit with observed flows.

6 RESULTS AND DISCUSSION

This chapter presents results of the main hydrological processes of the Elandsdrift-Wiesdrift floodplain and the impact of channelled and un-channelled valley bottom, riparian and non-riparian ponds on sub-basin hydrological responses. The first sub-section present the analysis of hydrological data collected within the floodplain. The hydrological data from the floodplain has been collected to establish the main hydrological processes of the Elandsdrift-Wiesdrift floodplain. The second section describes simulated flow from the four selected catchments. Flows were simulated with both the Pitman and ACRU model to establish the impact of wetland to streamflow.

6.1 HYDROLOGICAL PROCESSES IN THE ELANDSDRIFT-WIESDRIFT FLOODPLAIN

6.1.1 Rainfall

Monthly rainfall measured at four stations in the catchment with the mean annual precipitation for each is shown in Figure 6.1. The mean annual rainfall calculated from the four rainfall stations located within the catchment ranges from 467 mm a^{-1} to 628.6 mm a^{-1} (Figure 6.1). The catchment receives most of its rainfall in winter (from June to September); while summers months (between October and April) are mostly dry and receives lower rainfall (Figure 6.1). The highest rainfall was recorded in June for all the stations while the driest month was February (Figure 6.1).

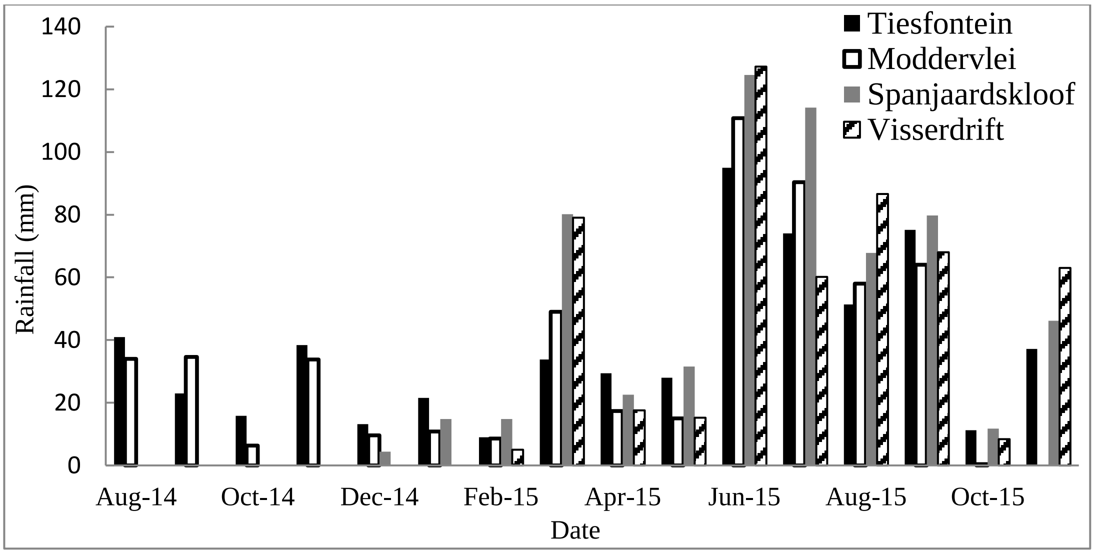


Figure 6.1. Mean Monthly Rainfall for the four gauging stations in the Nuwejaars river catchment.

The correlation co efficient ranged from 0.85 to 0.95 (Figure 6.2), indicating low spatial variability of rainfall in the Nuwejaars river catchment. There were very small differences between the rainfalls measured at the two gauges that are closer to the floodplain (CV = 0.90) (Moddervlei and Visserdrift) suggesting low spatial variability of rainfall inputs over the floodplain area.

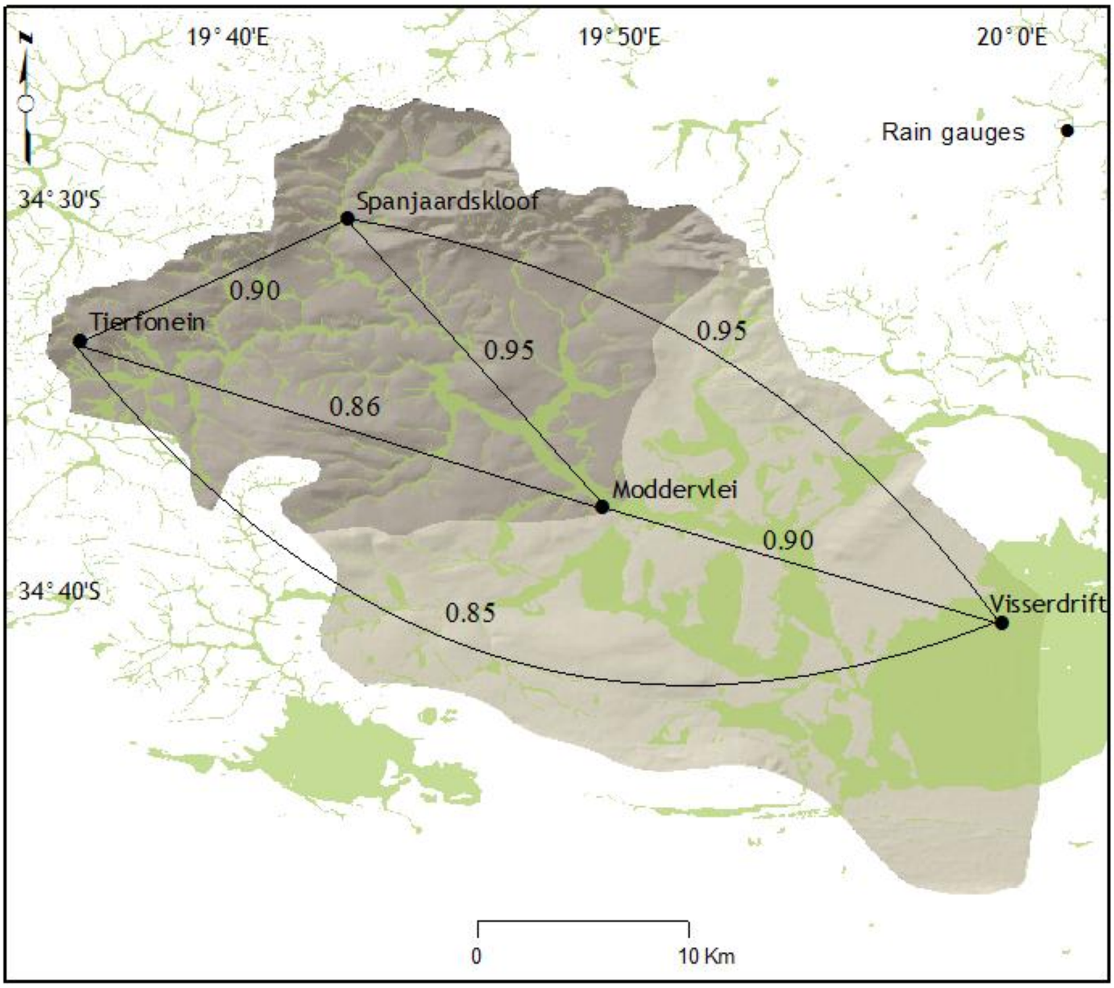


Figure 6.2. A map showing the correlation matrix for the different stations in the catchment.

The arithmetic mean was used to compute average rainfall for the Nuwejaars river catchment. Monthly distribution of catchment average rainfall from January to December 2015 is shown in Table 6.1. The total of mean rainfall for the catchment was 515.6 mm a^{-1}. June recorded the highest rainfall of the catchment with approximately 22% of the total of means, which has caused a significant increase to river flow in the catchment. February was the driest month in the catchment.

Table 6.1. Catchment average monthly rainfall for the Nuwejaars river catchment.

Months	Rainfall (mm)
January	14.25
February	9.35
March	60.50
April	21.75
May	22.45
June	114.40
July	84.70
August	65.95
September	69.10
October	11.30
November	49.60
December	15.85

6.1.2 Water levels and stream flow

The relationship between catchment average daily rainfall and water levels at Elandsdrift is illustrated in Figure 6.3. There are missing data for the period of November 2014 to December 2014 and from March 2015 to the beginning of June 2015. This is because data loggers were removed when there was no flow to avoid damage to the instruments and vandalism.

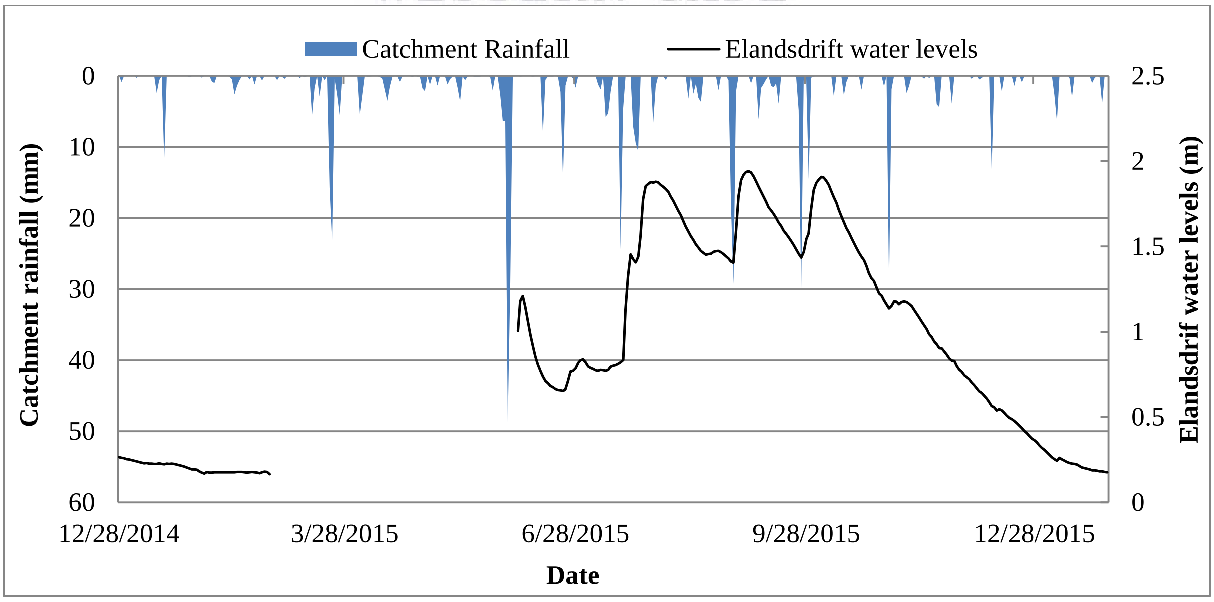


Figure 6.3. Water levels at Elandsdrift compared with catchment rainfall.

Higher water levels in winter and low water levels in summer in response to seasonal rainfall experienced in the catchment are noted (Figure 6.3). Water levels rapidly respond to rainfall. Similar variations in catchment average rainfall and estimated flow (Figure 6.4) are noted. However, it is important to note that flows were measured within a bridge with two culverts that has widths of 2.52m and 2.62m for left and right respectively. These culverts influence the depth hence the flow estimated for the bridge.

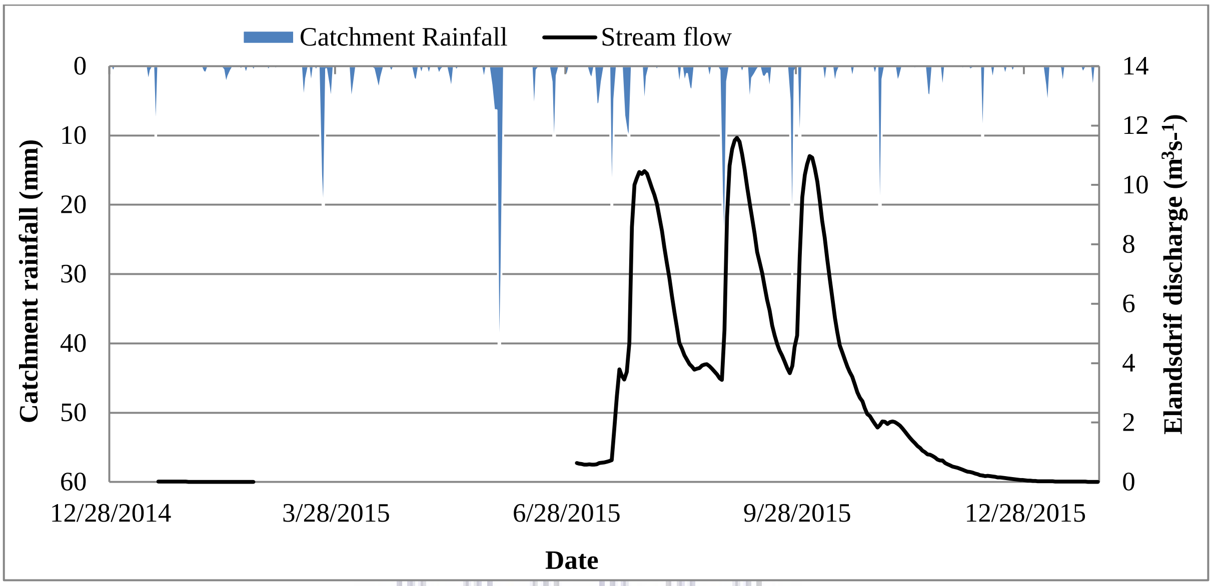


Figure 6.4. Stream flow at Elandsdrift compared with catchment rainfall.

6.1.3 Reference Evapotranspiration

In this study, evapotranspiration is referred to as reference evapotranspiration because it is assumed to be the rate of evapotranspiration from short green grass surfaces. Reference evapotranspiration computed using the Penman - Monteith equation for the two stations is shown in Figure 6.5. Seasonal and spatial variability are noted in the rate of reference evapotranspiration in the catchment. In summer, the rates of evapotranspiration varied from 2 to 6 mm/day in most days, while in winter, reference evapotranspiration rates varied from 1 to 2 mm/day. Reference evapotranspiration is higher in Visserdrift, which is in the lowland of the catchment compared with evapotranspiration in Spanjaardskloof weather station located in the mountainous areas of the catchment (Figure 6.5). Mean annual reference evapotranspiration rate for Vissersdrift and Spanjaardskloof are 1082 mm a^{-1} and 951 mm a^{-1} respectively and the monthly reference evapotranspiration for the catchment is shown in Figure 6.5.

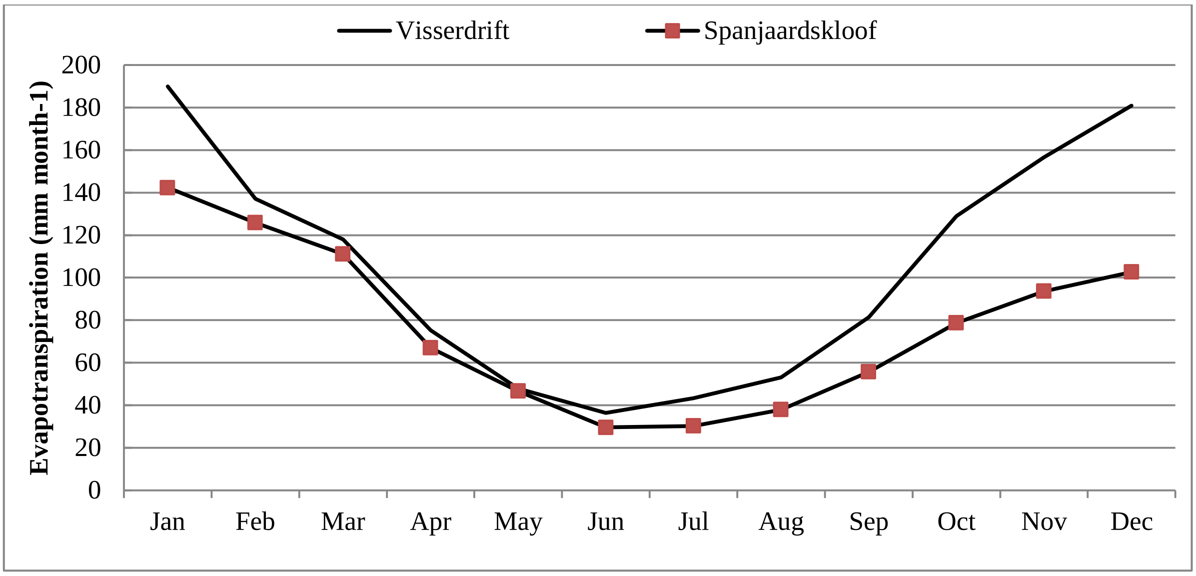


Figure 6.5. Monthly reference evapotranspiration rates measured at Vissersdrift and Spanjaardskloof.

6.1.4 The physical characteristics of the soil of the floodplain

Figure 6.6 summarises the results of soil particle sizes and infiltration rates for all transects within the floodplain (results are also summarised in table 1 and 2 in the appendices). Across the floodplain, soils are predominantly medium grained sandy loam soils.

Near the Elandsdrift Bridge (transect 1), soils exhibits higher sand content (ranging from 59% to 85 %) and the percentages of sand generally decrease in the deeper soils. The percentages of clay content are very low on this transect (ranging from 0.2% to 15%). There is no evidence of ponding along this transect, however infiltration rates measured were low. Soils moisture content was low within the top soil of this transects as the soils are exposed to the atmosphere for evapotranspiration.

The top soil of the second transect has higher sand content (30% to 86%). In conjunction with the first transect, percentages of sand decreases with deeper soils. However, silt also exhibit high content in this transect (with percentages of 22% to 56%), with very low clay content. During auguring, a series of clumps of clay amongst the coarse grained sandy and silts was revealed (Figure 6.7). The clay layer varies in depth and thickness within transect and it acts as a barrier or an aquitard that partially disconnecting flow of surface water to the deeper groundwater. Soil moisture content is very low within the surface, and however increases in deeper soils.

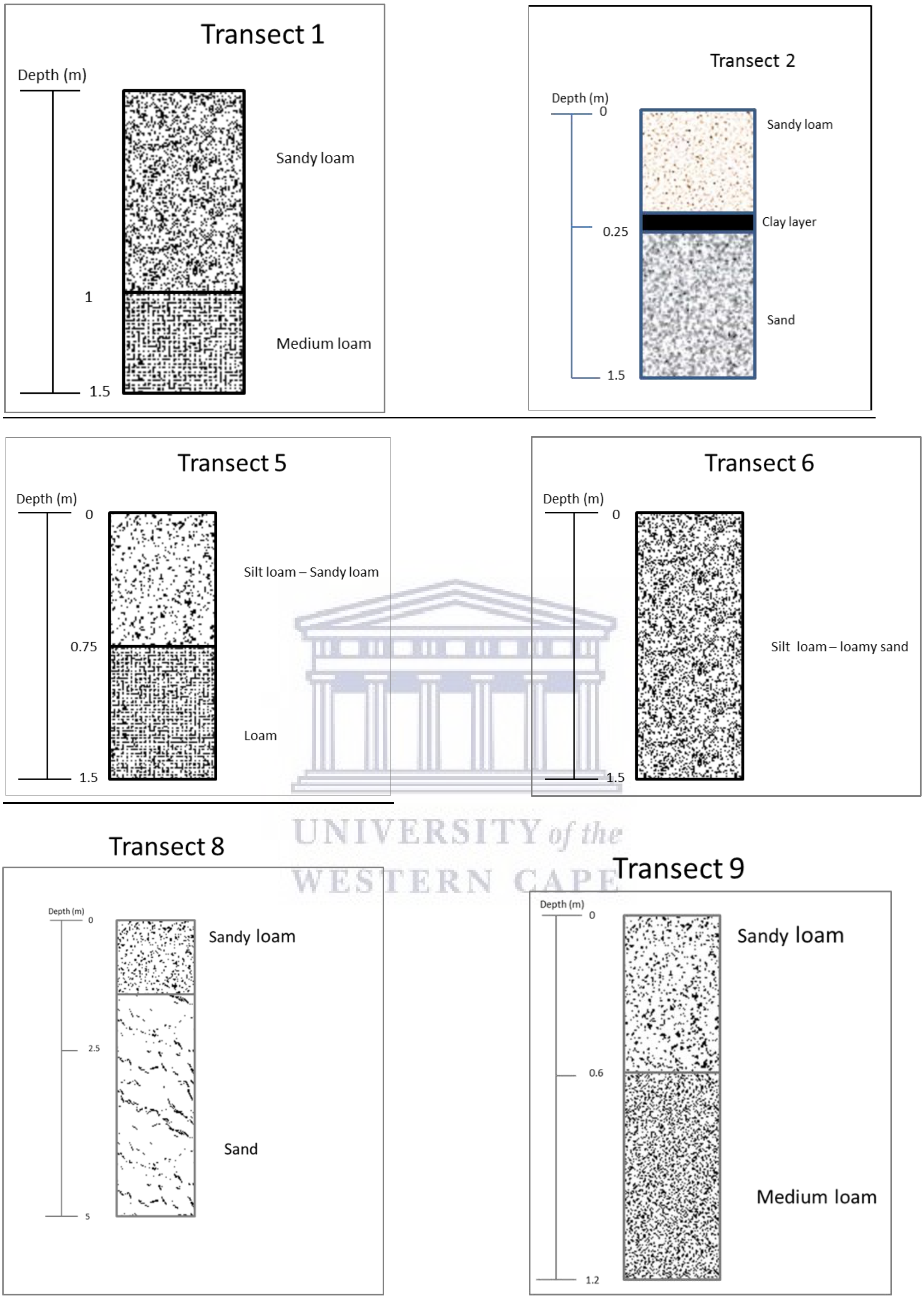


Figure 6.6. Soil profiles for the different transect in the floodplain.

The fifth and sixth transect are dominated by a combination of silt loam to sandy loamy soils. Average percentages of sand within this transect was 42.5%, 46.5% for silt and 13% clay. In contrast to the other transect, percentages of sand generally increases with depth. Soil moisture content is lower within the surfaces and increases with depth.

Figure 6.7. Typical clay plugs found at the second transect during auguring.

Sand dominates soil in the eighth transect, with moderate concentration of silt. In contrast to the other transects, sand generally increases in this transect with deeper soil. Concentrations of clay are generally lower. This soil is well drained as there is no evidence of ponding in the surface. The soil moisture content is also low at the surface and generally increases with depth.

Sand also dominate the ninth transect, with moderate percentages of silt (16% to 41%). Similar to the other transect, the percentages of sand decreases with deeper soil. Pit one of this transect has a lower moisture content at the surface.

Infiltration rates measured in the floodplain were generally low with hydraulic conductivity values that are > 0.005 cm s^{-1} for all transects. Lower infiltration rates within the catchment are a result of loamy soils within the soil surfaces and a clay layer. Clay layer act as an aquitard, which is a semi permeable aquifer that partially separate surface water to groundwater. Loamy soils on the other hand have lower infiltration rates that water that is generated through rainfall events ponds on the surface.

6.2 THE MAIN HYDROLOGICAL PROCESSES OF THE NUWEJAARS FLOODPLAIN

Despite gaps in the role played by groundwater within the floodplain, a number of observations were made. Based on the observations, the following points were made regarding the main processes of the floodplain. Soils play an important role in the formation of riparian and non-riparian ponds within the floodplain. Across the floodplain, soils are predominantly medium grained sandy loam soils with low hydraulic conductivity and infiltration rate values. Lower hydraulic conductivities imply lower infiltration, which in turn causes ponding during rainfall within the floodplain area. Moreover, the fine sediments deposited when the flow losses energy also contributes to ponding.

- Daily stream flow at the Elandsdrift Bridge estimated with the rating equation rapidly responds to catchment rainfall, with correlation coefficient of 0.989. However stream flow observed in days with no rainfall may be generated through the base flow. The mean total rainfall is 515.6 mm a^{-1} and generates an annual average stream flow of 3.046 $m^3 s^{-1}$.
- Flow gradually decreases and eventually reaches zero in response to low daily rainfall at the beginning of the dry season, (October to December). Rainfall occurring within these days is not significant enough to recharge the soil and generate runoff. Low rainfall in the dry season which results in flow decreasing and eventually ceasing shows that flow measured at the Elandsdrift Bridge/ Nuwejaars river is mostly generated through rainfall.
- The mean evapotranspiration for Visserdrift and Spanjaardskloof are 1082 mm a^{-1} and 951 mm a^{-1} respectively, giving a mean annual of 1016 mm a^{-1} for the catchment. The average rainfall for the catchment is 515.6 mm a^{-1}, thus evapotranspiration is higher and represent a net loss of water from the catchment and the floodplain.

Current understanding of the hydrology of Elandsdrift-Wiesdrift floodplain (Figure 6.8) suggests that the floodplain is dominated by precipitation, overland flow from the catchment area of the floodplain, and evapotranspiration. Piezometers were meant for groundwater monitoring to determine the interaction of the floodplain and groundwater. However, the process of cleaning up the piezometers took too long and thus could not be included in this thesis. Therefore the role of groundwater was ignored, thus inflows are through direct precipitation, overland flow from the surrounding catchment and over bank flooding from the stream to the wetland during high flows while outputs are through evapotranspiration, flow from the wetland to the river and infiltration to the ground.

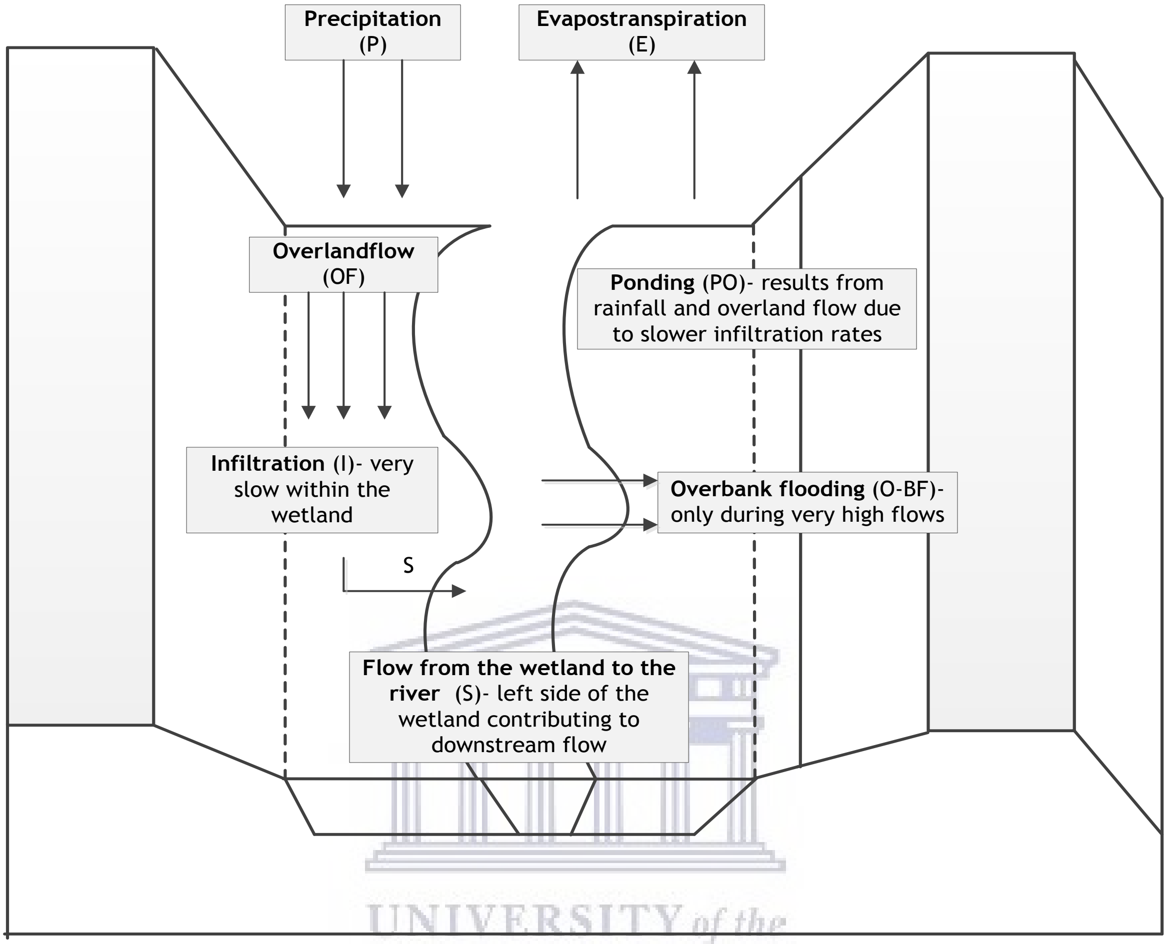


Figure 6.8. Current understanding of the main hydrological processes of the Elandsdrift-Wiesdrift wetland if groundwater is ignored.

6.3 HYDROLOGICAL MODELLING

This section presents simulated flow results and discussions from the four selected catchments. Flows were simulated with both the Pitman and ACRU model to establish the impact of wetland to hydrological response.

6.3.1 Mohlapetsi catchment

6.3.1.1 The relationship between objective functions and parameters

The variations of objective functions in the Pitman model compared with the soil moisture storage (ST) and the power of the moisture storage-runoff (POW) parameters are presented by Figure 6.14 and Figure 6.15, and the Mohlapetsi river catchment is used to illustrate the variation of the objective functions varied with ST and POW. There is no clear relationship between the objective function and the parameters, though in Figure 6.9, one could loosely infer that high RMSE values (at least 0.5) are obtained with ST value that are between 700 mm and 800 mm, while in the full range of the POW parameter (between 2 and 3.5) contains some satisfactory results (Figure 6.10).

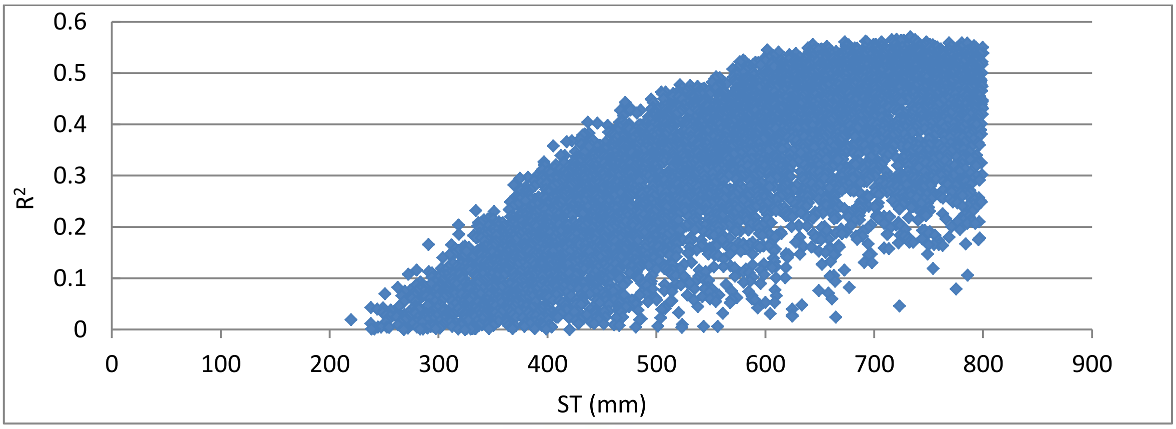


Figure 6.9. The relationship between the maximum soil moisture parameter (ST) and the root mean square error (RMSE) objective function for the Mohlapetsi catchment.

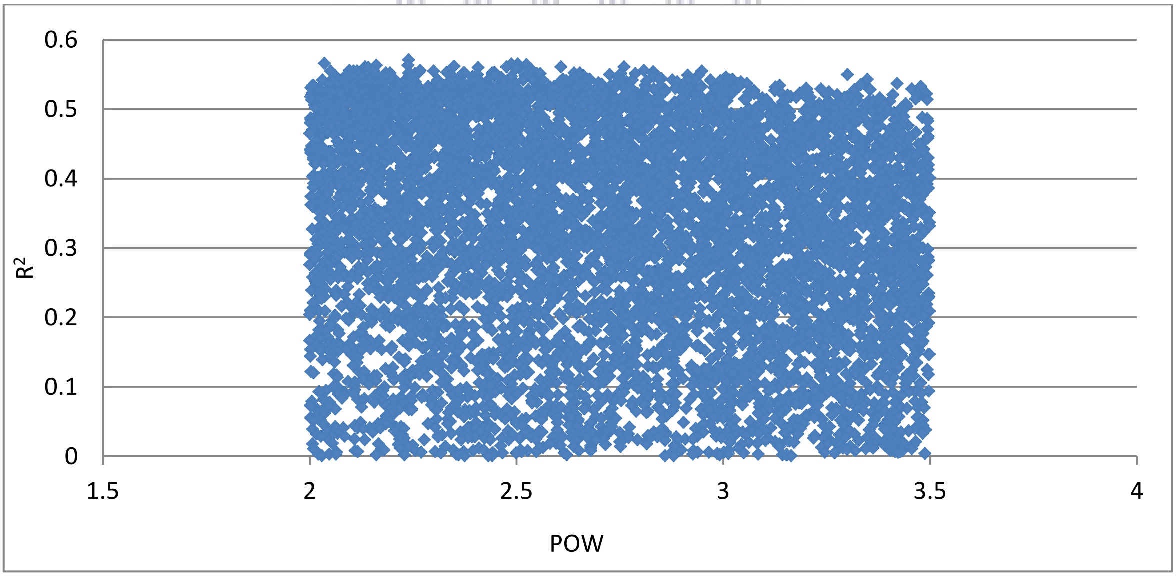


Figure 6.10. The relationship between the power of the moisture storage-runoff equation (POW) and the root mean square error (RMSE) objective function for the Mohlapetsi catchment.

6.3.1.2 Assessment of available flow gauge data

Daily and monthly observed flow data from two stream gauges (B7H011 and B7H013) situated in the Mohlapetsi river, downstream of the of the GaMampa wetland were first analysed. The aim of the analysis was to establish streamflow variations between the two gauges. The period covered for this analysis was 1970 to 1988, when both flow gauges were operational. Daily flows, daily mean flow and mean monthly flows for the two gauges were compared with each other to determine variations in flows. Flows within the two gauges follow similar seasonal variations (Figure 6.11). However, it is interesting to note that during the low flow months the downstream gauge B7H013 records lower flow compared to the upstream B7H011, which is counter intuitive, implying an impact of the wetland or abstractions from the river. The mean monthly flows for the wet season for B7H011 and B7H013 are 2.700 Mm^3/month and 2.924 Mm^3/month respectively, while the low flow season means are 0.842 Mm^3/month and 0.679 Mm^3/month, respectively. Given that there are no known abstractions between the gauges, and that the two gauges are downstream of the wetland, water might be lost to the groundwater aquifer, evaporation or is being absorbed by the lower extension of the wetland. Mekiso (2011) associates the stream flow variation at B7H013 with groundwater level fluctuations, which has been said to reflect rapid lateral flow. However, it remains unclear how water is lost during the dry season. It may not flow back into the channel and therefore bypass the gauge.

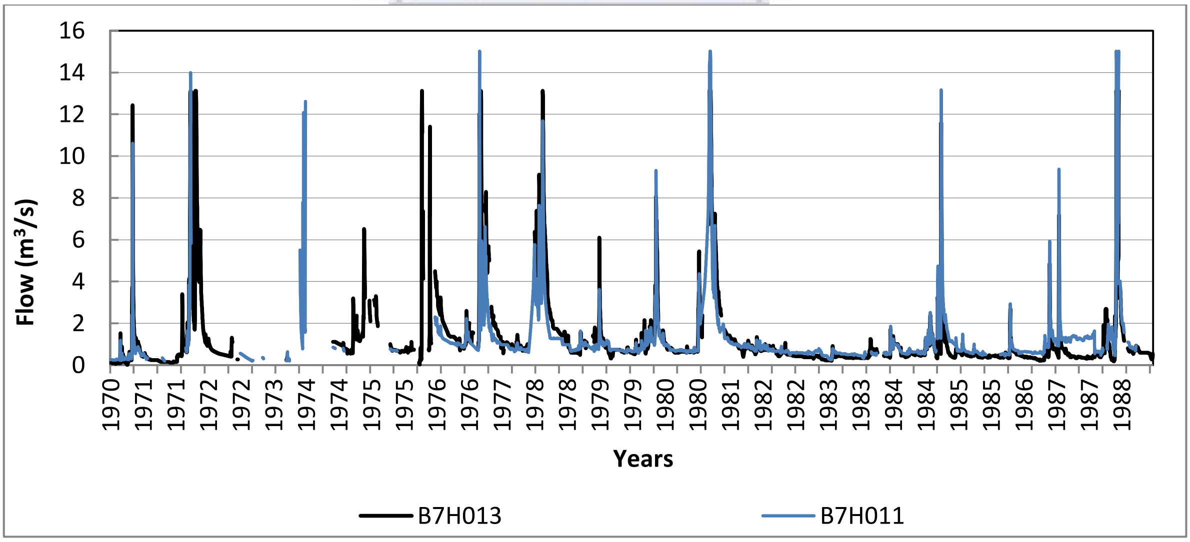


Figure 6.11. Time series comparison for flow gauges B7H013 and B7H011.

6.3.1.3 Simulation results by the Pitman model

Simulation results for the Mohlapetsi river catchment from 1971 to 2010 are presented in the following section. Changes of the values of some model parameters used were noted after incorporation of the wetland and the subsequent necessary recalibration of the model (Table 6.2). This is expected as the calibrated parameters for the setup without the wetland indirectly account for the wetland processes. The maximum soil moisture parameter (ST), which is the maximum water that could be stored in the soil decreased from 700 mm to

388 mm. The higher ST value in the initial setup based on the water resources assessment recommendations indicates that the size of the soil moisture store may have been made unnecessarily large to partly account for the storage capacity of the wetland which thus changed (decreased) after the incorporation of a module that explicitly accounts for a wetland. Incorporating the wetland module also resulted in an increase in groundwater recharge (GW) from 5 to 6 mm month^{-1}, the size of the riparian area (RSF) from 0.2 % to 0.5 % and time delay function parameters (TL) from 0.5 months to 0.6 months and a decrease in the value of the evaporation efficiency (R) parameter from 0.5 to 0.3.

Table 6.2. Parameters used to simulate stream flows with the Pitman model before and after inclusion of the wetland module and model performance statistics.

	Without wetland	With wetland
Parameters		
ZMIN	80.00	58.00
ZAVE	460.00	501.00
ZMAX	900.00	650.00
ST	780.00	680.00
POW	2.30	2.70
FT	30.00	40.00
GW	5.00	6.00
R	0.50	0.30
TL	0.50	0.60
GPOW	3.00	3.00
RSF	0.20	0.50
Objective Functions		
RMSE	0.56	0.56
RMSE (ln)	0.56	0.56
NSE	0.56	0.54
NSE (ln)	0.55	0.55
PBIAS	-6.65	-12.4
Mean	13.22	10.72

These changes are expected as the presence of a wetland would lead to an increase in the recharge as more water is made available through the wetland, an increase in the time taken to move water to the catchment outlet (the delay function performed by a wetland), and also an increase of the area of open water at the surface (and water in the soil) and the riparian zone which would result in more moisture availability thus more evaporation uptake is represented by a decrease in the parameter R (Kapangaziwiri, 2007). These changes indicate a response of the model to the wetland processes based on its conceptualisation used.

Annual rainfall for the Mohlapetsi river catchment from 1970 to 2010 is presented in Figure 6.12. Between 1981 and 1995 (Figure 6.12) rainfall was very low in the Mohlapetsi river, (with higher rainfall before and after 1995), indicating drought in the catchment. These years (especially 1982, 1983, 1991 and 1992) coincide with severe droughts reported by DEWFORA (2012) for the Limpopo river basin.

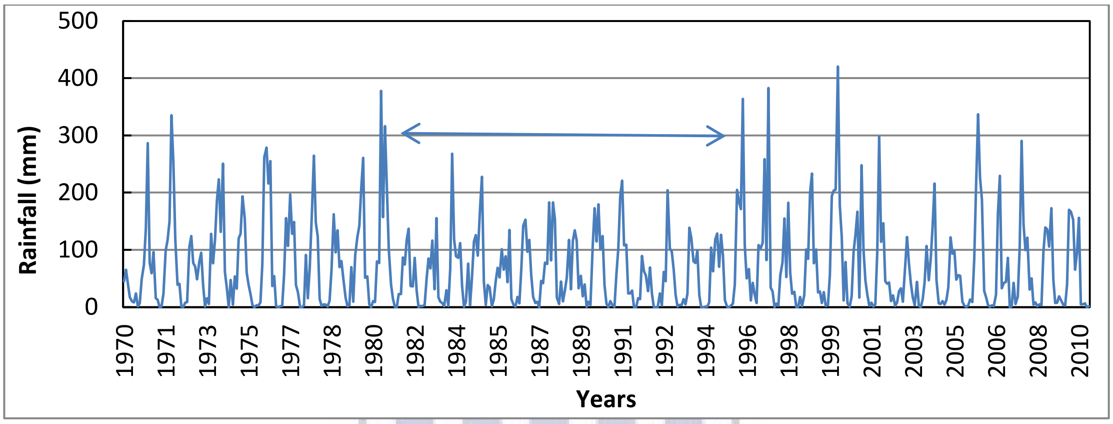


Figure 6.12. Monthly rainfall for the Mohlapetsi catchment.

Simulation results for the Mohlapetsi catchment are shown in Figure 6.13 and Table 6.2. The Pitman model simulation of monthly stream flow without the wetland module was satisfactory in terms NSE and PBIAS (Table 6.2). However, there is long term variability in flows between 1981 and 1995 (Figure 6.13) in response to the rainfall in the catchment whose records also indicate it was a drier period for the catchment (Figure 6.12).

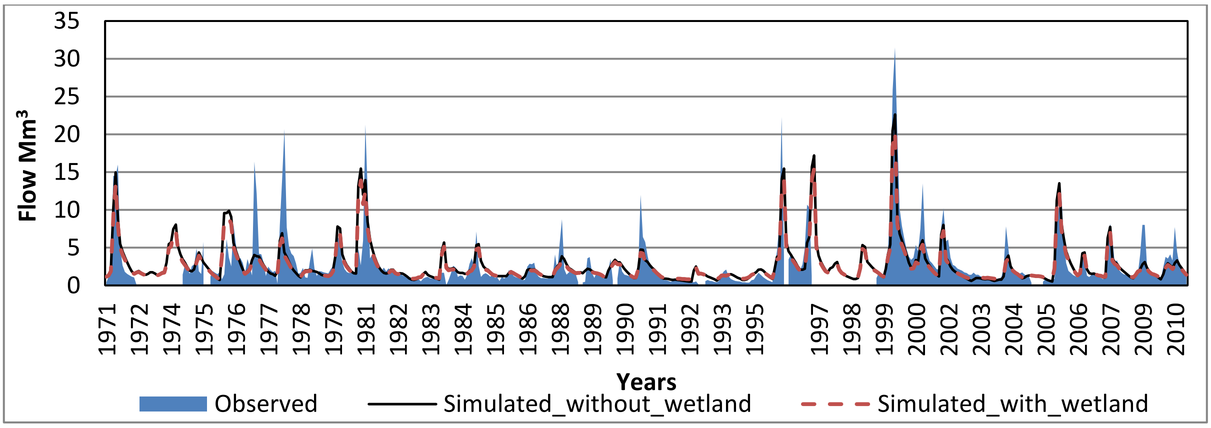


Figure 6.13. Observed and Pitman simulated flow before and after the inclusion of the wetland module.

This flow variability could also be a result of land use changes that can clearly be seen in land cover maps shown in Figure 6.14. The catchment has been largely modified to include build-up and agricultural areas from 1990 compared to the years after 2000. This has a direct influence on the rainfall that is converted to surface runoff within the catchment. Built up areas and agricultural practices (removal of vegetal cover) enhance surface runoff generation in a basin.

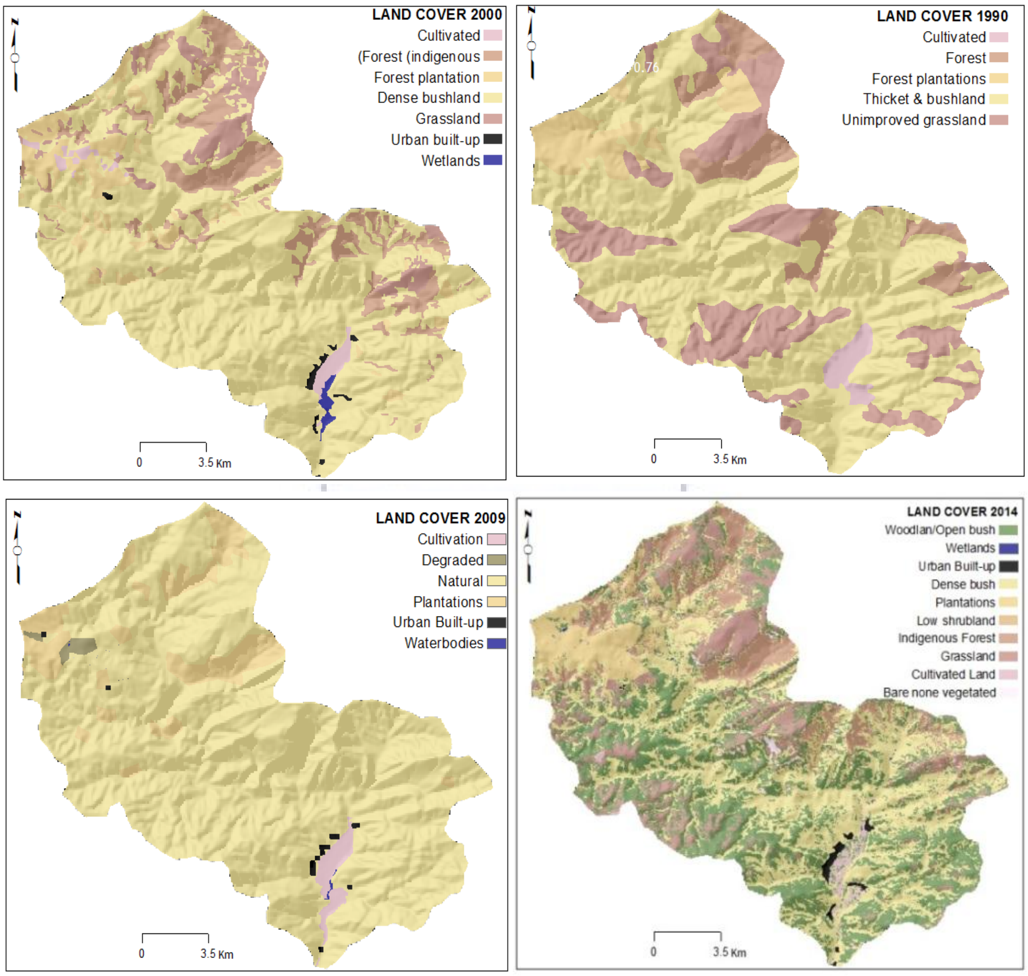


Figure 6.14. Different maps of the Mohlapetsi River showing land cover changes from 1990 to 2014 (National Land Cover, 1990, 2000, 2009 and 2014).

The long term variability of seasonal means of flow in the catchment challenged modelling within the basin. However, the overall modelling results were satisfactory and the model was able to capture the magnitude and timing of low flows satisfactory while the moderate to high flow were slightly over-simulated (Figure 6.15).

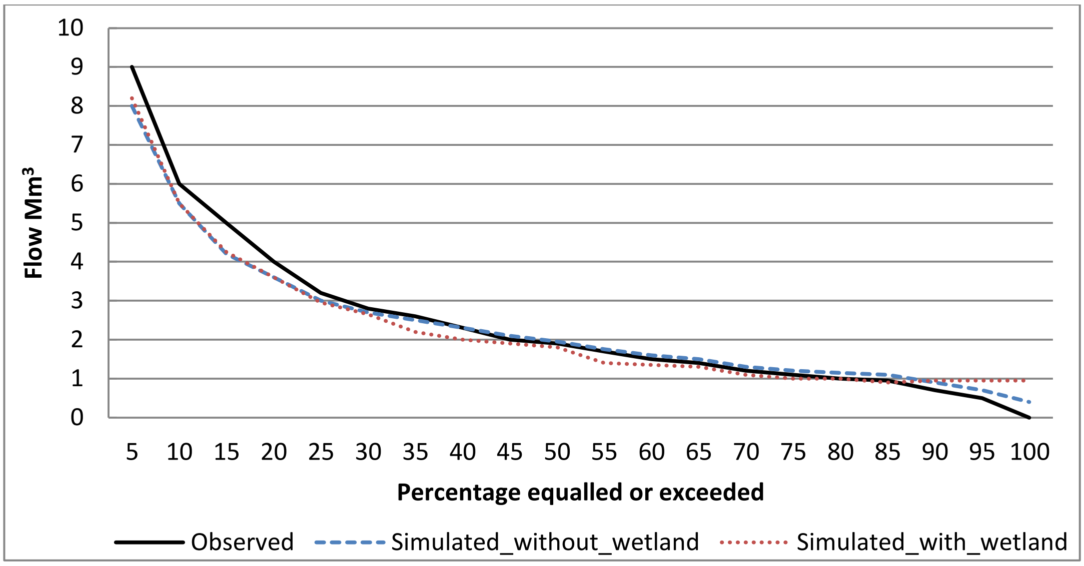


Figure 6.15. Flow duration curve for the Mohlapetsi River catchment before and after the inclusion of the wetland module.

After the inclusion of the wetland, the simulation was satisfactory (Figure 6.13) in terms of trends (NSE) with a minimum PBIAS. The overall water balance was also well reproduced by the model. The mean of the observed flow was 2.976Mm^3, while before the inclusion of the wetland module was 2.75 Mm^3 and further decreases to 2.581 Mm^3 after the inclusion of the wetland module. Low flows were well simulated while moderate high flows to high flows were under simulated after the inclusion of the wetland (Figure 6.15). The flood attenuation impact of the wetland on flow is not clear within Figure 6.13 (both simulated without and with the wetland module coincide with each other). However, parameter TL, (the time delay function) increases from 0.5 months (which is 15 days) before the wetland to 0.6 month (18 days) after the inclusion of the wetland showing that it will take longer for flow to travel downstream. Since the model is in monthly time steps and the impacts are in days and also taking into consideration the size of the catchment in relation to the wetland, the impacts of the wetland are mask within the model.

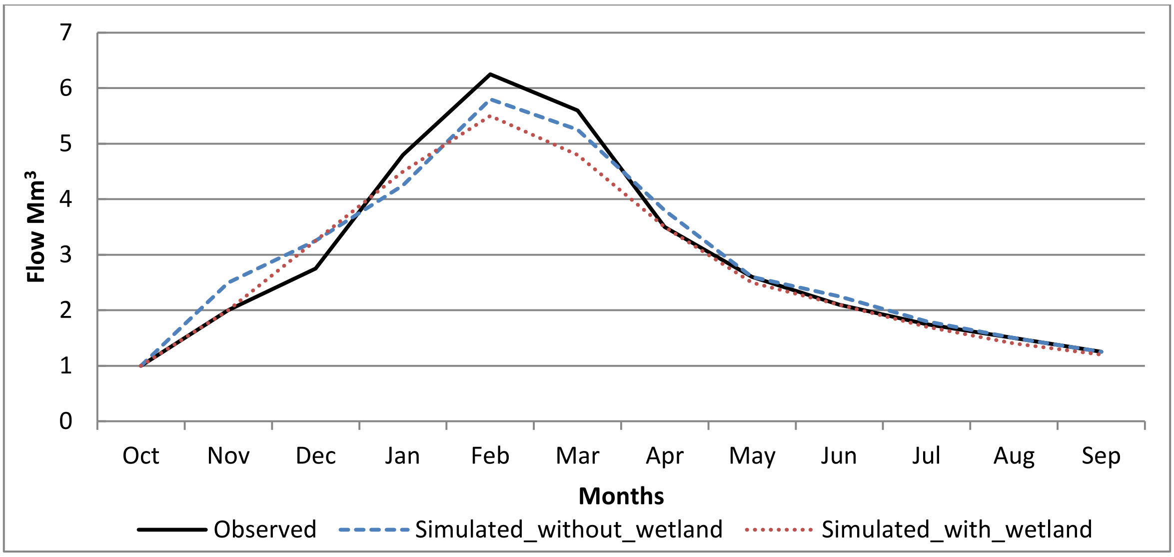


Figure 6.16. Monthly distribution of flow in the Mohlapetsi River before and after the inclusion of the wetland module.

6.3.1.4 Simulation with the ACRU model

Parameters used for the configuration of the ACRU model in the Mohlapetsi catchment are summarised in Table 6.3. For all the HRUs in the catchment, the quick flow response fraction was kept low (at 0.02) and was kept constant for all the HRUs, for better simulation of peak flows and low flows. The coefficient of base flow response (COFRU), which determines the rate at which groundwater is released from the intermediate zone to streamflow was assumed to be 0.0001 throughout the HRUs.

Table 6.3. Final set of parameters used in the Mohlapetsi catchment.

Parameters	Mohlapetsi1	Mohlapetsi2
QFRESP	0.020	0.020
COFRU	0.007	0.007
SMDDEP	0	0
FOREST	0	0
FPAW	0	0
CONST	0.500	0.500
EFRDEP	0	0

The daily time step ACRU model simulation was satisfactory in terms of trend (NSE) and good in terms of average magnitudes (PBIAS) (Table 6.4, Figure 6.17).

Table 6.4. Model performance statistics for the ACRU model.

Objective Function	ACRU
NSE	0.62
RMSE	0.63
PBIAS	6.17
Mean Observed	1.07
Mean simulated	1.01

The model was able to reproduce both the magnitudes and the timing of flows. The simulated mean daily flow from 1970-1999 was 1.013 m^3 s^{-1} (i.e. 2.628 Mm^3 $month^{-1}$), which is closer to mean simulated by the Pitman but 5.406% lower than the mean daily flow observed at B7H013.

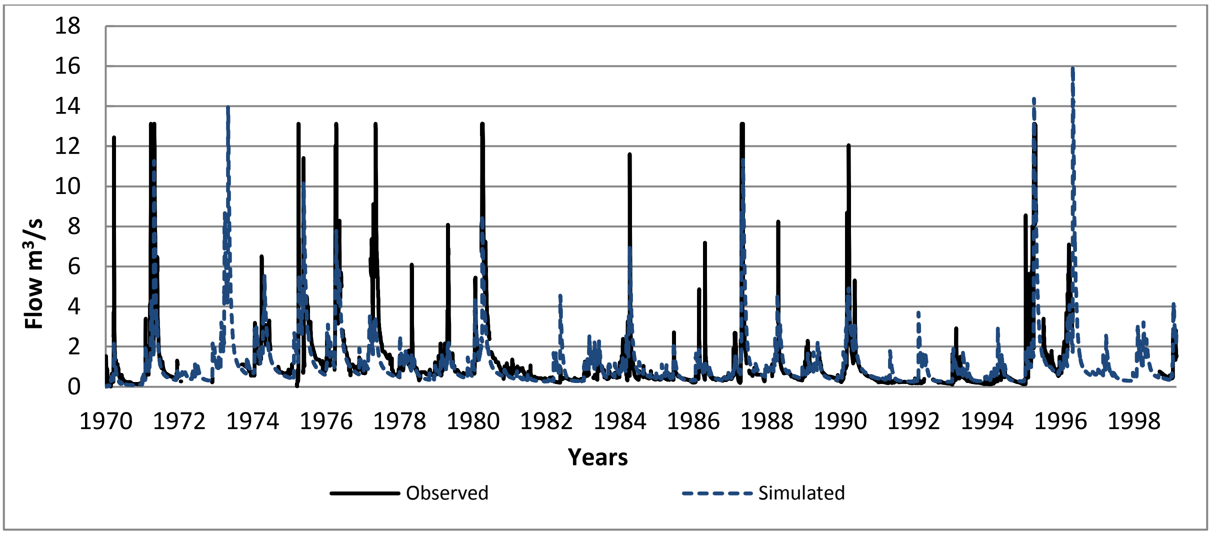


Figure 6.17. Observed and ACRU simulation in the Mohlapetsi catchment with the wetland.

Most high flows were over-estimated by the model (Figure 6.18). Figure 6.18 show flow duration curves for the catchment for the wet season (October to March) were most high flows occur. However, October and March flows were over simulated by the model, while November and December flows were well simulated. The model over-simulated high flows because of the long term variability of flows (1980 to 1995) that have been discussed in section 6.3.1.3.

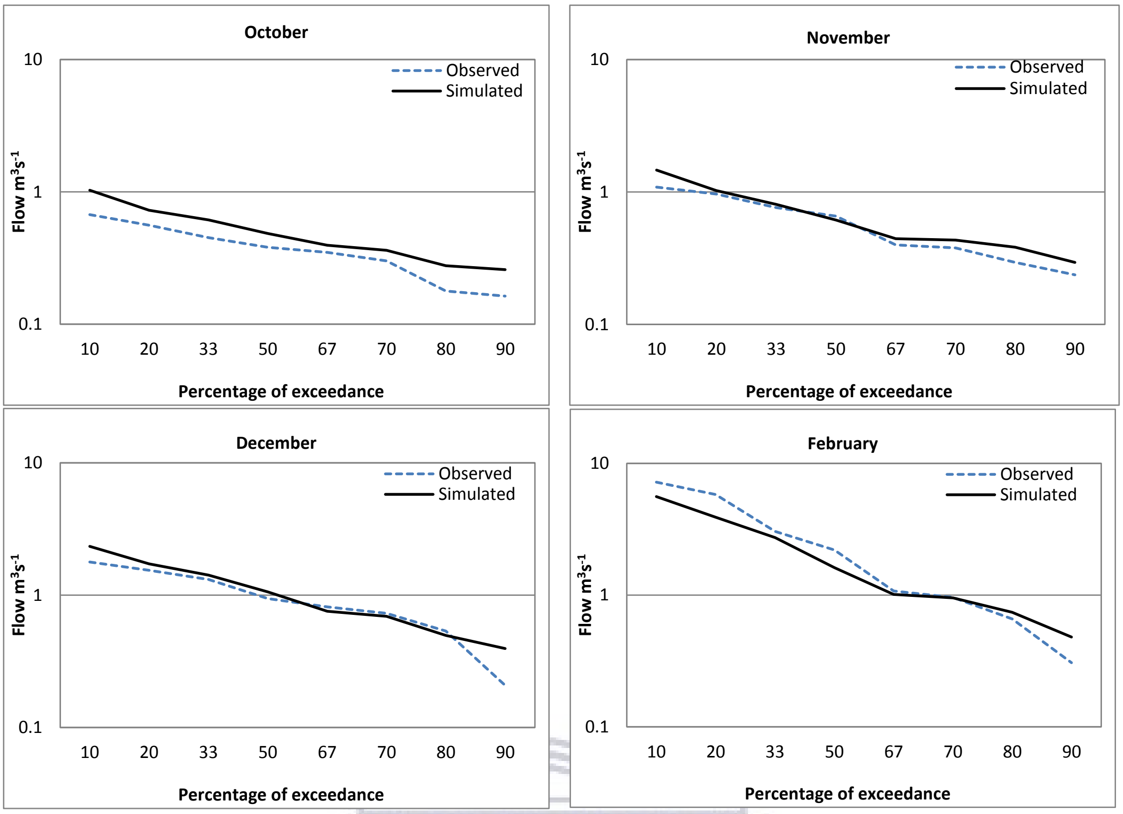


Figure 6.18. Observed and ACRU simulated Monthly flow duration curves for Mohlapetsi catchment from October to March.

Most low flows were well simulated by the model (Figure 6.19). June, July, August and September flows were well simulated while April and May were over simulated.

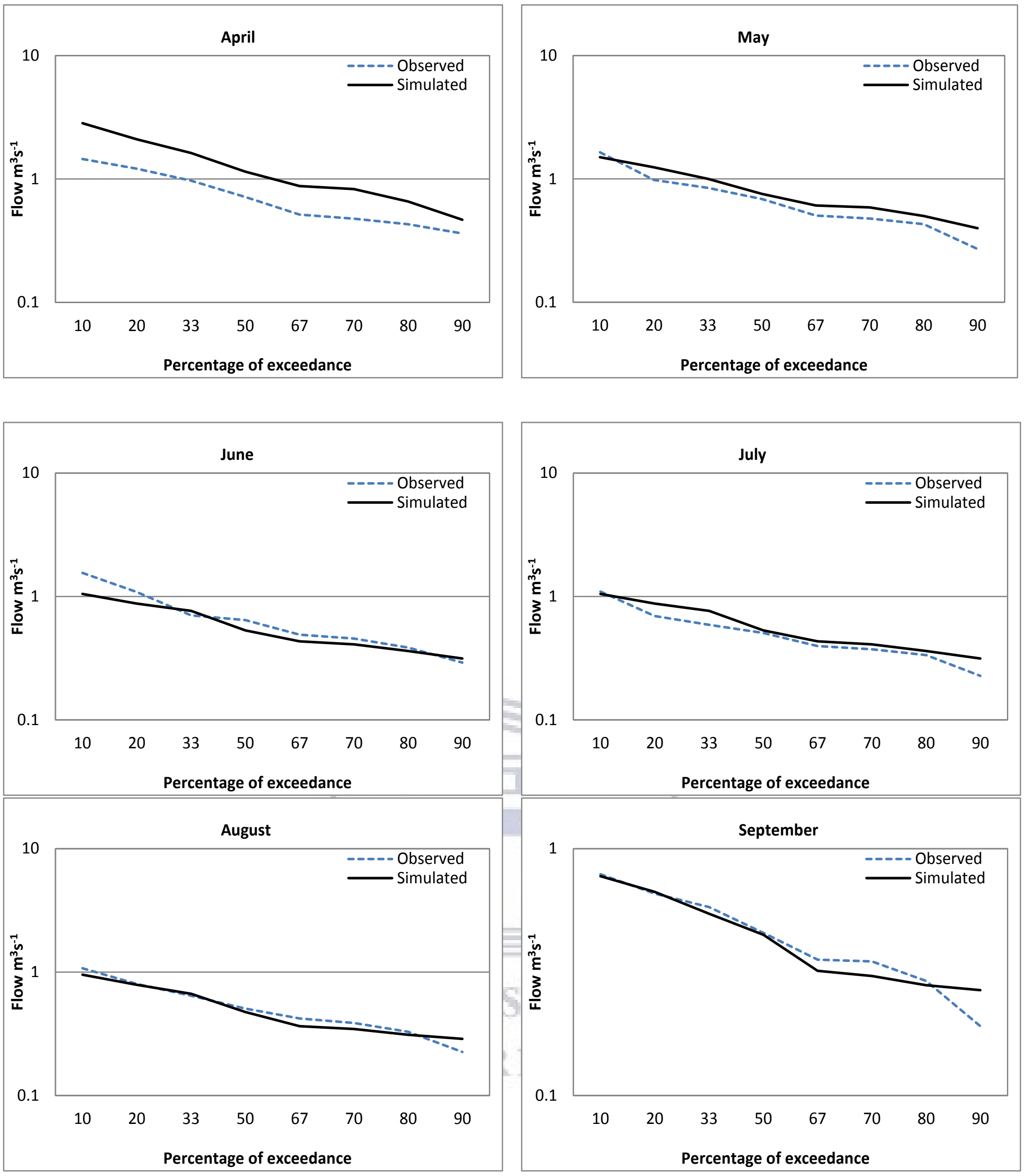


Figure 6.19. Observed and ACRU simulated Monthly flow duration curves for Mohlapetsi catchment for April to September.

6.3.2 Nuwejaars river catchment Results

6.3.2.1 Simulation with the Pitman model

Simulation results for the Nuwejaars river catchment from January 2015 to December 2015 are presented in the following section. The whole catchment was modelled and changes of the values of some model parameters used were also noted after incorporation of the wetland and the necessary subsequent recalibration of the model (Table 6.5). The maximum soil moisture parameter (ST), which is the maximum water that could be stored in the soil decreased from 395 mm to 293 mm. The higher ST value in the initial setup based on the water resources assessment recommendations indicates that the size of the soil moisture store may have partly accounted for the storage capacity of the wetland which thus changed (decrease) after the incorporation of a module that explicitly account for a wetland. Incorporating the wetland module also resulted in an increase in groundwater recharge (GW) from 4.5 mm month^{-1} to 9.3 mm month^{-1}, size of the riparian area (RSF) from 0.3% to 0.6% and time delay function parameters (TL) from 0.63 months to 0.7 months and a decrease in the value of the evaporation efficiency (R) parameter from 0.9 to 0.7.

Table 6.5. Parameters used to simulate stream flows with the Pitman model before and after inclusion of the wetland module.

Parameter	Without wetland	With wetland
Parameters		
ZMIN	21.00	14.00
ZAVE	345.00	256.00
ZMAX	950.00	708.00
ST	395.00	293.00
POW	3.93	2.80
FT	43.00	46.00
GW	4.50	9.30
R	0.90	0.71
TL	0.63	0.70
GPOW	3.00	3.00
RSF	0.30	0.60
Objective functions		
RMSE	0.75	0.69
RMSE (ln)	0.91	0.88
NSE	0.74	0.69
NSE (ln)	0.68	0.63
PBIAS	3.15	7.23
Mean	17.07	18.2

Pitman model simulations for the Nuwejaars river catchment without the wetland were good for NSE, RMSE and satisfactory for PBIAS (Table 6.5 and Figure 6.20). The model performance statistics indicate a good simulation, with an observed mean monthly flow of 10.4 Mm^3 and a simulated mean monthly flow of 11.57 Mm^3 before the inclusion of the wetland.

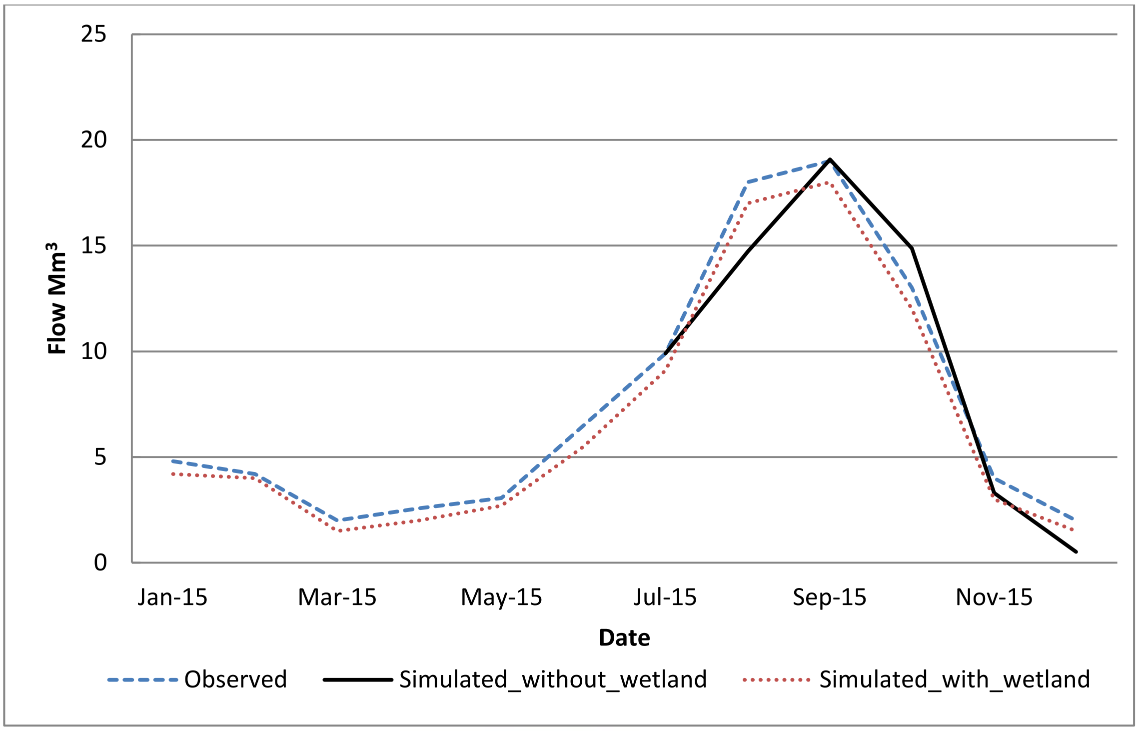


Figure 6.20. Observed and Pitman simulated flow before and after the inclusion of the wetland module.

The magnitude and timing of flows were well captured by the model. High flows were slightly under simulated while low flows were well simulated (Figure 6.20). The timing of flows was well captured by the model. After the inclusion of the wetland, the model was still able to satisfactory reproduce flow. However the model performed better before the inclusion of the wetland. The mean monthly flow increased to 18.2 Mm^3/month after the inclusion of the wetland from 17.07 Mm^3/month. Low flows were slightly over simulated while high flows were under-simulated. The length of the observed record is very small and no concrete conclusions can therefore be drawn.

6.3.2.2 Simulation with the ACRU model

Parameters used for the configuration of the ACRU model within the Nuwejaars catchment from January 2015 to December 2015 are summarised in Table 6.6. For the catchment area of the wetland, the quick flow response fraction was kept low (at 0.01), for better simulation of peak flows and low flows. The coefficient of base flow response (COFRU), which determines the rate at which groundwater is released from the intermediate zone to streamflow was optimum at 0.009, which is the value recommended for all basins by the model.

Table 6.6. Final set of parameters used in the Nuwejaars catchment.

Parameters	Nuwejaars
QFRESP	0.010
COFRU	0.009
SMDDEP	0
FOREST	0
FPAW	0
CONST	0.400
EFRDEP	0

The ACRU model simulation in the Nuwejaars river (Table 6.7 and Figure 6.21) was good in terms of trends (NSE), root mean square error (RMSE) and average magnitudes (PBIAS). The simulated daily mean was 3.7 m^3s^{-1} and is higher by 0.4 m^3s^{-1} when compared to the mean daily flow that was observed at the Elandsdrift Bridge of 3.306 m^3 s^{-1}.

Table 6.7. Model performance statistics for the Pitman Model before and after including the wetland module.

Objective Function	ACRU
RMSE	0.71
NSE	0.68
PBIAS	-13.25
Mean Observed	3.30
Mean Simulated	3.74

The magnitudes and timing of flows was satisfactorily simulated by the model. However, low flows between May and the beginning of August were over simulated by the model (Figure 6.21 and Figure 6.22). It is difficult to attribute a reason for such as huge difference in the low flows. This difference affects the overall simulation results. However, it is possible that there could be an error with the observations between May and the beginning of July, with the model failing to reproduce the magnitude of flows of that period. Flows between July and October were satisfactory simulated (Figure 6.22). Flows at the beginning of the dry season were satisfactorily simulated and are slightly over simulated as the dry season persist (Figure 6.22).

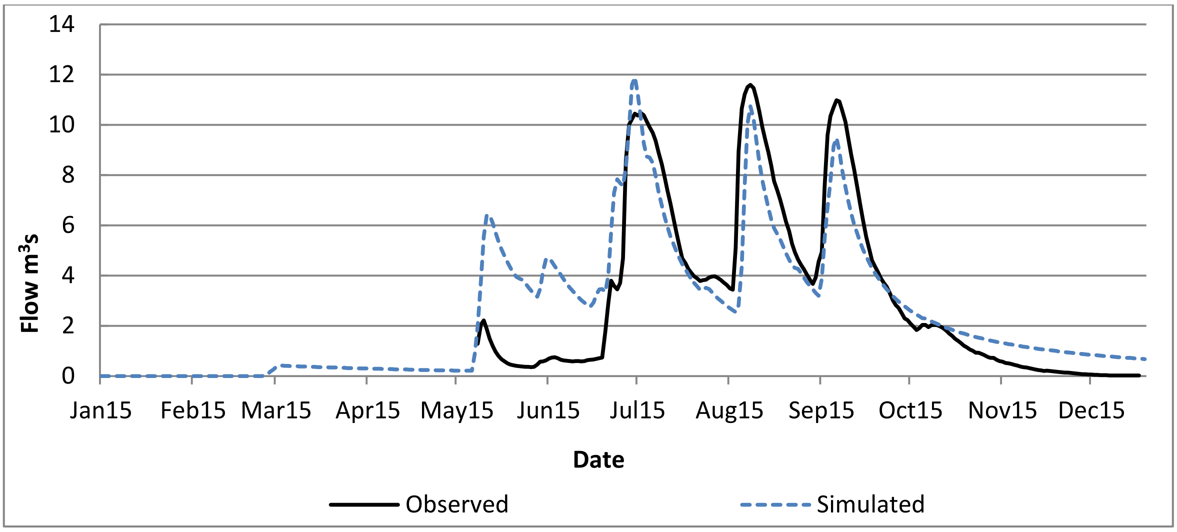


Figure 6.21. Observed and ACRU simulated flow for the Nuwejaars River.

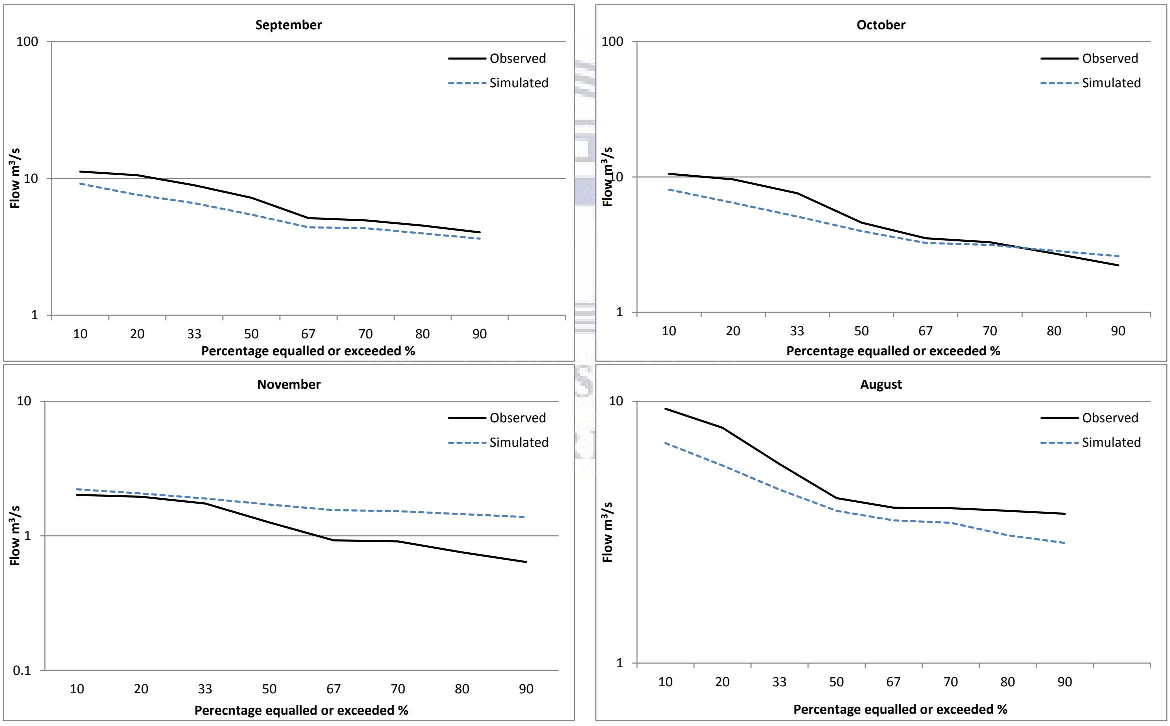


Figure 6.22. Flow duration curve for the ACRU model for the months that had flow for the Nuwejaars catchment.

6.3.3 The Bonnie Brook river catchment Result

6.3.3.1 Simulation with the Pitman model

Simulation results for the Bonnie brook river catchment from 1951 to 1981 are presented in the following section. The final parameters used for the Bonnie Brook river catchment before and after the inclusion of the wetland module are presented in Table 6.8. Notable are the changes in parameters of the model after the wetland module, indicating the effect of the wetland in the quaternary catchment. The maximum soil moisture parameter (ST) decreased from 296 mm to 270 mm indicating that the size of the soil moisture store may have partly accounted for the storage capacity of the wetland in the first setup. Incorporating the wetland module resulted in increase in groundwater recharge (GW) from 6 mm month^{-1} to 10 mm month^{-1}, size of the riparian area (RSF) from 0.6 % to 0.8 % and time delay function parameters (TL) 0.3 months to 0.4 months and a decrease in the value of the evaporation efficiency (R) parameter from 0.7 to 0.3. The changes in the parameters indicate that the model is trying to mimic the processes occurring in the catchment.

Table 6.8. Parameters used to simulate stream flows with the Pitman model before and after inclusion of the wetland for the Bonnie Brook River.

Parameters	**without wetland**	**with wetland**
Parameters		
ZMIN	23.00	11.00
ZAVE	344.00	417.00
ZMAX	711.00	881.00
ST	296.00	270.00
POW	4.70	4.00
FT	31.00	38.00
GW	6.00	10.00
R	0.70	0.30
TL	0.30	0.40
GPOW	3.00	3.00
RSF	0.60	0.80
Objective functions		
RMSE	0.65	0.64
RMSE (ln)	0.73	0.67
NSE	0.65	0.64
NSE (ln)	0.68	0.66
Objective functions		
PBIAS	2.78	-4.81
Mean	1.01	0.93

The results of the model performance before and after the inclusion of the wetland module for Bonnie Brook River are presented in Table 6.8 and Figure 6.23.

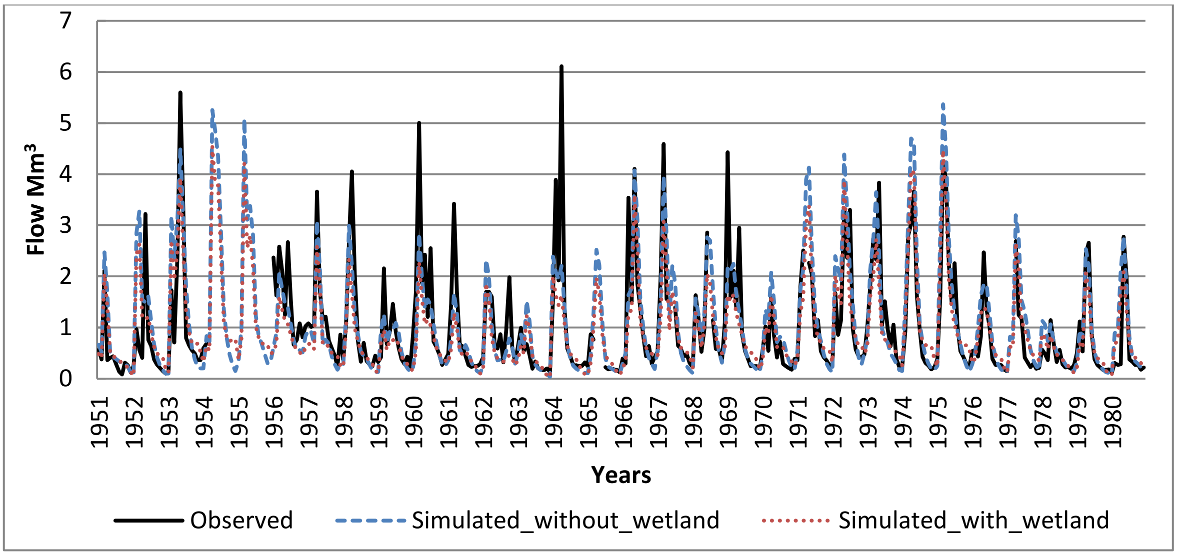


Figure 6.23. Observed and Pitman simulated flow before and after the inclusion of the wetland module.

The Pitman simulation without the wetland was able to satisfactorily reproduce the observed flows (Figure 6.23). The NSE and PBIAS indicate good model simulations. The magnitudes and timing of flows were reproduced well as were the low and high flows (Figure 6.24). The overall water balance was well reproduced by the model. The observed mean monthly flow was 1.005 Mm^3, while the simulated mean without the wetland module was 1.02 Mm^3 and 0.939 Mm^3 after the inclusion of the wetland.

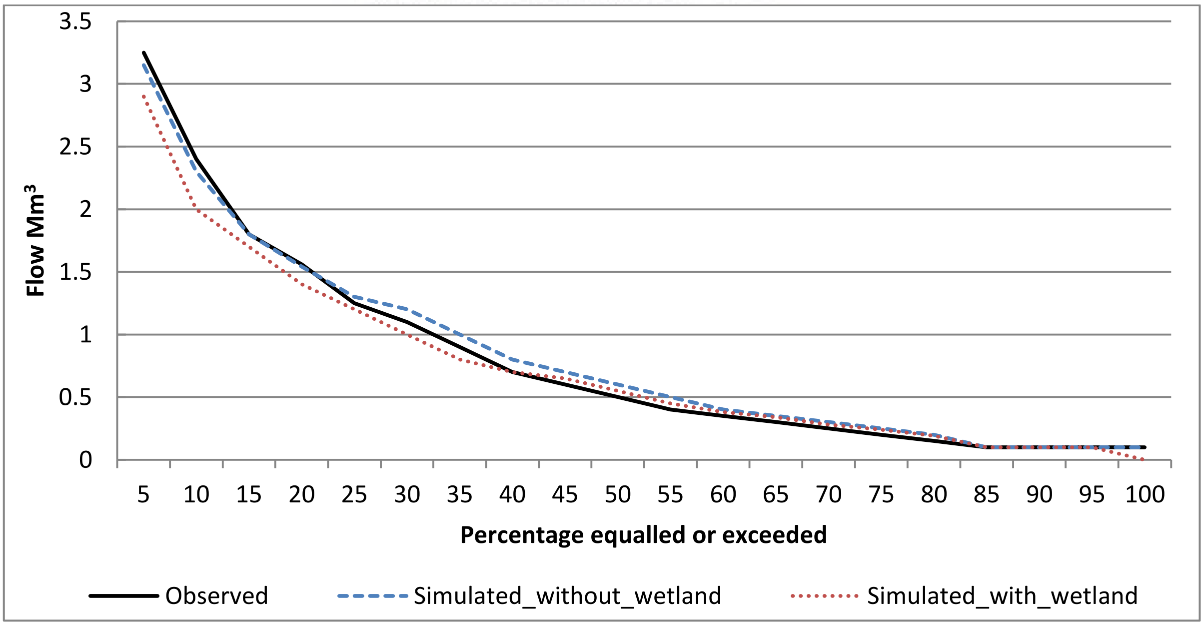


Figure 6.24. Flow duration curve for the Bonnie Brook River.

After the inclusion of the wetland, the model reproduced both low and high flows very well (Figure 6.24). Both the magnitude and timing of flows were well captured, even though some high flows were missed by the model. Medium to low flows were well simulated while high flows were slightly over-simulated after the inclusion of the wetland module (Figure 6.24). The seasonal distribution of flow within the catchment with the simulated flow is shown in Figure 6.25 and indicates a problem with the observed flow sequence, especially the high flows.

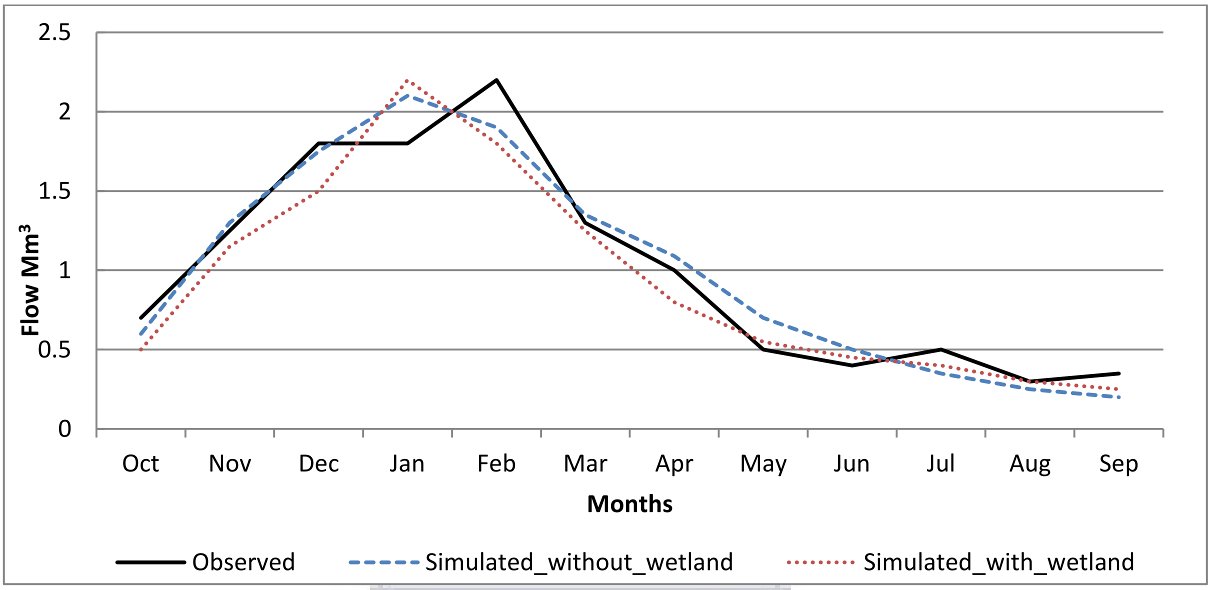


Figure 6.25. Distribution of flow in the Bonnie Brook river catchment with simulated flow.

6.3.3.2 Simulation with the ACRU model

Parameters used for the configuration of the ACRU model in the Bonnie brook catchment are summarised in Table 6.9. For the catchment, the quick flow response fraction was kept low (at 0.01), for better simulation of peak flows and low flows. The coefficient of base flow response (COFRU), which determines the rate at which groundwater is released from the intermediate zone to streamflow was optimum at 0.001, which is the value recommended for all basins by the model.

Table 6.9. Final set of parameters used in the Bonnie brook catchment.

Parameters	Bonnie brook
QFRESP	0.010
COFRU	0.001
SMDDEP	0

Parameters	Bonnie brook
FOREST	0
FPAW	0
CONST	0.050
EFRDEP	0

The ACRU model performed satisfactorily with respect to the trends (NSE) and the average magnitudes (PBIAS) (Figure 6.26 and Table 6.10). The observed mean daily flow for the catchment was 0.391 m^3s^{-1}, and the simulated mean was 0.397 m^3s^{-1}. Although the model failed to simulate most high flows, low flows were well simulated.

Table 6.10. Statistics and model performance for the ACRU model in the Bonnie Brook River.

Objective function	Value
RMSE	0.51
Nash-Sutcliffe	0.51
PBIAS	-1.66
Observed (Mean)	0.39
Simulated (Mean)	0.39

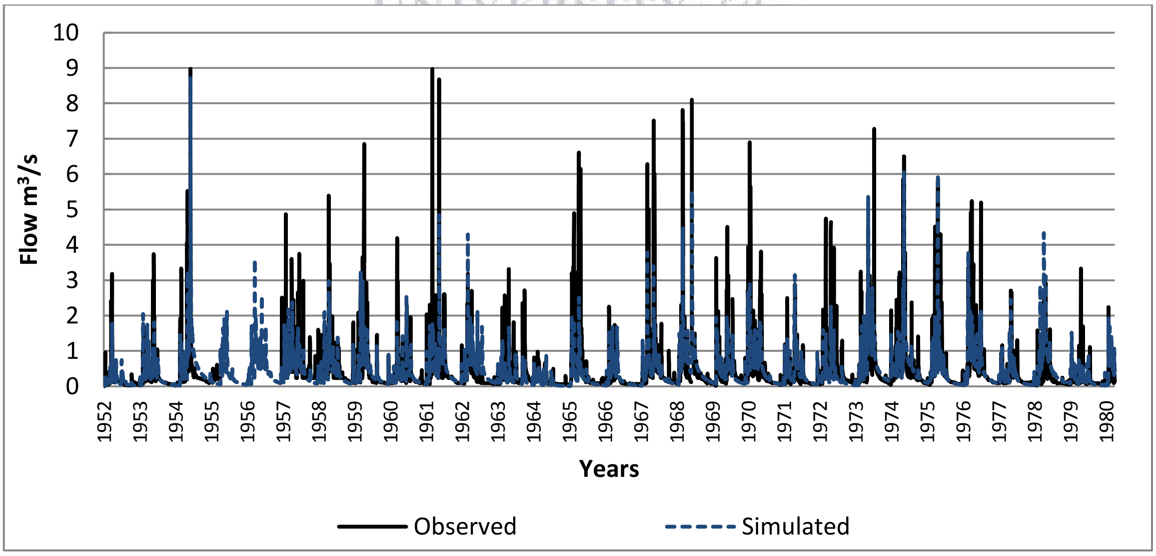


Figure 6.26. Observed and ACRU simulations for the Bonnie Brook river catchment.

Figure 6.27 and Figure 6.28 show the monthly flow duration curves for the catchment. Figure 6.27 shows the flow duration curves of the wet season (October to March) while

Figure 6.28 shows the flow duration curves of the dry months (April to September). The simulated flows are fairly representative of the observed flow. In all the wet months, flows which are greater than 1 m^3s^{-1} are under simulated except for March though, in general, the observed and simulated flows are quite very close to each other.

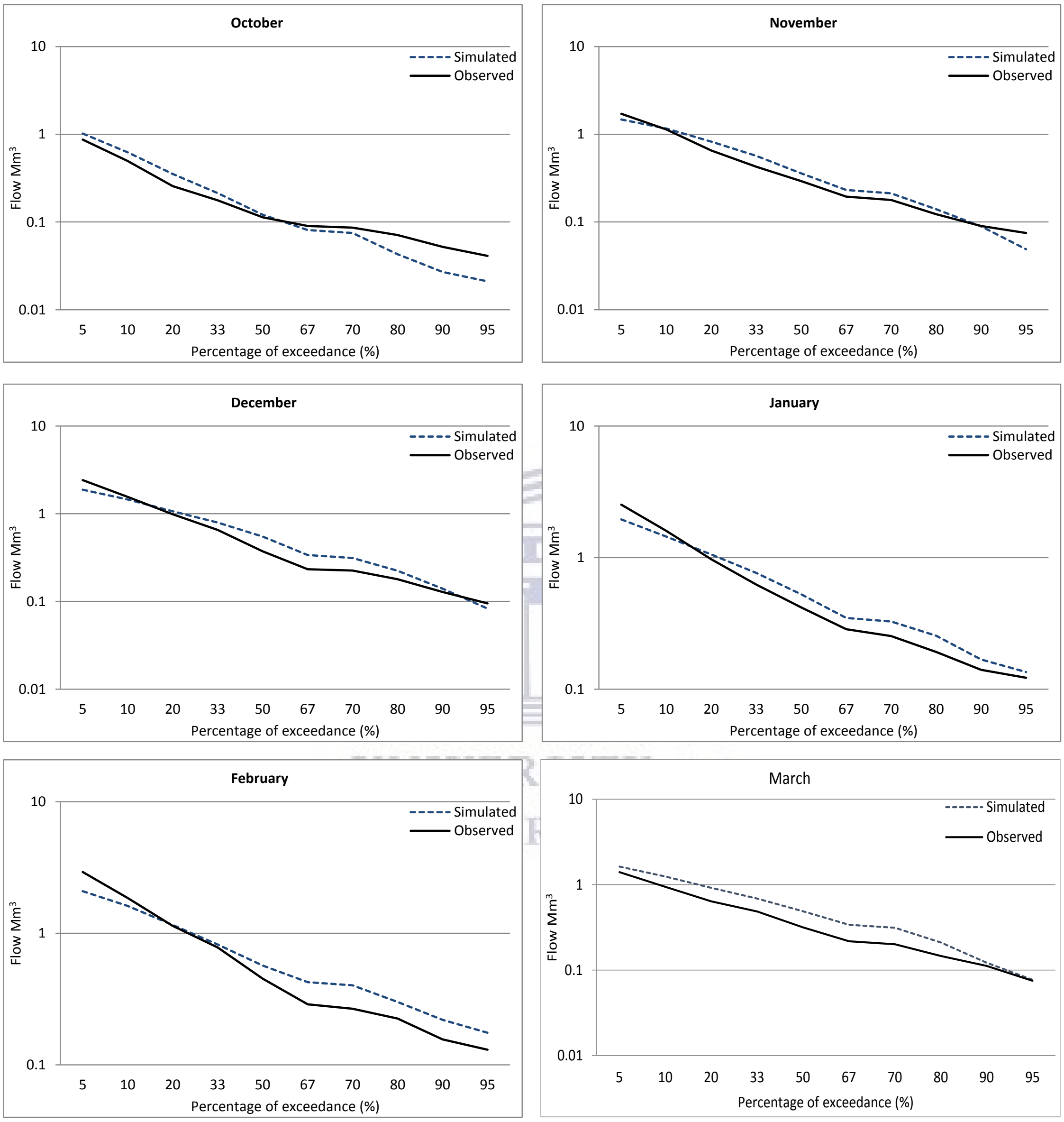


Figure 6.27. Monthly flow duration curves for the Bonnie Brook river catchment from October to March.

June, July and September flows were also well simulated, while in April, May and August flows were over-simulated.

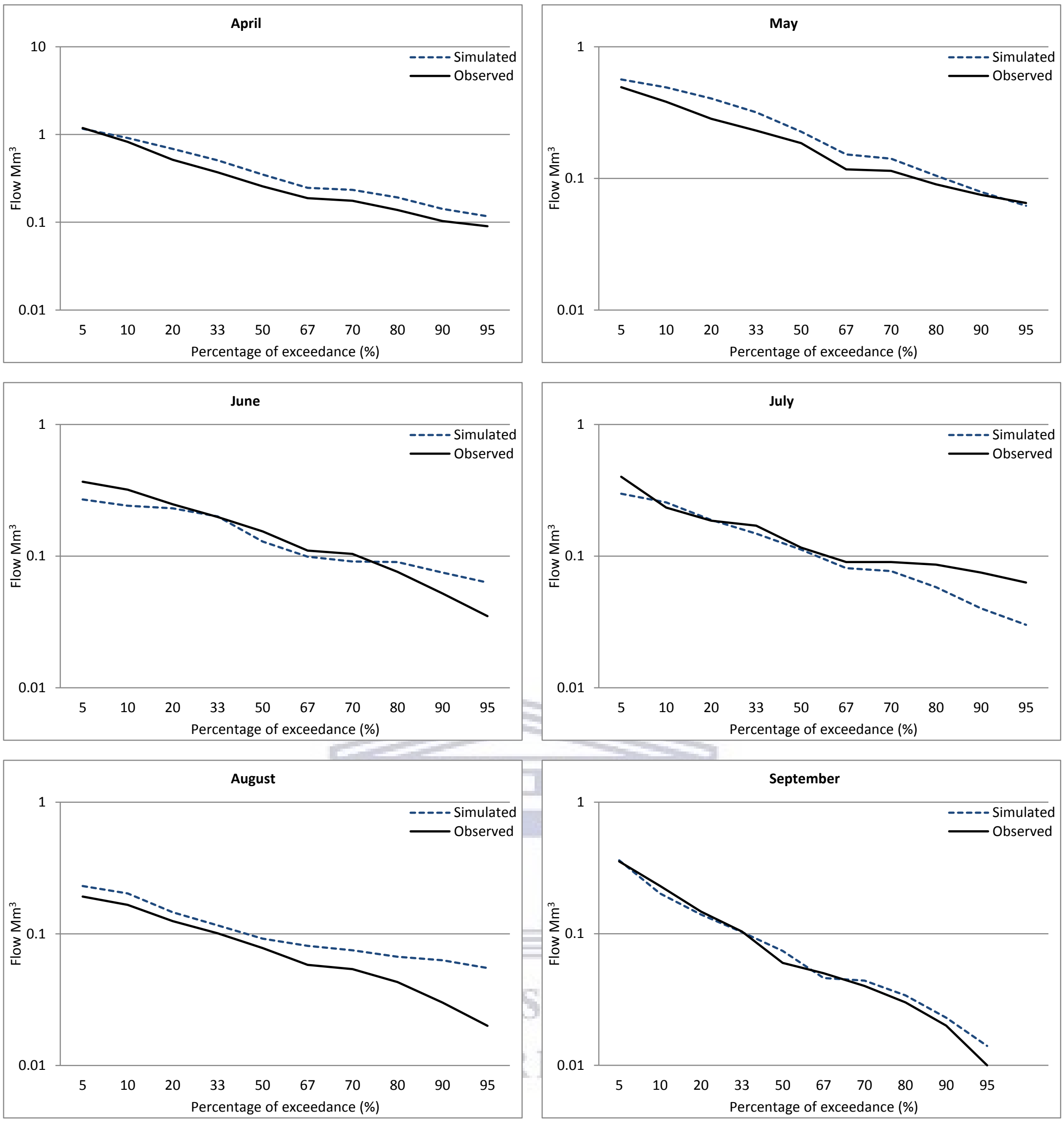


Figure 6.28. Monthly flow duration curves for the Bonnie Brook river catchment from April to September.

6.3.4 Lions River catchment results

6.3.4.1 Simulation with the Pitman model

Simulation results for the Lion’s river catchment from 1955 to 2005 are presented in the following section. The final parameters used for the Lions river catchment before and after the inclusion of the wetland module are presented in Table 6.11. Similar trends in parameter changes to those that are observed in the three other catchments are also observed in the Lion’s catchment before and after the inclusion of the wetland. The maximum soil moisture parameter (ST) decreased from 334 mm to 186 mm, indicating that the size of the soil moisture store may have partly accounted for the storage capacity of the wetland in the first setup. Groundwater recharge (GW) increased from 6 mm month^{-1} to 10mm month^{-1}, size of the riparian area (RSF) increased from 0.4 % to 0.84 % and the time delay function parameters (TL) increases from 0.25 month to 0.75 month while the value of the evaporation efficiency (R) parameter decreased from 0.5 to 0.16.

Table 6.11. Parameters used to simulate stream flows with the Pitman model before and after inclusion of the wetland for the Lion's river.

Parameters	Without wetland	With wetland
Parameters		
ZMIN	998.00	998.00
ZAVE	999.00	999.00
ZMAX	1000.00	1000.00
ST	334.00	186.00
POW	3.12	1.19
FT	44.55	9.70
GW	6.00	10.00
R	0.50	0.16
TL	0.25	0.75
GPOW	3.00	3.00
RSF	0.40	0.84
Objective functions		
RMSE	0.68	0.64
RMSE (ln)	0.56	0.51
NSE	0.65	0.62
NSE (ln)	0.51	0.51
PBIAS	-3.32	-9.44
PBIAS (ln)	-1.23	5.00

Table 6.11 and Figure 6.29 show the performance measures and statistics of the Pitman model before and after the inclusion of the wetland module. Before and after the inclusion of the wetland module the model satisfactorily reproduced flows observed at the outlet of the Lion's river catchment. The magnitude and timing of flows were also well captured, with the observed mean of 5.173 Mm^3 and a simulated mean of 4.917 Mm^3 and 4.299 Mm^3 before and after the inclusion of the wetland module respectively. Decrease in monthly flow indicates the impact of the inclusion of the wetland processes on stream flow. Without the wetland both low and high flows were well simulated by the model,

while after the inclusion of the wetland the low flows were well simulated but the moderately high to high flows were slightly under-simulated (Figure 6.30).

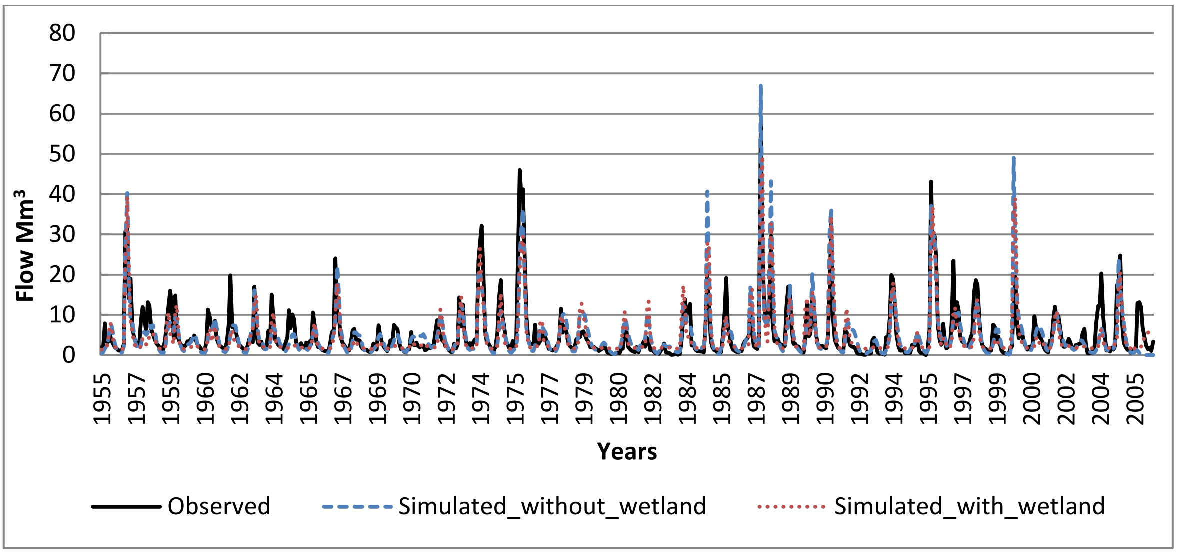


Figure 6.29. Observed and Pitman simulated flow before and after the inclusion of the wetland module.

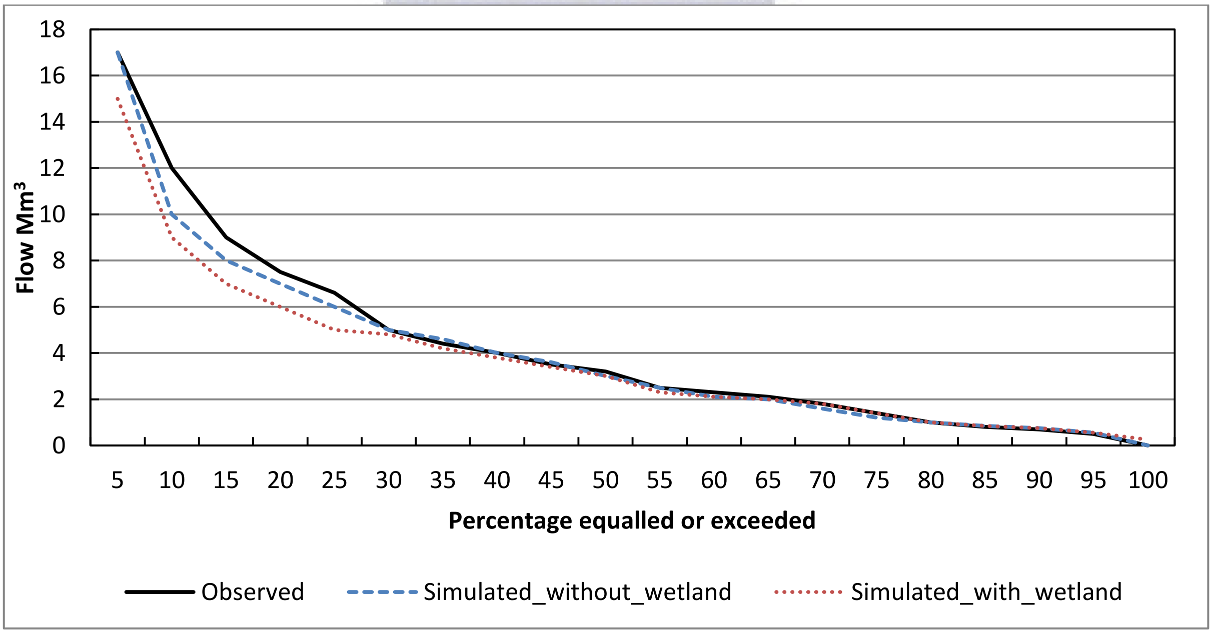


Figure 6.30. Flow duration curve for the Lion's river catchment before and after the inclusion of the wetland.

The flow duration curve indicates that the wetland module reduces high flows while contributing to low flow in the catchment. Flows with the wetland module are increasing from July. The seasonal distribution of flow within the catchment for observed and simulated flows is shown in Figure 6.31.

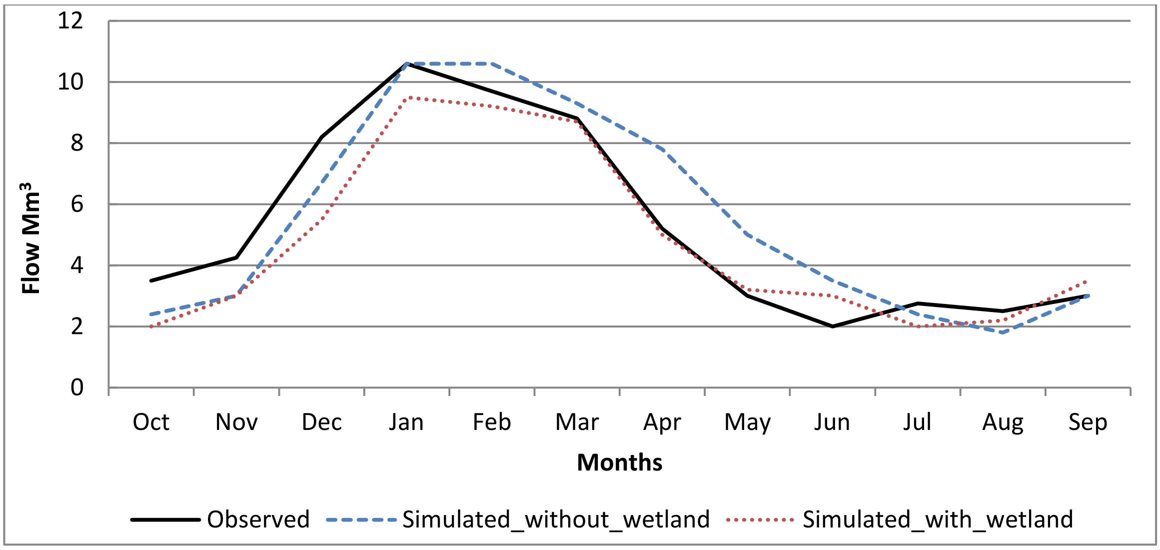


Figure 6.31. Distribution curve for the Lion's river catchment before and after the inclusion of the wetland.

6.3.4.2 Simulation with ACRU model

Parameters used for the configuration of the ACRU model in the Lion's catchment are summarised in Table 6.13. For the sub-catchment area, the quick flow response fraction was kept high than the other catchments (at 0.2), and was constant for all the sub-catchments. The coefficient of base flow response (COFRU), which determines the rate at which groundwater is released from the intermediate zone to streamflow was optimum at 0.0009, which is the value recommended for all basins by the model.

Table 6.12. Final set of parameters used in the Lion's catchment.

Parameters	Lion's
QFRESP	0.2000
COFRU	0.0009
SMDDEP	0
FOREST	0
FPAW	0
CONST	0.5000
EFRDEP	0

The ACRU model simulation of stream flow (Figure 6.32 and Table 6.13) was satisfactory in terms of trends (NSE) and average magnitude (PBIAS). The timing of the flows was produced well unlike some high flows which were not missed by the model. The mean daily flow for the catchment from the observed records was 1.464 m^3s^{-1}, while the simulated mean was 1.435 m^3s^{-1}.

Table 6.13. Statistics and model performance for the ACRU model in the Lion's river.

Objective functions	Values
RMSE	0.54
NSE	0.52
PBIAS	1.96
Observed (Mean)	1.46
Simulated (Mean)	1.43

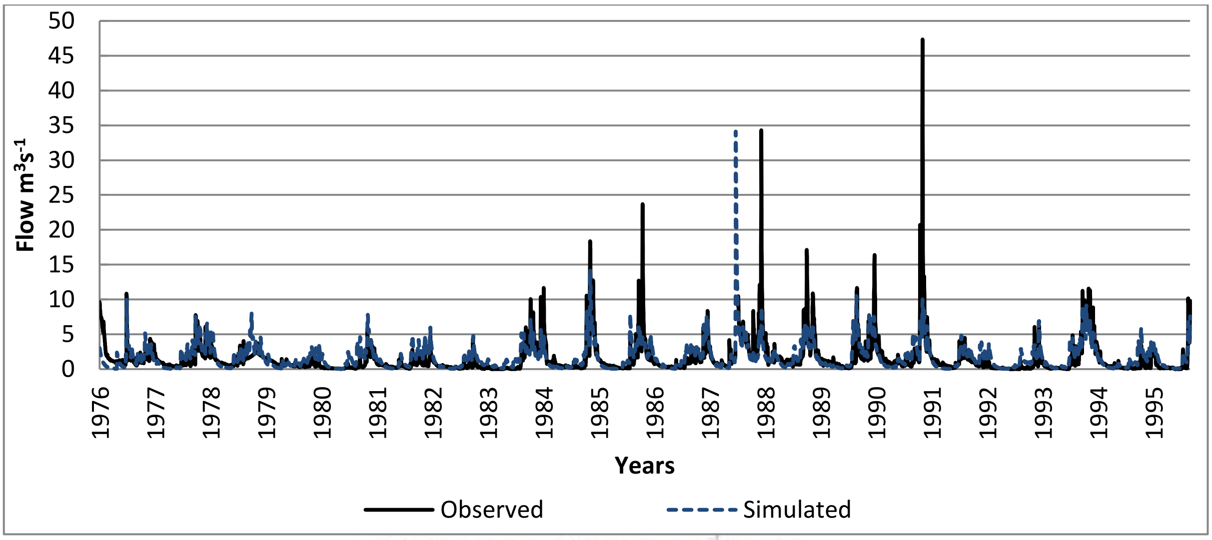


Figure 6.32. ACRU model simulations for the Lions river catchment.

Flows were over-simulated by the model from October to March (Figure 6.33).

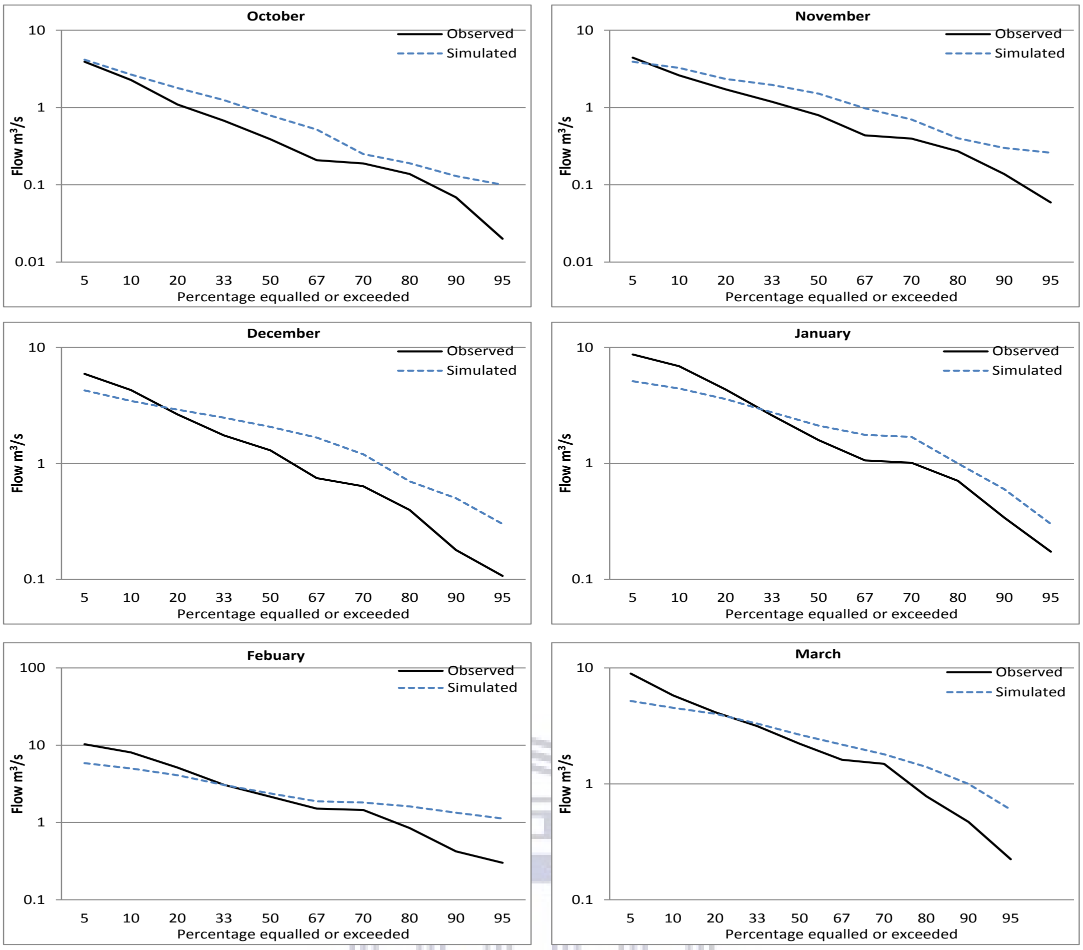


Figure 6.33. Monthly flow duration curves for the Lions river catchment from October to March.

Figure 6.34 shows flow duration curves from April to September, were most low flows occurs in the Lions River catchment.

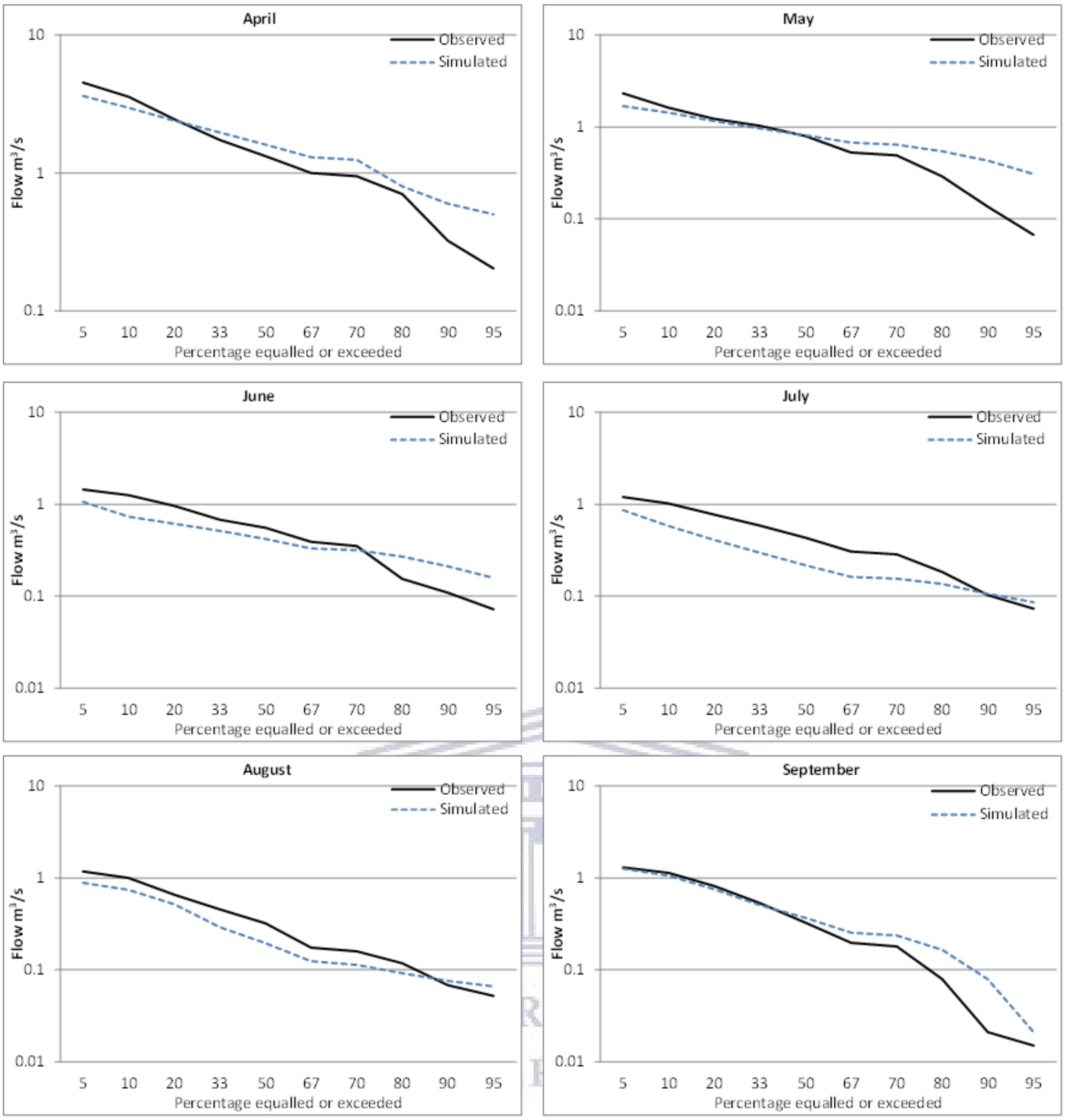


Figure 6.34. Monthly flow duration curves for the Lions river catchment

6.3.5 Closing remarks for hydrological modelling

The objective of this study was to represent the hydrological processes of wetlands and assess the performance of two hydrological models routinely used in South Africa. To achieve this objective, the Pitman and ACRU model were set up. The Pitman model experiment was repeated twice for each catchment where the first simulation was based on the standard approach used for the model which generally ignores wetlands and the second experiment incorporated the wetland module. The ACRU model was only setup once, with the wetland module included. Both models were manually calibrated to produce the best fit for the observed flows. Stream flow data at the outlet of each catchment were used for calibration.

The use of a non-dynamic parameter set makes simulations with especially the monthly Pitman model is a problem for more accurately mimicking runoff-runoff translation processes in a changing environment. This was especially observed in the Mohlapetsi catchment. More research on the use of varying parameter sets with the model would go a long way in correcting this and make the model more robust.

The daily ACRU model however, reproduced the flows better in the Mohlapetsi river catchment than the Pitman. However, the Pitman model performed slightly better in representing the hydrological processes and therefore the flow characteristics in the Bonnie Brook and the Lion’s river catchments. While this comparison is interesting for the models in terms of how they represent the wetland (and related) processes, it is clear that further research and development in this area is required as the simulations were all just about satisfactory. Granted, other factors such as the quality of the observed data may have had an impact on the simulation results.

7 CONCLUSIONS AND RECOMMENDATIONS

This study described how a combination of monitoring, surveys and hydrological models (Pitman and ACRU) can be used to understand the main hydrological processes of wetlands and the interaction of these processes with the processes occurring in the catchment. Monitoring and surveys of hydrological processes of the Elandsdrift-Wiesdrift floodplain has indicated that these processes are to a larger extent controlled by geomorphological and landscape setting of that area. Soil survey and the investigation of soil hydraulic characteristics indicated that soil in the floodplain plays a major role in the formation of riparian and non-riparian ponds. The results from this study indicated that the main hydrological processes resulting in ponding within the floodplain are rainfall and surface runoff. The results did not prove that the Nuwejaars River directly overflows to the floodplain. Moreover, Current understanding of the hydrology of Elandsdrift-Wiesdrift floodplain suggests that the floodplain is dominated by precipitation, overland flow from the catchment area of the floodplain, and evapotranspiration. The role of groundwater was not investigated in this study because of unforeseen challenges (the piezometers needed to be cleaned up and the process took too long thus groundwater data could not be collected), thus inflows are through direct precipitation, overland flow from the surrounding catchment and over bank flooding from the stream to the wetland during high flows while outputs are through evapotranspiration, flow from the wetland to the river and infiltration to the ground.

Theoretical understanding of the hydrological processes of wetlands helped in setting up the hydrological models incorporating wetland processes for the ACRU and Pitman models. This assisted the determination of the impact of the wetlands to catchments response.

Based on the hydrological modelling results, a certain degree of success was obtained in incorporating the hydrological processes of the selected wetlands in both the Pitman and ACRU models (NSE ranged from 0.510 to 0.75 with less than 15% PBIAS values). Most characteristics of the observed flows for the four catchments were satisfactorily simulated.

The inclusion of the wetland modules in the four catchments has shown that with the wetland modules included, the models represented actual processes and though the results were not very good, the models were set up to produce results for the right reasons. There is however potential for improvement of both models though there results could be potentially used in the water resources management considerations of catchments with wetlands. This was evident through the changes in parameters used (especially the Pitman model), which indicated sensitivity to the hydrological processes of the added wetlands. The changes in parameters used contributed to the understanding of variations of different components that influence runoff generation and the function of the wetlands.

Despite satisfactory results for all the catchments, a further improvement in the wetland modules, with more emphasis on methods that are used to estimate the parameters of the wetland is recommended. Parameters in the hydrological models should represent actual hydrological processes that influence runoff generation in basins. Estimation of wetlands parameters for the study was a challenge, and this is especially true for the wetland module of the Pitman model. There is currently no direct method that is used to estimate parameters such as AVC, AVP, RFC and RFP, thus the study recommends further studies that will develop method for parameter estimation of the wetland module.

The overall results from the ACRU and Pitman models indicate that the models can handle hydrological processes of wetlands well. The ACRU model has shown that it can more efficiently pick up daily variations. The Pitman model however has shown that at a monthly scale, the hydrological processes of wetlands can be masked and their impact on catchment water resources, especially for small wetlands, may be difficult to reproduce or observe.

Long term hydrological data is often the basic requirement in analysing the regime of hydrological processes which can be used to draw practical conclusions. This study however monitored the hydrological processes of the floodplain for 1 year and longer term monitoring of the hydrological processes is required to draw realistic conclusions. The study thus recommends that further studies be done in the floodplain to produce a huge bank of long term hydrological data.

Ground water and surface water have been deemed to be interconnected, and groundwater plays an important role in the water balance of a wetland. However, due to unforeseen challenges, the monitoring of groundwater in the floodplain was not possible and groundwater was thus ignored. This has created a gap and uncertainties which have affected the way in which the results were interpreted. The study thus recommends further studies which will include the monitoring of groundwater in the floodplain to ascertain the role (if any) that it plays in the sustenance of the wetland.

Soil samples collected within the floodplain were collected over one period/season. However the moisture content cannot be deemed representative of the moisture content of the floodplain throughout the year. Instruments that will continuously monitor moisture content of the soil (such as probes) and show how moisture content varies compared to rainfall and evapotranspiration are recommended in future studies in the floodplain.

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9 APPENDICES

Appendix Table 1.Physical characteristics of the soil within the Elandsdrift-Wiesdrif floodplain.(i.e. the first number on ID represent the number of transect, the second represent the number of augured hole in that transect and the third number represent the number of depth taken in each hole).

Pit	Transect	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture class	Bulk density	Soil moisture
1	1	0-15	7.4	22.4	70.2	Sandy loam	1.277	0.159
2	1	0-15	3	40.4	56.6	Sandy loam	1.072	0.212
3	1	0-15	14.2	26.6	59.2	Sandy loam	1.201	0.162
		20-50	10	21.2	68.8	Sandy loam	2.162	0.300
		50-80	15.4	38.4	46.2	Loamy	1.452	0.229
4	1	0-15	1.6	25.6	72.8	Sandy loam	1.238	0.592
		20-50	5.8	21.8	72.4	Sandy loam	2.033	0.311
		50-80	4.8	10.2	85	Loamy sand	1.910	0.319
5	1	0-15	7.2	19.4	73.4	Sandy loam	1.406	0.198
		20-50	0.2	34.8	65	Sandy loam	1.820	0.251
1	2	0-15	10.6	32.6	56.8	Sandy loam	1.396	0.094
		20-50	15.6	37.8	46.6	Loamy	1.711	0.361
		50-80	7.2	19.4	73.4	Sandy loam	1.995	0.347
2	2	0-15	5.6	26.8	67.6	Sandy loam	1.380	0.082
		20-50	4.8	29	66.2	Sandy loam	2.031	1.861
3	2	0-15	5.8	22.2	72	Sandy loam	1.193	0.110
		20-50	12	25.8	62.2	Sandy loam	1.805	0.230
4	2	0-15	7.8	38.8	53.4	Sandy loam	0.730	0.240
		20-50	5.2	8.8	86	Loamy sand	1.594	0.307
5	2	0-15	11	28	61	Sandy loam	1.584	0.054
		20-50	13.2	56.4	30.4	Silty loam	1.396	0.289
6	2	0-15	12.6	34	53.4	Medium loam	1.336	0.067
		20-50	7.2	55.2	37.6	Silty loam	1.667	0.322
1	5	0-15	18.6	67.6	13.8	Silt Loam	1.57	0.30
	5	20-50	19.2	72	8.8	Silt Loam	1.53	0.37
2	5	0-15	29.6	40	30.4	Clay Loam	0.66	0.14
	5	20-50	8	35.8	56.2	Sandy Loam	1.78	0.25
3	5	0-15	14.8	29.4	55.8	Sandy Loam	0.96	0.09

Pit	Transect	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture class	Bulk density	Soil moisture
	5	20-50	9.8	70.2	20	Silt Loam	1.55	0.25
4	5	0-15	16	35.6	48.4	Loam	1.03	0.11
	5	20-50	12.8	64.4	22.8	Silt Loam	1.82	0.31
5	5	0-15	5	38	57	Sandy Loam	1.36	0.20
	5	20-50	11.4	48.2	40.4	Loam	1.56	0.33
6	5	0-15	4.4	9.2	86.4	Loamy Sand	1.79	0.24
	5	20-50	10.6	48.6	40.8	Loam	1.58	0.29
1	6	0-15	8.2	74.4	17.4	Silt Loam	1.49	0.34
	6	20-50	3	59.2	37.8	Silt Loam	1.22	0.28
2	6	0-15	5.2	18.6	76.2	Loamy Sand	0.99	0.15
	6	20-50	4	26.8	69.2	Sandy Loam	1.84	0.36
3	6	0-15	8.6	22.8	68.6	Sandy Loam	1.73	0.17
	6	20-50	2.6	13.8	83.6	Loamy Sand	1.89	0.28
4	6	0-15	11.4	49.2	39.4	Loam	1.81	0.11
	6	20-50	4.8	11.8	83.4	Loamy Sand	1.58	0.29
5	6	0-15	4.4	15.4	80.2	Loamy Sand	1.67	0.13
	6	20-50	9	20.8	70.2	Sandy Loam	1.84	0.26
6	6	0-15	10.8	73.2	16	Silt Loam	1.55	0.18
	6	20-50	16	35.2	48.8	Loam	1.26	0.26
1	8	0-15	11.4	18	70.6	Sandy loam	1.594	0.254
		20-50	6	19.6	74.4	Sandy loam	1.743	0.309
2	8	0-15	10	13.4	76.6	Loamy sand	1.079	0.089
			8.4	41.2	50.4	Medium loam	1.624	0.282
3	8	0-15	2	45.2	52.8	Sandy loam	0.841	0.159
		20-50	5.4	23.2	71.4	Sandy loam	1.664	0.326
1	9	0-15	4	16.8	79.2	Loamy sand	1.467	0.076
		20-50	3	25.4	71.6	Sandy loam	1.693	0.238
2	9	0-15	3.8	21.6	74.6	Sandy loam	0.587	0.289
		20-50	3.8	41.4	54.8	Sandy loam	1.481	0.234
3	9	0-15	2	2.2	95.8	Sand	1.349	0.011
		20-50	1.8	22.8	75.4	Sandy loam	1.836	0.297
4	9	0-15	3	15	82	Loamy sand	1.332	0.396

Appendix Table 2. Hydraulic conductivities for the different transects in the floodplain.

Site	**Hydraulic conductivities**
1.1	0.00056
1.2	0.00025
1.3	0.00016
1.4	0.00002
1.5	0.00001
2.1	0.00005
2.2	0.00010
2.3	-0.00002
2.4	0.00007
2.5	-0.00002
5.1	0.00022
5.2	0.00007
5.3	0.00006
5.4	0.00012
5.5	0.00033
5.6	0.00180
6.1	-0.00002
6.2	0.00143
6.3	0.00041
6.4	0.00015
6.5	0.00317
6.6	0.00038
2.6	0.00003
8.1	0.00000
8.2	0.00042
8.3	0.00010
9.1	0.00015
9.2	0.00028
9.3	0.01685
9.4	0.00457