Application of SWAT+ model to assess the hydrology of irrigated agricultural catchments in Western Cape, South Africa

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"**I can do all things through Christ who strengthens me**"

ABSTRACT

Agricultural activities can modify hydrological processes in catchments. An in-depth investigation of the impact of agriculture on hydrological processes is thus crucial for sustainable water management and utilisation planning in agricultural catchments. Hydrological models are widely used as practical tools to estimate and understand hydrological processes at various scales in catchments. However, it is often challenging to represent hydrological processes accurately in agriculture-dominated areas due to their complexity and the structural inadequacy of models. Complexities driven by agricultural developments such as reservoirs, cultivation irrigation, and water transfers are often intricate and difficult to represent in detail.

The current study applied the SWAT+ hydrological model to the agriculture-dominated Twee and Leeu catchments in the Western Cape Province of South Africa. The SWAT+ model was preferred because it is versatile in representing multiple reservoirs and irrigation from multiple sources. The model application aimed to enhance the understanding of hydrological processes and the impact of agricultural water use on catchment hydrology, explore the capabilities and performance of this relatively new version of the SWAT in a complex catchment and provide baseline hydrology input for systems models that were used to formulate a water management plan for the catchment.

The SWAT+ model was able to represent the significant number of reservoirs in the catchment. In some cases, small farm dams had to be lumped together to deal with the model's structural inadequacy. The model performed well in terms of observed and simulated streamflow comparison. NSE and R^2 values above the standard of 0.5 were obtained for both catchments. Moreover, an NSE of 0.7 at a daily time-step simulation was obtained for the Leeu Catchment validation period, indicating a generally impressive SWAT+ performance.

The model indicated that hydrological processes in the area were largely dominated by evapotranspiration, which is expected of semi-arid regions. 55% of the total water input into the Twee quaternary catchment is lost through evapotranspiration, while 22% is converted into surface runoff. Interflow and groundwater flow account for 9% and 9% of the catchment water, respectively. The remaining 5% is distributed to soil moisture and groundwater storage. For the Leeu, the model simulated a loss of 67% of the precipitation through evapotranspiration. Interflow and surface runoff were estimated to be 25% and 24%, respectively. Groundwater

contribution to the stream accounts for 7%. Therefore, evapotranspiration and surface runoff are the dominant processes from a water balance perspective, whereas groundwater flow is also significant.

Agricultural activities impacted the hydrological system significantly, and this is mainly attributed to the construction of numerous reservoirs and the subsequent intensive irrigation in the dry summer periods. The model simulation revealed that the reservoir and irrigation reduced the annual average streamflow by 71% in the Twee Catchment. In the Leeu Catchment, reservoirs and irrigation resulted in an annual average streamflow reduction of 77%. Therefore, agriculture has significantly altered flow patterns in the catchment, particularly downstream areas, during drier years.

In conclusion, understanding of hydrological processes, reservoir and irrigation impact on catchment flow dynamics are the key outcomes that support decision-making regarding sustainable water management and utilisation planning. The broader outcomes, including spatially distributed flows and irrigation demand for different crop types, were used as baseline inputs for systems models that explored various water management options. SWAT+ thus played a crucial role in developing a water management plan for the area. Although the model exhibited some structural deficiencies in representing some catchment complexities, it fairly represented and enhanced our understanding of the hydrological dynamics of the Twee and Leeu Catchments. Additionally, the model has proven to be a versatile tool that can be applied for practical catchment water management in the agriculture-dominated catchments of South Africa.

Keywords: SWAT+, agro-hydrological modelling, hydrological processes, irrigation, reservoirs, agricultural water management

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List of Acronym

ACRU	:	Agricultural Catchments Research Unit
ARC	:	Agricultural Research Council
CFM	:	Cape Farm Mapper
CHIRPS	:	Climate Hazards Group InfraRed Precipitation with Stations
DFFE	:	Department of Forest, Fisheries, and the Environment
DWS	:	Department of Water and Sanitation
ET	:	Evapotranspiration
EWR	:	Environmental Water Requirements
FAO	:	Food and Agricultural Organisation
FRC	:	Freshwater Research Centre
GWFLOW	:	Groundwater flow also referred to as GW discharge in the thesis
HRU	:	Hydrologic Response Units
HWSD	:	Harmonised World Soil Database
IAHS	:	International Association of Hydrological Sciences
LATQ	:	Lateral flow
LSU	:	Landscape units
LUC	:	Land Use/Cover
MAP	:	Mean Annual Precipitation
NPC	:	National Planning Commission
PET	:	Potential Evapotranspiration
PUB	:	Predictions in Ungauged Basins
SANSA	:	South African National Space Agency
SAWS	:	South African Weather Services
SOTER	:	Soil and Terrain Digital Database
SU	:	Stellenbosch University
SURQ	:	Surface runoff
SWAT+	:	Soil and Water Assessment Tool Plus
TOT	:	Total Flow
WRC	:	Water Research Commission

CHAPTER ONE

INTRODUCTION

1.1 Background

Irrigated agriculture remains economically important in South Africa as it provides employment and upliftment to rural communities and brings in foreign exchange earnings (Baleta and Pengram, 2014). In the country, irrigated agriculture accounts for 30% of national agricultural production (Bonthuys, 2018) while producing approximately 90% of high-value export crops such as citrus, pome, stone, deciduous, and subtropical fruits (Van Niekerk et al., 2018). As of 2012, the National Planning Commission (NPC), through the National Development Plan (vision for 2030), has identified irrigated agriculture as a sector with the potential to create about one million new jobs by 2030 (NPC, 2012). The NPC stated that this would be achieved by expanding areas under irrigation by 50% and facilitating the collaboration between existing commercial farmers and land reform beneficiaries (NPC, 2012).

Since irrigation already consumes the largest proportion (63%) of available freshwater, expanding irrigated areas without additional increases in total water use was expected to be achieved by increasing agricultural water use efficiency (Baleta and Pengram, 2014). However, relying solely on increasing efficiency to provide for this expansion is unrealistic due to droughts, expansion of irrigation in areas without previously established withdrawals or sources, poor water management (Cele and Wale, 2018; Meinzen-Dick, 2014) and the expense of technological equipment needed for increasing efficiency.

Expanding areas under irrigation has already been started in many agricultural regions in the country. An increase in water demand with expanding irrigation has been reported, which, with the harsh impacts of droughts accompanied by poor water management, have exacerbated water-related conflicts among commercial and emerging farmers and overexploitation of water resources in water-scarce agricultural regions (Donnenfeld et al., 2018; Mabhaudhi et al., 2018; Paxton and Walker, 2018; Pengelly et al., 2017). These issues often mean that other water user groups such as domestic, industrial and the environment do not get the required supply as outlined in the National Water Act (Department of Water and Sanitation (DWS), 2023).

Increased water demand and water-related conflicts have elevated the need for targeted effective water resources management to ensure a balanced and sustainable water allocation among competing users in water-scarce agricultural catchments (Njoko and Mudhara, 2017). Developing effective and sustainable water management and allocation requires understanding how much water is available in a catchment (Hughes, 2019). Hydrological models are the most practical tools applied to produce variables for estimating hydrological processes and quantify water availability in space and time (Arnold et al., 1998; Beven, 2006; Hughes, 2004; Schulze, 1984). Hydrological models represent the various inputs, storages, and outputs of a catchment's water balance, including both the natural components and the additional impacts of human influence (Hughes, 2004a; Sivapalan and Blöschl, 2017).

In particular, hydrological models attempt to reproduce hydrological processes such as runoff, soil moisture, percolation/recharge, soil moisture and evapotranspiration at different spatial and temporal scales driven by rainfall as input (Glenday et al., 2021). Most hydrological models also comprise routines to represent human activities in a catchment, such as reservoirs, water transfers and withdrawals for irrigation (Bellin et al., 2016; Guug et al., 2020). Therefore, these models can simulate feedback between hydrological and human systems within a catchment. Such information is critical to addressing practical water resource problems (Hughes, 2004a) and improving decision-making capacity regarding sustainable water management and utilisation (Hughes et al., 2020). However, it is acknowledged that the information produced by hydrological models is associated with some degree of uncertainty emanating from input data, model structure and parameterisation (Beven and Alcock, 2012; Hughes et al., 2020).

1.2 Problem statement

The Twee (E21H) and Leeu River (E21G) Catchments are dominated by extensive irrigated agriculture. These catchments are located in the Koue Bokkeveld farming region in the Western Cape Province of South Africa. An extensive network of farm dams has been constructed in the catchments to store winter flows for crop irrigation during the dry summer season. The expansion of irrigated areas is underway, with emerging farmers allocated land through land resettlement programs but not possessing water rights (Paxton and Walker, 2018). The land reform beneficiaries do not hold water rights due to delays in the Validation and Verification (V&V) process, which is the first step towards transferring water rights from previously advantaged farmers to black disadvantaged emerging farmers (Pengelly et al., 2017). Expanding irrigation in this area places excessive pressure on already overstretched water

resources and results in conflicts, which intensified during the 2015 to 2017 drought (Paxton and Walker, 2018).

The overarching issue is that influential corporate farmers upstream of the catchments have dammed a significant portion of the streams, draining water from the upper watersheds. Corporate farmers transfer excess water to their other farms inside and outside the basin to the disadvantage of downstream farmers. Dry period water demand results in shortages for farmers downstream, forcing them to use river flows to meet their high demand to the disadvantage of environmental water requirements (EWR) (Paxton and Walker, 2018). Upstream farmers are expected to release water for downstream farmers in dry periods. If water is not released from upstream, conflicts occur (Paxton and Walker, 2018). When conflicts arise between commercial upstream and downstream farmers, emerging farmers are left without a fair share of water since they do not hold water rights, and EWRs are disregarded. For all these complex water-related issues, no detailed hydrological understanding and information exists that can be used as a baseline for managing the situation. Hence a detailed assessment of the hydrological processes of the Twee and Leeu catchment is conducted in this study.

1.3 Aim of the study

- To improve understanding of the hydrological processes and the impacts of agricultural water use on flow regime in the Twee and Leeu River catchments to support the development of a sustainable water resource management plan.

1.4 Specific objectives of the study

I. To assess the capability and applicability of the SWAT+ model in simulating the hydrological processes in the intensive irrigated Twee and Leeu Catchments.

II. To assess the impact of numerous small reservoirs and irrigation on the hydrological system in the Twee and Leeu River Catchments.

1.5 Significance of the study

Physically based hydrological models with lesser data requirements are often preferred to reproduce hydrological processes in intensively irrigated agricultural catchments in data-scarce regions. However, in most of these models, the representation of a dense network of farm dams and water withdrawals from the system for irrigation is oversimplified due to model structural inadequacies. For instance, spatially distributed farm dams are lumped and presented as one dam at an outlet of sub-basin. Moreover, groundwater is not considered as a source of irrigation,

while in agricultural catchments, it is used to supplement surface water for irrigation, particularly in semi-arid areas (Samimi et al., 2020).

The relatively new version of the SWAT model (SWAT+) applied in this study offers flexibility in representing a spatially distributed farm dam network (Bieger et al., 2017; Wu et al., 2020). Furthermore, the model can represent water withdrawal from a river channel, aquifer, and reservoirs to irrigate crops and account for conjunctive surface and groundwater use for irrigation (Arnold et al., 2018).

The SWAT+ model setup in this study follows an approach to represent irrigated agriculture in a detailed manner. Such an application of the new model version has not been reported in the literature. Therefore, it explores the limits of applicability of this new version of the SWAT model in representing complex irrigated agricultural catchments. Thus, the study aims to offer insights into its applicability and contribute to the discussion on future development perspectives regarding representing farm dams and irrigation in spatially distributed hydrological models. Ultimately, the study reaches towards the frontiers of socio-hydrology (Sivapalan et al., 2012), a recent approach that seeks to represent more effectively human elements within hydrological models.

The hydrological information produced in this study provides baseline input into systems models set up under the broader Water Research Commission project (WRC project number: C2020/2021-00607) that developed a water management plan for the study catchments. These tools include an Agent-Based Model (ABM), which is implemented to explore various management water scenarios, and a novel Water Sharing Tool, which assesses the impact of different water-sharing strategies on the user and ecosystem. The hydrological outputs, such as simulated flows and irrigation demand from this study's modelling task, were used as input to the ABM and the water-sharing tool. It is also anticipated that the calibrated hydrological model produced in this research will provide spatially representative daily flow for an existing water allocation tool that is currently used in the study catchments.

1.6 Outline of the study

This thesis is made up of seven chapters, including the introduction chapter. Information contained in each chapter is briefly described below.

Chapter 2 presents the discussion of water availability status and use in South Africa. A review of dominant hydrological processes in agricultural catchments and human-made hydrological infrastructure commonly found in agricultural catchments was also conducted. Hydrological models routinely used in South Africa for water resource management are reviewed. This was followed by a discussion of uncertainties in modelling agricultural catchments. **Chapter 3** presents the study area description and conceptualisation of catchment hydrology of the Twee and Leeu. **Chapter 4** provides the details of the methodology for this study. This includes processing the data gathered for the model setups and the calibration approach. **Chapter 5** presents the results from the modelling tasks of this study. **Chapter 6** contains a discussion of the results of the models set up. **Chapter 7** provides conclusion and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

South Africa is classified as a water-scarce country. The country's scarce water resource is one of the most important factors limiting food security assurance and the development of the economy. As a result, the extent of water scarcity has become a critical subject of research by hydrologists with a keen interest in exploring the resilience of hydrological systems. Quantifying hydrological cycle components is crucial in ascertaining how much water is available at a catchment scale. A quantitative understanding of water availability is a prerequisite for sustainable water resource management and development. This chapter reviews studies and reports on water resources to discuss the status quo of water availability and usage in South Africa. This is followed by a discussion of the theoretical and empirical understanding of dominant hydrological processes in agricultural catchments. This section also describes the impacts of human activities on the hydrological processes of a catchment. Furthermore, hydrological models routinely applied to quantify and represent hydrological processes of irrigated agricultural catchments with extensive spatial distributed network of human-made hydrological infrastructure are reviewed.

2.2 Overview of water resources in South Africa

Much of South Africa is considered semi-arid. The country receives an annual average rainfall of about 497 mm/year, almost half the world's annual mean rainfall of 860 mm/year (Pitman, 2011). It has been estimated that only 9% of the country’s rainfall is converted into runoff, 4% recharges groundwater storage, while the largest proportion (87%) is lost through evapotranspiration (Colvin et al., 2016; Kahinda and Boroto, 2009). The combined average flow (also referred to as mean annual runoff) of all the rivers in South Africa is estimated to be 49 000 million cubic metres per annum, including river flow from Swaziland and Lesotho (Department of Water and Sanitation (DWS), 2020). The estimated total available yield is 13 227 million cubic metres (Council for Scientific and Industrial Research (CSIR), 2010), with surface water contributing 10 240 million cubic metres, followed by return flow with a contribution of 1 899 million cubic metres and groundwater adding 1 088 million cubic metres per year (Department of Water Affairs and Forestry (DWAF), 2004a).

Since South Africa experiences low and erratic rainfall, dams have been constructed to ensure a reliable water supply. It was reported that there are more than 5 102 registered dams in the

country, and the vast majority of these dams are classified as small dams (including farm dams) and are privately owned (Department of Water and Sanitation (DWS), 2020; Viljoen and Van Der Walt, 2018). As of 2010, the state owned approximately 569 dams, each with a capacity exceeding one million cubic metres and making up a total storage capacity of over 32 400 million cubic meters when combined. State-owned dams are estimated to capture and store about 70% of the country's mean annual runoff (Council for Scientific and Industrial Research (CSIR), 2010; Viljoen and Van Der Walt, 2018). Privately owned dams are not well monitored; therefore, the total volume of runoff they capture is unknown (Colvin et al., 2016). Inter-Basin Transfer (IBT) schemes were also developed to improve the reliability of water availability and supply (Department of Water and Sanitation (DWS), 2020). About 26 IBT schemes have been constructed in South Africa, with a yearly contribution of 3 000 million cubic metres to available surface water yield. In addition, groundwater development has been implemented in many areas of the country to supplement the water supply for domestic use and irrigation requirements (Department of Water and Sanitation (DWA), 2013). DWS (2020) estimated that the country's groundwater potential is approximately 7 500 million cubic metres per annum. However, the estimated groundwater volume currently exploited is between 3 000 and 4 000 million cubic metres per annum (Department of Water and Sanitation (DWS), 2020; Mwendera and Atyosi, 2018).

South Africa's agricultural sector is the largest water user, representing 63% of the total water use (Department of Water and Sanitation (DWS), 2020). The following are domestic use, which accounts for 25% of the total water use. The remaining 12% is shared among other users such as industrial use and power generation (DWS, 2020; Viljoen and Van Der Walt, 2018).

Although South Africa has invested significantly in water resource infrastructure to enhance water security, it is reported that the increasing water demand is outstripping the reliable supply (Department of Water and Sanitation (DWA), 2013; Department of Water and Sanitation (DWS), 2020). DWS (2020) further suggested that the factors leading to this situation are prolonged droughts, population growth and economic development and a limited number of large dams to capture runoff when good rains are received. However, it has also been reported that South Africa has reached the limits of developing surface water resources; therefore, the country is not in a position to build more dams and IBT schemes to keep up with the growing water demands (Department of Environmental Affairs (DEA), 2012; Viljoen and Van Der Walt, 2018)

Although the DWA (2013, 2010) suggest that there is a potential to extend groundwater development to supplement the current water supply, this may not be a sustainable strategy to meet the growing water demand, as the DWS (2020) reported that groundwater levels exhibited a significant decline between 2015 and 2016. Therefore, the abovementioned issues have called for the strict management of available water resources (Department of Environmental Affairs (DEA), 2012; Viljoen and Van Der Walt, 2018)

2.3 Hydrological processes of agricultural catchments

Numerous hydrological investigations have been conducted in the past two decades to understand catchment processes (e.g. Beven and Kirkby, 1979; Hughes, 2007; Li and Sivapalan, 2011; Müller et al., 2009; Nepal et al., 2014; Uhlenbrook et al., 2004). However, many of these studies did not include agricultural activities such as irrigation. It is understood that hydrological processes in agricultural catchments can differ from processes occurring in natural catchments. This is due to modifications farming operations make to catchment physical characteristics (Kienzle and Schmidt, 2008; Nkwasa et al., 2022; Schulz et al., 2021; Tigabu et al., 2019). Dominant hydrological processes that are known to be significantly affected by agricultural practices include infiltration, runoff and evapotranspiration. A brief description of how agronomic practices influence these hydrological processes is presented below. Although rainfall is not directly affected by farming practices, it is briefly discussed in this subsection, as it is a primary input into the catchment water balance (Hughes, 2006, 2004b).

2.3.1 Rainfall

South Africa is characterised by strongly seasonal rainfall which is unevenly distributed across the country (Du Plessis and Burger, 2015; Roffe et al., 2021). Studies suggest that rainfall can vary significantly at a catchment scale (Dias et al., 2015; Kidd, 2001; Morris et al., 2016; Stefanidis and Stathis, 2018). This phenomenon is especially true in mountainous catchments with complex and diverse topography (Arora et al., 2006; Buytaert et al., 2006; Hughes and Wright, 1988; Stefanidis and Stathis, 2018). Considerable uneven spatial distribution of rainfall results highly variation of hydrological processes within a catchment (Arora et al., 2006; Gan et al., 2019; Singh et al., 1995). Hence the spatial variability of rainfall input to a model is critical for reliable simulation of hydrological processes in a catchment (Hughes and Wright, 1988; Lee et al., 2019; Singh and Kumar, 1997).

2.3.2 Impact of agronomic practices on infiltration, runoff and evapotranspiration

Soils play a significant role in partitioning rainfall into infiltration and runoff processes (van Tol and van Zijl, 2022). Studies investigated hydrological processes at a plot scale pointed out that intensive tillage has substantial impact on runoff behaviour in agricultural catchments (Ahuja et al., 1998; Igor et al., 2020; Xu and Mermoud, 2001). Tillage practice breaks down the soil structure and result in increased soil total porosity and reduce bulk density and water holding capacity (Bordoni et al., 2019; Igor et al., 2020; Lobb et al., 2007). These conditions promote high infiltration rates thereby reduce surface runoff (Bormann and Klaassen, 2008; Moussa et al., 2002; Mwendera and Feyen, 1994). On the other hand, studies report that frequent irrigation events in semi-arid agricultural catchments result in continuous water available in soil profile that lost through evapotranspiration (Krishna, 2019; Liebhard et al., 2022; Liu et al., 2022). Consequently, consistent high evapotranspiration rates are reported to occur in intensively irrigated catchments (Riediger et al., 2014; Tulip et al., 2022).

2.4 Human-made hydrological infrastructure in agricultural catchments

Farm dams and water transfer infrastructure have become an integral part of agricultural catchments' landscape in semi-arid regions (Callow and Smettem, 2009; Habets et al., 2014). Studies conducted in many dry parts of the world have reported a rapid increase in the number of farm dams since the 1940s (Habets et al., 2018; Hughes and Mantel, 2010; Meigh, 1995; Schreider et al., 2002). Although farm dams proved to be of economic importance in farming areas of dry regions (Ashraf et al., 2007; Khlifi et al., 2010; Rosa et al., 2020), their cumulative hydrological impacts at a catchment scale have been identified and detailed in numerous studies (e.g. Araújo and Medeiros, 2015; Habets et al., 2014; Hughes and Mantel, 2010; Meigh, 1995; Rabelo et al., 2022).

Based on simulations, investigations report similar outcomes: that farm dams can cause a reduction of 0.2% in annual stream discharge (Hughes and Mantel, 2010), and this reduction in annual streamflow can reach 32% (Meigh, 1995). Since farm dams capture the flow draining through upper watershed tributaries (Araújo and Medeiros, 2015; Habets et al., 2014), they cause discontinuity of flow paths connectivity (Callow and Smettem, 2009; Hughes, 2007) as the spilling frequency from a dam connected to a tributary tends to be significantly low (Araújo and Medeiros, 2015; Qiguang et al., 2017; Rabelo et al., 2022). As a result of these impacts, studies observed drastically reduced flows downstream in agricultural catchments (Abouabdillah et al., 2014; Callow and Smettem, 2009; Habets et al., 2014; Nathan and Lowe, 2012).

2.5 Basic principles of irrigation scheduling

Irrigation scheduling forms a crucial management input to crop production, in many regions around the world, particularly in semi-arid areas. (Yazar et al., 1996). Irrigation scheduling is defined in the literature as the method of determining the appropriate timing and amount of water to apply to the crop for optimal production and to improve water productivity (Goldhamer et al., 2001; Lamm et al., 2015; Jones, 2004; Enciso et al., 2009). Irrigation is commonly scheduled based on direct soil water measurements (Smith and Mullins, 2002), soil water balance (Allen et al.,1999) and plant water stress (Jones, 1999). Agronomists found that soil water-based irrigation schedules are inaccurate and ineffective in enhancing water productivity (Lamm and Rogers, 2015; Jones, 2004, 1999, 1990). Their studies argue that this is because plant physiology directly responds to changes in water status in roots and leaves, not to changes in soil water content.

The reviewed study further highlighted that water status in these plant organs depends on soil water content in the root zone and transpiration demand (Lamm and Rogers, 2015; Jones, 2004). The studies found out that the plant becomes stressed when the water status in leaves does not meet transpiration demand and there is a soil water deficit at the root zone (Lamm and Rogers, 2015; Jones, 2004). This affects the potential and actual plant growth rate (Jones, 1990; Schulze, 1984; Wang et al., 2015). As a result, researchers suggest that the most precise irrigation scheduling is based on plant water stress (Annandale et al., 2011; Jones, 2004; Lamm and Rogers, 2015; Veysia et al., 2017), as this approach is an integration of soil water and evapotranspiration approaches (Davis et al., 2009; Gu et al., 2020; O'Shaughnessy et al., 2017).

2.6 Hydrological Models

The existence of hydrological models goes back to the 1850s, with several ground-breaking upgrades taking place to account for numerous components of the hydrological cycle since the 1960s (Singh, 2018). These models were developed and improved based on the understanding of key hydrological processes acquired from field investigations at plot and hillslope scale, represented in a series of equations (Beven, 2006; Hughes, 2010; Hughes, 2004a). The ultimate goal of developing and applying models is to provide useful hydrological information to support decisions about sustainable water resource management (Arnold et al., 1998; Hughes, 2004b; Schulze, 1984).

Several studies reveal that since the mid-20th century, there has been human intervention in catchments (Montanari et al., 2013; Savenije et al., 2014; Sivapalan et al., 2012) practising

economic activities dominated by irrigated agriculture (Nazemi and Wheater, 2015a; Pouladi et al., 2019; Wada et al., 2017). This resulted in a tighter connection between human activities and hydrological systems (Sivapalan et al., 2012). However, although human intervention is understood to significantly modify hydrological processes through land use dynamics, irrigation and water management strategies such as dams and water diversions (Ashraf et al., 2007; Riediger et al., 2014; Waha et al., 2013), most field studies investigated factors that influence the hydrological processes to improve hydrological models have neglected the spatiotemporal impacts of human activities on water systems (Bellin et al., 2016; Nazemi and Wheater, 2015a). This resulted in classic hydrological models treating human activities as an external force or boundary condition in hydrological systems (Sivapalan, 2015; Sivapalan et al., 2012; Srinivasan et al., 2017). Gleick et al. (2013) and Sivapalan (2015) further argue that when these models are applied in developed catchments, they are highly likely to produce biased hydrological information that can lead to severe shortcomings in water resource management decisions.

To generate fairly accurate relevant information to support decisions regarding water resource management, Hughes (2004a) suggests that a hydrological model needs to have the capability to execute a combined simulation of natural hydrology and human impacts, such as reservoirs and irrigation, at a catchment scale. The International Association of Hydrological Sciences (IAHS), through the Panta Rhei scientific decade initiative (Montanari et al., 2013), also emphasised the necessity of incorporating human components in hydrological models when modelling developed catchments. Since the early 2000s to date, progress in incorporating fairly detailed representations of human activities in hydrological models has been made, even though the representation in some models is still relatively simplified (Bieger et al., 2017; Hughes et al., 2020; Hughes and Mantel, 2010; Singels et al., 2010).

Hydrological model can be classified into lumped, semi-distributed and fully distributed (Sidle, 2021). The classification of hydrological models based on their spatial structure is comprehensively documented. Thus, this section does not encompass the classification of hydrological models; rather, it describes semi-distributed models. Semi-distributed models strike a balance between lumped and fully distributed models (Glenday et al., 2021). Semi-distributed model types offer a fairly detailed representation of spatially distributed catchment physical characteristics including human-made hydrology structures, without intensive data requirements of fully distributed models (Tanner, 2013). These model types are preferred to simulated the hydrology of developed catchments in data scarce areas like South Africa

(Hughes, 2004a). Three semi-distributed hydrological models that have undergone refinements since they were developed to improve the representation of present-day catchment conditions and are routinely applied in South African catchments for water resource management are reviewed in this subsection. The review is limited to the inclusion of selected agricultural-related developments in these hydrological models.

2.6.1 ACRU

The spatial variability in land cover, soils and rainfall in the Agricultural Catchments Research Unit (ACRU) model is accounted for by dividing the catchment area into sub-catchments and hydrologic response units (HRU) by using the model in distributed mode (Jewitt and Schulze, 1999; Kienzle and Schmidt, 2008). The model represents various hydrological processes and the impacts of land use/cover properties on these, including routines to simulate irrigation and account for farm dams (Kienzle and Schmidt, 2008; Schmidt et al., 2009). Irrigation requirements are simulated daily based on soil water budget components and crop parameters (Jewitt and Schulze, 1999).

The agricultural components, namely, irrigation and farm dams, were introduced in the model as part of a study focused on creating an agro-hydrological and agro-climatological atlas for Natal (Schulze, 1984). Since then, the model has been modified to refine the presentation of these agricultural components (Schulze et al., 2004; Singels et al., 2010; Tarboton and Schulze, 1991). Several hydrological studies have tested and applied the ACRU model in agricultural catchments, and the farm dams were included in the model setups as abstraction points for irrigation (Kienzle and Schmidt, 2008; Moult et al., 2009; Shabalala, 2018) and to assess their impacts on streamflow (Tarboton and Schulze, 1992). When a catchment with multiple farm dams is being modelled using ACRU, dams are placed at the outlets of delineated sub-catchments (Tarboton and Schulze, 1992, 1991). If many dams exist in a sub-catchment, their capacities are lumped and modelled as a single dummy dam located at the outlet of the sub-catchment (Clark, 2018; Shabalala, 2018).

Initially, when the agricultural component was introduced in the ACRU model, irrigation could be set up in one of the three scheduling options: plant demand, soil moisture deficit and fixed amount cycle (Schulze, 1984; Tarboton and Schulze, 1991). If the irrigation in the model is set up based on plant demand, water is applied to the soil profile when plant available water drops below the specified fraction at which plant water stress is activated (Schulze, 1984). When this scheduling option is used, irrigation is only initiated to prevent plant water stress. When

irrigation in the ACRU model is based on soil moisture deficit, water is applied to refill the soil profile to field capacity when soil moisture has dried below the specified threshold value (Kienzle and Schmidt, 2008). Schulze (1984) explains that, for example, irrigation water can be applied to 80% of field capacity in this scheduling option, assuming that 20% will be contributed by natural rainfall. Irrigation practice can also be set up based on a fixed amount (in mm) in a fixed number of days or a growing season cycle, with the cycle interrupted by a threshold amount of rainfall on a given day (Schulze, 1984; Warburton et al., 2010).

Additional irrigation scheduling options were incorporated through the refinements of the model structure (Moult, 2005; Moult et al., 2009, 2009). Some of the newly added options are described as follows. Refill the soil profile at the specified moisture depletion level. This scheduling option is similar to soil moisture deficit; the difference between these two is that in a moisture depletion-based schedule, a fixed depletion threshold (below field capacity) to trigger irrigation is specified in mm instead of a fraction. For instance, when soil moisture content drops 30mm below field capacity, 25mm of irrigation is applied, assuming that 5 mm will be filled by rainfall (Moult, 2005). Precise information about actual field irrigation is required to set up a schedule that considers changes in irrigation amounts during the growing season (Moult et al., 2009, 2009; Moult, 2005). For all the scheduling options available in the ACRU model, water for irrigation is sourced from either a dam or, a river or a combination of these two water sources (Schulze et al., 2004; Tarboton and Schulze, 1992). The application of irrigation for each event depends on water availability from the sources (Kienzle and Schmidt, 2008; Moult, 2005).

2.6.2 Pitman Model

Since the Pitman model (Pitman, 1973) is widely used in Southern Africa for water resource assessments and management (Hughes, 1992), it has undergone several revisions to ensure that its structure accounts for spatial variation of catchment physical characteristics such as rainfall, land use/cover and soils and the development impacts (Hughes, 2013, 2007). The revisions done in Pitman resulted in several versions of the model (Hughes, 2007). One of the model's most recent versions is applied through an integrated software package, Spatial and Time Series Information Modelling (SPATSIM) (Hughes and Forsyth, 2006). SPATSIM represents a semi-distributed implementation of the model, whereby the spatial variability of catchment characteristics is facilitated through modelling each defined sub-basin with independent hydro-meteorological inputs and parameter sets (Hughes, 2004c; Hughes et al., 2006). The model also

incorporated components to represent the impacts of human activities, such as distributed farm dams and water abstractions for irrigation (Hughes, 2007, 2004c).

The Pitman model has been applied in developed catchments to estimate the impacts of farm dams on natural hydrology and simulate water abstraction from the system (Hughes et al., 2020, 2006; Hughes and Mantel, 2010; Oosthuizen, 2018). The representation of distributed farm dams in Pitman is at the sub-basin scale and so requires lumping all the dams' capacity within each sub-basin to form one dam storage, which is then defined at the outlet of a sub-basin using the parameter: maximum small dam storage capacity "DSTORE" (Hughes, 2007; Hughes and Mantel, 2010). The proportion of the sub-basin contributing simulated runoff to the dam is defined with the parameter: percentage of sub-basin above dams "DAREA" (Hughes et al., 2020; Hughes and Mantel, 2010). Water abstractions for irrigation purposes are presented using either one of two parameters, namely, irrigation area from dams (km^2) "IrrAreaDmd" and irrigation area (km^2) "AIRR" (Hughes et al., 2006; Oosthuizen, 2018). IrrAreaDmd is used to define a dam as a source for irrigation, while AIRR is used to abstract irrigation water directly from the river channel. Irrigation water demand (mm) is a required input to specify the amount of water to be abstracted from the sources (Hughes, 2004c). The model performs irrigation operations if the currently available water in the storage is sufficient to meet irrigation requirements (Hughes and Mantel, 2010).

2.6.3 SWAT+

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998) is considered an eco- and agro-hydrological model as it was designed to be suitable for application in intensive agricultural catchments for modelling hydrological processes and the impacts of agricultural practices on water resources (Gassman et al., 2007; Srinivasan et al., 2010). In the last twenty years since its inception, the model has emerged as one of the most extensively utilised models globally, demonstrating its ability to assess human activities' effects on hydrological systems (Bieger et al., 2019; Srinivasan et al., 2010; Wu et al., 2020; Xie and Cui, 2011).

Even though the applications of SWAT across the world exhibited the model's flexibility and effectiveness in evaluating feedback between hydrological and human systems, several model weaknesses and limitations have been identified and revealed. For instance, (i) it was pointed out that the reservoir module in the model was simplistic, resulting in limitations in the spatial representation of a dense network of reservoirs and less accurate estimation of reservoir releases (Khan et al., 2017; Rabelo et al., 2021; Wu et al., 2020; Xie and Cui, 2011), (ii) SWAT

models agricultural land use through a single growing cycle annually (Neitsch et al., 2011), therefore neglecting multiple cropping cycles within a year, which are in reality practised in agricultural catchments (Nkwasa et al., 2020; Van Griensven et al., 2012).

The SWAT development group, in collaboration with scientists worldwide, has addressed several of the identified issues (Chen et al., 2017; McInerney et al., 2018; Gassman et al., 2007; Wu et al., 2020). However, the developers realised the need for further modifications and improvements in the model structure to enhance its capabilities to represent the present-day catchment conditions as realistically as possible (Bieger et al., 2017; Wu et al., 2020; Yen et al., 2019). These significant modifications resulted in SWAT+, a revised version of the SWAT model (Arnold et al., 2018; Bieger et al., 2017). Due to its recent introduction, SWAT+ has only been applied in a limited number of studies (Arnold et al., 2018; Bieger et al., 2019; Msigwa et al., 2022; Nkwasa et al., 2020; White et al., 2022; Wu et al., 2020). The studies highlighted that SWAT+ provides greater flexibility in spatially representing objects, such as HRU, aquifers, reservoirs, and hydrologic interactions between the objects, to ensure that catchment physical characteristics are accounted for reasonably. Additional spatial elements are integrated into SWAT+ to enhance the model's ability to simulate human utilisation of land and water resources. These include canals, pumps, animal herds, and water rights (Bieger et al., 2017).

The landscape characteristics of agricultural catchments, such as a dense network of farm dams, can be spatially represented as realistically as possible in SWAT+. Reservoirs are no longer required to be placed at sub-basin outlets; they can be defined anywhere in the catchment but on a channel or a stream. The SWAT+ model can take account of land use dynamics such as a wide variety of crops growing at the same time and multiple cropping cycles and agricultural management operations such as tillage and irrigation (Bieger et al., 2017; Nkwasa et al., 2020), that are commonly practised in farming catchments (Msigwa et al., 2022). The land use dynamics in the model can be represented through the plant community file constituted under the land use file (Figure 2.1). The timing of planting and harvesting for individual crops within the community is defined in the management schedule file (Msigwa et al., 2022; Nkwasa et al., 2020).

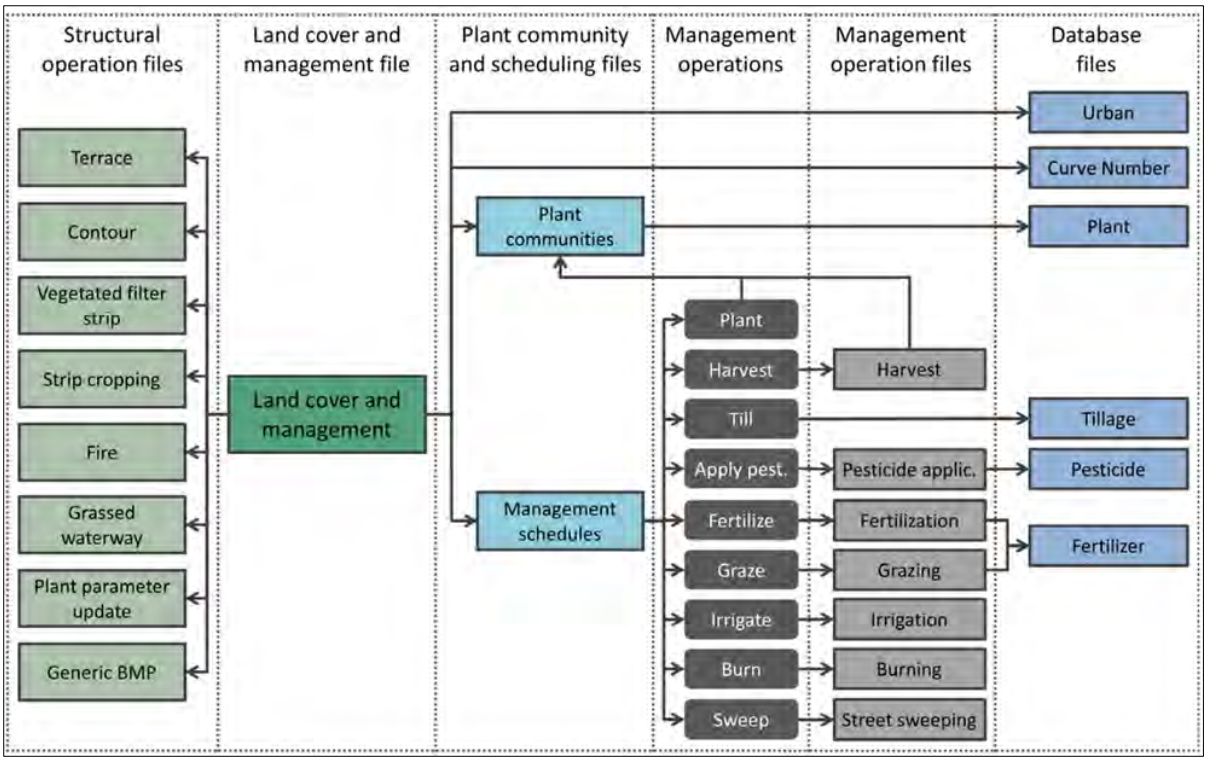

Figure 2. 1: Organisation of the land use/cover and management files in SWAT+ (Bieger et al., 2017).

Management operations in SWAT+ can be presented using management schedules (Figure 2.1) or decision tables, or both. However, decision tables are argued to offer greater flexibility in representing agricultural management practices (Nkwasa et al., 2020). Irrigation can be scheduled manually or through automatic irrigation functions. When irrigation is implemented through manual scheduling, data regarding the exact amount for specific dates is required as input into the model (Arnold et al., 2012). As a result, this scheduling option is hardly used as the required information is not always readily available (Chen et al., 2020). Therefore, irrigation is mostly represented through one of the two auto-irrigation scheduling functions based exclusively on plant water stress or soil water deficit (Arnold et al., 2018; Chen et al., 2017; Nkwasa et al., 2020; Padhiary et al., 2020). Water for irrigation can be abstracted from a reservoir, river channel, or aquifer.

A combination of two water sources can be used in one irrigation schedule, one as a primary source and the other as a backup. For instance, a reservoir or river channel can be used as the primary source and an aquifer as a backup (Arnold et al., 2012). The complex set of rules and conditions for scheduling irrigation applications, such as HRU to be irrigated, water sources, irrigation amount, water stress threshold or soil water deficit threshold to trigger irrigation, as well as the threshold for switching from a primary to a backup source, are specified in decision tables (Arnold et al., 2018). If, for example, the user did not specify the irrigation amount and

source in the decision table, the model assigns a default amount of 25.4 mm for irrigation from any source with sufficient available water (Chen et al., 2017). When the specified irrigation amount exceeds the required amount to fill the soil profile up to field capacity, the surplus is returned to the water source (Dechmi et al., 2012; Neitsch et al., 2011) and not taken into account in the calculation of the daily soil water balance (Dechmi et al., 2021).

2.7 Uncertainties in modelling agricultural catchments

Although there have been improvements in hydrological models over the last decades to ensure that catchment physical characteristics are represented as realistically as possible, the issue of uncertainty in hydrological modelling remains (Liu and Gupta, 2007; Nazemi and Wheater, 2015a). This issue has been a major concern in hydrological modelling (Beven, 1996, 1993) and resulted in IAHS giving it targeted attention through the Predictions in Ungauged Basins (PUB) initiative (Sivapalan et al., 2003). Sources of uncertainty and proposed approaches to reduce uncertainty in hydrological simulations have been discussed by hydrologists across the world to contribute to the PUB initiative (e.g. Beven, 2016; Kapangaziwiri et al., 2012; Liu and Gupta, 2007; Refsgaard et al., 2006; Wagener and Gupta, 2005; Wagener and Montanari, 2011). However, the question of how best these uncertainties can be reduced in modelling remains (Beven, 2006; Wagener and Gupta, 2005). Beven (2006) further argues that the approach to completely avoid uncertainties in hydrological modelling is the “Holy Grail” of scientific hydrology.

Nevertheless, hydrologists advise that good modelling practice requires understanding uncertainties and their sources so that they can be appropriately considered in modelling and communicated accordingly to water management decision-makers, thereby allowing for an appropriate degree of confidence in the model outputs (Beven, 2016; Faulkner et al., 2007; Kapangaziwiri et al., 2012; Reichert and Borsuk, 2005; Wagener and Gupta, 2005). The cited literature detailed that uncertainties in hydrological modelling emanate from the following sources: input and baseline data, parameters, and model structure. Uncertainties related to input and baseline data, as well as parameter and model structural uncertainty, are reviewed in this subsection.

2.7.1 Input and baseline data, parameters, and structural uncertainty

Ensuring that hydrological models capture the spatial variability of catchment physical characteristics and development impacts resulted in additional data requirements. The data required to set up hydrological models are often either not readily available or are of poor

quality, especially in Southern African regions (Hughes, 2007; Kapangaziwiri et al., 2012; van Tol and van Zijl, 2022). Many studies on uncertainties related to information for setting up and driving a hydrological model have focused primarily on hydro-meteorological data and omitted soil parameters (e.g. Tumbo, 2015; Wagener and Montanari, 2011), while soil parameters are also considered an important input (Beven, 1983), which significantly influences runoff processes (Harrison et al., 2022; Smit and van Tol, 2022). Furthermore, there is an increasing concern regarding the data about human systems within a catchment scale (Nazemi and Wheater, 2015a, 2015b; Westerberg et al., 2017).

2.7.1.1 Input and baseline data uncertainty.

The model-forcing input data, such as rainfall, remains a dominant source of uncertainty in hydrological modelling in most cases, especially in data-scarce regions like South Africa (Hughes, 2013, 2007; Kapangaziwiri et al., 2012). Since the rainfall input in hydrological modelling should be as spatially and temporally representative as possible (Pitman and Bailey, 2021), the sparse distribution of rainfall stations and high spatial variation of rainfall in catchments make the uncertainty associated with this input unavoidable (Du Plessis and Schloms, 2017; Hughes, 2013; Hughes and Mantel, 2010). The availability of rainfall data is further reduced by the steady decline of rainfall gauges in operation (Hughes, 2007; Pitman and Bailey, 2021). Satellite-based products such as Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) and Climate Research Unit (CRU) are often used to fill the gaps in available rainfall records or are used as the sole rainfall data source for hydrological simulations. However, Luo et al. (2019) and Pitman and Bailey (2021) found that CHIRPS data can considerably underestimate rainfall in South African catchments, especially in winter rainfall areas. Hughes et al. (2020) and Shi et al. (2017) reported similar findings for CRU rainfall. Hughes et al. (2020) demonstrated that CRU rainfall data can introduce a high level of uncertainty in model setups and outputs.

Detailed information about human dynamics is required to accurately simulate development impacts on hydrology (Nazemi and Wheater, 2015a). The streamflow is affected by upstream water abstractions, transfers and diversion, and the exact data about these human actions is rarely available (Kapangaziwiri et al., 2012). Accurate representation of water transfers and abstractions for irrigation purposes in a hydrological model requires sufficient information about the actual amount of water and timing of irrigation as well as the amount to be transferred from one storage to another, as input into the model (Arnold et al., 2018; Hughes et al., 2020; Woo et al., 2021; Wu et al., 2020). Due to the unavailability of this information, automatic

irrigation functions are used in hydrological models to represent water abstractions (Arnold et al., 2018; Chen et al., 2020; Dechmi et al., 2021), and many assumptions are made regarding irrigation techniques, volumes of water storages and transfers (Beharry et al., 2021; Nazemi and Wheater, 2015a; Woo et al., 2021; Wu et al., 2020). Nazemi and Wheater (2015a) and Westerberg et al. (2017) note how the assumptions made due to the lack of such data introduce significant uncertainty in modelling the impact of human activities on hydrological systems.

2.7.1.2 Parameter uncertainty

Hydrological models simulate processes such as infiltration and runoff based on soil parameters of different soil types (Bormann and Klaassen, 2008; Schmocker-Fackel et al., 2007). Model applications in specific sites where soil parameters were measured and used as input into the model demonstrated reasonably accurate results and reported to reduce parameter calibration uncertainty (e.g. Gagkas et al., 2021; van Tol et al., 2021; Wahren et al., 2016; van Tol et al., 2015; van Tol and van Zijl, 2022). Unfortunately, the soil datasets available in South Africa (e.g. Agricultural Research Council Land Types Database (ARC Survey, 1972)) do not include direct measurements of many of the soil hydraulic properties required for hydrological modelling (Paterson et al., 2015; van Tol and van Zijl, 2022). This is because the soil information available was mainly compiled for agricultural purposes (Paterson et al., 2015). Furthermore, it is argued that conducting a survey of spatial variation of soil hydraulic properties is expensive and time-consuming (Smit and van Tol, 2022).

An effort to transform the Land Types (ARC Survey, 1972) into suitable information for hydrological modelling has been made by (Schulze et al., 2004), and the updated soil information has been used in the ACRU model. However, the values of soil parameters of broader Land Types, considered a single unit, were averaged (van Tol and van Zijl, 2022). Alternatively, soil hydraulic parameters from the Soil and Terrain Digital Database (SOTER) are used for hydrological modelling. Although the SOTER database for South Africa is considered very detailed in terms of spatial resolution (Dewitte et al., 2013; Dijkshoorn, 2003), it misses some important required properties for hydrological modelling (Shangguan et al., 2014), as it was developed based on ARC Land Types Survey (Dijkshoorn, 2003; Dijkshoorn et al., 2008). While there are missing parameters such as maximum rooting depth and saturated hydraulic conductivity in the SOTER database, estimates for important available soil parameters were made using a Pedotransfer functions approach (Batjes, 2004). Therefore, it can be conceded that the soil information generally used in South Africa for hydrological modelling is of decent but not good quality.

2.7.1.3 Model structural uncertainty

Structural uncertainty is an inherent attribute of hydrological modelling that stems from the oversimplification of assumptions and/or epistemic errors made in the selection of which catchment dynamics to represent, the way they are represented and the equations used to represent them (Beven, 2016; Gupta et al., 2012; Hublart et al., 2015; Renard et al., 2010). Spatial and temporal representation of hydrologic state variables and processes is determined by the model structure, interacting with the scale of needed input data, which processes can be explicitly represented, and how model outputs and model uncertainty can be evaluated (Liu and Gupta, 2007; Neuman, 2003; Renard et al., 2010). Hence, these studies conclude that model structure uncertainty is most obviously imposed by lumped and oversimplified approaches for representing hydrological features of the system at a coarse spatial and temporal scale. The studies further note that lumped and oversimplified approaches result in inadequacies of a model structure in capturing all relevant hydrological components in a catchment (Liu and Gupta, 2007; Renard et al., 2010).

Since a dense network of reservoirs characterises agricultural catchments, a significant source of model structural uncertainty can lie in lumping all reservoirs into a single reservoir storage at the outlet when modelling such catchments (Clark, 2018; Hughes and Mantel, 2010; Oosthuizen, 2018). Lumping reservoirs does not account for spatial variation of hydrological processes within sub-catchments (Hughes and Mantel, 2010; Rabelo et al., 2021) as processes occurring among reservoirs differ depending on the reservoir surface area, the size of the channel the reservoir is connected to or pattern of drainage network feeding the reservoirs (Habets et al., 2018; Araújo and Medeiros, 2015; Qiguang et al., 2017). Studies had shown that the simplistic representation of lumping reservoirs results in not adequately capturing hydrological discontinuity, which can manifest in considerable delays in flows (Abouabdillah et al., 2014; Callow and Smettem, 2009; Rabelo et al., 2021). A related uncertainty issue is associated with not capturing short-term variations in reservoir storages and spillage volumes if a monthly time-step operating model is applied (Hughes and Mantel, 2010).

The reality in agricultural areas is that irrigation amounts and events correspond to crop phenological stages (Jones, 2004, 1990; Nkwasa et al., 2022), and a crop can be irrigated from different sources such as reservoir, river channels and aquifers in a single growing season depending on the availability of water in each source (Bieger et al., 2017; Neitsch et al., 2011). However, many hydrological models apply constant irrigation amounts to crops over the entire growing season and only consider surface water sources for irrigation (e.g. Chen et al., 2017;

Hughes and Mantel, 2010; Kienzle and Schmidt, 2008; Moult et al., 2009; Oosthuizen, 2018; Warburton et al., 2010). The model's inadequacies in representing changes in irrigation water requirements over time and abstractions from all available different water storages can lead to inaccuracies in model predictions of streamflow, agricultural water use, and other fluxes and stores in the catchment that may be of interest (Habets et al., 2018; Lebon et al., 2022). Without field data to evaluate these outputs, the degree of this inaccuracy would remain uncertain.

Many hydrological models are built in such a way that they consider soil hydraulic parameters constant throughout the simulation period. They often account for spatial variation of soil characteristics, however, their parameterisation remains constant over time (Alletto and Coquet, 2009; Bormann et al., 2007; Bormann and Klaassen, 2008). However, hydrological models behave very sensitively towards soil parameters (Bormann et al., 2007; Grangeon et al., 2022; van Tol et al., 2022). Hydraulic properties of agricultural soils are reported to be constantly changing throughout a single growing season due to agronomic practices (Alletto and Coquet, 2009; Bormann and Klaassen, 2008; Grangeon et al., 2022; Kool et al., 2019). Therefore, the inability of hydrological models to account for temporal variations of soil parameters adds to model output uncertainties related to the model structure. Although measure the spatiotemporal variation of soil parameters is costly and time-consuming (Angulo-Jaramillo et al., 2000; Smit and van Tol, 2022; van Tol and van Zijl, 2022), neglecting their temporal variability in hydrological modelling is heavily criticised as due to limits the accuracy in simulating runoff dynamics in agricultural catchments (Bormann et al., 2007; Bormann and Klaassen, 2008; Grangeon et al., 2022).

2.8 Selection of a model

The selection of a hydrological model is primarily influenced by the objectives of the modelling exercise (Tanner, 2013). The other factors that influence model selection include input data availability, a model's capability to represent dominant features, and the process of a catchment to be modelled (Glenday et al., 2021). For this research, model selection criteria were primarily based on the model's ability to represent spatially distributed farm dams as realistically as possible and to consider the combined utilisation of surface and groundwater for crop irrigation within a single growing season while requiring a reasonable amount of data. The reviewed hydrological models above can represent the hydrological processes in agricultural catchments. However, ACRU and Pitman models represent spatially distributed farm dams and irrigation water abstraction in a relatively simplified approach by lumping dams, and not considering

groundwater for irrigation, which is often used in semi-arid agricultural areas as a backup to surface water.

Even though the SWAT+ is not a gridded numerical model like MIKE SHE (which would be unrealistically due to its intensive data requirements), the model offers flexibility regarding the detailed representation of hydrological structures with an extensive spatial distribution (Wu et al., 2020). SWAT+ can also represent water abstraction from multiple sources for crop irrigation in a single irrigation schedule and include groundwater as a backup source (Arnold et al., 2018; Bieger et al., 2017). However, there is still an option in the model to set groundwater as a primary source of irrigation. The level of detail SWAT+ offers in representing spatially distributed reservoirs and water abstraction from different sources for irrigation was the first factor that led to the selection of this model in the current study.

Data availability and quality are essential for semi-arid agricultural catchments, which experience extreme climatic events such as droughts and floods. A successful application of a hydrological model in such catchments requires detailed data about catchment physical attributes and attributes of cultivated crops and reservoir and irrigation operations (Samimi et al., 2020). However, such data is not always readily available in regions such as Southern African countries (Hughes and Farinosi, 2020; Kapangaziwiri et al., 2012). The SWAT+ is suitable for simulating hydrological processes in semi-arid agricultural catchments in the data-scarce region as the model is distributed, detailed, and requiring a reasonable amount of data. Moreover, the SWAT model has inbuilt functions such as a weather generator auto-irrigation and contains a database with soil and crop parameters to infill missing data, thereby coping with data unavailability issues (Samimi et al., 2020). Therefore, the SWAT+ model was preferred for this study as it is a detailed distributed model that requires a reasonable amount of input data.

The other important factor that contributed to the decision to select SWAT+ for this study is the fact that the model allows the delineation of upland and lowland (riparian zone) landscape units (LSU) based on the DEM to improve the representation of hydrological processes at hillslope and valley floors (Bieger et al., 2019). This was relevant to quantitatively represent the flow processes described in the conceptual model developed in this study reasonably. Furthermore, the SWAT+ model has recently been applied successfully in irrigated agricultural catchments (Čerkasova et al., 2023; Nkwasa et al., 2023, 2022, 2020; Wu et al., 2020).

2.9 Summary

Many arid to semi-arid regions in the world experience water scarcity because of low rainfall amounts and highly variable rainfall patterns. Farm dams are constructed in agricultural catchments of semi-arid regions to ensure water availability for irrigation in dry periods. Literature notes that farm dams and agronomic practices such as irrigation modify catchment hydrological processes. Therefore, a detailed investigation of hydrological processes and how the hydrological regime responds to farming developments is crucial to support decisions regarding sustainable water management in agricultural catchments.

Over the last decade, efforts have been made to improve the capability of hydrological models to represent reservoirs and agronomic practices as realistically as possible so that detailed studies of hydrological processes in agricultural catchments can be carried out. Even though hydrological models have undergone refinements, they still vary in their capabilities to represent agricultural developments. The differences in models' capabilities to account for conditions of agriculture catchments largely stem from their structural adequacies. For example, the ACRU and Pitman models reviewed above lump farm dams, while the SWAT+ is more flexible in representing spatially distributed farm dams.

Although hydrological models remain essential practical tools to provide insights into the hydrological processes to improve decision-making capacity regarding sustainable water management, information that these models produce is often associated with a certain degree of uncertainty resulting from a combination of sources such as input data limitation, model structure and parameter estimation. The literature highlighted that there is no proven best way of reducing uncertainty in hydrological modelling. However, applying a hydrological model with a structure that allows the spatial representation of distributed hydrological state variables in a catchment as realistically as possible can help reduce uncertainty to a certain degree. However, large amounts of data are required to evaluate the accuracy of model outputs at different scales. Where data are unavailable to verify all simulated hydrological processes of interest, the degree of accuracy would remain uncertain. In such cases, it is critical to communicate uncertainty transparently to stakeholders and decision-makers to foster confidence in model results and support robust water resources management strategies.

CHAPTER THREE

CATCHMENT HYDROLOGY CONCEPTUALISATION

3.1 Introduction

This chapter gives an overview of the catchment's hydrology. It begins with a brief overview of the study area characteristics such as location, demographics, land, and water use. The overview is followed by a conceptualisation of the catchment hydrological processes which is a departure from the standard report of catchment physical characteristics. The catchment's physical characteristics are used to produce a detailed conceptual model which is critical for an appropriate set up of the model. This chapter also details some of the data processing approaches necessary for the conceptual model. The conceptualisation describes the catchment's physical characteristics and how they influence the flow regime in detail, simultaneously informing model development for this study.

3.2 Study area description

3.2.1 Location of Koue Bokkeveld

The study area combines two quaternary catchments, E21H and E21G, of the Twee and Leeu Rivers, respectively. These quaternary catchments cover an area of 66 250, 83 hectares (ha) combined and form part of the Koue Bokkeveld secondary catchment (E21). The Koue Bokkeveld (33° 7' 59" South, 19° 22' 59" East) is located east of Ceres town on the northern side of the Western Cape Province, South Africa (Vos, 2014) (Figure 3.1). The landscape of the catchment is complex, with defining attributes including topography, geology, soils, vegetation, climate, and hydrology (Vos, 2014). These attributes are analysed and detailed in this chapter.

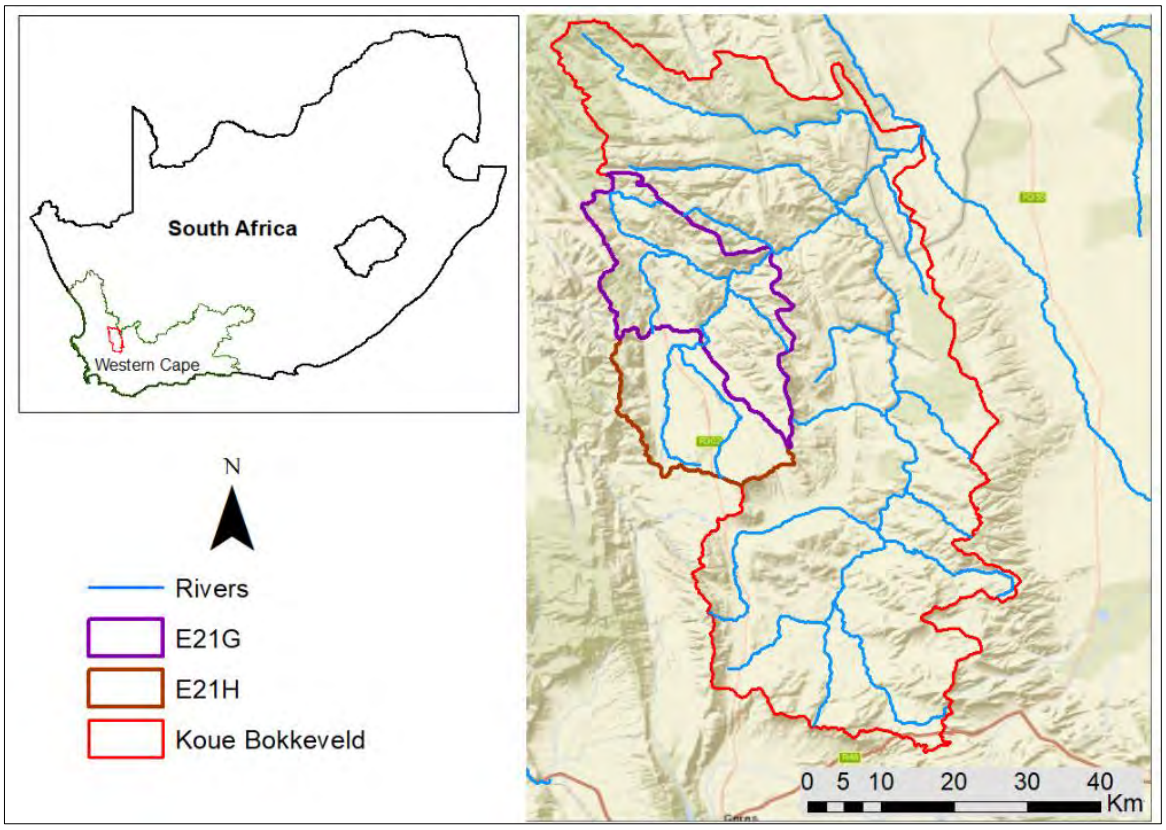

Figure 3.1: The Leeu (E21G) and Twee (E21H) Catchments are situated in the Koue Bokkeveld secondary catchment (E21) in the Western Cape Province of South Africa.

3.1.2 Land and Water resource utilisation

Irrigated agriculture is the primary land use in the catchments (Dube, 2006; Tanner et al., 2020). The growing season in the study catchments generally starts in October and ends in May of the following year, with intensive irrigation occurring within this period (Dzikiti et al., 2018). However, crops such as blueberry are grown between April and September (Steyn et al., 2023), while triticale is generally grown in winter. The dominating crops grown in the area are deciduous (apples and pears) and stone fruits (apricot, nectarine and peach) (Anchor Environmental Consultants (AEC), 2007; Dube, 2006; Vos, 2014). Agriculture has expanded significantly to include annual crops such as potatoes and onions, particularly in the Leeu Catchment (Vos, 2014). Irrigation constitutes 98% of water use in the catchments (DWFF, 2005). Irrigation water is stored in farm dams. Groundwater is abstracted during summer to supplement irrigation water from dams and rivers (DWFF, 2005; Vos, 2014).

3.1.3 Demography

The Koue Bokkeveld area, where Twee and Leeu quaternaries are situated, accommodates one small town called Op-die-Berg. The town is considered an agricultural service centre and Agri-village and was established approximately 50 years ago (Vos, 2014). The total population of

Witzenberg local municipality, where the town falls, was recorded to be 142 466 as of 2017 (including the 11 000 population of Op-die-Berg) (Witzenberg Municipality, 2017). This local municipality's total population consists of 74% coloured, 18% black, and 8% white. The recorded unemployment was 5 339 people in this local municipality (Witzenberg Municipality, 2017). Agriculture provides employment to the majority of the population in the area.

3.2 Catchment hydrology conceptualisation

The 4th scientific objective of the Prediction in Ungauged Basins (PUB) initiative emphasises the importance of understanding runoff processes before developing a hydrological model and applying a hydrological model in ungauged catchments (Sivapalan et al., 2003), especially in areas where water management issues are apparent (Tetzlaff et al., 2007). Such an understanding can significantly contribute to decision-making about water resources management, particularly regarding issues related to land use management (Hughes, 2010). It is critical first to understand how the spatial arrangement of the catchment's physical characteristics, such as topography, land cover/use, soils and geology, and landscape organisation, influence flow pathways when conducting a hydrological assessment study for management purposes.

This study developed a conceptual model to understand and describe how water flows through the catchment landscapes. Water flows described in the conceptual model include the surface and subsurface flows and their interaction. The term "conceptual model" used in this study refers to the description of what is known about catchment processes, flows and their connections in the form of diagrams. It does not refer to a “conceptual numerical model” with a series of equations developed based on an understanding of catchment processes. The conceptual model for this study was generated based on the information derived from analysing digital datasets for catchment physical characteristics. These datasets include Stellenbosch University 5-meter DEM, land use/cover, soils and geology, and rainfall records (Table 3.1). Information about springs observed by farmers in the catchments was also incorporated into the development of the conceptual model. Information related to springs was accessed from the data gathered through the workshops conducted in the study catchment through the broader Water Research Commission project (No. C2020/2021-00607) completed by Gwapedza et al. (2024).

There were several studies conducted prior (Dunne and Black, 1970; Hewlett and Hibbert, 1967; Thomas et al., 1998) and during the PUB initiative decade (Tetzlaff et al., 2007; Schmocker-Fackel et al., 2007; van Tol et al., 2010; Wolock et al., 2004), to explore hydrological processes at hillslope and small catchment scale. Also, several studies have described flows through Table Mountain Group (TMG) geology, which dominates catchments in South Africa (e.g. Hughes, 2010; Lin et al., 2014; Tanner, 2013; Xu and Beekman, 2019). Terminologies and approaches used in these previous studies to describe dominant runoff processes across typical catchment landscapes and aquifers are adopted for the conceptual model of the current study. Geographic Information System (GIS) techniques were used to analyse and visualise the terrain and spatial distribution of the physical characteristics of the catchment.

3.3 Method to Develop a Conceptual Model

3.3.1 Catchment and stream network delineation

To describe surface water flow patterns of the Twee (E21H) and Leeu (E21G) catchments, the catchment area was divided into sub-catchments with major tributaries draining from upper watersheds. The sub-catchments were delineated using the 5-metre SU-DEM in ArcGIS 10.8. Detailed surface flow direction and accumulation for each sub-basin feeding into the main channel were also created from the DEM in ArcGIS 10.8. The delineated flow direction and accumulation showed that water in each sub-basin of the catchments flows from upper watersheds through multiple minor tributaries draining from steep-sided rock mountains and into a major tributary feeding into the main river channel. The major tributary channels are located at the central valley in each sub-basin, and the main river channel flows in the centre of the valley floor. The floodplain along the main river channel at the centre of the valley was delineated using the TauDEM plugin tools in ArcGIS 10.8.

Table 3.1: Information about datasets used to develop a conceptual understanding of runoff processes of Twee and Leeu catchments.

Dataset	Resolution	Data source	Name of data sources in full
DEM	5 meters	SU & GeoSmart Space	Stellenbosch University and GeoSmart Space
Land cover	20 meters	DFFE (https://egis.environment.gov.za/gis_data_downloads, last assessed 29 June 2021) and CFM (https://gis.elsenburg.com/apps/cfm/, last assessed 26 September 2021).	Department of Forest, Fisheries, and the Environment. Cape Farm Mapper.
Soil map	250 and 20 meters, respectively	ARC & FAO (https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c3f7cfd5-1f25-4da1-bce9-cdcdd8c1a9a9, last accessed 05 July 2021).	Agricultural Research Council. Food and Agricultural Organisation.
Reservoir	20 meters	SANSA	South African National Space Agency.
Climate	Daily	SAWS, FRC, Kunje, DaKaur, Du Toit farms	South African Weather Services
Geology	250 meters	Map from RU Geology Department, and literature	Rhodes University, Department of Geology.

3.3.2 Topographic analysis

The study area is characterised by diverse mountainous terrain, with elevations exceeding 2 000 meters above sea level (Figure 3.2). The highest point within the catchments ranges from 1 628 to 2 040 meters. The majority of the study catchments encompass steep hillslope with an elevation ranging from 993 to 1,472 meters. The lowest areas, confined to narrow valley floors, descend to 515 meters.

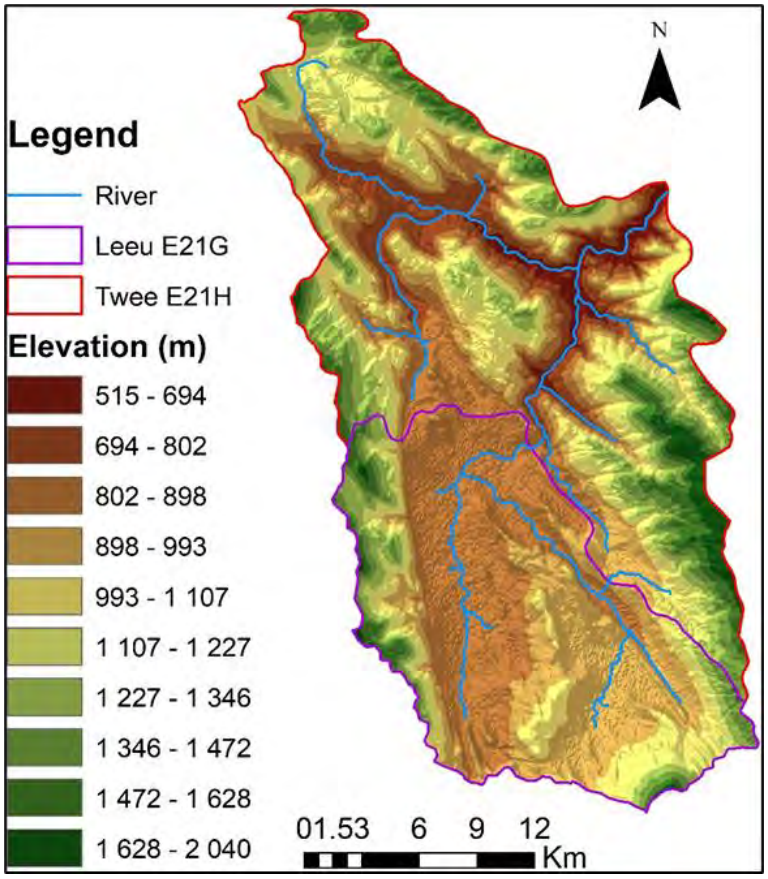

Figure 3.2: Map showing the general relief of the study catchments. **Source:** DEM (Geosmart and Stellenbosch University, 2021).

The topographic information derived from the DEM was analysed following the approach used by several hydrology studies that explored the relationship between the topography and hydrological behaviour of a catchment (Beven and Kirkby, 1979; Savenije, 2010; Winter, 2001; Wolock et al., 2004). These studies delineated the topography into hydrological landscape/topographic units termed plateau, hillslope, and wetland. Likewise, this current study classified the topography into the plateau, hillslope and valley floors (wetland) with an extra unit termed toeslope, as they highlight hydrological landscape units with different flow/runoff behaviour (Figure 3.3). The classification of the landscapes is based on the Height Above Nearest Drainage (HAND), computed using the vertical drop (distance down) tool of TauDEM in ArcGIS 10.8 (Tarboton, 2017; Tarboton et al., 2015). Since the study area is mountainous, hillslopes were defined as the largest proportion (60%) of the catchment area. The valley floors make up 20%, while the plateau and toeslope landscape units share an equal proportion of the remaining 20%. For better visualisation, a sub-basin of the Twee Catchment

was extracted and used to demonstrate the delineated topographic units (hydrological landscape units) (Figure 3.2).

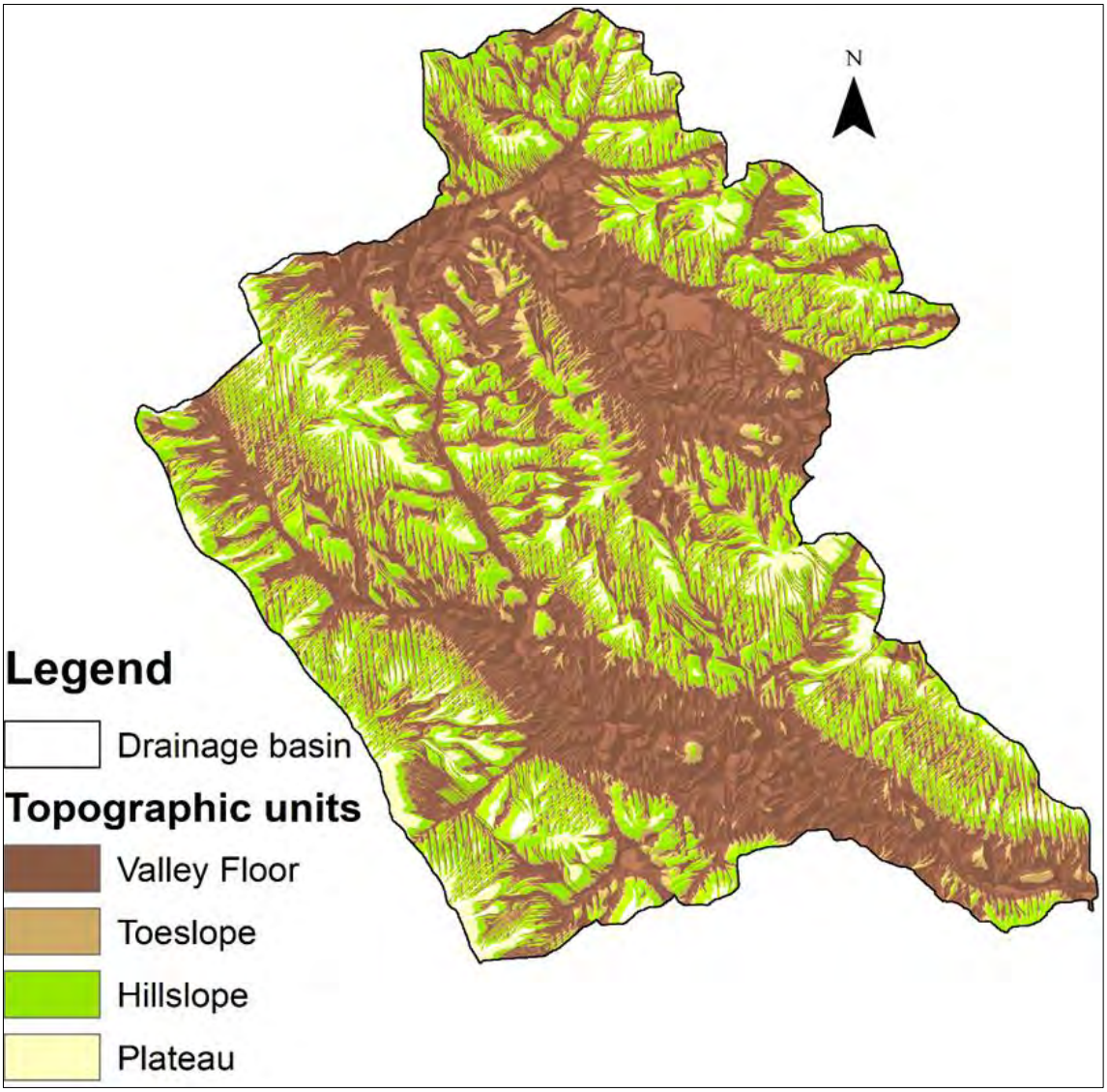

Figure 3.3: Extracted drainage sub-basin of the Twee Catchment to demonstrate the delineated hydrological landscape units (topographic units).

3.3.3 Land use/cover distribution

Two land cover/use digital datasets (Table 3.1) were combined to make a single land cover map. The map was used to analyse the spatial distribution of land cover types in the study area. The map showed that the catchment is predominately covered by fynbos shrubs (68%), followed by cultivated areas (19%) and natural grass (5%). Waterbodies, including rivers and artificial farm dams, also had notable coverage of the catchment (5%). The other land cover types, which include black wattle trees (alien invasive species) and bare rock, collectively cover 3% of the study catchment area (Figure 3.4 and 3.5).

The land cover map was overlaid on the topographic units' map to visualise the spatial distribution of the land cover types across the catchment landscape. This demonstrated that the narrow valley floors of the catchment are almost entirely used for agriculture, and the hillslope areas, which are the largest landscape of the catchment, are covered by fynbos shrubs. The dispersed grass is at hilltops and plateau units (Figure 3.4). In Figure 3.5, the fynbos shrubs were made invisible (hollow) on the map to ensure the visualisation of the catchment's slope (the area not coloured for any land cover type on the map is fynbos shrubland).

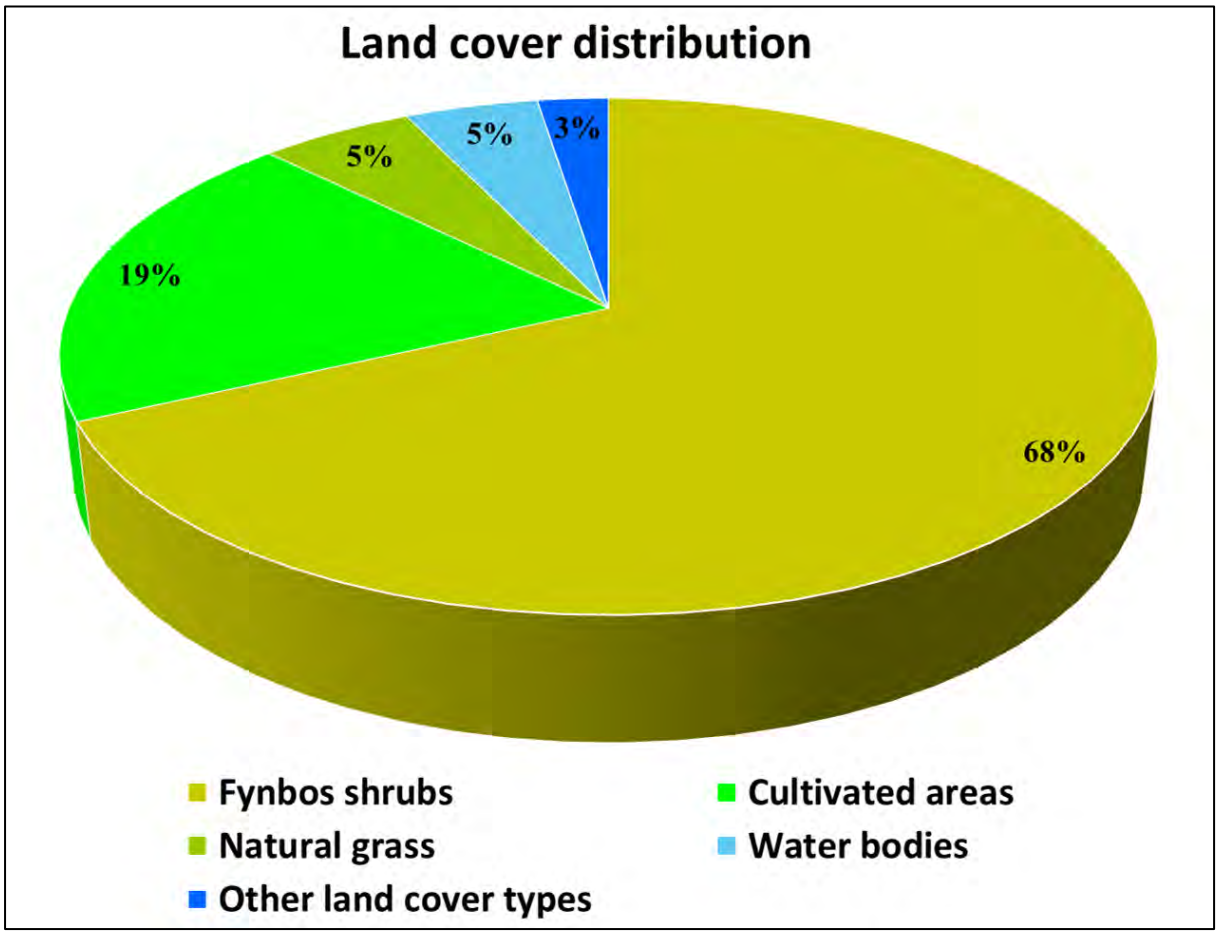

Figure 3.4: The land use/cover distribution in the Twee and Leeu Catchments.

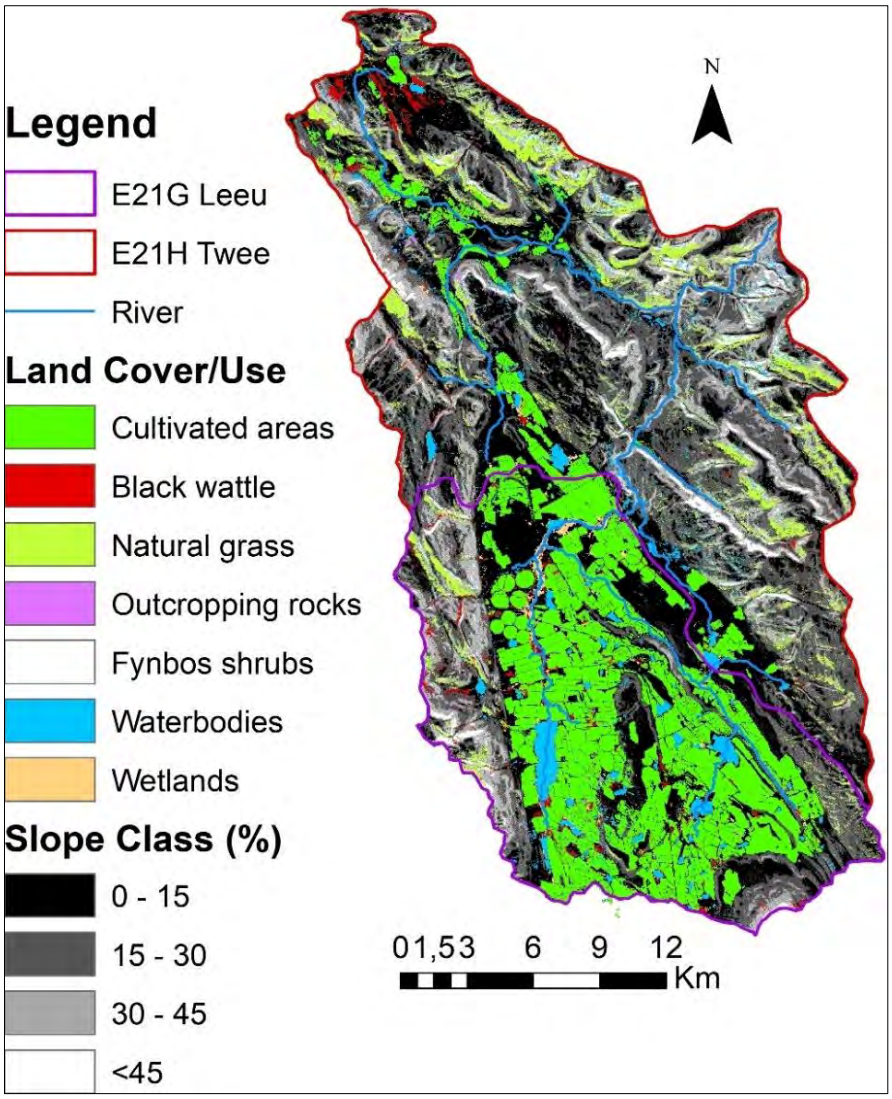

Figure 3.5: Land cover/use spatial distribution across catchment slopes. **Source:** Land cover (DFFE, 2020 and CFM, 2021), DEM (Geosmart and Stellenbosch University, 2021).

3.3.4 Soil distribution

The relationship between soil and topography makes relating soils to landscape units relevant. Soils tend to follow topographic and geological positions and play a role in shaping the landscapes. Since detailed national information about soil types and forms in not readily available in South Africa, the ARC Land Type database is considered the best readily available dataset that provides information relevant to soil types. Land Types were defined as areas with uniformity of topographic units, soil patterns and macroclimate zones (Lambrechts and MacVicar, 2004; Paterson et al., 2015). Figure 3.6 illustrates that the study catchment consists of seven broader Land Types with associated soils.

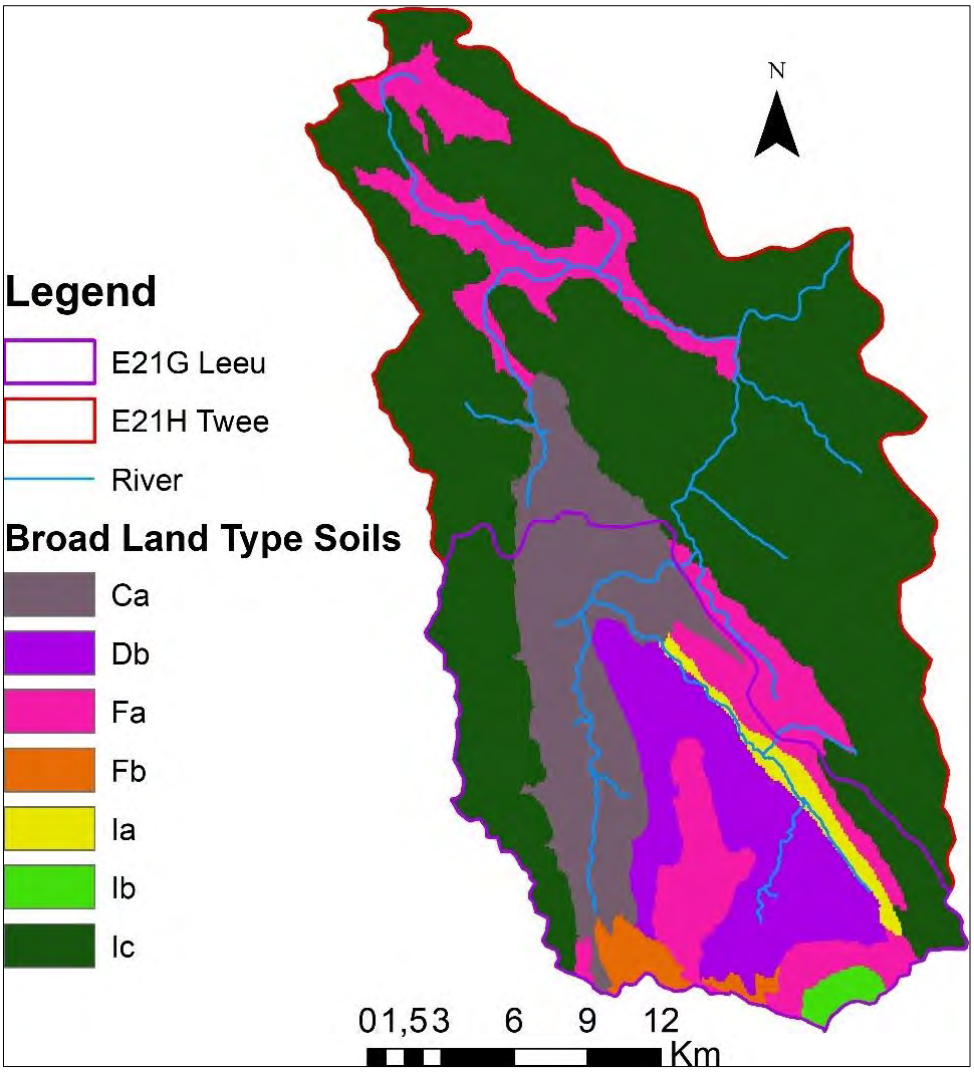

Figure 3.6: The spatial distribution of the broader Land Type Soils. **Source:** ARC Land Type Survey Staff. (1972 – 2006).

The dominating Land Type (Ic) in the study area comprises rocky shallow sandy soils. This Land Type soil covers the entire steep hillslopes and plateau landscapes, which make up almost 65% of the catchment area combined. Since the catchment is mountainous and rocky, even valley floors are covered with loose and shallow soils with little organic matter, overlaying either weathered or solid rock. General descriptions of broader soil types present in the study catchments are presented in Table 3.2.

Table 3.2: Description summary of dominant soils in the study area

Broader soil code	Soil form/s	General description
Ca	Longlands	Sandy, overlaying clayey
Db	Estcourt	Sandy over structured, blocky subsoil
Fa	Mispah	Shallow intact soil overlying weathered rock
Fb	Mispah	Shallow soils on hard of weathering rock
Ia	Dundee	On river floodplains
Ib	Soil comprises 60-80% rock	Shallow and/or rocky soils on steep slopes
Ic	Soil comprises >80% rock	Shallow and/or rocky soils on steep slopes

3.3.5 Geology

The geology of the Cape Fold Belt, where the study catchment is located, is complex (Blewett and Phillips, 2016; Booth and Shone, 2002; Booth, 2020). Describing subsurface flows in this area requires understanding geological formations and arrangements. To understand the structure and arrangement of geological formations underlying the topography of the catchment, geohydrological studies conducted in the area were extensively reviewed (DWAF, 2007, 2005, 2003; Brown et al., 2003). This was followed by drawing a geological cross-section (by hand) from a hard copy geology map of the study area obtained from the Geology Department, Rhodes University (Figure 3.7).

The major geological formations from which the catchment is formed include fractured quartzitic sandstones and shale aquitard (Figure 3.8). The quartzite rocks belong to the Peninsula and Nardouw formations, with a potential to have aquifer systems with high water yields (Lin et al., 2014; Seeke et al., 2020; Xu and Beekman, 2019). The Cedarberg shale aquitard separates these formations. The two rivers under study are situated in different formations. The cross-section illustrates that underneath the high plateaus in the Twee River catchment, there is fractured quartzitic sandstone of the Peninsula formation, which is also outcropping in that landscape unit. The steep hillslopes and the Twee River sit on the fractured sandstone of the Nardouw geological formation, while the Leeu River is directly in contact with shale aquitard, which overlays the Nardouw formation. The quartzitic sandstone of the Peninsula has a deep aquifer system on the Twee River side and becomes a shallow aquifer on the Leeu River quaternary.

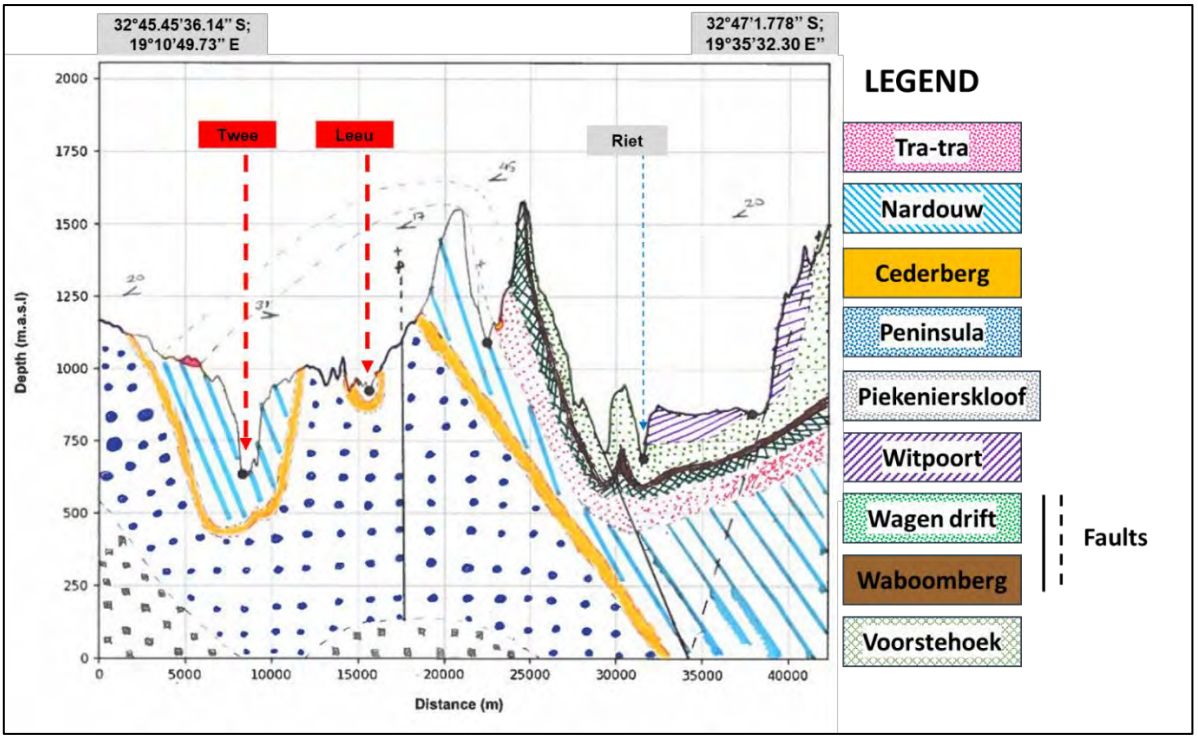

Figure 3.7: Geological cross-section for the Twee and Leeu catchments. The red arrows point to the two rivers (Twee and Leeu) on which this study focused.

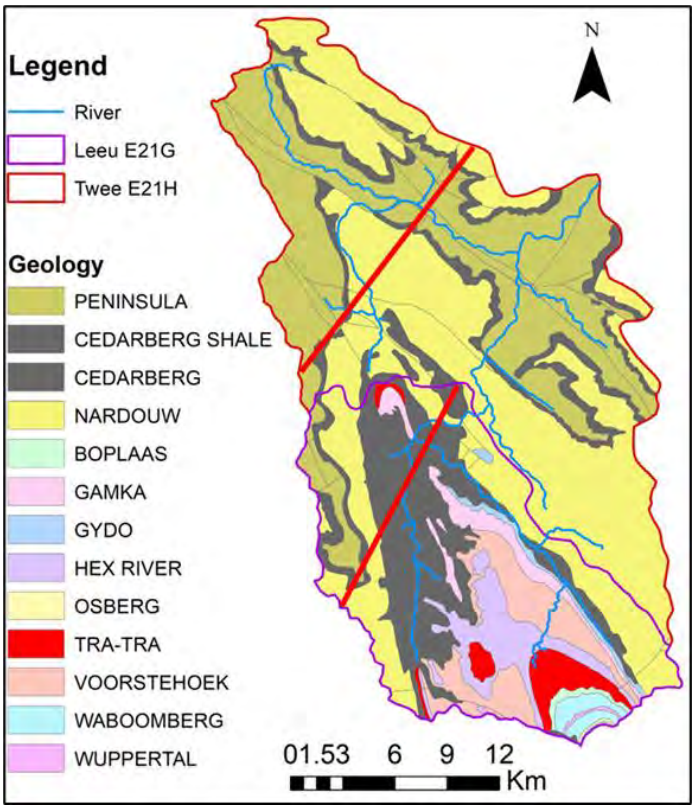

Figure 3.8: Map showing the spatial distribution of dominant geological formation is the study catchments. The red line in solid line in the map show cross-sections. **Source:** Council for Geosciences (1977).

3.3.6 Rainfall distribution

Characterisation of rainfall spatial variability is critical for understanding water balance processes in a catchment. Due to complex topography and orographic effects, rainfall variability tends to be high in mountainous catchments. The diverse topography and orographic effect are known to increase rainfall with elevation, especially on windward slopes and lower rainfall on the leeward side (Hughes and Wright, 1988; Singh et al., 1995; Singh and Kumar, 1997). Despite this knowledge, accurate analysis and understanding of rainfall distribution in mountainous catchments are constrained by sparse and unevenly distributed rain gauge networks (Du Plessis and Schloms, 2017; Duethmann et al., 2013; Prudhomme and Reed, 1999). These factors prevail in the study catchment, where the sparse operating rainfall gauges are mainly situated at lower elevations (Figure 3.9). This makes the available rainfall records poorly representative of the catchment-wide rainfall characteristics.

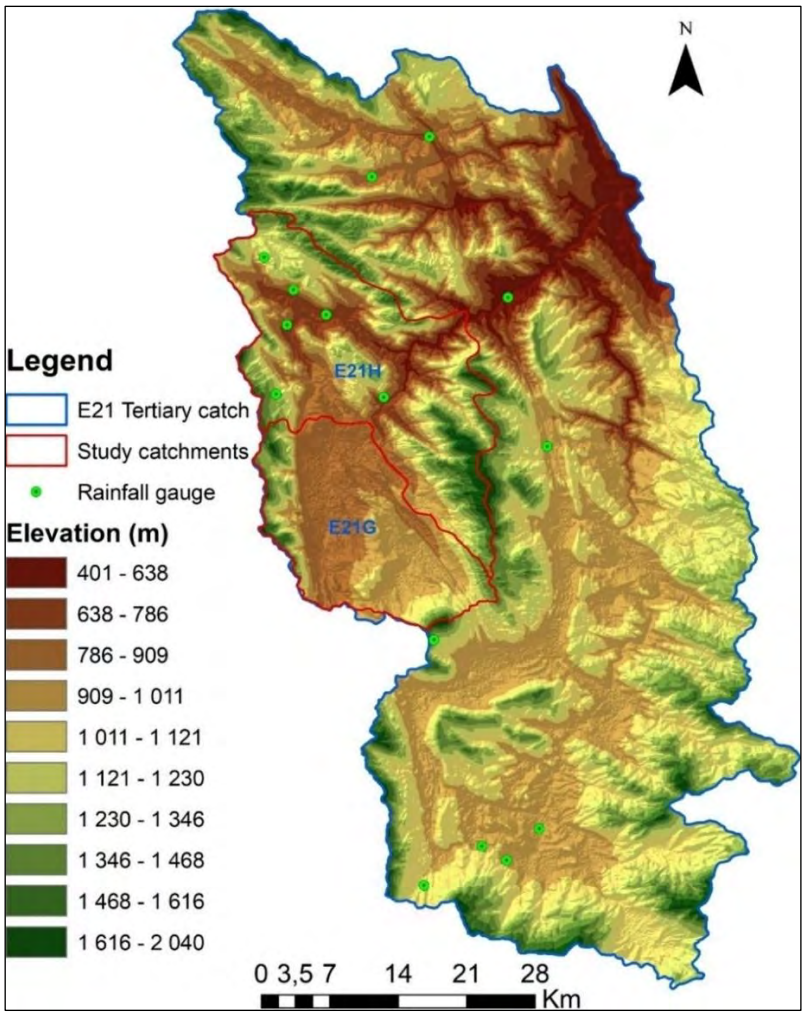

Figure 3.9: Rainfall gauges used to derive rainfall spatial distribution on different elevations. **Source:** Rainfall gauges (SAWS and local farms); DEM (Geosmart and Stellenbosch University (2021)).

Interpolation is one method used to estimate rainfall amounts for ungauged locations through deriving rainfall spatial distribution based on the records from a limited number of existing gauging stations. There are several methods available for rainfall interpolation, and they have been applied and compared (Duethmann et al., 2013; Goovaerts, 2000; Jacquin and Soto-Sandoval, 2013; Mair and Fares, 2011; Morris et al., 2016; Putthividhya and Tanaka, 2013). These methods include Thiessen polygon, inverse distance weighting, isohyetal and kriging. Studies that compared these methods revealed that ordinary kriging produces better estimations and smoother spatial distribution maps (Goovaerts, 2000; Mair and Fares, 2011; Putthividhya and Tanaka, 2013). For this study, rainfall interpolation was done using records from 15 stations including 9 stations that are outside the boundaries of the study catchments, using ordinary co-kriging in ArcGIS 10.8.2 geostatistical analysis tool (Figure 3.10 and Tabe 3.3). The stations outside the study catchments were included to supplement the limited number of gauges within the study catchments, some of which have short rainfall records (Table 3.3).

Besides the fact that ordinary kriging has produced better interpolation results in some studies, the co-kriging approach was selected as it allows the inclusion of the DEM in the interpolation process to consider elevation, unlike other methods. Incorporating elevation information improves rainfall estimation for areas at higher elevations (Duethmann et al., 2013; Goovaerts, 2000; Guan et al., 2005; Mair and Fares, 2011; Putthividhya and Tanaka, 2013)

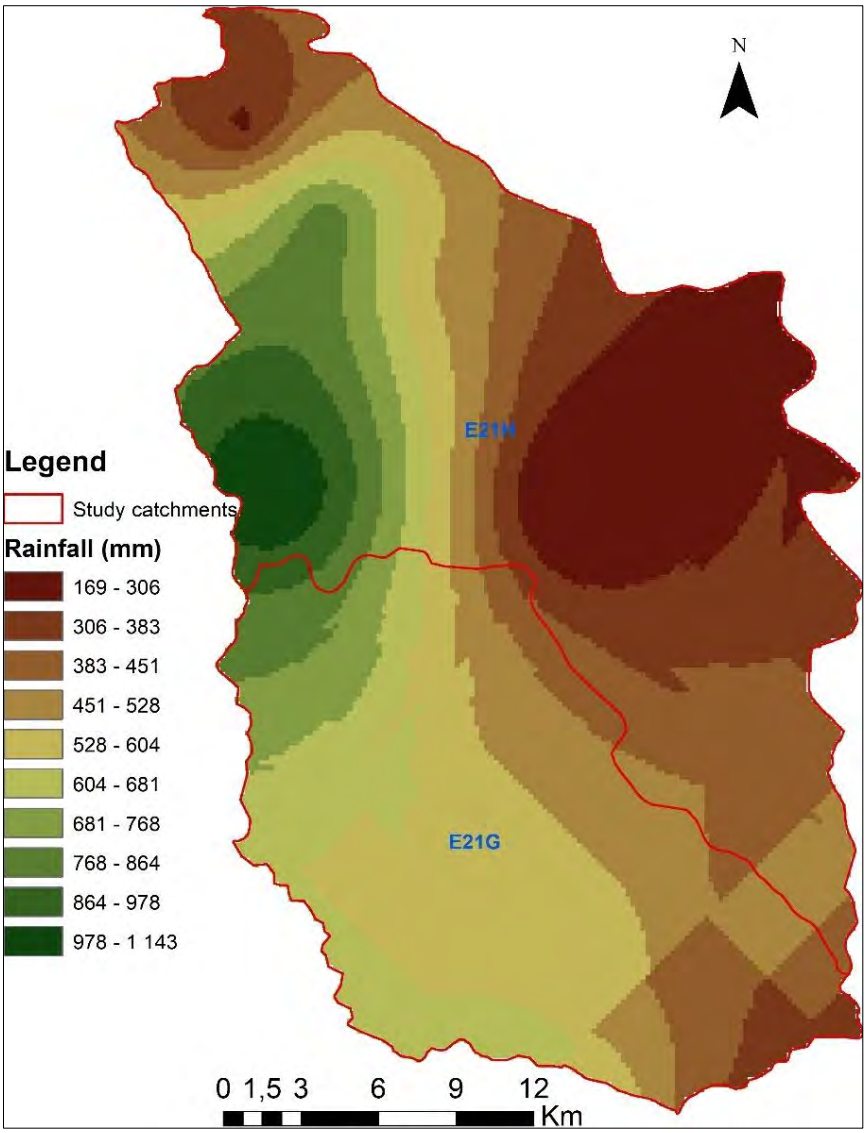

Figure 3.10: Interpolated rainfall spatial distribution within the Twee (E21H) and Leeu (E21G) Catchments.

Table 3.3 Details of rainfall gauges used to derive rainfall distribution for the Twee and Leeu catchments.

Within study catchment boundaries				
Gauge name	**Gauge owner**	**Record length**	**Coordinates**	**Elevation (m)**
Kunje	Kunje Farm	1990-2016	19.205, -32.6735	730
Suiker	FRC Farm	2021-2022	19.241, -32.664	724
Balies	FRC	2021-2022	19.294, -32.74	781
Zuur	FRC	2021-2022	19.184, -32.611	1152
Ysterplaat	Ysterplaat Farm	2003-2021	19.211, -32.641	804
Roelofs	SU	Jan – Dec 2022	19.195, -32.737	1247

Outside study catchment boundaries				
Gauge name	**Gauge owner**	**Record length**	**Coordinates**	**Elevation (m)**
Krommiriver	SAWS	1990-2021	19.283, -32.537	827
Grootriver	SAWS	2006-2021	19.408, -32.648	501
Zonderwater	SAWS	2006-2021	19.444, -32.785	954
Excelsior Ceres	SAWS	1993-2021	19.34, -32.963	958
Bokkeveldkloof	SAWS	1990-2021	19.331, -33.189	1035
Die erf	SAWS	1994-2021	19.407, -33.166	992
Odessa	SAWS	1990-2021	19.437, -33.137	957
Matjiesrivier	SAWS	1998-2021	19.336, -32.5	739
Malabar Farm	SAWS	1990-2010	19.384, -33.153	979

3.4 The conceptualisation of flow pattern and pathways

In this study, the landscape units of each sub-basin were assumed to correspond with four dominant hydrological regimes or flow behaviour: surface runoff, lateral/interflow, infiltration, and deep percolation influenced by surface topography, land use, soils and geology. Figures 3.11 and 3.12 illustrate the simplified conceptual flow behaviour of the Twee (E21H) and Leeu (E21G), respectively. The Twee and Leeu Rivers and their associated quaternary catchment landscapes are characterised by a plateau and narrow valley floors separated by a considerably steep hillslope (Figure 3.11 and 3.12, respectively). The plateau areas of the study catchment are flat, covered by sparse grass and fast-draining shallow sandy soils with outcropping quarzitic sandstone rocks of the Peninsula Formation. These features favour vertical flow (percolation), resulting in high groundwater recharge. High amounts of surface runoff (overland flow) are generated from the steep rocky sides of the mountains of the catchments, given the sparse fynbos shrubs and a thin layer of sandy soil at this landscape unit.

Residents and farmers in the catchment shared information about several springs (infiltrated/percolated water re-emergence) at different hillslope elevations, contributing to the surface runoff. The farmers reported that the springs vary in size and behaviour. Those occurring at higher elevations tend to initiate tributary streams that flow to the main river channel. However, some springs generate deep pools of water that spill and flow into the main channel.

The presence of springs and seeps could be due to various factors, depending on the elevation, soils, and geology. At a much higher elevation on the hillslope, re-emergence is assumed to result from the saturation of the shallow sandy soils (Points A and B in Figure 3.11 and 3.12, respectively). Further down the steep hillslope, springs could result from groundwater flow diverted by major fractures in the aquifer system or by encountering an aquitard such as a shale layer within the quartzite formations. These conditions are likely to occur in areas with Peninsula and Nardouw aquifer systems since they tend to have a dense fracture network (Lin et al., 2014) and some variable minor intermittent shale layers. Water re-emergence from fractures aligning towards the surface has also been observed by Hughes (2010) in Grahamstown, which also lies on the Cape Fold Belt geology. Water re-emergence due to saturation of soils overlying an impermeable layer has been observed by van Tol et al. (2010b) at higher elevations in the Bedford catchment. aquitard

The groundwater table on the upland plateau may rise significantly due to the high recharge occurring at this point. When this happens in regions with steep slopes and an unconfined aquifer, the groundwater table can intersect the surface further downslope. The intersection of the groundwater table with the surface results in springs (Winter, 2001; Wolock et al., 2004).

A large proportion of the surface runoff generated along the hillslope during storm events and re-emerging subsurface water flow is captured by dams located at the toeslope, and a portion is infiltrated. It is assumed that during the first few rainfall events of the wet season, a considerable amount of hillslope runoff that reaches the valley floors infiltrates there. Cultivation may promote high infiltration rates at this landscape position. The **Fa** soil type is shallow and overlies a weathered (fractured) rock at the valley floors of the Twee Catchment. The **Fa** soil favours high infiltration rates (van Tol et al., 2010b) as this type of soil is a young formation from unconsolidated materials (Macvicar et al., 1977; Tekle, 2004). Part of the runoff infiltrated on the valley floors can be assumed to recharge an aquifer beneath **Fa** soil. The **Ca** at the toeslope to valley floors in the Leeu Catchment favours interflow formation as it consists of high clay content underneath sand (van Tol et al., 2013, 2010a).

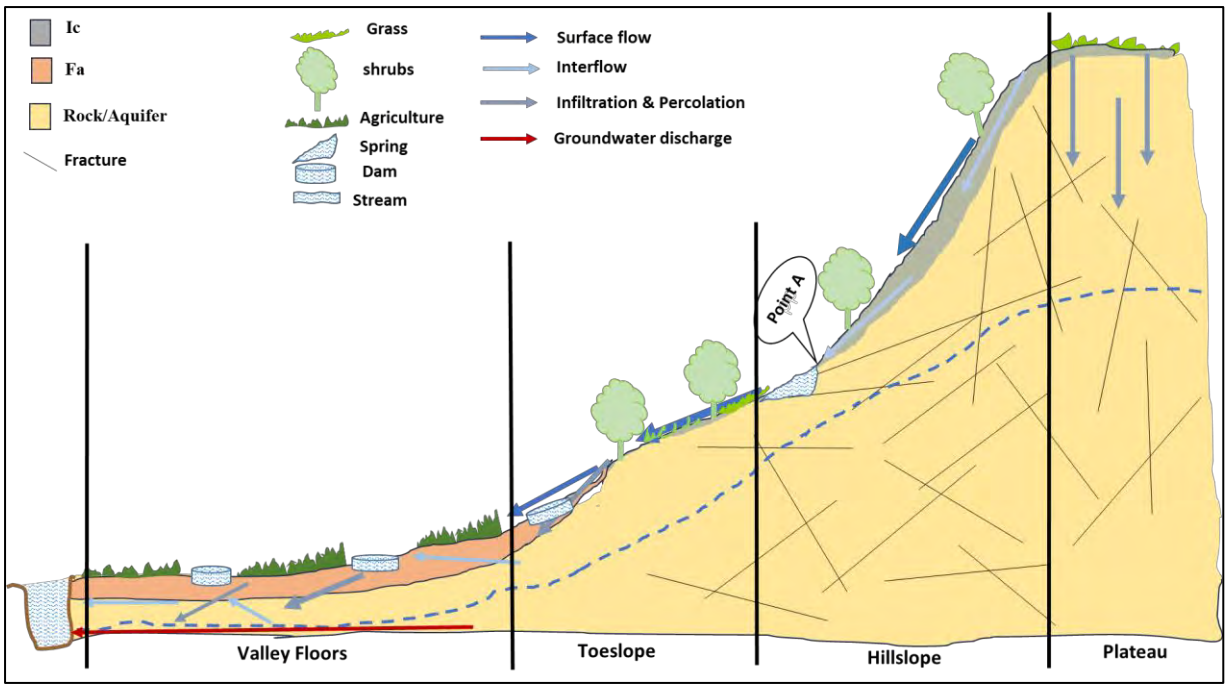

Figure 3.11: Simplified conceptual flow behaviour of the Twee River catchment (E21H). The main aim of the diagram is to runoff processes at different landscapes of the catchments. Therefore, only soil types that cover the catchment's bigger area are shown in the diagram.

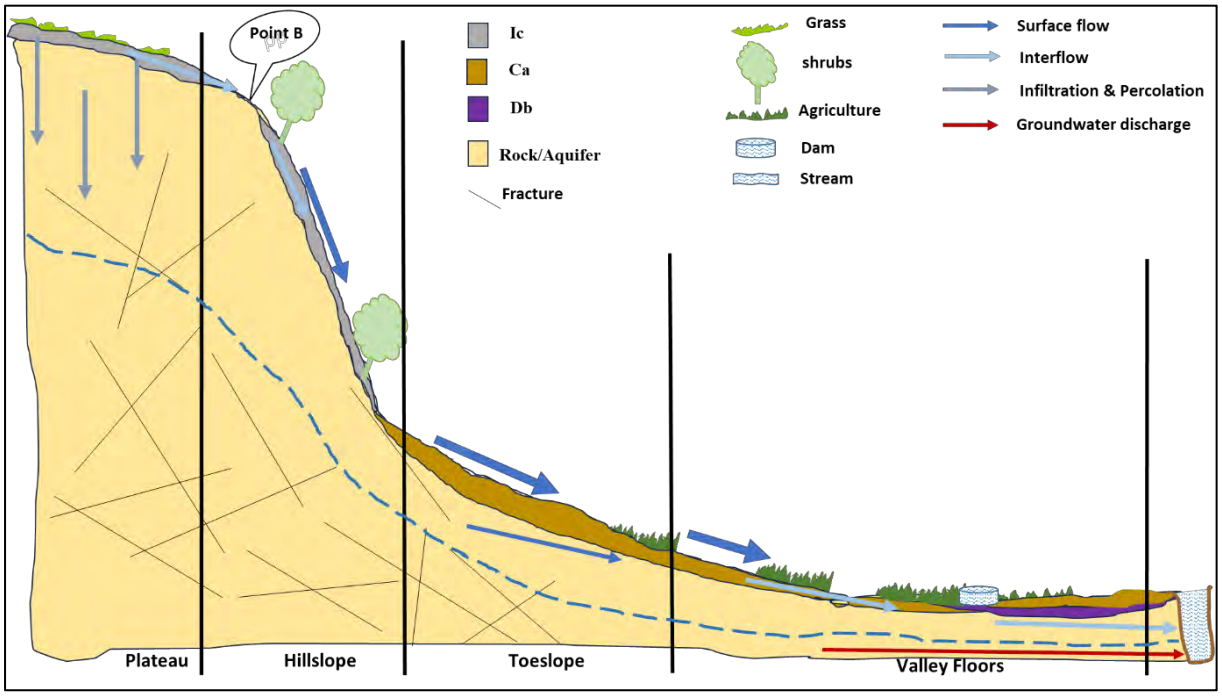

Figure 3.12: Simplified conceptual flow behaviour of the Leeu River catchment (E21G). The main aim of the diagram is to runoff processes at different landscapes of the catchments. Therefore, only soil types that cover the catchment's bigger area are shown in the diagram.

Also, a saturation excess overland flow can be expected in this unit of the catchment landscape as the **Ca** soil tends to be saturated for longer (Huyssteen et al., 2010; van Huyssteen et al., 2007). **Db** soils at valley floors of the Leeu Catchment are also characterised by high clay content (Stolk and van Huyssteen, 2019). Therefore, this condition at valley floors favours a continuous interflow in **Db** soils. **Ia** soils are characterised by large pores allowing considerable interflow (Macvicar et al., 1977).

Fynbos shrubs and riparian vegetation are assumed to have access to water for a longer duration due to saturation at the toeslope and high groundwater table along the river channels. The presence of fynbos shrubs at the hillslope could indicate that cracks in the weathered rocks serve as a water supply for fynbos shrubs. The invasive alien plants (black wattle) dominate along the river channels, likely accessing water from saturated soils and groundwater since they tend to have a fairly long root system. Groundwater discharge to the river is expected to be high due to high percolation at recharging areas and the fact that the rivers are sitting on the Nardouw aquifer system. However, the amount and duration of groundwater discharge to the stream also depends on how much groundwater is abstracted in the area.

CHAPTER FOUR

HYDROLOGICAL MODELLING

4.1 Introduction

The SWAT+ model was set up for this study to simulate hydrological processes and the impact of farm dams and irrigation on the hydrology of the Twee and Leeu Catchments. These two catchments were modelled independently. The selection of the SWAT+ hydrological model for this study was guided by the model's flexibility in representing some of the catchment processes and complexities reported (see sections 2.8 and 3.2.2). Figure 4.1 illustrates the steps followed in setting up the model for both catchments and types of data used in each step.

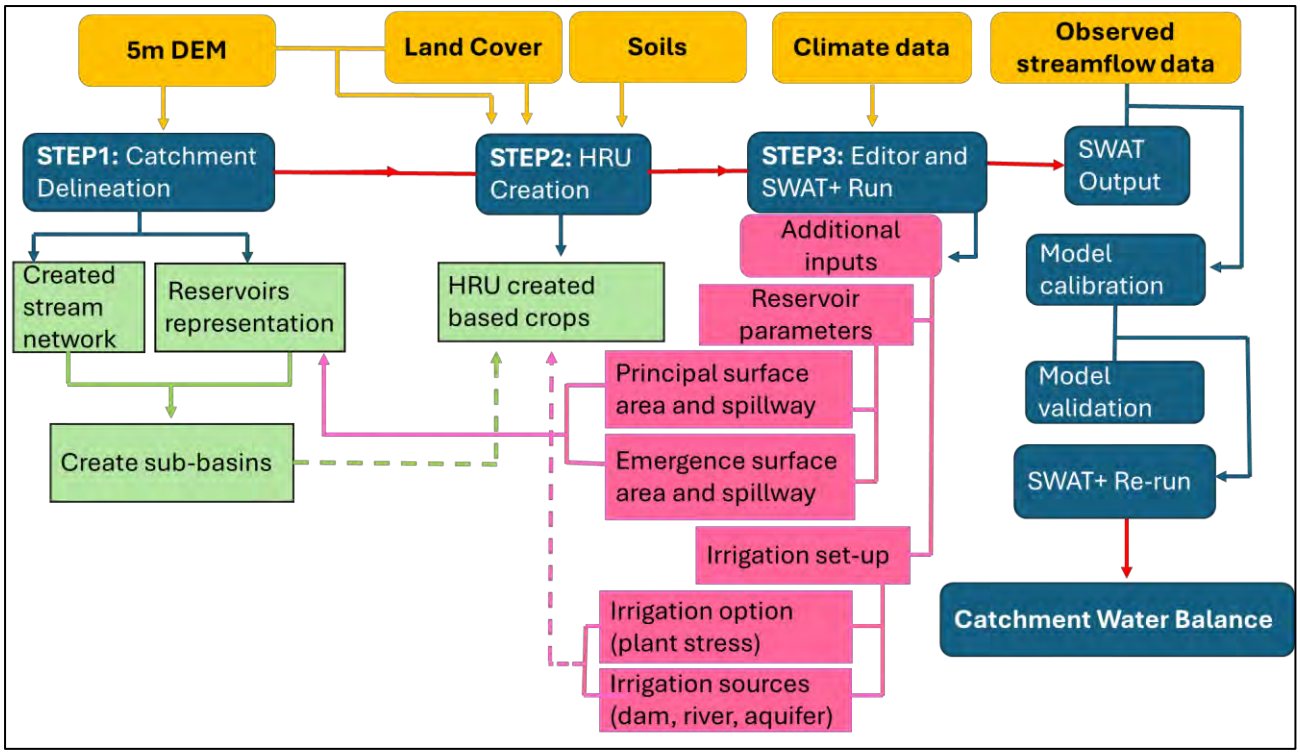

Figure 4.1: A conceptual flow diagram of the SWAT+ model setup (Methodological framework)

4.2 SWAT+ model structure

SWAT+ distributes the catchment area into sub-basins connected by a stream network. Landscape units (LSU), which separate upland hydrological processes from lowland ones, are created within sub-basins. Each LSU consists of a set of hydrologic response units (HRUs) (Figure 4.2). Reservoirs in each sub-basin are separated from the LSU's (Bieger et al., 2017). Reservoirs can be fed by upland flow and can be presented in the main river channel.

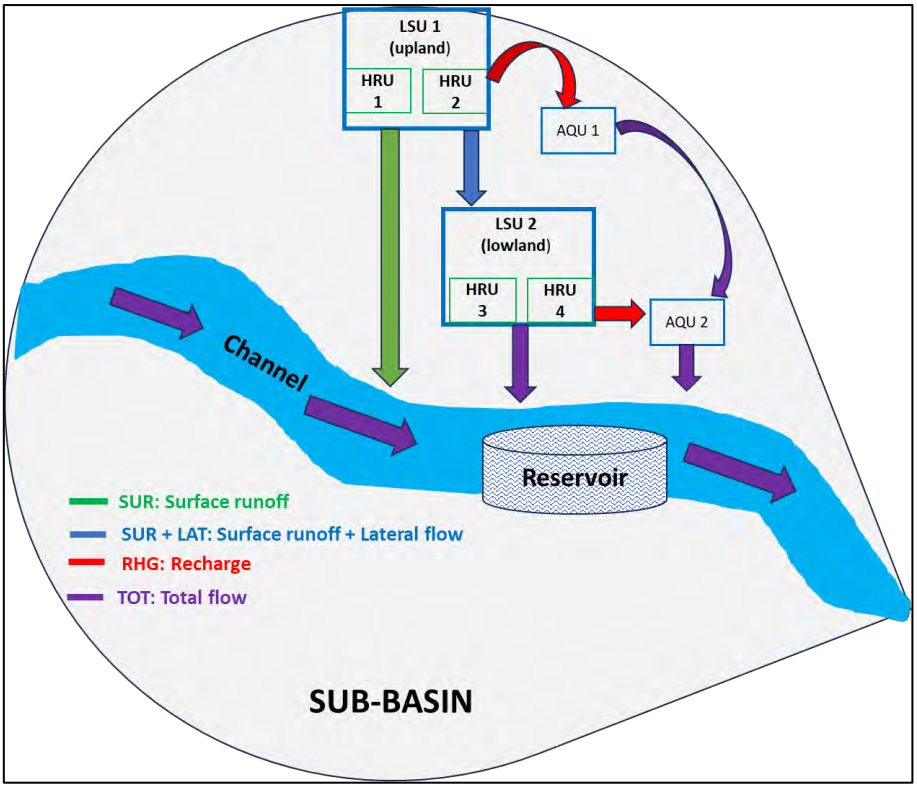

Figure 4.2: Schematisation of water flow paths between SWAT+ spatial objects. **LSU** = Landscape unit, **HRU** = Hydrologic response unit, **AQU**=Aquifer. Adapted from Bieger et al. (2017).

In the SWAT+ model, total flow (TOT) refers to the sum of surface runoff and lateral flow for HRUs and LSUs (Bieger et al., 2017). Groundwater flow through aquifers and discharge to the channel is also referred to as TOT.

The flow output from HRUs is aggregated at the LSU scale and can be routed to various spatial features within the catchment, including channels, reservoirs, or aquifers. This means that a fraction of surface runoff generated at upland LSU can be directed straight to the channel, and the remainder routed to the riparian zone (valley floor) (Bieger et al., 2019). In the setup for this study, SWAT+ model default routing (water flow paths) was maintained, where water is routed via the channel from LSU at uplands through lowlands LSU, filling the reservoir and eventually reaching the main river channel (Figure 4.2). Where there is a reservoir between the upland and lowland LSUs, the water flowing from the upland will fill the reservoir and spill into the lowland LSU. Groundwater recharge occurs in aquifers at the upland LSUs of the study area, and the groundwater from upland LSUs moves through the lowland LSU aquifer to reach the river channel as a baseflow. Additionally, the groundwater moving through the lowland LSU aquifer becomes accessible to riparian vegetation.

The SWAT+ model calculates hydrological cycle based on the water balance equation, expressed as:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 1$$

where SW_t is the final soil water content (mm H_20), SW_0 is the initial soil water content on day i (mm H_20), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_20), Q_{surf} is the amount of surface runoff on day i (mm H_20), E_a is the amount of evapotranspiration on day i (mm H_20), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_20) and Q_{gw} is the amount of return flow on day i (mm H_20).

The hydrological processes the SWAT+ model can simulate include surface runoff, lateral flow, groundwater discharge and evapotranspiration (Bieger et al., 2017). Surface runoff in the model is estimated based on Soil Conservation Service Curve Number (SCS-CN) or the Green and Ampt infiltration method (Arnold et al., 1998). In the model set-up for this study the SCS-CN was used to predict surface runoff, as this approach is more commonly applied at present. The SCS-CN equation is:

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 2$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm H_20), R_{day} is the rainfall depth for the day (mm H_20), I_a is the initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm H_20), and S is the retention parameter (mm H_20). Additional description regarding the variables of the SCS-CN equation are detailed in Arnold et al. (1998) and Neitsch et al. (2011).

The lateral flow in the soil profile (0-2 m) is calculated simultaneously with percolation (Arnold et al., 1998). In SWAT, lateral flow occurs when the water content of the soil exceeds its water content at field capacity (Bieger et al., 2015). The following equation is used by the model to estimate interflow:

$$Q_{lat} = 0.024 \cdot \left(\frac{2 \cdot SW_{1y,excess} \cdot K_{sat} \cdot slp}{\emptyset_d \cdot L_{hill}}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots 3$$

where Q_{lat} is the lateral flow (mm d^{-1}), $SW_{1y,excess}$ is the drainable volume of water stored in the saturated zone of the hillslope per unit area (mm H_20), K_{sat} is the saturated hydraulic conductivity of the soil (mm· h^{-1}), slp is the increase in elevation per unit distance, $\emptyset_d$ is the drainable porosity of the soil (mm mm^{-1}) and L_{hill} is the hillslope length (m).

Groundwater discharge in the model occurs when the amount of water stored in the shallow aquifer bypass the threshold value defined by the user. The discharge to the river channel is estimated using the following equation:

$$Q_{gw} = \frac{8000 \cdot K_{sat}}{L_{gw}} \cdot h_{wtbl} \quad \ldots\ldots 4$$

where Q_{gw} is the groundwater discharge to the river channel on day i (mm H_20), K_{sat} is the saturated hydraulic conductivity of aquifer (mm/day), L_{gw} is the distance from the ridge or subbasin divided for the groundwater to the channel (m) and h_{wtbl} is the water table height (m).

Three options for estimating potential evapotranspiration (PET) are available in SWAT model and these are Hargreaves, Priestley-Taylor and Penman-Monteith. Solar radiation, air temperature, wind speed, and relative humidity are required for Penman-Monteith for estimating PET (Arnold et al., 1998). In the SWAT+ model set-up for this study Penman-Monteith equation was used to estimate PET (Allen et al.,1999):

$$\lambda ET = \frac{\Delta(R_n - G) + P_a C_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \quad \ldots\ldots 5$$

where R_n is the net radiation, G is the soil heat flux, $e_s - e_a$ represents the vapour pressure deficit of the air, P_a is the mean air density at constant pressure, C_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances. Further details of the variables in the equation can be found in (Allen et al.,1999).

The water balance of a reservoir in the SWAT model is simulated based on the following equation:

$$V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep} \quad \ldots\ldots 6$$

where V is the volume of water in the reservoir at the end of the day (m^3 H_20), V_{stored} is the volume of water stored in the reservoir at the beginning of the day (m^3 H_20), V_{flowin} is the volume of water entering the reservoir in the day (m^3 H_20), $V_{flowout}$ is the amount of water flowing out of the reservoir in the day (m^3 H_20), V_{pcp} in the volume precipitation into the reservoir in the day (m^3 H_20), V_{evap} is the volume of evaporated (m^3 H_20) and V_{seep} is the volume water lost though seepage (m^3 H_20).

4.3 Data acquisition and processing for the SWAT+ model setup

The data required to set up and run the SWAT model include topographical (DEM), land use, soils and meteorological data. Additional input datasets, such as reservoir and irrigation data, may be necessary for SWAT, but their inclusion is optional and depends on the specific goals of setting up the model. (Gassman et al., 2007). Observed streamflow data are essential for comparing with simulated flow during the model calibration and validation. Observed data for evapotranspiration (ET), soil moisture and crop yield can also be used, if available, to evaluate the model performance further. The datasets used to set up and run the SWAT+ model for this current study are detailed below.

4.3.1 Topographical data

A Digital Elevation Model (DEM) with the 5-metre resolution for the catchment was obtained from GeoSmart and Stellenbosch University in the Western Cape Province of South Africa (shown in Figure 3.4 above).

4.3.2 Land use/cover (LUC) data

The 2020 LUC information was obtained from the Department of Forestry, Fisheries and the Environmental (DFFE) website (https://egis.environment.gov.za/gis_data_downloads, last assessed 29 June 2021), in a raster format. The land use/cover digital dataset consists of two-level classes. In level 1 class, LUC types are grouped into 9 classes, while in level 2 are grouped into 24 classes. For this study, level 1 classification was used. For simplicity, LUC classes that cover less than 1% of the study area were combined with other land LUC. For instance, built-up and mine/quarries were merged with outcropping rocks, while barren land was merged with shrubland. The DFFE LUC map does not specify the specific types of crops grown in the area; instead, it has a class name “cultivated land”. The LUC class “forested land” was renamed “invasive alien plant” as the area classified forested in the DFFE LUC is, in fact, covered by black wattle in the study area. Water bodies class (dams) were excluded in the LUC map prepared for the model setup, as the SWAT+ model converts them into a single land use “wetland” if presented in the LUC map. Therefore, the best way to represent dams in the model was to manually place them during the watershed delineation stage of the model setup process.

It was essential to have different crop types grown in the study area presented in the LUC map for the model setup, as the study also looked at modelling irrigation demands for crop types grown in the catchments. Therefore, polygons of the crops grown in the catchments were digitised from Cape Farm Mapper (CFM) of the Western Cape Department of Agriculture

(https://gis.elsenburg.com/apps/cfm/, last assessed 26 September 2021) and were merged with DFFE land use/cover information to substitute the LUC classified cultivated land. The crop information available in CFM is for the period between 2017 and 2018.

To assign irrigation sources effectively, crops grown on each farm were given identifier codes that link them to that specific farm. Therefore, apples grown in three different farms would be uniquely identified as appl1, appl2 and appl3 (see Appendix 1 & 2 for farm spatial distribution). Disaggregating crops according to farms made it easier to assign irrigation sources associated with the farms where the crops are grown. The same was done for all other crop types. SWAT+ plant codes given to the different LUC classes to link them to the model plant database are detailed and can be viewed in Appendix 3, as they cannot be clearly visible in the Legends of the maps prepared for the model set-ups (Figure 4.3). New SWAT codes were created for the LUC types that are not in the default SWAT+ plant database, and the database was updated so that the model could recognise these new crop types. Figure 4.3 shows the LUC map, prepared and used for setting up the model for the modelled catchments.

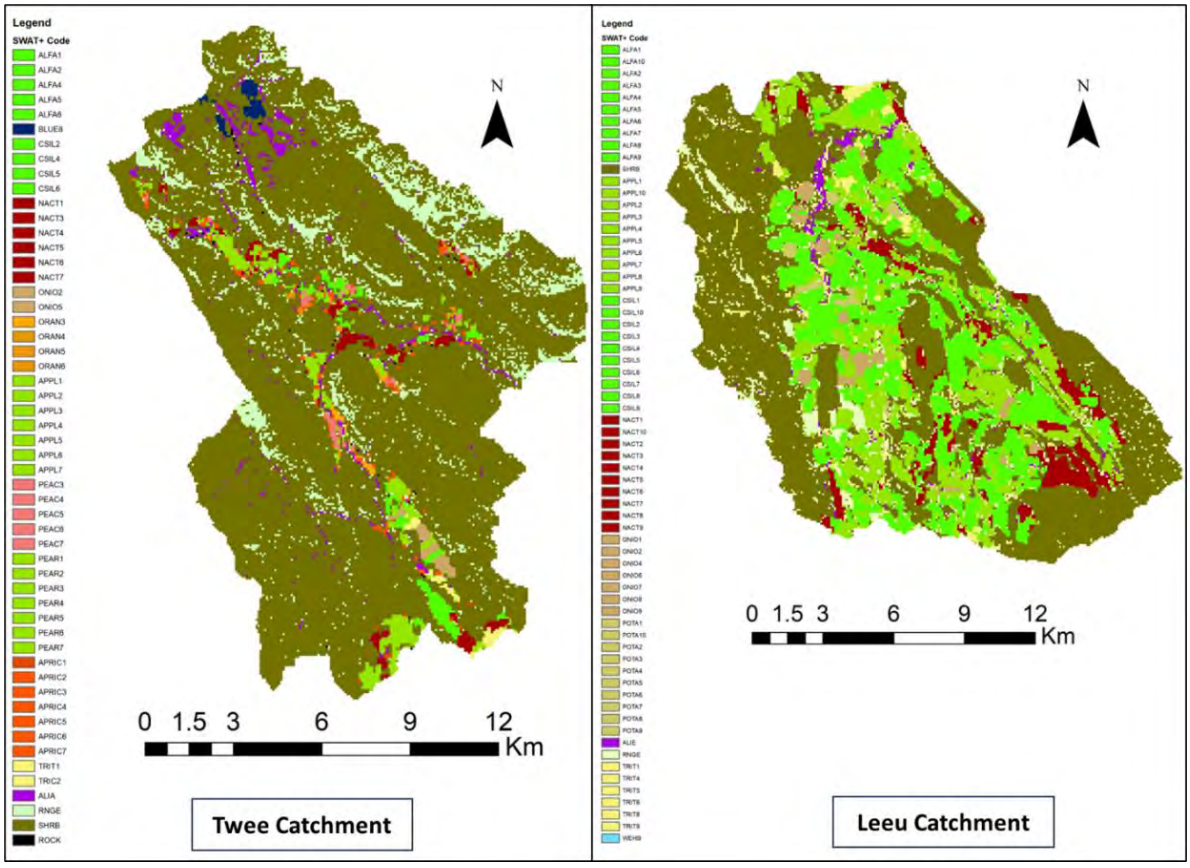

Figure 4.3: The land use/cover maps used to create HRUs in the SWAT+ model set for the Twee and Leeu Catchments.

It is acknowledged that adopting default crop parameter values in the SWAT database is not ideal. However, due to unavailability of data regarding parameters of the crops grown in the study area, crop parameters in the SWAT database were adopted for the modelling exercise of this study. Values of parameters such as maximum rooting depth, canopy hight and stomatal conductance for LUC types such as apple, blueberry, orange, onion, potato, lucerne, triticale, small grain crops and natural grassland were adopted from the SWAT+ plant database. Where possible, locally estimated values of parameters of crops grown in the study area were used. For example, values of parameters like initial leaf area index and biomass were obtained from Fruitlook (https://fruitlook.co.za/portal/my-fields, last assessed 5 October 2023). Values of parameters for crops such as nectarine, peach, plum, and apricot were compiled from the Crop Production Guidelines publications by the South African Department of Agriculture and Agricultural Research Council (ARC) (Department Agriculture, and Forestry (DAF), 2016; 2016). Since nectarine, peach, plum, and apricot are not in the SWAT+ plant database, to fill the gaps in crop parameter information compiled from the DAF, values of parameters for "orchards" in the SWAT+ plant database were adopted. Apple parameter values in the database were used for pear. Parameter values for fynbos shrubs and black wattle, compiled by Glenday et al. (2021) for their SWAT model setup for the Berg catchment in the Western Cape, were adopted for this study.

4.3.3 Soil data

The shapefile of the soils of the study catchment was obtained from the Agricultural Research Council (ARC) of South Africa. Three broader soil types present in the Twee and seven broader soil types in the Leeu (according to the ARC Land Type Survey database, 1972) were identified in the soil map provided by ARC (Figure 4.4). However, the ARC dataset does not contain all the soil parameters required for the SWAT+ model. Therefore, the Soil and Terrain Databases (SOTER) and the Harmonised World Soil Database (HWSD.mdb) soil maps in shapefile format were downloaded from the Food and Agriculture Organisation (FAO) website to supplement ARC soil parameters (https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/c3f7cfd5-1f25-4da1-bce9-cdcdd8c1a9a9, last accessed 05 July 2021). The shapefile attribute table showed that both study catchments have three soil types according to FAO soil classification (Table 4.1). The attribute table of HWSD also showed three different raster values known as Global Mapping Units (MU Global) representing soil types (Batjes et al., 2009). The ARC soils have a better

spatial distribution because while FAO indicates three soil classes in the study area, the ARC data contains seven soil classes (Table 4.1).

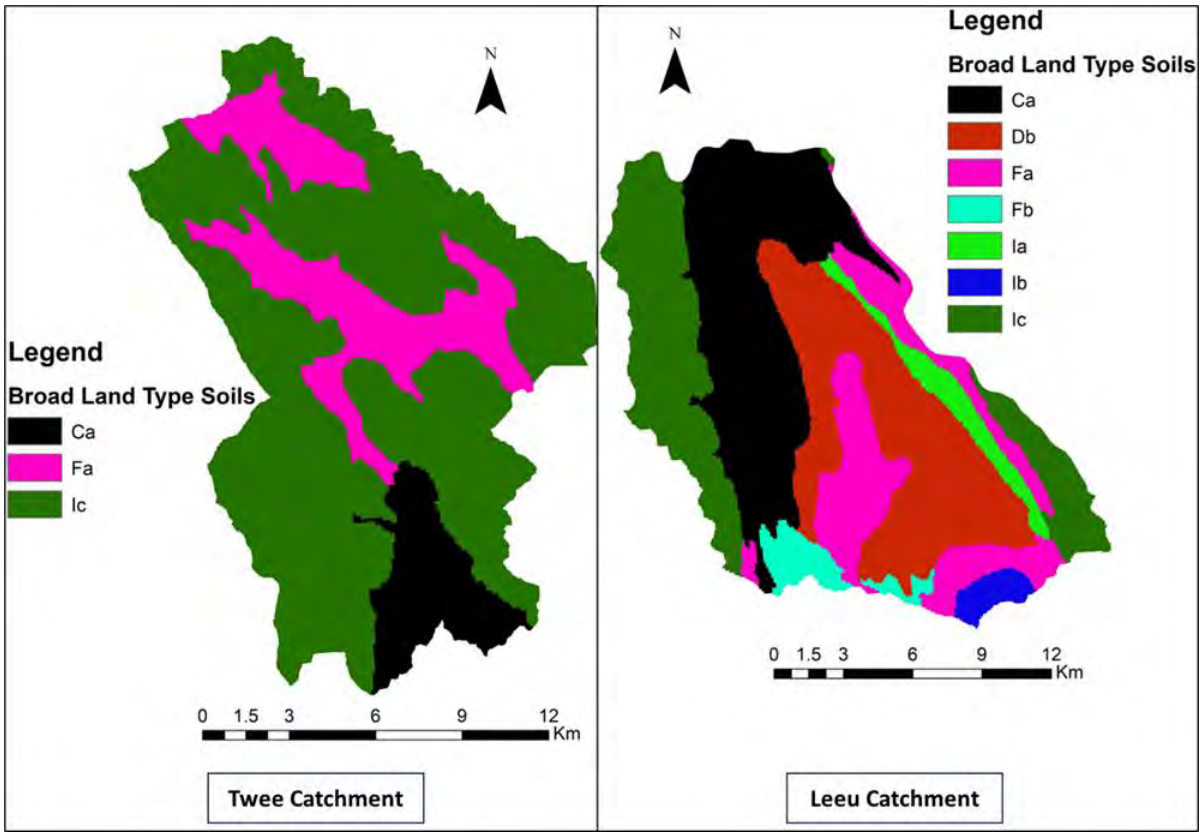

Figure 4.4: Soil maps used to create HRUs in the SWAT+ model for the Twee and Leeu catchments.

Table 4.1: A spatial overlay in GIS indicates three HWSD mapping units corresponding to the three FAO soil types. More than one type of ARC soil corresponds to a single FAO soil class.

HWSD MU Global	FAO Soil class code	ARC Soil class code
29743	LPq	Ia
		Ic
29918	ARa	Ca
29948	LVh	Fa
		Db
		Fb
		Ib

The relevant soil parameters obtained from FAO data were used to supplement the parameters of corresponding ARC soils. The outstanding soil information required by the SWAT model, which was not found in SOTER of FAO or ARC, was derived from the default SWAT user-soil

database. This was done by downloading a custom SWAT12.mdb (Microsoft Access format) available online (http://drgungorese.blogspot.com/2014/04/swat-using-soil-data-for-non-us-study.html, last assessed 08 July 2021) supplied by Gungor, (2014). The custom SWAT12.mdb database includes soils from around the world and their physical and chemical properties. The custom SWAT12.mdb was constructed using data from FAO's 1:5000000 scale World Soil Map (version 3.6) (Gungor, 2014).

The SWAT soil database has an identifier (SEQN) that matches an identifier in the FAO soil properties database (SU_CODE90), and this was used to locate the corresponding soil types in the SWAT database (Table 4.2). Thus, combined soil information from the SWAT user soil database, SOTER of FAO, and ARC was inputted into the model.

Table 4.2: HWSD MU, SU CODE90, and SEQN values used to locate soil types similar to those of the study catchment in the SWAT soil database.

HWSD MU Global (raster value)	FAO SU_CODE90	SEQN	SWAT soil class code	FAO code	ARC code
29743	103	103	Jc23-2a-103	LPq	Ia Ic
29918	43	43	Fo8-2ab-44	ARa	Ca
29948	106	106	Jc26-2-3a-106	LVh	Fa Db Fb Ib

4.3.4 Meteorology data

The climate data used to run the SWAT model includes daily rainfall, maximum and minimum temperature, relative humidity, wind speed and solar radiation. Generally, the values of these variables are obtained from records of observed data (for instance, local weather stations). Alternatively, the meteorological data can be generated using an inbuilt SWAT weather generator module (WGEN). The WGEN option is mainly used to simulate values of climate variables when observed data are unavailable (Senent-Aparicio et al., 2021). Climate Forecast Reanalysis (CFR) is used for SWAT's WGEN, and the simulated climate variable values are then checked against a set of weather stations across the world. In this study, records of observed data for daily rainfall, temperature, relative humidity, and wind speed (for the period of 1999 – 2015) from South African Weather Services (SAWS) were used to force the SWAT model. Since SAWS does not have records for solar radiation, daily values for this weather

parameter were simulated using WGEN. However, the records from WGEN ended in 2014. Therefore, to fill in *missing* daily records from 2014 to 2015, the value "-99" was used to inform the model as advised in the SWAT weather data documentation guide (Arnold et al., 2012).

Observed rainfall records were obtained from six SAWS rainfall stations and several farm stations (Kunje farm, Ysterplaat farm, CederFruit farm, and Roelofs). SAWS rainfall stations are located outside the boundaries of the study catchment. The records from farm stations came in different temporal scales (some daily and others monthly). As covered in section 3.3.6, creating a rainfall surface was critical. The Mean Annual Precipitation (MAP) of all stations was computed to generate the rainfall surface. The resultant rainfall surface was used to select grid points for which to create "dummy" rainfall stations following the method of Nolte et al. (2021):

$$\sum_{t=1}^{365} P_e = P_{grid} = \sum_{t=1}^{365} (k \cdot w_1 \cdot P_{1,t} + k \cdot w_2 \cdot P_{2,t}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

Where P_e is estimated rainfall within the centre of the grid cell; P_{grid} is the interpolated estimate for MAP in a grid cell; $P_{1,t}$ and $P_{2,t}$ represent rainfall at two stations closest to the centre of the grid cell at day t; k is a constant factor; w_1 and w_2 are weighting factors assigned to station rainfall based on the relative distance to the grid cell. Between the years 2001 and 2003, the records of the observed rainfall stations ($P_{1,t}$ and $P_{2,t}$) had gaps that were filled with rainfall values from Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS). A validation of the method using one of the observed (Kunje) stations yielded an R^2 of 0.99, indicating that the method realistically reproduced the temporal distribution of the observed rainfall. The observed and simulated stations' MAP matched well, but the average P_e daily rainfall was slightly higher by 2%. A total of thirty-nine P_e stations representative of catchment rainfall gradient and spatial distribution were used in the model set-up.

4.3.5 Farm dam information

The additional data incorporated into the model set up for this study includes the properties of farm dams present in the study catchments. The information about the spatial distribution of dams in the catchment was obtained from the South African Space Agency (SANSA) in shapefile format. The properties of the dams, such as the year the dam was constructed, the owner of the dam, the purpose of the dam, the dam surface area and capacity, were included in

shapefiles obtained from SANSA. Data regarding dams available in CFM was also used to validate dam size information from SANSA.

Farm dams were represented as reservoirs in the model so that they could be used as the primary source for crop irrigation. The SWAT+ model requires the year and month the reservoir became operational, the reservoir surface area and the volume of water stored when the reservoir water levels reached the principal spillway, and the reservoir surface area and volume of water stored when the reservoir levels reached the emergency spillway.

Additionally, controlled release rules were not defined, as there is no information about the farm dam operations in the study catchments. Therefore, assigning the dam total storage capacity volume for the emergency spillway and not defining controlled release rules allow reservoirs in the model to overflow to the river downstream when they are filled to total storage capacity. This approach replicates a simple fill and spill condition, generally occurring in farm dams with no control structures.

4.4 SWAT model set up for the Twee and Leeu catchments.

4.4.1 Watershed delineation

The DEM was used to delineate the modelled catchments. A detailed channel and stream network was created from this DEM by QSWAT+. A detailed channel and stream network was required to explicitly represent as many dams as possible in the model setup, as a dense network of farm dams exists in the modelled catchments. To create a detailed stream network in QSWAT+, the contributing flow area required to make a channel and stream was set to 0.11 and 0.9 km^2, respectively. In the model, the stream network connects subbasins, while the channel collects the subbasin area's runoff (from all its HRUs within LSUs) and routes the runoff into the stream network. The outlets for both catchments were manually added on the streamline at the end of the basin. This was followed by manually placing existing farm dams as reservoirs on the subbasin channels and/or streams according to their spatial distribution.

Twee and Leeu Catchments have multiple farm dams on tributaries and streams, and numerous off-channel dams exist. Not all the dams existing in the catchments could be presented exactly as they are in the set ups, as the model could not represent more than three reservoirs close to each other on a single small channel. Off-channel dams can be explicitly represented as ponds in the SWAT+; however, the model does not allow irrigation from a pond. Therefore, to ensure that all the storages in the catchments are adequately represented and can be used for crop

irrigation in the model, some farm dams, including off-channel dams, were lumped. The criteria of lumping and representing lumped dams in the model set-up is detailed in the below.

The Twee catchment, which covers an area of 20 310 hectares (ha), consists of eighteen farm dams. Seven farm dams with a surface area greater than 5 ha were directly represented in a channel in the model setup, according to their spatial distribution. Farm dams with a surface area of less than 5 ha and located in a single small tributary were lumped, and their combined surface area and capacity were assigned in a dummy reservoir placed at the end of the contributing area. Two dummy reservoirs were presented in the model setup, one dummy reservoir representing three combined dams and the other representing two. Three farm dams with a surface area of less than 5ha were directly represented in a channel based on their spatial distribution as they do not share a tributary with another dam. However, parameters such as surface area and capacity of each of the three off-channel dams were combined with those of the nearest dams with less than 5 ha represented based on their spatial distribution within a channel. Therefore, lumping some of the dams resulted in a model setup for the Twee Catchment with twelve reservoirs.

The Leeu catchment has an area of 26 140 ha with seventy-three farm dams. Twenty-three farm dams with surface area above 10 ha were directly represented in the channel and stream. More than five farm dams in the same river channel are found in this catchment. More than three dams in a single channel could not be represented in the model. Therefore, if dams in the same tributary exceeded three, they were lumped, as well as those with areas less than 5 ha and their combined area and volume were assigned to a dummy reservoir placed at the end of the flow contributing area. Fourteen off-channel farm dams were identified in the dam shapefile from SANSA. Since all water storage in the catchment had to be used for irrigation in the model, capacities of the existing off-channel dams were presented in the nearest dummy reservoir placed at the end of the flow-contributing area to represent the lumped dams. Seven dummy reservoirs were placed in the model setup, each representing six farm dams, including the off-channel dams. Consequently, the model setup for the Leeu catchments consists of 30 reservoirs.

Creating a detailed channel and stream network resulted in the model generating numerous small sub-basins. The model created over 40 small sub-basins for the Twee and the Leeu Catchments. The created sub-basins were merged into 33 sub-basins in the model setup for each catchment to make them correspond to the water management areas in the study catchments (Figure 4.5). The DEM inversion method in the QSWAT+ was used to delineate

the upland and lowland/riparian LSUs. This method reverses DEM elevations, recalculates the "flow" direction and calculates the area that contributes to the reverse of flow into each point (flow accumulation) (Dile et al., 2022). Points, where this reverse flow accumulation surpasses a specified ridge threshold are considered ridges. This is closely related to the method of defining streams. The exact threshold area (0.9 sq. km) set for stream delineation was retained as a ridge threshold for LSU creation.

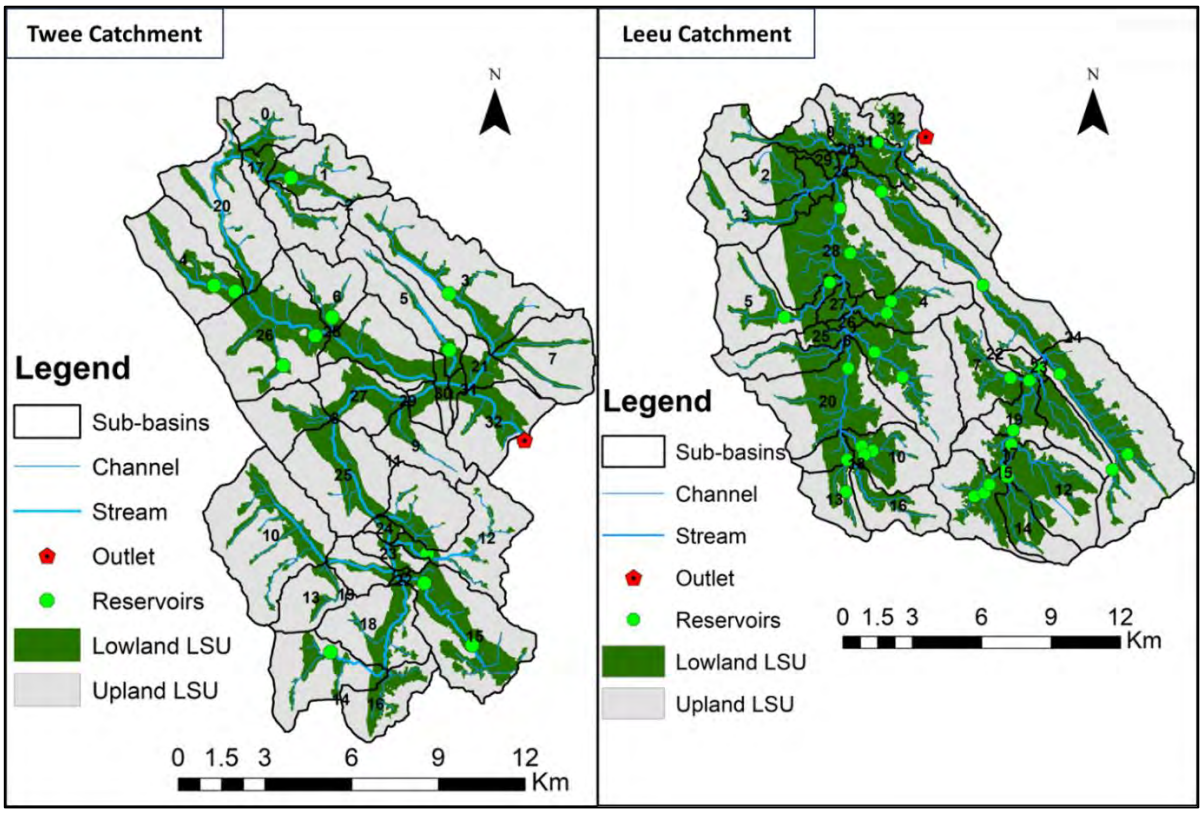

Figure 4.5: Merged sub-basins, channel and stream network, upland and lowlands LSU created, and reservoirs presented during watershed delineation in the model setup process for the Twee and Leeu Catchments.

4.4.2 HRU definition

The slope of the study catchment was divided into four classes. The decision to categorise the slope in the QSWAT+ into three classes was influenced by the topographic units created in the conceptual model (Figure 3.2) presented in the section above. The fourth topographic unit, the plateau, was considered in the third slope class as it is at the top of the mountain. The slope classes were specified as follows: 0-50%, 50-100%, 100-9999%. The 0- 50% slope class represents valley floors, where cultivation dominates. Toeslope is presented with a slope class of 50-100%, while hillslopes, including plateau, are presented with a slope class of 100-300%.

Single and multiple HRU options are available in the SWAT+ model for defining HRU. Multiple HRU option was selected for defining HRUs in the model setups for this study. This option generates multiple smaller HRUs consisting of distinct combinations of land use, soil type, and slope within each LSU.

This option is reported to improve model accuracy in representing hydrological processes (Haverkamp et al., 2002; Gassman et al., 2007). For this study, it was preferred so that the model considers all land use and soil types in the HRU definition, even those that cover an area of less than 1% of an LSU, to ensure that all irrigated crops are represented in HRUs. In this case, the option of the filter by land use, soil and slope was used. The threshold for land use and soil was set to 0% to ensure that all different LULC and soil types are captured when HRU's are being generated, while the threshold for slope was kept at 20% with the aim of restricting the model from creating many HRUs. Nonetheless, the SWAT+ model generated 2072 HRUs for the Twee and 2940 for the Leeu catchment.

4.4.3 Aquifer parameterisation

SWAT+ default aquifer parameters were adjusted to represent local conditions. The parameters were adjusted based on the knowledge acquired from previous groundwater and geological studies conducted in the study area (Brown et al., 2003; DWAF, 2003). The aquifer parameters adjusted in the model include specific yield, groundwater flow, baseflow rate, depth mid-slope surface to water table and water table depth for return flow (groundwater discharge to the stream) to represent the dynamics of the high water yielding fractured aquifer system. However, the values of these parameters were adjusted differently for the modelled catchments as these two catchments have slightly different aquifer systems along valley floors. For the Twee catchment, parameters were adjusted to represent the conditions of the unconfined aquifer system, while for the Leeu, were adjusted to relate to the conditions of the semi-confined aquifer system due to the shale aquitard layer confining the regional aquifer. For simplicity reasons, the values of aquifer parameters were kept consistent across the modelled area for each study catchment. In HRUs with outcropping rocks, the parameter value for cracks was increased to logically represent the occurrence of direct percolation into highly fractured quartzite outcropping rocks. Since only Twee has outcropping rocks (according to the obtained landcover map), this was done in the model setup for this catchment.

4.4.4 Irrigation setup in the model

Irrigation application can be manually scheduled by the user in the model or implemented through the SWAT+ auto-irrigation function. To implement manual irrigation in the model, precise information about the timing and amount of water applied to the irrigated fields for each irrigation event is required. Due to a lack of such information, irrigation for this study was implemented through the SWAT+ auto-irrigation function. Two auto-irrigation functions are available in the SWAT+: water stress and soil water deficit. Although soil water deficit function is considered a close representation of actual field irrigation, where irrigation is scheduled according to changes in soil water content (Chen et al., 2017), it does not consider crop potential or actual transpiration determined by leaf area index and stomata conductance. The water stress trigger is based on crop water demand (Arnold et al., 2018) and is a function of both crop and soil conditions. Therefore, it takes into account that crop water uptake is primarily determined by the maximum transpiration, soil layer and root zone depth (Padhiary et al., 2020). Since the study catchments have different crop and soil types and irrigation demand is known to vary by crop and soil type, irrigation for this study was implemented through the water stress function. Furthermore, the water stress auto-irrigation function is considered the most relevant option for modelling irrigation conditions in catchments located in semi-arid regions where evapotranspiration demand tends to be high (Dechmi et al., 2021; Samimi et al., 2020). The water stress is computed based on the following equation:

$$wstr = 1 - \frac{E_{t,act}}{E_t} = 1 - \frac{w_{actualup}}{E_t} \quad \ldots\ldots\ldots\

Reservoirs and river channels were defined as the primary source for irrigation and an aquifer as a backup source. HRUs of land use within an area of a particular farm with a reservoir/s were primarily irrigated from a reservoir on that farm. HRUs identified to be located in a farm with no reservoir were primarily irrigated from the nearest river channel. HRUs under the land use "appl1", for example, were all irrigated from reservoir/s in "farm 1" as they belong to the same farm, and "appl3" land use HRUs were irrigated from the closest river channel as this land use covers a farm with no dams (see Appendix 3 and 4 for farm spatial distribution). This approach is applied to all other land-use HRUs.

An aquifer that is in the same sub-basin as the targeted HRUs was used as an irrigation backup. According to the data gathered through WRC project (No. C2020/2021-00607) workshops, farmers have highlighted that they sometimes irrigate twice a day, but the amount applied in each irrigation event was not indicated. This study presumed that the farmers in the catchments follow the common irrigation rule of thumb, which is to apply 25 mm during each irrigation event. Therefore, the amount of irrigation in the model was set to go up to a maximum of 50 mm for each application when irrigation is required to account for two irrigation events of 25 mm per day. Given the variety of irrigation methods like micro sprinkler, drip, and centre pivot used in the catchments, it was decided to use sprinkler-medium as an irrigation method in the model. Sprinkler-medium strikes a balance between the other different methods mentioned. Furthermore, the sprinkler-medium irrigation method in the model is assumed to have a reasonably high irrigation efficiency, with 85% of the amount of applied water used for crop needs.

In terms of switching between the water sources, it was defined in the model that up to 95% of the reservoir's total capacity should be used for irrigation. The threshold for water abstraction was set high as reservoirs are mainly used for irrigation in the catchments. When the specified threshold is reached, the aquifer is used as the backup for irrigation. When a river channel is used for irrigation, the model automatically determines the amount available in the river and compares it with the amount defined for an irrigation application (Arnold et al., 2012). If the amount of river flow is insufficient to meet the irrigation demand at a specific time, the model does not perform irrigation. In the model set ups for this study, it was defined that when the amount of river flow is less than the specified amount for irrigation, water must be abstracted from an aquifer to meet irrigation demands.

4.4.5 Running the SWAT+ model

Before running the models for the Twee and Leeu catchments, the Penman-Monteith method was set to estimate potential evapotranspiration (PET) based on temperature, relative humidity, solar radiation and wind speed (Allen et al., 1998). The SWAT model uses PET to determine evapotranspiration. For this study, Penman-Monteith was preferred as it is considered a suitable method to represent the ET condition of semi-arid areas (Eini et al., 2023; Yimer et al., 2023).

The model for both Twee and Leeu Catchments was run for sixteen years, from 1999 to 2015. The first five years, which included years with CHIRPS rainfall, were used to warm up the model. The model for each catchment was run for three different scenarios. The first scenario was considered natural, where cultivated crops were not included in the land cover map used in the model setup, and reservoirs and irrigation were not represented. The various aspects of anthropogenic change were gradually incorporated into the model to evaluate the comparative magnitude of the effects of various anthropogenic interventions. In the second scenario, cultivated crops were included in the model setups and the reservoirs were represented. Crop irrigation from reservoirs, river channels and aquifers were then represented in the third scenario. The study mostly reports on the results from the model setup with reservoirs and irrigation, which is representative of present-day conditions.

4.5 SWAT+ Model Calibration, Validation and Performance Evaluation

4.5.1 Model calibration approach

The SWAT+ model can be calibrated manually or using automatic calibration software such as the SWAT+ Calibration Uncertainty Programming (CUP) and Integrated Parameter Estimation and Uncertainty Analysis Tool Plus (IPEAT+). For this study, the SWAT+ model was manually calibrated. Physical catchment properties were represented as far as possible, as demonstrated by the conceptual model and subsequent data preparation; this was done to reduce model input data uncertainty and improve reliability of the outputs. The calibrated parameters were selected based on the understanding of dominant catchment processes acquired from the conceptual model developed in the study. The most sensitive parameters to adjust were determined from studies that applied SWAT and performed a model parameter sensitivity analysis in irrigated agricultural catchments (Chen et al., 2020; Dechmi et al., 2021; Marahatta et al., 2021; N'guessan et al., 2023; Rivas-Tabares et al., 2019; Wei et al., 2021). The set of parameters selected for calibration and their description are presented in Table 4.3. The changes applied to the values of parameters calibrated are detailed in Table 4.4.

Table 4.3: Description of SWAT+ model parameters selected for calibration.

Parameter name	Description of abbreviation	Unit
bd	Bulk density	(mg/m^3)
awc	Soil Water Holding Capacity	Mm_H_2O/mm
epco	Plant uptake compensation factor	-
esco	Soil evaporation coefficient	-
cn2	SCS runoff curve number	-
revap_min	Threshold depth of water in shallow aquifer for "revap"	m
revap_co	Fraction of PET to calculate revap	-
perco	Percolation coefficient	Fraction
k	Saturated hydraulic conductivity	Mm/h
latq_co	Lateral flow travel time coefficient	-
alpha	Baseflow recession constant	days
flow_min	Minimum aquifer storage to allow return flow	m
bf_max	Baseflow rate	mm

Table 4.4: Parameter value ranges tested, and final change applied to the value for each calibrated parameter in the models for Twee and Leeu Catchments.

Parameter	Type of change	Object	Value ranges evaluated		Final value change applied	
			Min	Max	Twee	Leeu
bd	pctchg*	HRU	-5	-45	-0.35	-15
awc	pctchg*	HRU	-5	-50	-0.45	-10
epco	absval**	HRU	0.3	1	1.00	1.00
esco	absval**	HRU	0.5	1	1.00	0.4
cn2	pctchg*	HRU	-25	+5	-0.15	-15
cn2	pctchg*	HRU	+5	+30	+20	+20
revap_min	absval**	Basin	10	50	10	30
revap_co	absval**	Basin	0.05	0.1	0.05	0.2
perco	absval**	HRU	0.3	0.95	0.9	0.75
k	absval**	HRU	5	35	-	20
alpha	absval**	Basin	0.0002	0.3	0.002	0.07
latq_co	absval**	HRU	0.35	1	0.525	1

flow_min	absval**	Basin	5	20	15	10
bf_max	absval**	Basin	0.5	2	1.2	1.85

***pctchg**: means changing an initial parameter value by a specified percentage of its original value.

****absval**: means replacing an initial parameter value. The first **cn2** represents the cultivated area. The second **cn2** represents mountainous areas.

The parameters were calibrated with an iterative trial and error process to match observed low flows and obtain a good statistical model performance while ensuring that parameter values are within a range representative of catchment physical conditions. Although the main focus was to accurately match low flows as they are greatly affected by irrigation (Dechmi et al., 2021; Tanner et al., 2022), effort was also made to fairly match high flows. The values used for parameters at the start of the calibration process were also derived from the studies where sensitive parameters to calibrate were identified (Chen et al., 2020; Dechmi et al., 2021; Marahatta et al., 2021; N'guessan et al., 2023; Rivas-Tabares et al., 2019; Wei et al., 2021). Two parameters were adjusted at a time, and hydrographs and flow duration curves of the simulated and observed were visually compared. This process was repeated until low flows were reasonably matched, and it was deemed that satisfactory objective function values indicating model performance reliability had been obtained.

The degree of value adjustment for calibrated parameters was decided based on understanding the catchment's physical characteristics. For instance, sandy soils dominate in the catchments and are cultivated. Soils with high sand content generally have low **Bd** and **AWC,** and cultivation further lowers these soil properties. These conditions favour high infiltration and low surface runoff, particularly in flat landscape units. Therefore, to reasonably represent high infiltration rates and low surface runoff in cultivated areas, it was logical to reduce values of parameters such as **Bd** and **AWC** in HRUs with cultivated crops by a maximum of 35% and 45%, respectively. It was also determined to be cogent to reduce **CN2** by a maximum of 15% in HRUs of cultivated crops to represent high infiltration rates induced by cultivation practice. However, in HRUs for hillslope areas, which are mainly covered by sparse grass and fynbos shrubs, it was reasonable to increase **CN2** to a maximum of 30% to represent the high surface runoff generated in this landscape position. The value of **esco** was increased, and **revap_co** was reduced for all HRUs to represent ET conditions consistent with catchments in semi-arid regions. The parameter **epco** value was increased to maximum in HRUs with black wattle to allow water uptake from deep soil layers as this vegetation type has a deep root system.

To replicate prolonged groundwater discharge to the Twee stream as the catchment sits on the fractured aquifer, which has direct contact with the riverbed, values of aquifer properties such as **bf_max** and **flow_min** were increased while **alpha** was reduced. For the Leeu Catchment, **bf_max** and **alpha** were increased while **flow_min** was reduced to mimic ephemeral groundwater discharge that occurs when the water table in the fractured aquifer overlaid by a shale layer (that the Leeu riverbed is sitting on) is high enough during the rainy season. To represent the high interflow rate induced by a fractured rock in the unsaturated zone (at Twee) and less permeable shale layer (at Leeu) underlaying draining soils, the **latq_co** value was increased.

The model for the Twee quaternary catchment was calibrated against observed streamflow data obtained from the Freshwater Research Centre (FRC). The length of observed streamflow data is three years, starting from 2013 to 2015. Therefore, the model for the Twee Catchment was calibrated for those three years and was not validated. The model for the Leeu Catchment was calibrated and validated against the observed streamflow data from the Department of Water and Sanitation (DWS). The model was calibrated for six years and validated for six years.

4.5.2 Performance Evaluation

Several statistical indicators are commonly employed to evaluate the performance of a hydrological model. In this study, Nash-Sutcliffe efficiency (NSE) was utilised as the primary objective function during both the calibration and validation phases. Pearson's correlation coefficient (r) and coefficient of determination R^2 were the additional statistical criteria employed to evaluate the model's performance quantitatively.

NSE quantifies the degree to which the plot of measured streamflow data against modelled streamflow aligns with the 1:1 line (Moriasi et al., 2007). It is computed using the following equation:

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \quad \ldots\ldots 9$$

Where Q_m^t is the modelled streamflow at a given time step; Q_o^t is the observed flow at a given time step; $\overline{Q_o}$ is the mean of the observed flows.

The NSE range is from -∞ to 1.0, with NSE = 1 being the optimal value. Moriasi et al. (2007) suggest that model performance is generally deemed satisfactory when the NSE exceeds 0.50. Values equal to or less than 0.0 suggest that the mean observed value provides better predictions

than the modelled value. In this case, the model performance is considered unacceptable (Moriasi et al., 2007).

The coefficient of determination R^2 describes the proportion of variance in measured data explained by the model and ranges between 0-1. Higher value of R^2 means less error variance. A value greater than 0.5 is generally deemed acceptable for the coefficient of determination R^2 (Moriasi et al., 2007).

CHAPTER FIVE

RESULTS

5.1 Introduction

This chapter presents the SWAT+ outputs obtained for the modelled Twee and Leeu Catchments. The results are presented in the following four sections.

I. Calibration and validation of the SWAT+ model.
II. Estimates of selected hydrological processes.
III. Impacts of reservoirs and irrigation on catchments hydrology.
IV. Reservoir hydrological dynamics in relation to abstraction for irrigation.
V. Irrigation and yield for different crop types.

The results for irrigation and yields for crops within an area of Farm 3 were chosen to be presented in this section as the crop yield was obtained from this farm. Also, it would not be possible to represent irrigation and yields of all crops and farms in this thesis due to time constraints.

5.2 Calibration and validation result

The streamflow calibration at the Twee FRC gauging station yielded a good agreement between the simulated flow (from a scenario with dams and irrigation) and observed flow. This is supported by visually comparing the simulated and observed hydrographs and by statistical indicators employed to evaluate the model (Figure 5.1; Table 5.1). The hydrographs show that the model simulated the catchment flow pattern satisfactorily. However, the model under-simulated the peak flows for most of the calibration period and only reasonably simulated low flows in the wet season. Flows during the dry season are slightly under-simulated by the model, and this is also visible in the flow duration curve (FDC).

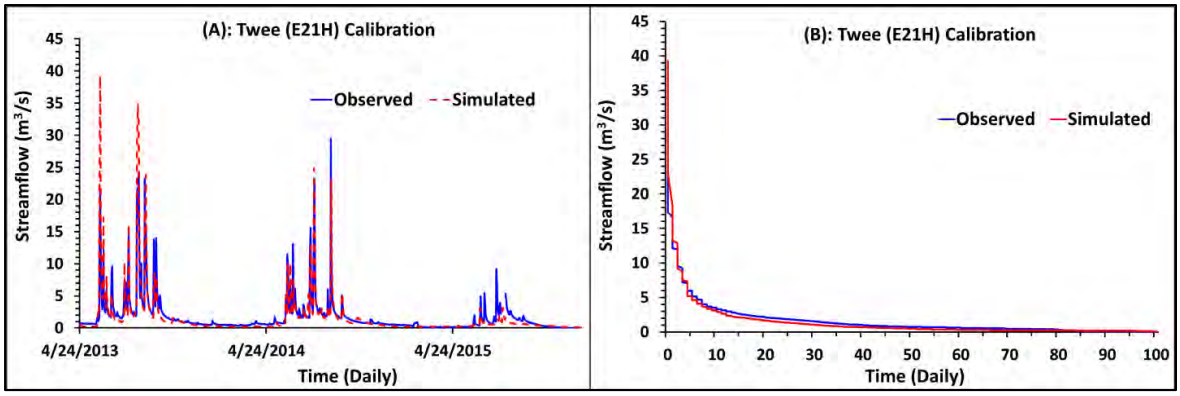

Figure 5.1: Hydrography (A) and FDC (B) for Twee FRC gauging station for calibration period 2013 to 2015.

Even though the calibration and validation of the streamflow at the Leeu catchment outlet resulted in a good fit of modelled and observed flow (Figure 5.2; Table 5.1), it can be seen from the hydrographs and FDC of modelled and observed data (Figure 5.2) that the model under simulated peak flows in the first half of calibration and overstimulated on some days in the year 2007 and 2008. Within the validation period, the model over-simulated peak flows most of the time, while there were days when peak flow was slightly under-simulated between 2010 and 2014 (Figure 5.2). Low flows in wet and dry seasons were reasonably simulated during the calibration period. In validation years, low flows were slightly overstimulated in the wet season. Low flows were reasonably simulated in the dry season, with some small peaks occurring just after the wet season. Intermediate flows are generally under-simulated in both the calibration and validation periods.

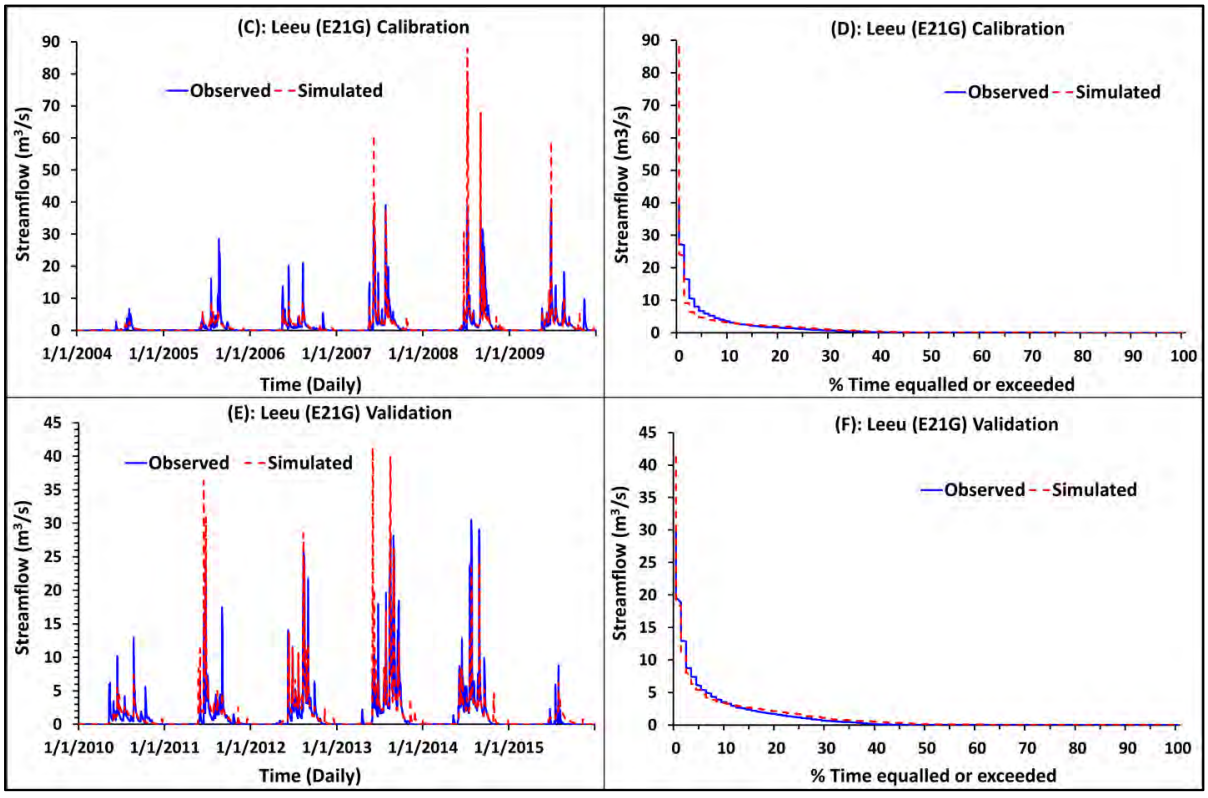

Figure 5.2: Hydrography (A) and FDC (B) for Leeu DWS gauging station for calibration period 2004 -2009 and validation period 2010 - 2015.

NSE and R2 values above the 0.5 standard were obtained for the calibration of the Twee and Leeu Catchments. Table 5.1 indicates that NSE values 0.67 and 0.68 were attained for the Twee and Leeu, respectively. An improved NSE of 0.70 was obtained for the Leeu validation period.

Table 5.1: Calibration and validation statistics.

Catchment	Simulation	Warm-up period	Statistic period	R^2	NSE
E21H (Twee)	1999-2015	1999-2003 (5yrs)	Calibration: 2013-2015	0.79	0.67
E21G (Leeu)	1999-2015	1999-2003 (5yrs)	Calibration: 2004-2009	0.68	0.68
			Validation: 2010-2015	0.71	0.70

5.3 Simulated hydrological processes.

The critical hydrological processes reported in this section include SWAT+ simulated evapotranspiration (ET), surface runoff (surq), lateral flow (latq), which is referred to as interflow thought out this study, and groundwater flow (GWflow), which is also referred to as groundwater discharge within this study.

5.3.1 Simulated hydrological processes for the Twee Catchment

Figures 5.3 A & B show the simulated annual average and seasonal variation of the hydrological processes of the Twee Catchment from 2004 to 2015. The results demonstrate that 55% of the total water input into the Twee quaternary catchment is lost through evapotranspiration, while 22% is converted into surface runoff (Figure 5.3A). Interflow and groundwater flow account for 9% and 9% of the catchment water, respectively. The remaining 5% is distributed to soil moisture and groundwater storage of the catchment.

It can be seen from the seasonal distribution of the hydrological processes graph (Figure 5.3B) that high surface runoff and interflow are generated due to high rainfall and low ET generally occurring during this winter period (Figure 5.3B). The simulated runoff for the catchment reaches 69 mm/month in the rainy period, and there is a notable increase in interflow in the middle of the wet period. Evapotranspiration rates increase considerably and exceed 60 mm/month between the spring and summer (September to February). The model simulated noticeable irrigation (irr) amounts between November and April, which contributed to high ET rates. There are also visible irrigation amounts for blueberries from May to September. The groundwater flow to the river is relatively consistent throughout the seasons of the year, with a slight increase from September to January.

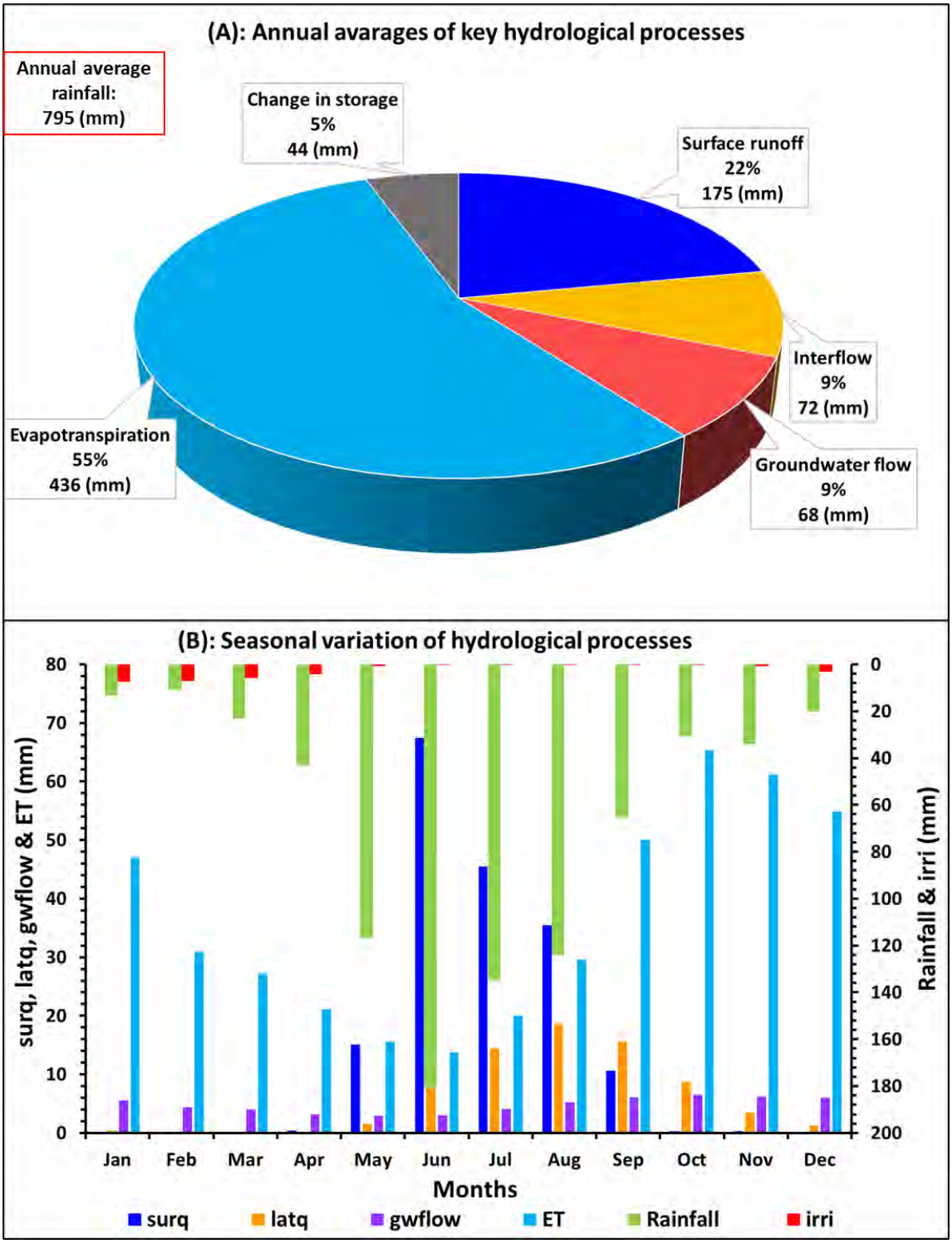

Figure 5.3: Simulated annual averages (A) and seasonal variation (B) of hydrological processes of the Twee Catchment from 2004 to 2015. SURQ = Surface runoff, LATQ = Lateral flow (it is referred to as interflow in this study), GWFLOW = Groundwater flow (also referred to as groundwater discharge in this study), ET = Evapotranspiration, Irri = Irrigation.

Figure 5.4 presents simulated monthly averages of runoff processes for the Twee Catchment over the simulation period. Surface runoff appeared to be a dominating runoff process exceeding 150 mm/month in rainy seasons of wet years. The results also show that the catchment experiences a rapid interflow response, amounting to 20 mm/month during rainy season. Furthermore, vertical runoff processes (percolation/groundwater recharge) of up to 20 mm/month in rainy season occur in the catchment. The results also show consistent groundwater discharge in the Twee Catchment, which maintains streamflow during the dry season.

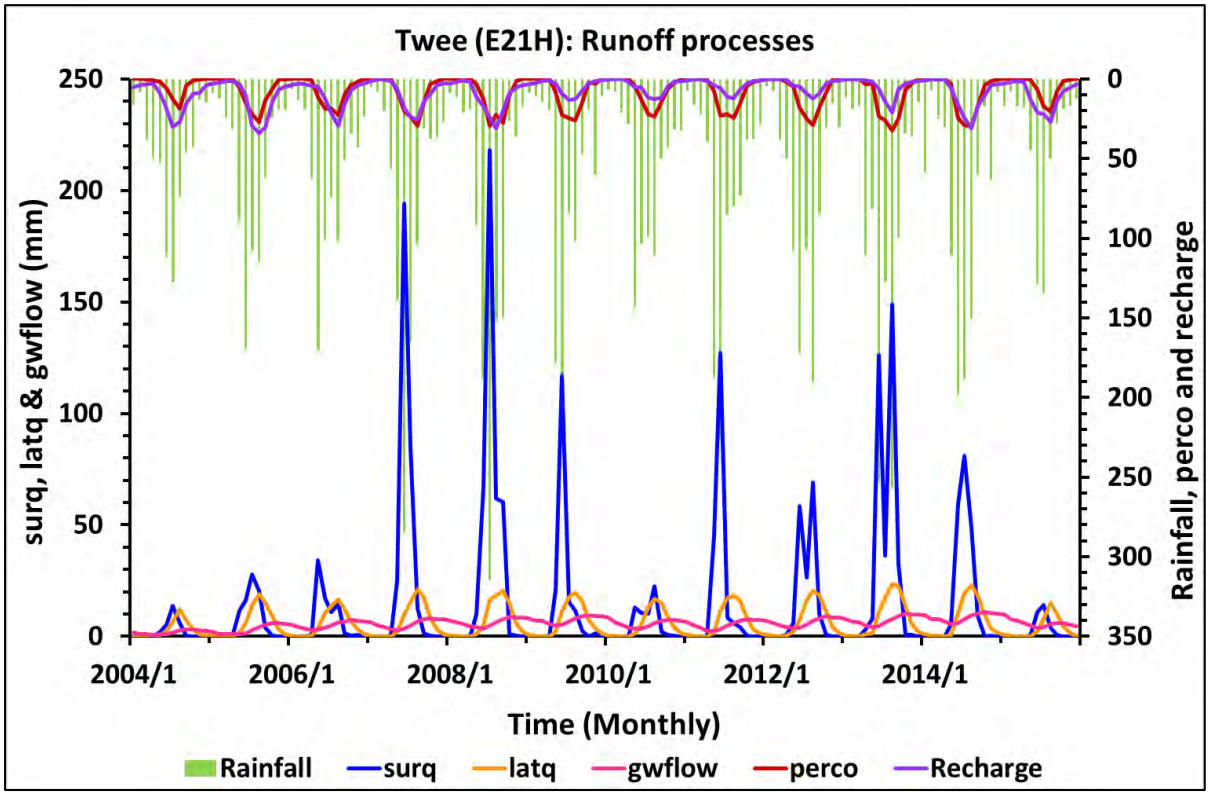

Figure 5.4: Time series of rainfall and simulated monthly averages of runoff processes for the Twee Catchment for the period between 2004 and 2015.

5.3.2 Simulated hydrological processes for the Leeu Catchments

The annual average estimates of key hydrological processes for the Leeu Catchment and their seasonal variation from 2004 to 2015 are presented in Figure 5.5. 67% of rainfall in the Leeu quatenary leaves the catchment storage through evapotranspiration. Interflow and surface runoff annual avarages over the simulation priod were estimated to be 179 mm/yr and 178 mm/yr, representing 25% and 24% of the catchment's mean rainfall, respectively. Groundwater contribution to the stream accounts for 7%. The estimated net change in storage for the Leeu is -22 %.

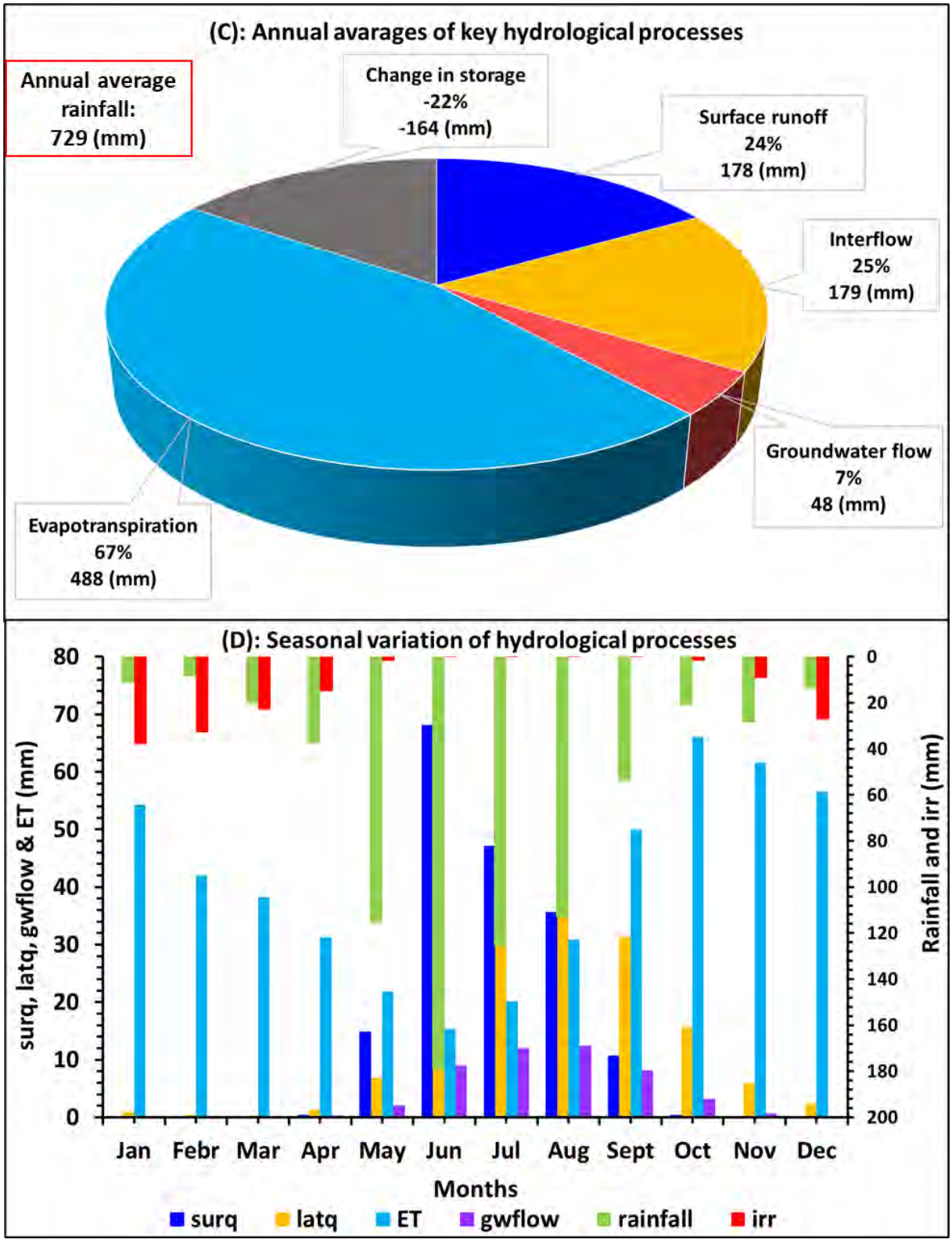

Figure 5.5: Simulated annual averages (A) and seasonal variation (B) of water balance components of the Leeu catchment from 2004 to 2015.

As shown in the seasonal variation graph (Figure 5.5D), the peak of the rainy season is between May and August, resulting in high surface runoff and interflow within this period. Groundwater flow is also noticeably high during the wet season. High evapotranspiration rates that range between 50 to 70 mm/month occur between dry spring and summer season, and within this period, there is high irrigation demand. Irrigation for cash crops like onion and triticale in the Leeu catchment appears between May and September.

The results of runoff processes for the Leeu catchment are shown in Figure 5.6. Surface runoff and interflow are almost equally dominant processes in the catchment. However, during wet years (2007 to 2009 and 2011 to 2013), extremely high surface runoff ranging between 150 and above 200 mm/month in rainy season occurs. Meanwhile, interflow reaches and exceeds 40 mm/month in rainy seasons almost throughout the simulation years. The results also show that groundwater flow in the catchment responds quickly, following the seasonal variations of percolation and recharge.

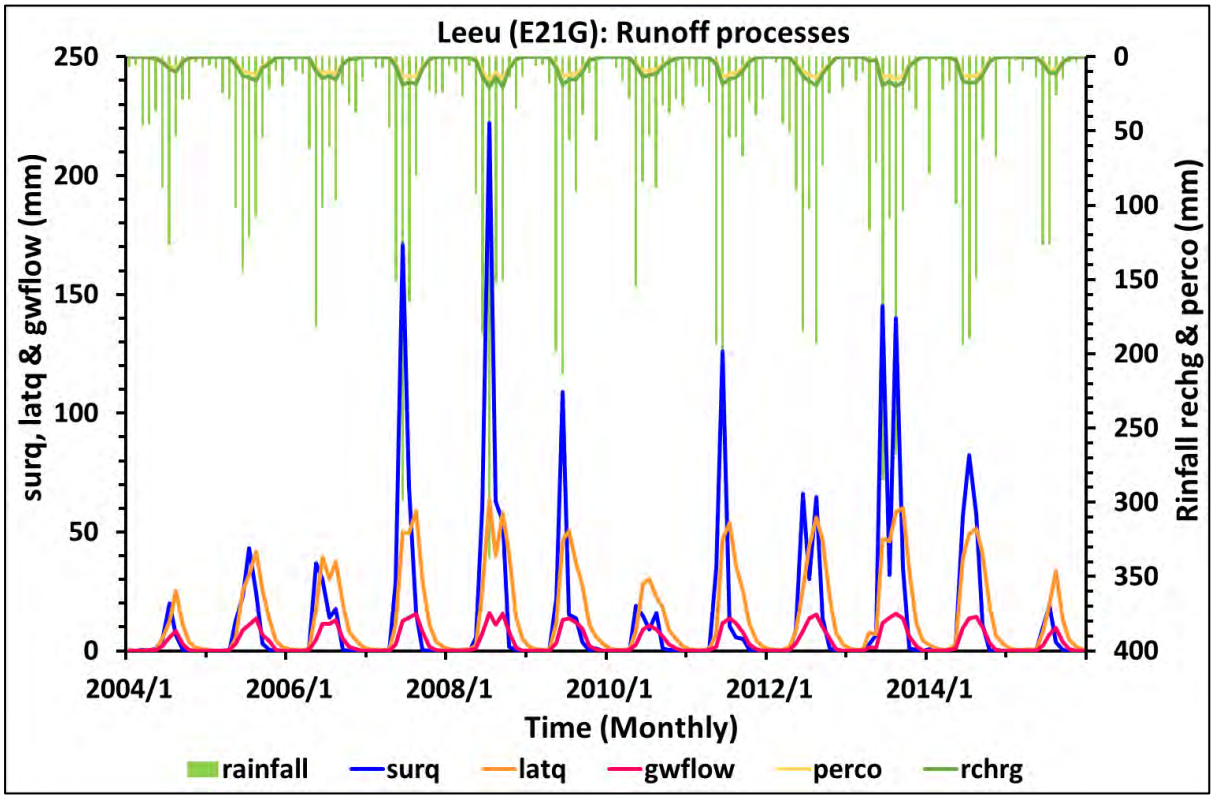

Figure 5.6: Time series of rainfall and simulated monthly averages of runoff processes for the Leeu Catchment for the period between 1995 and 2021.

5.4 Impact of reservoirs and irrigation on catchment hydrology regime

Comparison of simulated streamflow data from three model runs for Twee and Leeu quaternary catchments (scenarios 1,2 and 3, as explained in section 4.4) was carried out as

shown in Figures 5.7 and 5.8, respectively. It is clear from simulations that the dams and irrigation significantly impact the natural streamflow.

5.4.1 Reservoir and irrigation impact on Twee Catchment hydrology

As shown in Figure 5.7A, incorporating reservoirs reduced the simulated natural average daily flow (from 2004 to 2015) in the Twee catchment from 3 m^3/s to 1.6 m^3/s. and adding irrigation resulted in a further reduction of 0.2 m^3/s, on daily average streamflow. Furthermore, as shown in the FDC (Figure 5.7B), in a scenario where reservoirs and irrigation are not included, flows greater than 1 m^3/s would occur in the catchment river at least 100% of the time. However, with the prevalence of reservoirs and irrigation in the catchment, river flows that are above or equivalent to 1 m^3/s occur only 30% of the time.

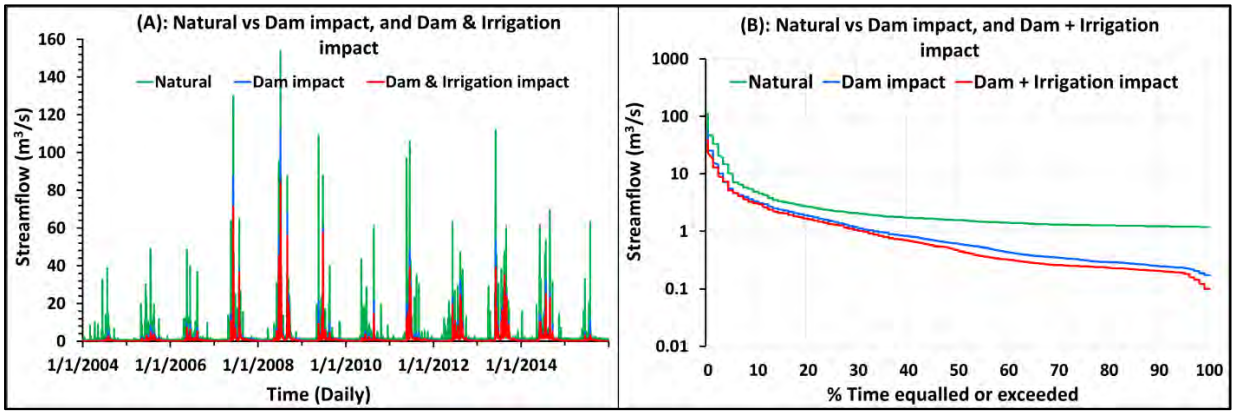

Figure 5.7: Comparison of Hydrographs (A) and FDC (in a logarithmic scale) (B) of a naturalised scenario, dam impact scenario, and dam and irrigation impact scenario for the Twee Catchment.

5.4.2 Reservoir and irrigation impact on Leeu Catchment hydrology

The difference in simulated Leeu streamflow under three different modelled scenarios is shown in Figure 5.8. The inclusion of reservoirs resulted in the reduction of simulated daily average streamflow from 3.05 m^3/s to 1.43 m^3/s (Figure 5.8C). Adding crop irrigation together with reservoirs in the model resulted in a further reduction of 0.49 m^3/s on daily average simulated streamflow. Consequently, reservoirs and irrigation reduced the daily average streamflow to 1.13 m^3/s. As shown in the FDC (Figure 5.8D), river flows exceeding or equivalent to 1 m^3/s in a scenario considered natural for the Leeu Catchment occurs 40% of the time. In scenarios with reservoirs and both reservoirs and irrigation river flow above 1 m^3/s occur for only about 15% of the time.

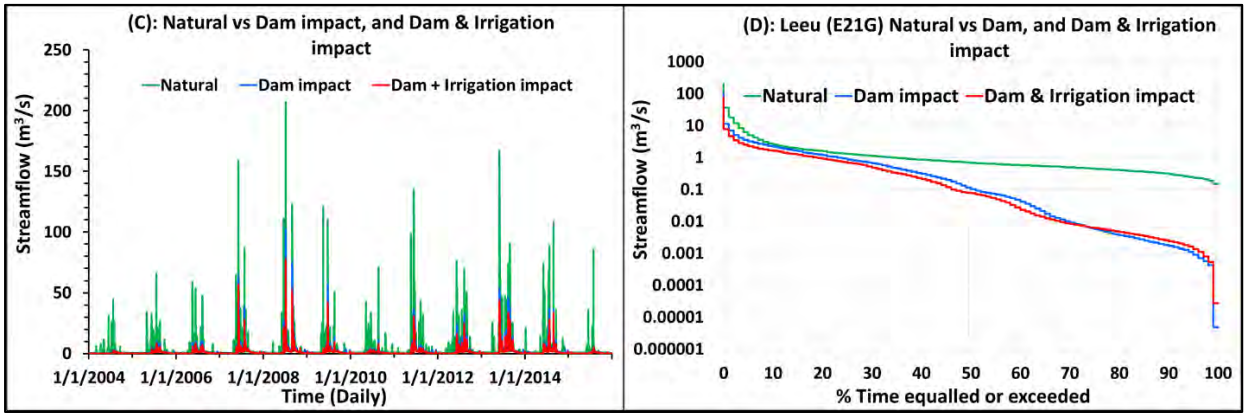

Figure 5.8: Comparison of Hydrographs (C) and FDC (in a logarithmic scale) (D) of a naturalised scenario, dam impact scenario, and dam and irrigation impact scenario for the Leeu Catchment.

5.5 Impact of water abstractions on reservoir hydrological dynamics

Reservoirs are the primary water source for irrigation in both modelled catchments, with some cultivated areas irrigated mainly from a river channel. Since a significant amount of irrigation water was abstracted from the reservoirs, the hydrological dynamics of reservoirs before irrigation were compared to the reservoir's hydrological dynamics after water abstraction for crop irrigation to observe how these dynamics changed with irrigation implementation in the model. Reservoir hydrological dynamics reported in the study include water levels and spillage (overflow).

5.5.1 Impact of irrigation abstractions on selected Twee Catchment reservoirs

Figure 5.9 illustrates reservoir water levels for the Twee catchment when water is abstracted for crop irrigation. In a scenario with no water withdrawal, reservoir water levels remain consistently high, with slight fluctuations reflecting wet and dry seasons. When irrigation is added, water levels in most reservoirs fluctuate significantly, reflecting filling in the rainy season and emptying due to water abstraction during the irrigation season. Overall, water withdrawal for irrigation resulted in a considerable decline in water levels. For instance, after water abstraction for crop irrigation, the average water volume in reservoirs 1, 3 and 4 was reduced by 50%, 85% and 34%, respectively. Water levels in Reservoir 4 from 2007 exceeded total storage capacity in the rainy season and remained reasonably high even during growing seasons when irrigation demands were high, as this reservoir is located in the part of the catchment receiving higher rainfall. Although Reservoir 1 is also located near Reservoir 4, where there is high rainfall, the water levels in Reservoir 1 only exceeded total capacity in the rainy seasons of wet years 2008, 2013, and 2014 and dropped significantly during the growing

season. There is insignificant fluctuation of water levels in Reservoir 3 as water levels only exceeded 0.5 Mm^3 in between the years 2013 and 2014 and did not drop below 0.2 Mm^3 during the entire simulation period.

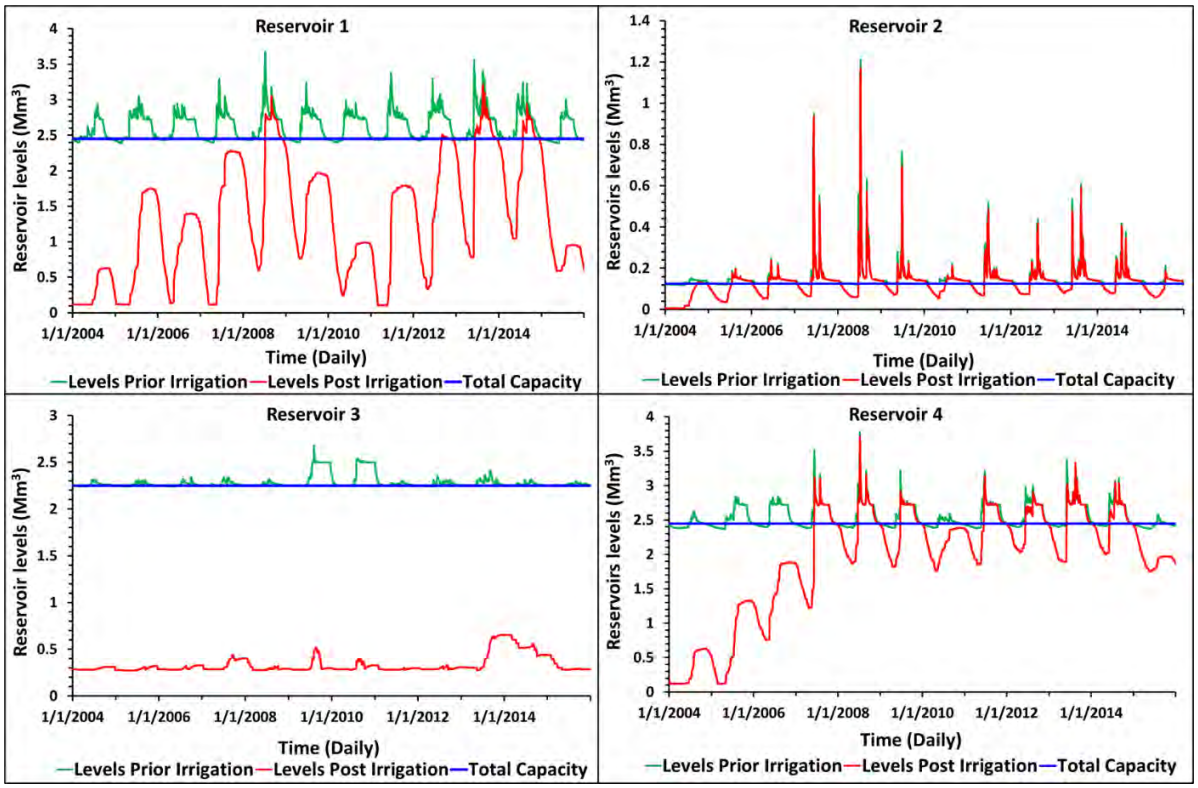

Figure 5.9: Reservoir water levels under the irrigation and no-irrigation scenarios for the Twee catchment. Reservoirs 2 and 3 are located upstream of the eastern side of the catchment. Reservoirs 1 and 4 are located midstream on the western side of the catchment.

Figure 5.10 demonstrates the amounts of spillage from the presented reservoirs before and after irrigation withdrawals. The hydrographs and FDCs in Figure 5.10 show that in a scenario where there is no irrigation, there is reasonable spillage from reservoirs, which occurs up to about 50% of the time, except reservoir 3, which only started to have some spillage from 2010 and overflowed 25% of the time. Although the graph for reservoir 3 in Figure 5.10 does not show any spillage in years prior to 2010, it is evident in Figure 5.9 (Reservoir 3) that water levels in this reservoir slightly exceeded total storage capacity years before 2010 under natural scenario.

Irrigating from the reservoirs considerably reduced spillage and resulted in reservoirs 1 and 4 spilling less than 20% of the time. Reservoir 3 registers zero spillage 100% of the time, while Reservoir 2 spills for up to 45% of the time. Although Reservoirs 2 and 3 are located upstream and in the catchment area with little rainfall, reservoir 2 fills and spills quickly as it has a significantly smaller total storage capacity than reservoir 3.

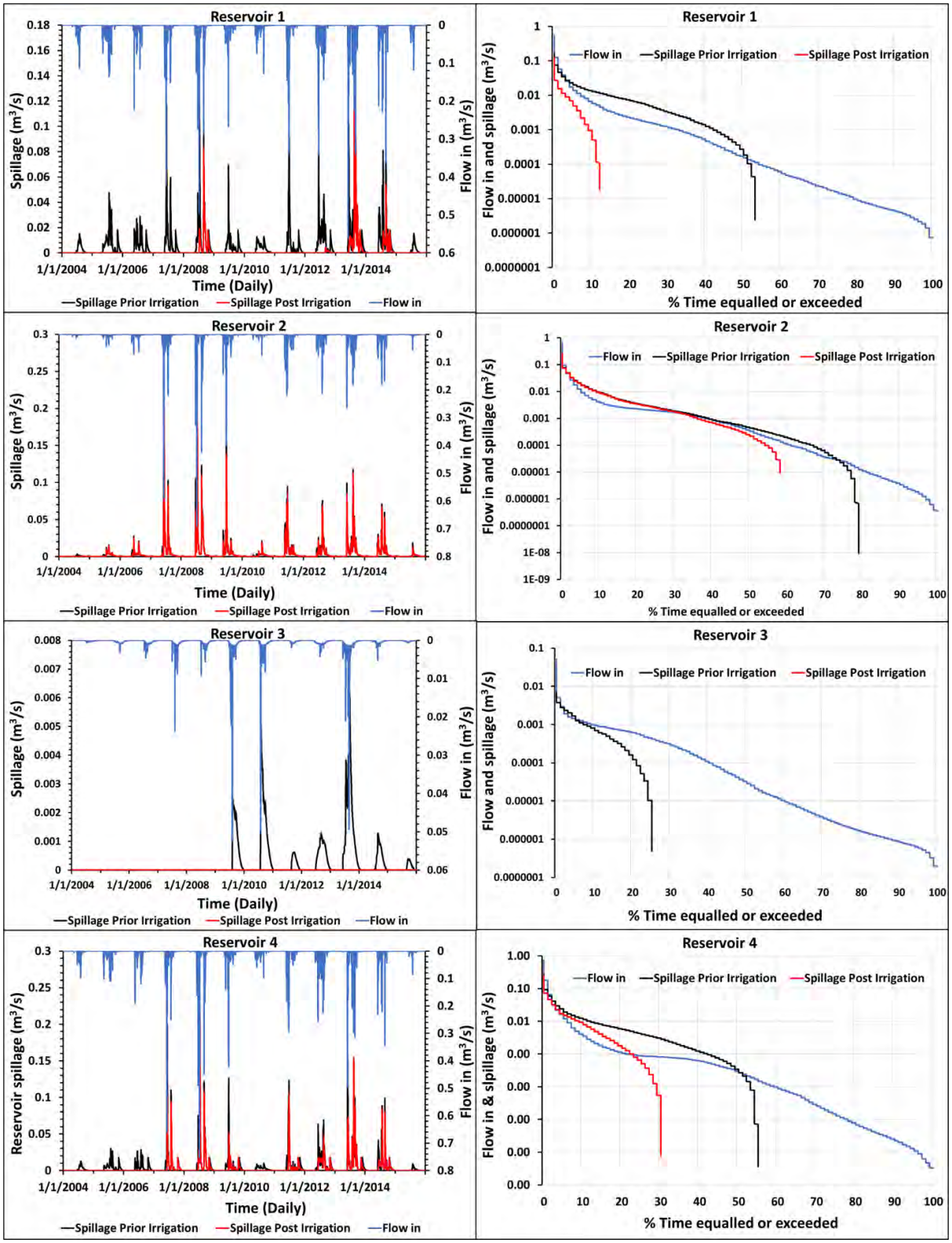

Figure 5.10: Reservoir spillage amounts and duration when there is no water abstraction and when there is irrigation from reservoirs for the Twee catchment. A logarithmic was used for FDC since the overflow amounts are significantly low.

5.5.2 Impact of irrigations abstractions on selected Leeu Catchment reservoirs

A comparison of reservoir water levels with and without irrigation abstractions is presented in Figure 5.11. The pattern exhibited in the Leeu reservoirs is similar to that of the Twee reservoirs for both no-irrigation and irrigation scenarios. Water levels remain close to the total storage capacity of reservoirs with slight seasonal variations in the no-irrigation scenario while irrigation substantially fluctuates, corresponding to filling and water abstraction. Contrastingly, the Leeu exhibits a significant decline in water levels for the irrigation scenario as there is high irrigation demand due to large, irrigated areas in the catchment. When irrigation is introduced, average water levels for Reservoirs 6, 7 and 8 are reduced by 71%, 76%, and 71% respectively. However, water levels in reservoir 3 in the Twee Catchment showed the highest decline of 85%, compared to water levels in all other presented reservoirs.

Water levels in Reservoirs 5 and 7 reached total storage capacity only in 2013, while in Reservoir 6 slightly exceeded the total storage capacity. Water levels in Reservoir 8 never reached the total storage capacity throughout the simulation period, as the reservoir is located downstream and used to irrigate numerous cultivated areas. During the growing season, which is between October and April, water levels in Reservoirs 6 and 7 drop below 0.2 Mm^3 throughout most of the simulation period, except reservoir 5, where levels do not drop below 1.8 Mm^3 since the year 2009 as the reservoir has a bigger storage capacity and is located in the main river channel. Furthermore, in reservoir 8, water levels remained above 1 Mm^3 between the years 2014 and 2015, even during the irrigation period.

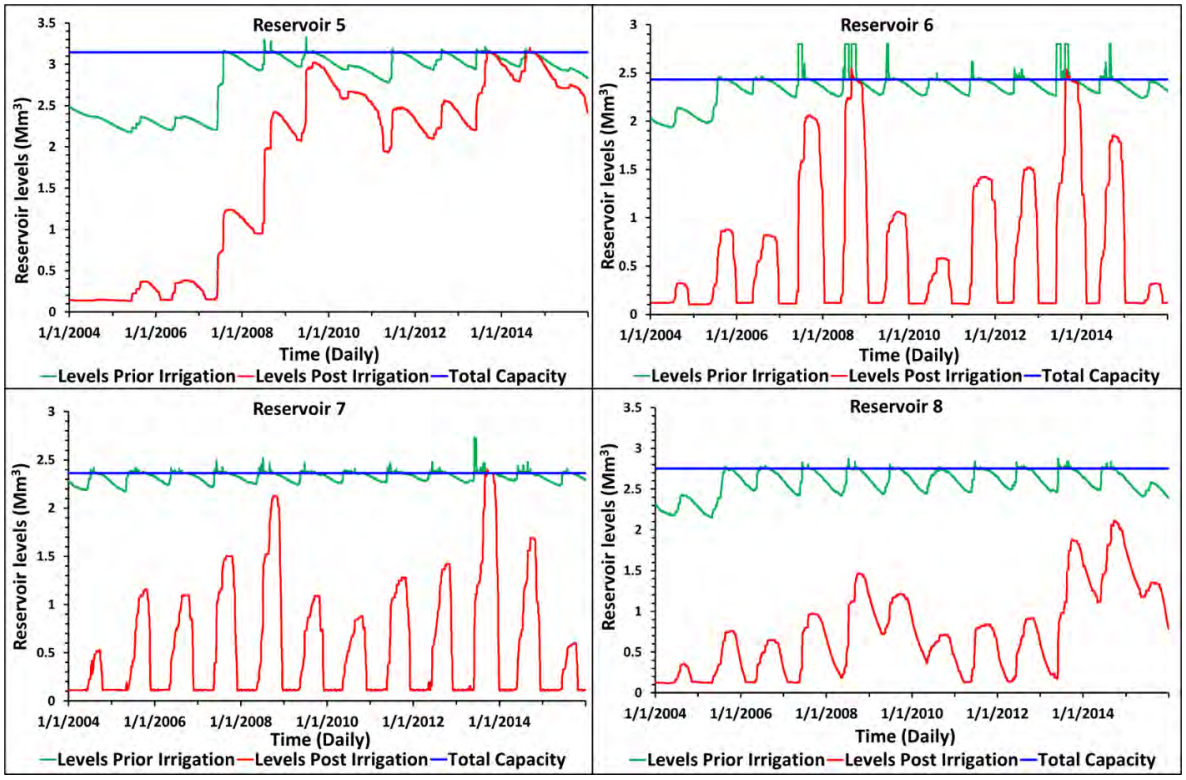

Figure 5.11: Reservoir water levels under the irrigation and no-irrigation scenarios for the Leeu catchment. Reservoir 8 is located downstream. Reservoirs 6 and 7 are upstream, and Reservoir 5 is located midstream.

A comparison of the amount and duration of spillage from the reservoirs before and after irrigation is shown in Figure 5.12. The results show that the reservoirs overflowed for most years without irrigation. Reservoir 7, which had noticeable spillage throughout the entire simulation period, is located upstream in a catchment area with high rainfall. Under the scenario considered natural, reservoirs 6 and 7 overflowed more than 20% of the time. Spillage in reservoir 8 occurred at least 10% of the time, while reservoir 5 spilled less than 10% of the time.

In a scenario where irrigation is represented, a significantly small amount of spillage occurs for a very short period, which does not exceed 1% of the time in most reservoirs presented for the Leeu Catchment. The results also show that Reservoir 8 did not overflow during the simulation. Reservoirs 5 and 7 overflowed in the rainy season of 2013 and 2014, while reservoir 6 spilled in 2008 and 2013, which were all wet years. These hydrological conditions in the Leeu reservoirs were expected due to high irrigation demand as large, cultivated areas in the catchment are irrigated mainly from the farm dams.

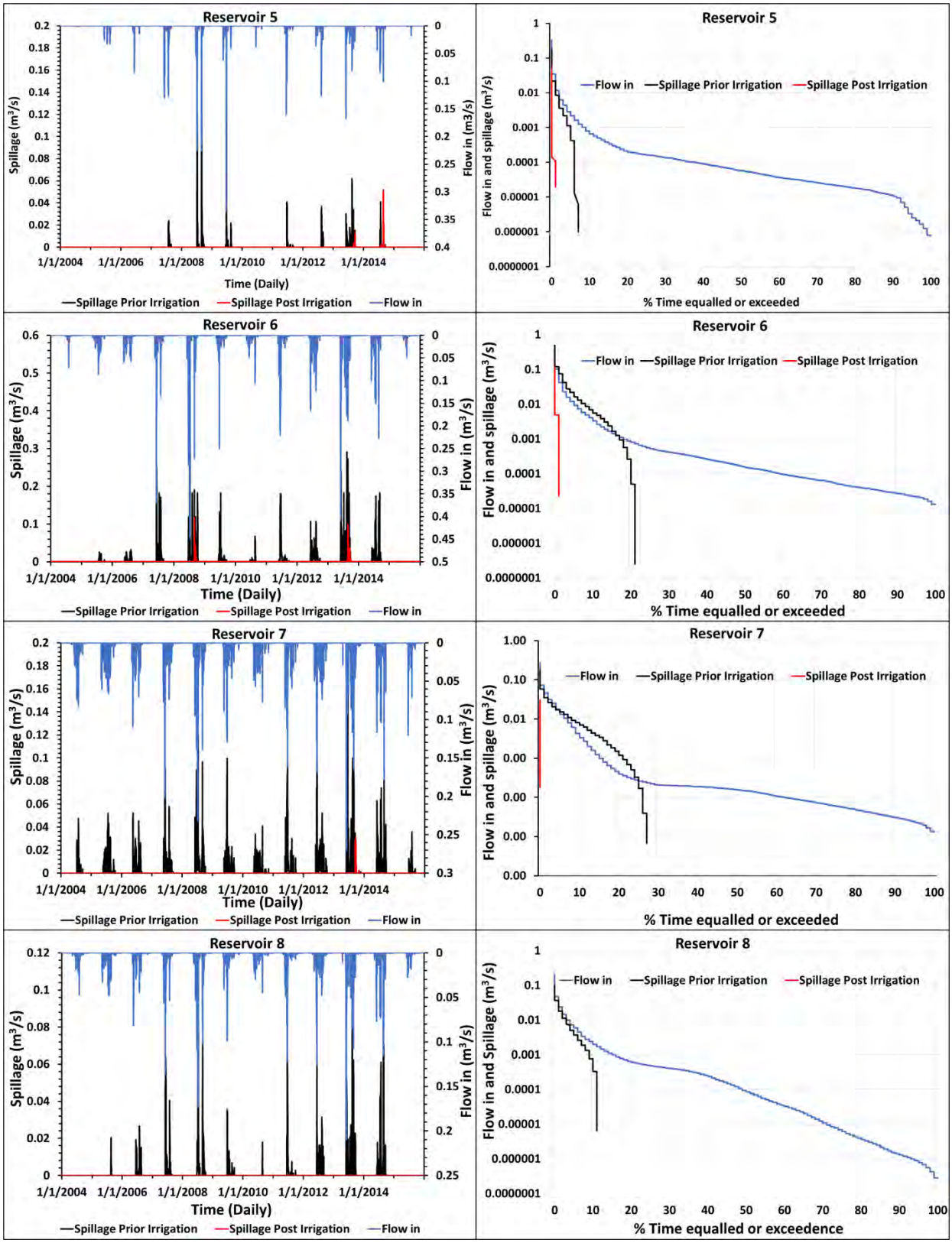

Figure 5.12: Reservoir spillage amounts and duration when there is no water abstraction and when there is irrigation from reservoirs for the Leeu catchment. A logarithmic was used for FDC since the overflow amounts are significantly low.

5.6 Simulated crop irrigation and yield

5.5.1 Crop irrigation

Eleven crop types were included in this study's modelling exercise, as mentioned in section 4.3 in chapter 4, but only three of those are reported in detail in this section. The presented crops are those of the farm (Farm 3) where observed crop yield was obtained. However, monthly simulated irrigation depths of dominating crops in the Twee Catchment are also shown in this section to show the water requirements for other crops briefly. Figure 5.13 shows the rainfall, soil moisture, and irrigation application to selected crops from 2012 to 2015. The focus is mainly on irrigation simulation with some references to rainfall and simulated soil moisture. The length of the irrigation period for each crop in each year can be visualised in appendix 5 - 7. Simulated monthly irrigation depths for different crop types are presented in Figure 5.14.

SWAT+ model simulated irrigation between November and May every year during the simulation period. However, the length of the irrigation period in the growing season varies from crop to crop and depends on the length of the rainfall season in a particular year. For instance, irrigation for apples started in January and stopped in March in the growing season 2012-2013, but in seasons 2013-2014 and 2014-2015, the last irrigation events were triggered towards the end of April since the rainfall only started to occur in May. The year 2015 had a considerably short rainy season as little rainfall started to occur at the end of May and stopped in August, resulting in irrigation for apples starting in December in this particular year.

Irrigation for nectarines started in December and stopped at the end of April, except in 2015, when irrigation stopped in May and started in November. The model started to trigger irrigation for the citrus from December to May in the growing season 2012-2013. For the season 2014-2015, irrigation occurred from early January to late May; in 2015, irrigation started in November. Even though the irrigation period for citrus ended later (May) compared to that for nectarines (April), irrigation events for nectarines were more frequent than those for citrus, which were scattered.

The results also show that the potential growth of crops declines when soil moisture drops below 20 mm, resulting in irrigation being triggered by the model to prevent crop water stress. When irrigation is required, 40 mm is applied at each irrigation event. The difference in water demands of different crop types is reflected in the number or frequency of irrigation events triggered in the model instead of the irrigation amounts. Therefore, the results demonstrate that

nectarines require more water than apples and citrus fruits, as the irrigation events for nectarines are more frequent than those of other crop types (Figure 5.13).

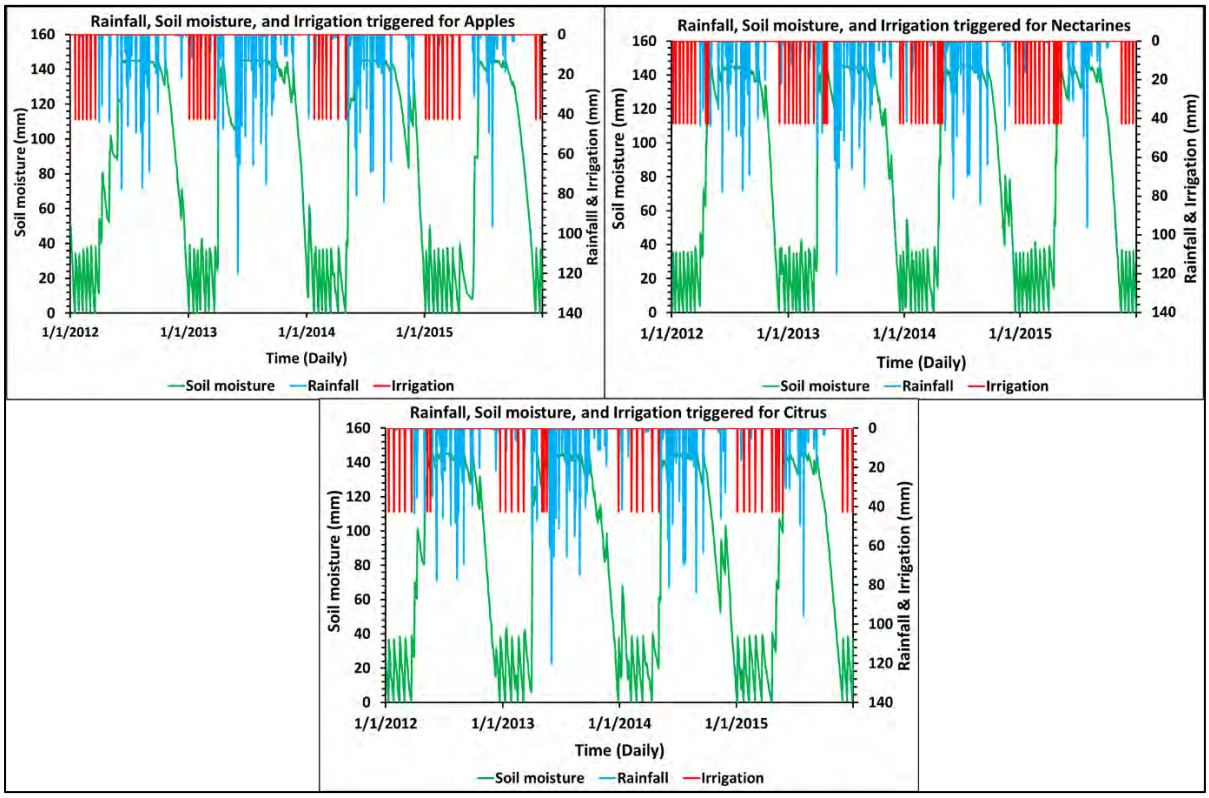

Figure 5.13: Rainfall, simulated soil moisture, and irrigation events triggered for presented crop types.

Monthly irrigation depths for different crops are included (Figure 5.14A) to demonstrate the simulated irrigation period of the blueberry crop, as it has a different growing season than the other crops grown in the Twee catchment. Additionally, Figure 5.14A shows the simulated changes in monthly irrigation depths over the irrigation period for each crop. It is evident in Figure 5.14A that the model correctly simulated the irrigation period of the blueberry crop, which is mainly between April and September. Figure 5.14B shows that blueberry has a higher irrigation depth than all other crop types, exceeding 2500 mm in 2012 and 2015. Stone fruits like nectarine and apricot follow blueberries with high annual irrigation depth exceeding 600 mm monthly. Apple and pear have the lowest irrigation depth among other crop types, which only surpassed 500 mm in 2015.

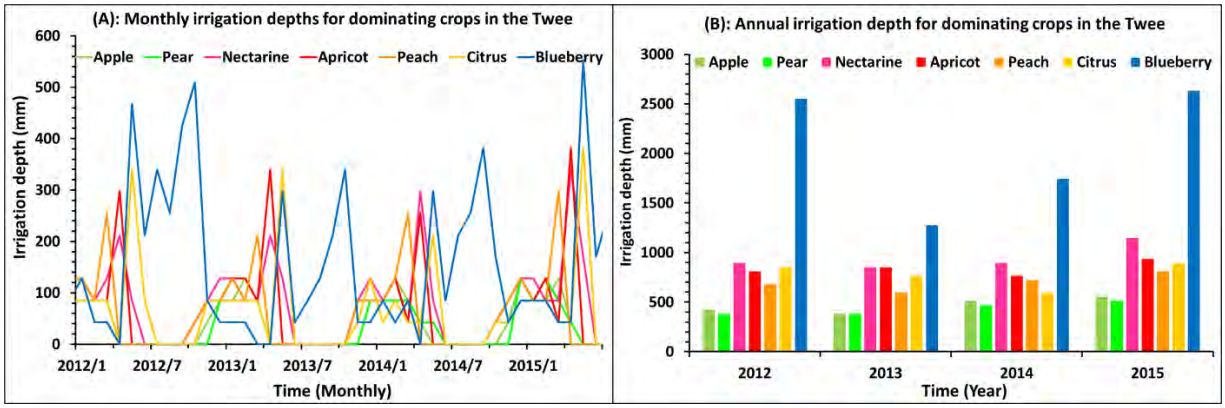

Figure 5.14: (**A**) Shows monthly irrigation depths for different crops to illustrate irrigation depth variation over the growing seasons of different crops. (**B**) Demonstrates annual irrigation depths of crops from the year 2012 to 2015.

5.5.2. Crop yield

The obtained observed crop yield data were averaged yields for 2015 to 2020. Therefore, since the simulation period for this study ended in 2015, the observed crop yield averages from 2015 to 2020 were compared with the simulated crop yields of 2015 for farm 3 (Figure 5.14). Given that the observed crop yield was available as an average over 5 years, the simulated yield was not calibrated against the observed. The simulated yields were only compared to the observed crop yield averages to determine how close the model output was to the actual yield simulated crop yield.

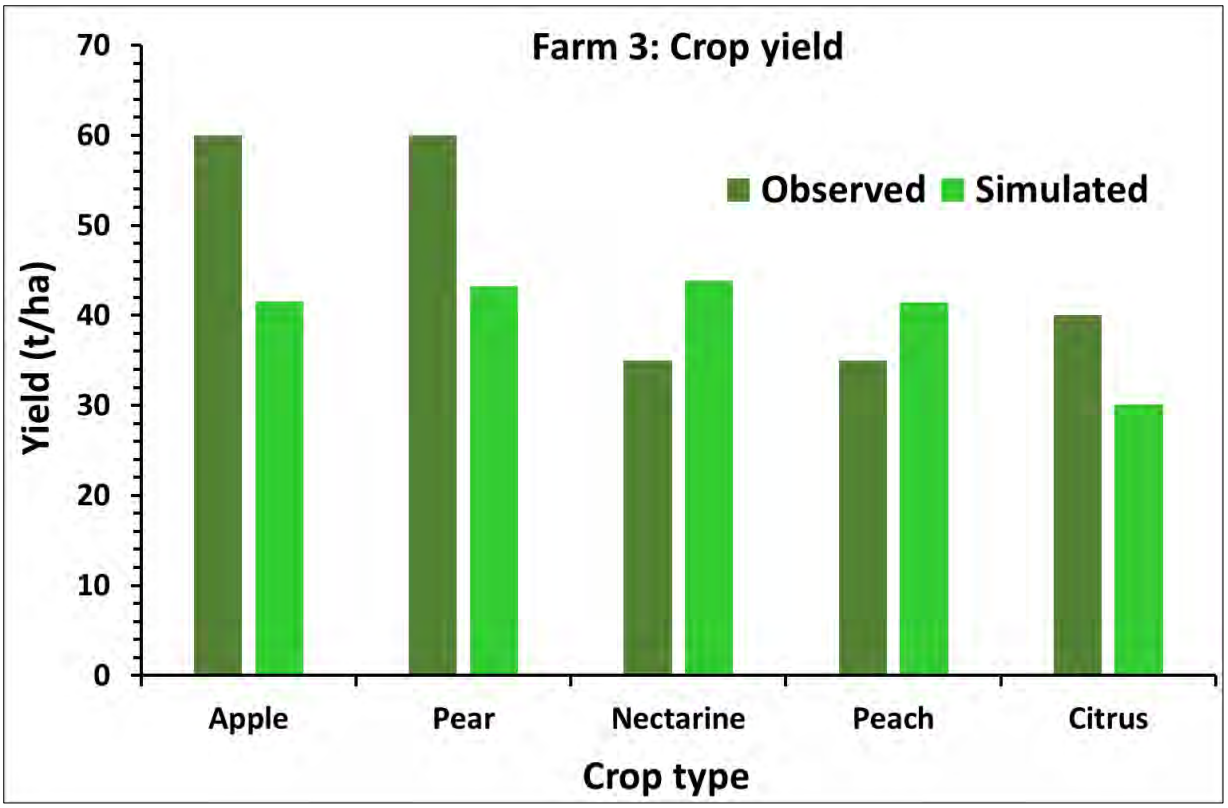

Figure 5.15: Comparison of simulated crop yield against observed average crop yield from 2015 – 2020.

The model over simulated nectarine and peach yields by 25% and 18%, respectively. Meanwhile, the yield for apples was under-simulated by -31% and pears by -28%. The citrus yield was also over-simulated in the model.

Table 5.2: Percentage difference between observed average yield and simulated absolute yield of different crops (2015 – 2020).

Crop	Average observed (t/ha)	Simulated (t/ha)	% Difference
Apple	60	42	-31
Pear	60	43	-28
Nectarine	35	44	25
Peach	35	41	18
Citrus	40	30	-25

CHAPTER SIX

DISCUSSION

6.1 Introduction

The outline of this discussion chapter corresponds to the sub-sections of the result chapter. This chapter also includes brief reflections on modelling complex irrigated agricultural catchments.

6.2 Model performance

The model evaluation statistics suggest a generally acceptable model performance in simulating the Twee and Leeu streamflow's. This demonstrates the capability of the SWAT+ model in simulating the hydrology of an agricultural catchment. Even though the model performed well in simulating the streamflow of the Twee Catchment, it failed to match the peak flow of the observed accurately. The model for the Leeu Catchment had similar results, particularly during the calibration period, although there were some years when peak flow was over-simulated. A strong rainfall gradient characterised by very high rainfall in ungauged high-elevation areas may have influenced the observed peak flows. Unfortunately, the rainfall used in the model was derived from surface rainfall created from the records of stations at lower elevations (as explained in 3.3.6); this could have impacted the peak flow simulations. A similar issue was reported by Bieger et al. (2014) for the Gorge Region in China and by Wei et al. (2021) for the Southern Peru catchment, who suggested that in such situations, it is worthless to attempt to accurately match the peaks of the observed and simulated.

The current study focused on accurately simulating low flow as Dechmi et al. (2021), Tanner et al. (2022) and Wei et al. (2021) suggest that they are strongly impacted by irrigation. However, the low flows of the summer, the growing season, were slightly under-simulated for the Twee. Chen et al. (2017) reported that auto-irrigation overestimates crop irrigation compared to actual field irrigation, as it does not suspend irrigation post-harvest. Similarly, the auto-irrigation function used for implementing irrigation in the model may have resulted in higher water removal from the river channel to irrigate HRUs within an area of a farm downstream, mainly dependent on river flows for irrigation. Furthermore, the auto-irrigation function applies the same amount of water whenever irrigation is required while, in fact, irrigation amounts and timing change with changes in crop phenological stages and the constant amount of irrigation by the model may also have resulted in over-abstraction. Samimi et al. (2020) highlighted that lack of field data to set up manual irrigation in the model or verify results when auto-irrigation function is used often leads to inaccuracies in model prediction of

water abstraction, affecting accuracy in streamflow simulation. For this study there were unfortunately no data available to verify irrigation related model predictions to obtain best fit of simulated and observed low flows.

6.3 Catchment water balance processes

SWAT+ model reliably simulated the temporal variability of hydrological processes of the modelled catchments. Hydrological processes in both catchments maintain a substantial inter-annual variation throughout the entire simulation period following high seasonal rainfall. However, seasonality has a minor impact on groundwater flow, particularly for the Twee catchments.

Although the simulated ET appeared to be the largest water balance output, it is believed to be relatively lower for a semi-arid intensively irrigated catchment with numerous dams. Volschenk, (2017) estimated that the ET amount is above 700 mm in the Koue Bokkeveld region where the study catchments are situated. Adjusting the values of parameters, **ESCO** and **EPCO** that are used to adjust ET amounts have proven to be insufficient to increase the ET rate in the modelled Catchments to be close to the amounts estimated by Dzikiti et al. (2018) and Volschenk (2017). A similar case of simulated low ET by the SWAT model when using estimation was reported by Bieger et al. (2014), who attributed this issue to crop parameters in the SWAT database. Also, in the modelling exercise for this study, values of most parameters for many crops were adopted from the SWAT plant database. Furthermore, Samimi et al. (2020) argue that the parameters of crops in the SWAT database are not representative of crop varieties grown in semi-arid conditions.

A steep mountainous landscape that receives high winter rainfall ensures that the catchments have a high rainfall runoff conversion ratio. A large fraction of the rapid surface runoff generated along hillslopes of the catchments during the short rainy season is captured by farm dams.

As expected, interflow responded quickly in both Twee and Leeu Catchments as it predominantly occurs after rainfall events during wet periods and increases towards the middle of the rainy season. The increase in interflow in both catchments could be induced by high unsaturated zone storage provided by fractured quartzite rock, which fills up during the early part of the wet season and resulting in high interflow values for the remainder of the rainy season. Hughes, (2010) found that, in a region similar to the study area, where Cape Fold Belt geology with outcropping rocks dominates, significant interflow occurs from fractured

quartzite rock in an unsaturated zone. For the Leeu Catchment, the quick high interflow could also be promoted by high clay content beneath sandy in areas with **Ca** and **Bb** soils. Stolk and van Huyssteen (2019) and Smit and van Tol (2022), in their hydropedological studies, found that these soil types have high clay content, which converts infiltrated water through overlaying sand into interflow.

The Twee Catchments experience consistent groundwater discharge, sustaining streamflow during the dry season. The sustained groundwater discharge to the Twee River indicates that the catchment's aquifer system stores a considerable amount of water from high infiltration rates promoted by draining sandy soil and highly fractured outcropping quartzite rocks. The positive net changes of 5% (water stored in the unsaturated zone and shallow aquifer) also contribute to keeping the water table in the catchment high, thereby supporting prolonged baseflow. This is key as it indicates that the groundwater component in the Twee catchment could be a relevant water resource for resilience in the dry season during drought years.

In the Leeu Catchment, groundwater discharge appears to occur during the wet season and stops during the dry season. Even though the Leeu riverbed lays on the shale layer, a prolonged groundwater discharge to the stream was expected as a high water-yielding fractured quartzite aquifer dominates the catchment. The short duration of groundwater discharge in the modelled Leeu could be related to less groundwater storage as there are no outcropping fractured rocks, which would promote high direct percolation to recharge the aquifer. The rapid decline in groundwater contribution to the Leeu River (evident in the observed) at the beginning of the dry season mirrors the overuse of groundwater in the catchment to meet high irrigation demands. DWAF (2005) reported groundwater water stress in the Leeu catchment due to over-abstraction of this resource. DWA (2012), in their groundwater resource assessment study in the Leeu, found that the catchment is experiencing a groundwater deficit of -4.53 million cubic metres per annum. This means the Leeu catchment cannot support more groundwater resource development.

The results for the Leeu catchment show a decline change of 22% in net storage. The negative change in storage is often considered a water deficit (Rivas-Tabares et al., 2019; Wei et al., 2021) or an error in water balance (Leng et al., 2020; Marahatta et al., 2021). In reality, there are water transfers from the Twee into the Leeu catchment, which were not represented in the model as there was no information on the actual amounts transferred into the catchment. Based on the modelling results, without transfers supplementing water availability, irrigation demand

in the Leeu Catchments outstrips the water yield in the dry season. Irrigation demand exceeding catchment water yield may have resulted in incorrect water balance. Error in the water balance could also be caused by inaccurate simulation of other fluxes. Dechmi et al. (2021), Samimi et al. (2020) and Srinivasan et al. (2010) indicate that calibrating against streamflow only when modelling irrigated catchments is not sufficient as other hydrological processes are likely to be inaccurately simulated and result in erroneous water balance if they not verified. For instance, Rivas-Tabares et al. (2019) and Wei et al. (2021) calibrated SWAT for a semi-arid irrigated catchment against streamflow and reported good model performance statistics, although other hydrological processes were inaccurately modelled and resulted in erroneous water balance.

Similarly, for the Leeu catchment, good model performance statistics were obtained while there was an error in water balance. In this instance, a multi-component calibration that involves verifying the accuracy of simulated hydrological dynamics of reservoirs, irrigation, as well as crop yield and biomass, which represent significant components like ET and soil moisture, is suggested by Dechmi et al. (2021) and Samimi et al. (2020) to improve the reliability of model outputs. Unfortunately, for this study, the uncertainty in the simulated hydrological processes remains due to the complexities related to anthropogenic intervention and the unavailability of observed data to verify the accuracy of other simulated critical hydrological water balance processes.

Considering the net change in storage, neither catchment can support irrigation expansion. The Leeu Catchment is already in deficit. The water surplus in the Twee Catchment is vital for environmental flow requirements and, therefore, cannot be allocated for new demands. However, further groundwater development in the Twee Catchment can be explored to supplement surface water to irrigate the existing cultivated lands during the dry season of severe drought years. Environmental requirements would also need to be carefully considered when exploring further groundwater developments in the catchment.

6.4 Impact of reservoirs and irrigation on catchment hydrology

The river flows reaching the catchment outlets are often relatively low in developed catchments compared to the flows in the catchment in a natural state (Rivas-Tabares et al., 2019; Sheng et al., 2023). In this study, hydrographs from a model run that included reservoirs and irrigation were compared to hydrographs from a model setup considered to represent the natural conditions of the catchments. The comparison showed a reduction in average daily flows by 71% when reservoirs and irrigation were incorporated in the model. A similar situation

occurred in the Leeu catchment, with a 77% reduction when reservoirs and irrigation are represented. Evidently, the farm dam delays and reduces the flow reaching downstream areas of the catchments. While the study reveals that reservoirs and water withdrawals significantly diminish river flows, a noteworthy observation is the substantial outflow from the catchment during the short-wet period. Since the catchments are mountainous, the substantial outflow at the outlets is from surface runoff generated from steep hillslopes in the vicinity of the outlets.

These results also demonstrate that a complete discontinuity of hydrological connectivity can occur in the study catchments during dry years, as almost 90% of the minor flow generated in the upper watershed is intercepted by dams. This model results-based argument are also be supported by the outcome of a study by Rabelo et al. (2022), Ribeiro Neto et al. (2022) and Rabelo et al. (2021), who modelled the impact of a dense network of farm dams on the hydrology of semi-arid catchment in Brazil and found out that the impact is more significant in dry years when discontinuity of flow path occurs. Farm dams and irrigation in Twee and Leeu are causing early hydrological droughts downstream that intensify during meteorological droughts, which are a common feature of the region. Therefore, this means that farmers downstream, mainly relying on river flow for crop irrigation, are vulnerable to water scarcity, and these conditions threaten environmental health.

6.5 Impact of water abstraction on reservoir hydrological dynamics

Most farm reservoirs are primarily located on tributaries (Habets et al., 2014; Mantel et al., 2016) and generally have no release structures and farmers have their own operation rules (Rabelo et al., 2022). Farmers are usually not willing to share their operation rules and this was the case in the study catchments (Gwapedza et al., 2024). As a result, recorded information regarding the temporal variability of hydrological dynamics regarding water levels and the frequency and duration of spillage is unavailable. Hence, the simulated reservoir information was not compared or calibrated against any hydrological dynamics mentioned in section 5.5. Although simulated reservoir hydrological dynamics were not compared to any observed data, the SWAT+ model reasonably simulated reservoir temporal dynamics considering the fluctuations in water levels, which mirror the wet season and dry season, as well as emptying due to water abstraction for irrigation.

In a scenario with no irrigation, the results showed that water levels in presented reservoirs for both catchments rise and exceed storage capacity during the rainy season. This is also reflected in spillage from the reservoirs during the wet season, even though the overflow was quite small

in some reservoirs. Reservoirs under this scenario frequently overflow in rainy seasons since water levels remain constantly high with minor seasonal variations, therefore quickly exceeding maximum storage capacity on rainy days. Rabelo et al. (2022) and Ribeiro Neto et al. (2022) reported similar reservoir hydrological behaviour based on the results of their studies that modelled the impact of farm dams on catchment hydrology. Based on field observation, Rabelo et al. (2021) also reported that spillage in reservoirs that constantly have high water levels occurs quickly. Only Reservoir 8 did not overflow the entire simulation period of the natural scenario. This may be because this reservoir is located downstream of the Leeu catchment, which has numerous reservoirs upstream and thus may never receive sufficient inflow to overflow.

In a scenario where irrigation is implemented, water levels in most reservoirs, e.g., Reservoir 1 and almost all represented Leeu reservoirs, rarely reach the maximum storage capacity. Water levels in reservoirs 3 and 8 did not reach the total storage capacity during the simulation period when irrigation was added to the model setups. The significant reduction of 85% and consistent low water levels in Reservoir 3 after adding irrigation can be explained by the high-water requirements of blueberries which cover an area of 87.43 ha (Figure 5.14 A & B), as all HRUs of this crop were irrigated from this reservoir. Also, the irrigation period of this crop appeared to be relatively long compared to other crops, and a lengthy growing season means more water is required to satisfy water needs for every phenological stage of the crop. The fact that the reservoir is in an area of the catchment that receives low rainfall may have contributed to the reservoir water level not reaching maximum storage capacity in the rainy season. Reservoir 8 is located downstream below few reservoirs located upstream; hence water levels rarely reach the total storage capacity.

6.5 Crop yield

The model performance was further evaluated by comparing the simulated crop yield with the annual average (over five years) observed crop yields. Even though there is a notable difference between simulated yield and observed yield, it can be argued that the model performed reasonably in simulating crop yield, considering that the yield was not calibrated. Differences were expected, given that the simulated yield is compared to an average yield over five years. Apart from these reasons, the other factor that may have resulted in the under-simulation of the apple, pear, and citrus yields is that default parameter values of these crops in the SWAT+ plant database were used. Also, given the water scarcity in the catchment, farmers are moving towards varieties that require less water for optimum growth. Therefore, the observed yield is

of the varieties suitable for dry conditions. This agrees with the claim by Samimi et al. (2020) that the crop parameters in the SWAT database do not adequately represent the parameters of crop varieties that grow well under the conditions of semi-arid regions. Incorporating locally recorded values of parameters for stone fruits in the model may have resulted in a slight difference between the observed and simulated yield of these crops. However, SWAT+ default parameters were adopted to fill gaps in the compiled information of stone fruit parameters; hence, the observed yield could not be accurately matched. The difference between observed and simulated was expected, as Bieger et al. (2014) further argue that crop parameters in the SWAT databases are not sufficiently representative of crop varieties grown in areas outside the United States.

6.6 Reflections on modelling complex irrigated catchments using SWAT+

Due to data and model structural limitations, there were unavoidable compromises in modelling the study catchments. For instance, water transfers across basins were not represented in the model set up because of the unavailability of data regarding the quantity of water being transferred from the Twee to Leeu catchment. Farmer were not willing to share information regarding water use and transfers. Springs, one of the fundamental hydrological processes in the catchments, were not accounted for in the modelling exercise as the SWAT+ model structure does not allow the representation of spring. In the SWAT model, off-channel dams used in the catchment as additional can be explicitly represented as ponds. However, the SWAT+ model does not consider ponds as irrigation sources. Therefore, to ensure that all the off-channel dams are accounted for and can be used for irrigation in the model, they were lumped, and their combined volume was represented in dummy reservoirs placed in a channel, as explained in section 4.4.1.

Although the SWAT+ performance in terms of simulating streamflow and other water balance components in the study catchments has been reported to be relatively acceptable, significant challenges were faced during the model implementation. The model was undergoing development, and this posed implementation challenges for users. For example, every time an updated version was released, the model had to be re-setup for the newly updated components to work properly. Such updates sometimes occurred at intervals such as a week, making the tool's application very disruptive. Consequently, models for this study had to be re-set up four times. Some model updates were implemented based on user experiences shared through a “Google SWAT+ User Group”. The current study specifically contributed with experiences from using the irrigation functions. Although irrigation updates were eventually made, the

model version with updated irrigation only became available more than three months after suggestions on improvements were made. These are some of the risks of using a newly developed version of a model, as well as frustrations when uncovering significant model errors as the modelling process unfolds. Tools in the public domain must be thoroughly tested before they are available to users to optimise user ease of use and the duration spent on implementing the model. Nevertheless, the SWAT+ model has proven to be a valuable tool for simulating hydrological processes in complex agricultural catchments, but a finalised version of the tool is needed before end-users can enjoy a seamless application of the tool.

6.7 Summary

Despite the complexities and lack of data, the model seemed to capture the main hydrological dynamics of these catchments. In the case of this study, the availability of field data like yearly crop yield, irrigation, and groundwater amounts used to supplement surface water could have been vital in improving the model performance and reliability of the model predictions. Nonetheless, the model represented the seasonality and quantities of surface, subsurface runoff and vertical processes, irrigation seasonality, and reservoir water dynamics in relation to withdrawals and their impacts on catchment hydrology with high confidence. The confidence in irrigation timing and amounts could have been improved by verifying the results with field data.

Important data that can be realistically collected for research like this study include water transferred between storages and across basins, crop parameters, and irrigation timing and amounts. Obtaining local soil data is another critical component for setting up a model for irrigated catchments. However, collecting soil data can be highly challenging considering the high financial and time costs. Fortunately, le Roux et al. (2022) have developed a more reliable South Africa soil input database for future SWAT studies. Furthermore, incorporating precise information about the mentioned dynamics, including soft data about agronomic activities, is also crucial to incorporate in the setup to have a good model that can reasonably simulate processes of interest prior to calibration. Using good quality data to set up a model minimises calibration, which can be challenging and time-consuming and result in errors in other hydrological processes, mainly when only streamflow is used for calibration (Arnold et al., 2015). Crop yield and biomass (affected by ET and soil moisture) are also crucial for the multi-calibration process to ensure reliable water balance outputs.

Although SWAT+ is a semi-distributed model that strikes a balance between a detailed representation of dynamics and data requirements, certain aspects of the model can be improved to account for more features and accurate processes in semi-arid agricultural catchments. One of the aspects of the model that can be improved is adding ponds as one of the irrigation sources, as ponds (off-channel dams) are used as additional water storage for irrigation in semi-arid catchments. The auto-irrigation function in the model is important to cope with data scarcity issues; however, this function does not suspend irrigation even when harvest time is specified, as also noticed by Chen et al. (2020) and Dechmi et al. (2021) and this results in unrealistic irrigation simulation which affects the reliability of water abstraction and streamflow predictions. This issue can be addressed by refining the auto-irrigation function algorithm to suspend irrigation based on crop maturing and harvest time.

The other aspects of the SWAT+ model that can be improved are related to the spatial scale at which the model produces the outputs. The model, in its current form, produces water balance components output at HRU and basin scale. In South Africa, modelled hydrological processes at a sub-basin scale are relevant as water management issues are often addressed at the sub-basin level (Hughes, 2013), and this is also the case in the study catchments. Therefore, the spatial scale at which the model produces output does not align with the scale at which water management decisions are made in many regions, including South Africa. Furthermore, since the SWAT+ model generates thousands of HRUs, it makes analysing hydrological data at the HRU scale unrealistic and working with basin-scale outputs means trading off the spatial variability of hydrological water balance processes.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion

Sustainable water management and allocation planning are key strategies to ensure the possibility of expanding areas under irrigation while reducing water-related conflicts. In water-scarce catchments that are already highly developed, a detailed assessment of the resilience and vulnerability of hydrological systems to further developments also becomes essential in consideration of expanding irrigation. Hydrological models are practical tools to assess catchment hydrology's response to anthropogenic impact and generate important information to support water management. This study set up SWAT+, evaluated its performance in reproducing hydrological processes of the Twee and Leeu Catchments, and assessed the impacts of farm dams and irrigation on catchment hydrology.

The version of the SWAT model (ArcSWAT2012) represents one reservoir in a sub-basin and only one water source can be used for irrigating a field. The SWAT+ has been introduced by the developers as a semi-distributed model that can represent more than one reservoir in a sub-basin. Being relatively new, SWAT+ capabilities to represent numerous intensively distributed farm dam and irrigation from different sources in a single irrigation schedule has not been previously tested. In this study, the SWAT+ model, a new version of SWAT demonstrated the ability to represent spatially distributed farm dams in a detailed manner and irrigation from different water sources. Furthermore, its ability to align with much of the qualitative understanding presented in the conceptual model makes it an invaluable tool for providing foundational hydrological data to guide decisions regarding water resources management. With the availability of sufficient data, the accuracy of model simulation of hydrological processes can be improved, thereby producing a more reliable catchment water balance.

The modelling results provided insight into the hydrological processes, their seasonal variability in the catchments, and the impact of farm dams and irrigation on the hydrological system. Strong seasonal variability of rainfall-runoff processes suggests that expanding irrigated area in the catchments would require the construction of more farm dams to store some winter flow to irrigate newly developed lands. However, modelling results indicated that the existing farm dams and irrigation are already causing hydrological drought downstream, threatening ecological reserve, and exposing downstream farmers to water scarcity. Concerning water availability and irrigation demand, the catchments are vulnerable and less resilient to

further developments. The high irrigation demands in the Twee and Leeu catchments already necessitate strict management of available water resources to survive water stress during dry years. Water conservation and surviving water stress would also include prioritisation of crops that demand less water, such as apples and pears.

Overall, it can be concluded that the SWAT+ acceptable modelled hydrological processes and the impacts of small farm dams and irrigation on flow regime of the Twee and Leeu Catchments. However, a more accurate simulation of hydrological processes in such catchments requires sufficient quality data to adequately represent catchment physical features including human made hydrological structures and irrigation in the model setup. Additionally, observed data of more than one hydrological component and agronomic component is important to verify the accuracy of model simulations. Despite catchment complexities and lack of data, the findings of this study modelling exercise underscore the significance of SWAT+ in comprehensively depicting the hydrological dynamics of the modelled catchments, providing valuable insights for effective water resource management.

7.2 Recommendations

A few aspects of the modelling exercise in this study can be deepened in future hydrological studies in the study catchment or other similar catchments. These aspects include hydrological and human dynamics that could not be explicitly represented in the modelling set ups of this study due to data scarcity issues and model structural inadequacy. For instance, water transfers between storages and across the basins were not represented in the current study due to the unavailability of data regarding the quantity being transferred. It would be crucial to account for this dynamic in future hydrological modelling studies as it significantly impacts catchment water balance. Also, to improve the reliability of the simulation of hydrological water balance processes, setting up manual irrigation in the model would be recommended to realistically account for changes in crop water demand that change with different crop phenological stages. However, large amounts of data will be required to sufficiently represent these dynamics in the model setup.

Groundwater is an important strategic source used conjunctively with surface water for crop irrigation in irrigated agricultural catchments in semi-arid regions. Even though groundwater abstraction was not thoroughly examined in the modelling outputs of this study, it is worth recommending that when SWAT+ is used for detailed modelling of groundwater abstraction, especially in areas with complex geology, it should be coupled with MODFLOW (Aliyari et

al., 2019) or “gwflow” module for SWAT+ (Bailey et al., 2020). This is because the aquifer storage depletion is unrealistically accelerated in the SWAT+ due to an oversimplified representation of aquifer storage. Furthermore, springs exist in the study catchments, and spring water is pumped into irrigation dams. Therefore, since springs are an important hydrological feature, it would be essential to account for springs in future modelling exercises, and this can be practically done by modifying the SWAT+ codes.

A database for parameters of varieties of crops under irrigation in South Africa, similar to the soil input database developed by le Roux et al. (2022), can be created in collaboration with agronomists and use of Fruitlook team for SWAT application in local agricultural catchment. Using parameters of crop varieties grown locally when modelling South African agricultural catchments would be helpful to improve the simulation of important water balance fluxes such as ET and soil moisture and agronomic features like irrigation, crop yield, and biomass. Currently, the crop parameters in the SWAT database do not adequately represent crop varieties grown in semi-arid areas.

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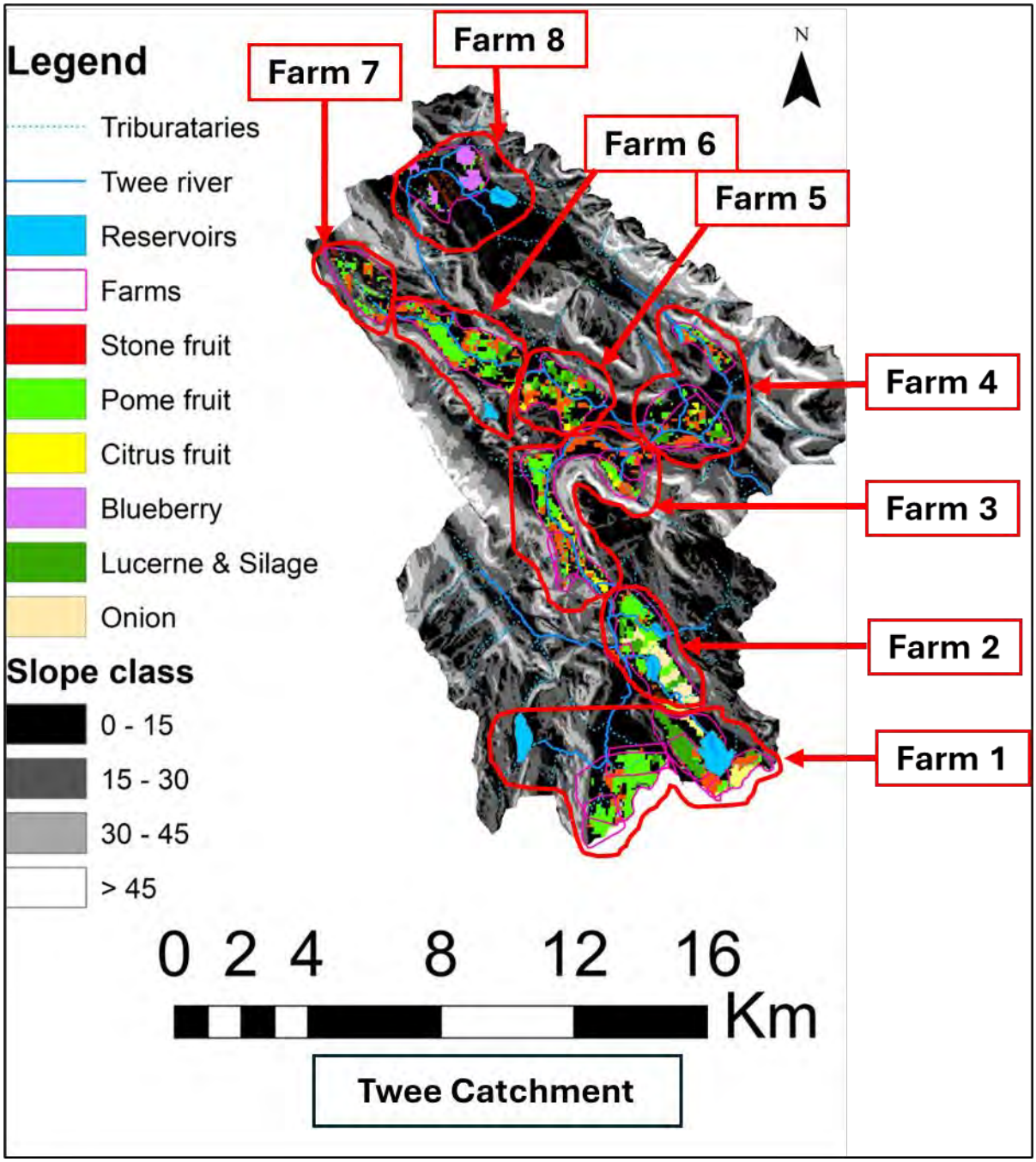
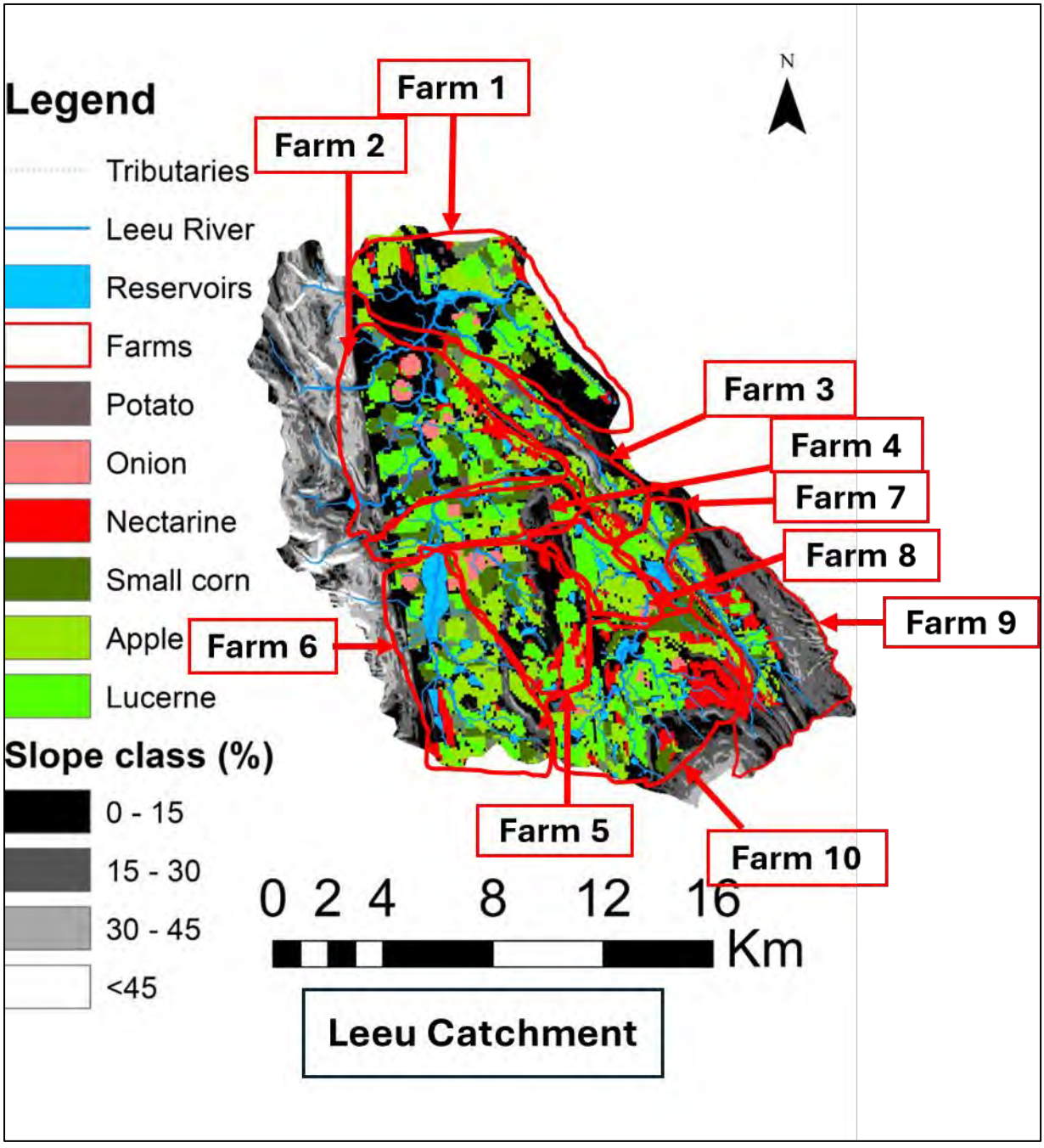
APPENDIX

Appendix 1: Farm spatial distribution. Crops in the model setup for the Twee Catchment were presented according to these farms.



Appendix 2: Farm spatial distibution. Crops in the model setup for the Leeu Catchment were presented crops according to these farms. Since the actual boundaries of farms in the Leeu Catchment are not well known, the boundaries of farms in this appendix were drawn based on delineated sub-basins.

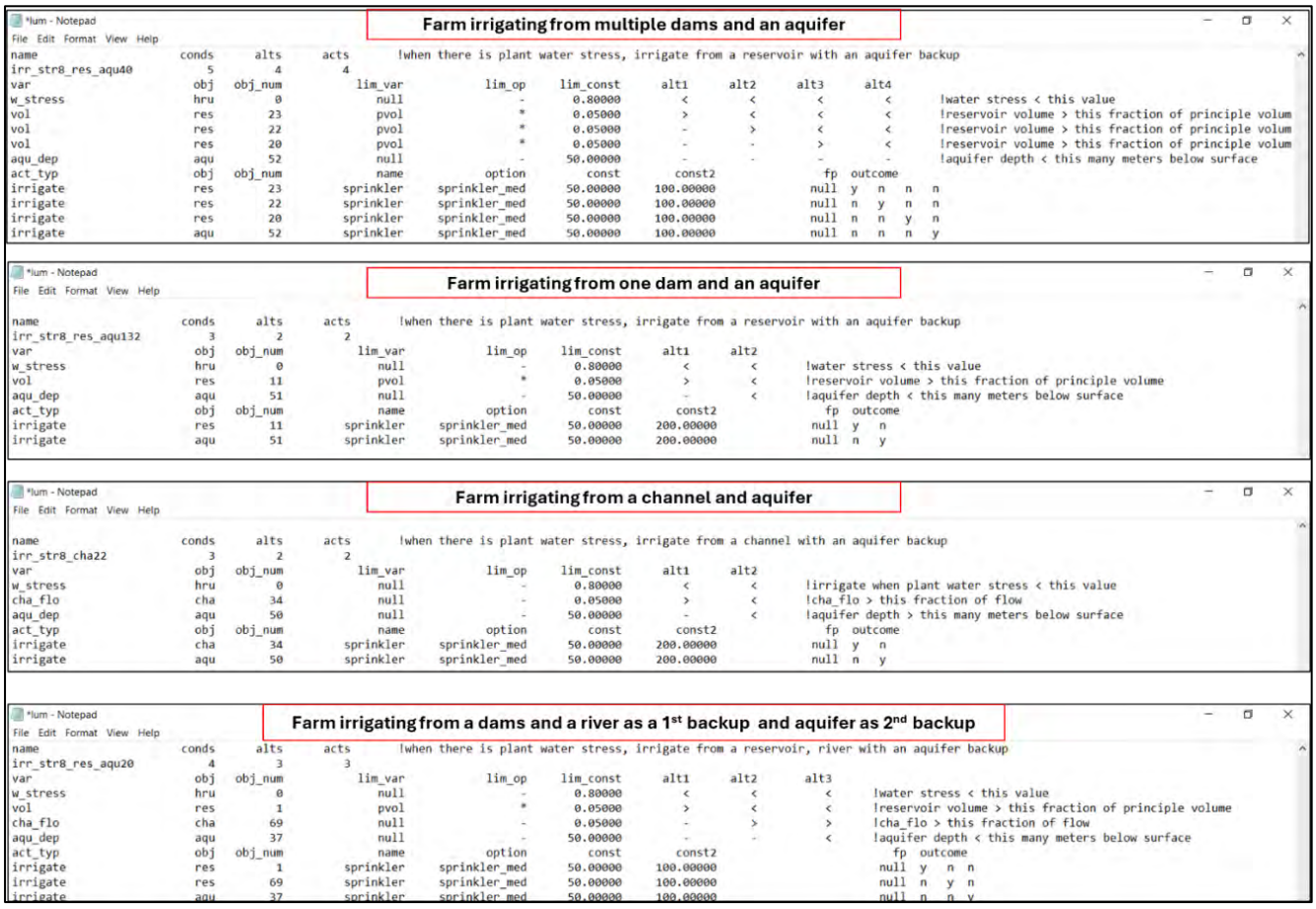


Appendix 3: New code used to link the land cover type to the SWAT+ model plant database.

DFFE and CFM Land cover	Codes used to link LUC types to the model	
	TWEE (E21H)	LEEU (E21G)
Fynbos shrubland	SHRB	SHRB
Natural grassland	RNGE	RNGE
Herbaceous wetland		WEHB
Outcropping rocks	ROCK	
Invasive alien plants (Black wattle)	ALIE	ALIE
Apple	APPL1	APPL1
	APPL2	APPL2
	APPL3	APPL3
	APPL4	APPL4
	APPL5	APPL5
	APPL6	APPL6
	APPL7	APPL7
		APPL8
		APPL9
		APPL10
Pear (for Twee) & Potato (for Leeu)	PEAR1	POTA1
	PEAR2	POTA2
	PEAR3	POTA3
	PEAR4	POTA4
	PEAR5	POTA5
	PEAR6	POTA6
	PEAR7	POTA7
		POTA8
		POTA9
		POTA10
Nectarine	NECT1	NECT1
	NECT3	NECT2
	NECT4	NECT3
	NECT5	NECT4
	NECT6	NECT5
	NECT7	NECT6
		NECT7
		NECT8
		NECT9
		NECT10
Apricot	APRI1	
	APRI2	
	APRI3	
	APRI4	
	APRI5	
	APRI6	
	APRI7	

Peach	PEAC3	
	PEAC4	
	PEAC5	
	PEAC6	
	PEAC7	
Citrus	ORAN1	
	ORAN2	
	ORAN3	
	ORAN4	
	ORAN5	
Blueberry	BLUE8	
Lucerne/Alfalfa	ALFA1	ALFA1
	ALFA2	ALFA2
	ALFA4	ALFA3
	ALFA5	ALFA4
	ALFA6	ALFA5
		ALFA6
		ALFA7
		ALFA8
		ALFA9
		ALFA10
Small corn	CSIL2	CSIL1
	CSIL4	CSIL2
	CSIL5	CSIL3
	CSIL6	CSIL4
		CSIL5
		CSIL6
		CSIL7
		CSIL8
		CSIL9
		CSIL10
Onion	Onio2	Onio1
	Onio5	Onio2
		Onio4
		Onio6
		Onio7
		Onio8
		Onio9
Triticale	TRIT1	TRIT1
	TRIT2	TRIT2
		TRIT4
		TRIT5
		TRIT6
		TRIT8
		TRIT9
Wetland		WEHB

Appendix 4: Examples of irrigation scheduling decision tables for different farms.



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Farm irrigating from multiple dams and an aquifer

```
name                conds   alts    acts    !when there is plant water stress, irrigate from a reservoir with an aquifer backup
irr_str8_res_aqu40      5      4       4
var                   obj  obj_num    lim_var         lim_op     lim_const     alt1    alt2    alt3    alt4
w_stress              hru        0       null              -       0.80000        <       <       <       <       !water stress < this value
vol                   res       23       pvol              *       0.05000        >       <       <       <       !reservoir volume > this fraction of principle volum
vol                   res       22       pvol              *       0.05000        -       >       <       <       !reservoir volume > this fraction of principle volum
vol                   res       20       pvol              *       0.05000        -       -       >       <       !reservoir volume > this fraction of principle volum
aqu_dep               aqu       52       null              -      50.00000        -       -       -       -       !aquifer depth < this many meters below surface
act_typ               obj  obj_num       name         option        const      const2                  fp  outcome
irrigate              res       23   sprinkler   sprinkler_med     50.00000   100.00000                null  y   n   n   n
irrigate              res       22   sprinkler   sprinkler_med     50.00000   100.00000                null  n   y   n   n
irrigate              res       20   sprinkler   sprinkler_med     50.00000   100.00000                null  n   n   y   n
irrigate              aqu       52   sprinkler   sprinkler_med     50.00000   100.00000                null  n   n   n   y
```

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Farm irrigating from one dam and an aquifer

```
name                conds   alts    acts    !when there is plant water stress, irrigate from a reservoir with an aquifer backup
irr_str8_res_aqu132     3      2       2
var                   obj  obj_num    lim_var         lim_op     lim_const     alt1    alt2
w_stress              hru        0       null              -       0.80000        <       <       !water stress < this value
vol                   res       11       pvol              *       0.05000        >       <       !reservoir volume > this fraction of principle volume
aqu_dep               aqu       51       null              -      50.00000        -       <       !aquifer depth < this many meters below surface
act_typ               obj  obj_num       name         option        const      const2                  fp  outcome
irrigate              res       11   sprinkler   sprinkler_med     50.00000   200.00000                null  y   n
irrigate              aqu       51   sprinkler   sprinkler_med     50.00000   200.00000                null  n   y
```

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Farm irrigating from a channel and aquifer

```
name                conds   alts    acts    !when there is plant water stress, irrigate from a channel with an aquifer backup
irr_str8_cha22          3      2       2
var                   obj  obj_num    lim_var         lim_op     lim_const     alt1    alt2
w_stress              hru        0       null              -       0.80000        <       <       !irrigate when plant water stress < this value
cha_flo               cha       34       null              -       0.05000        >       <       !cha_flo > this fraction of flow
aqu_dep               aqu       50       null              -      50.00000        -       <       !aquifer depth > this many meters below surface
act_typ               obj  obj_num       name         option        const      const2                  fp  outcome
irrigate              cha       34   sprinkler   sprinkler_med     50.00000   200.00000                null  y   n
irrigate              aqu       50   sprinkler   sprinkler_med     50.00000   200.00000                null  n   y
```

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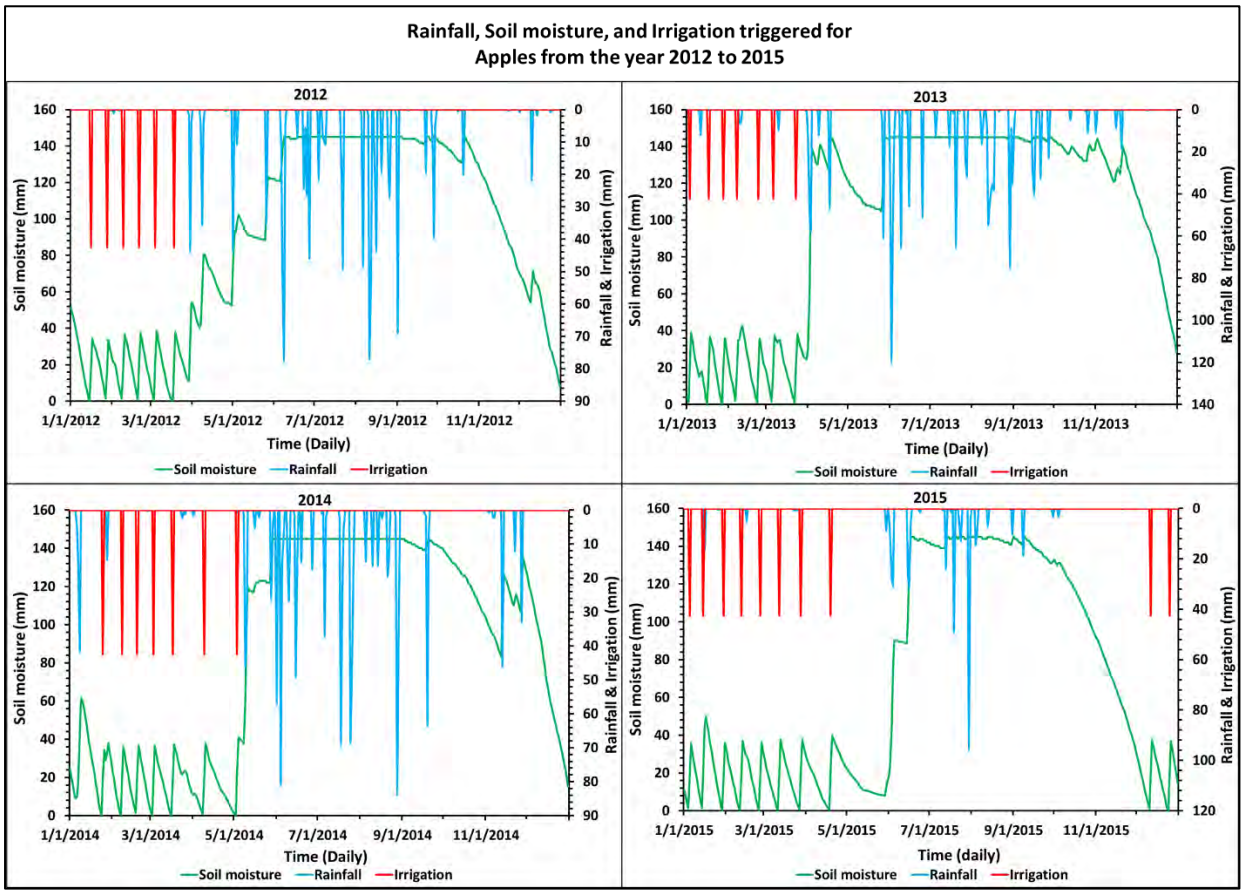
Farm irrigating from a dams and a river as a 1st backup and aquifer as 2nd backup

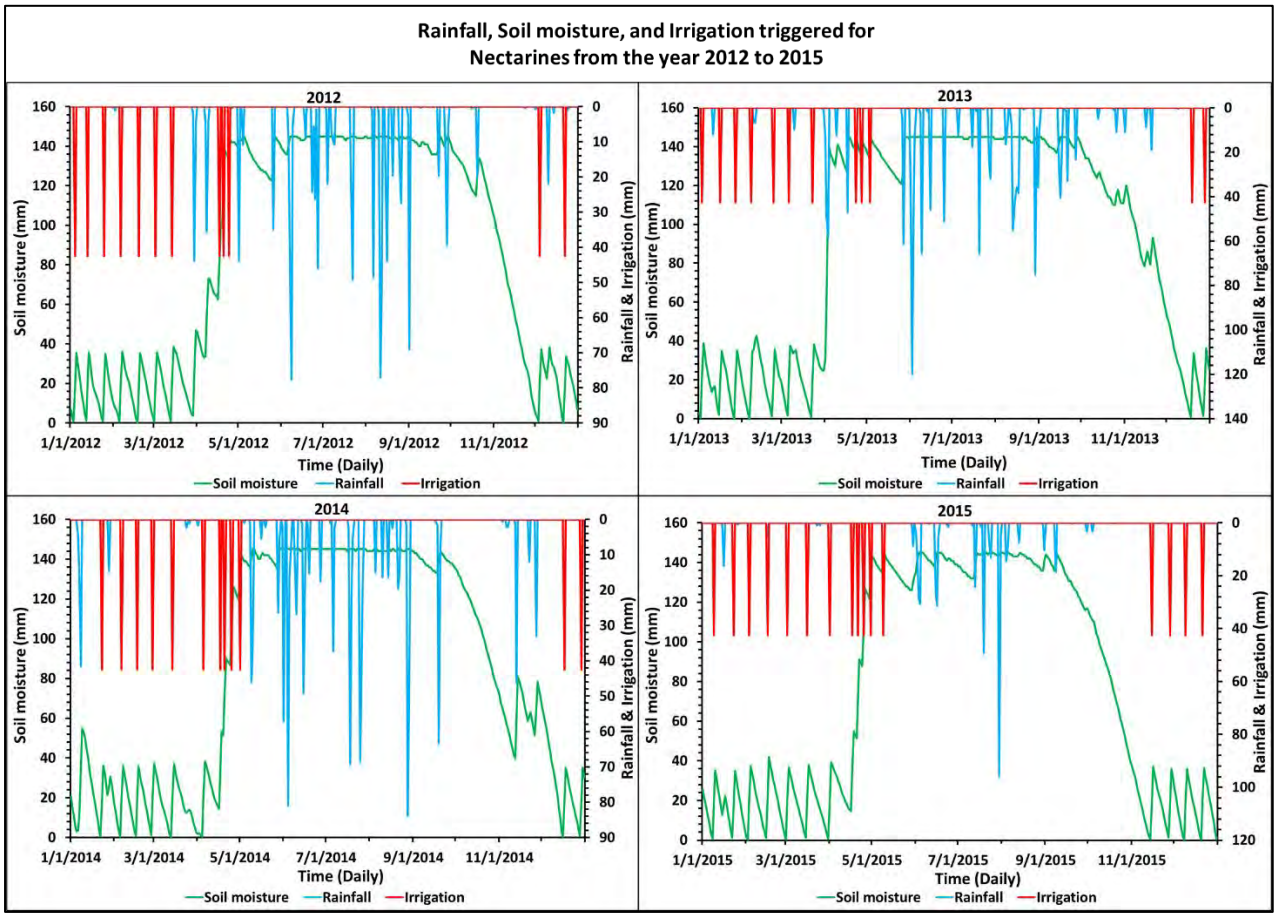
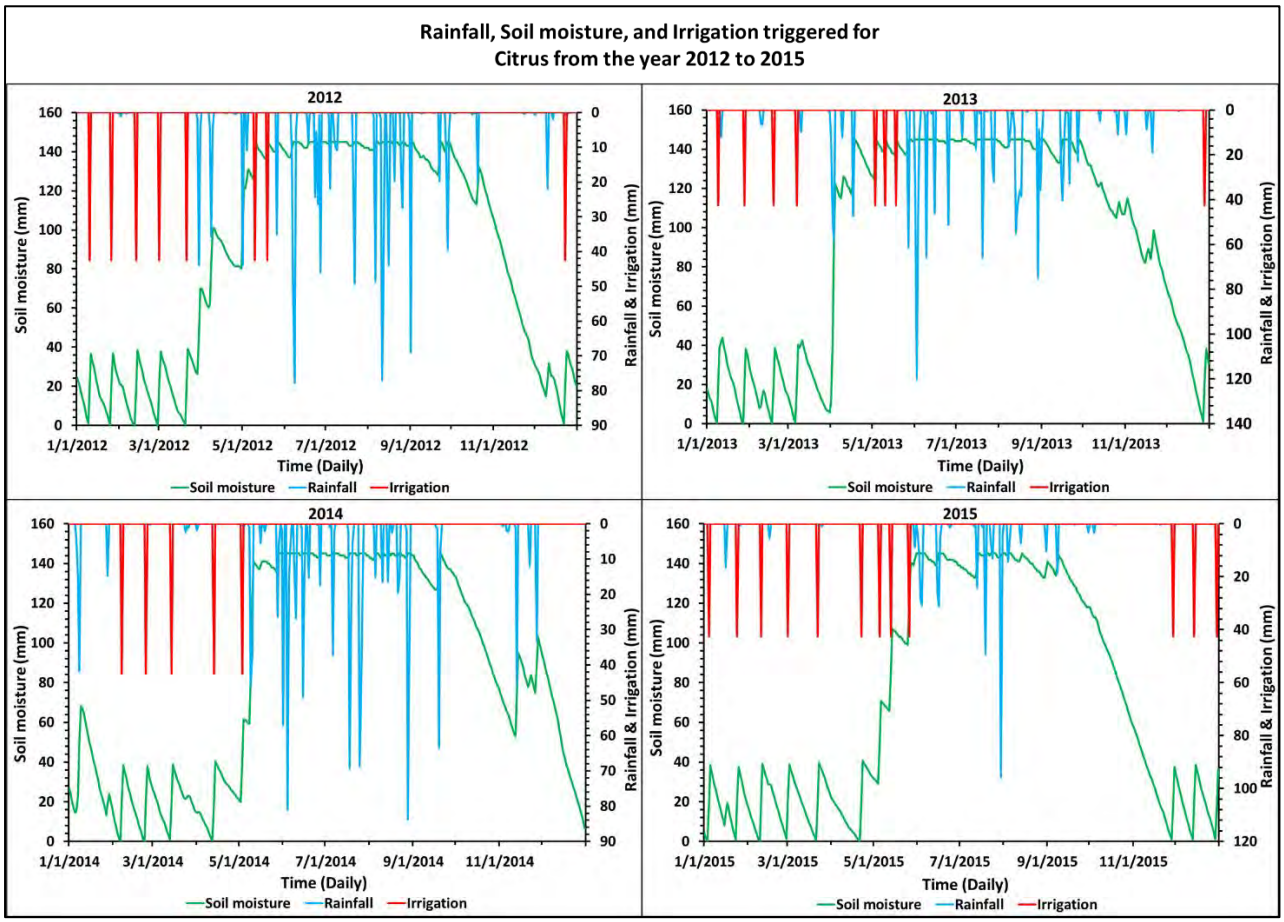
```
name                conds   alts    acts    !when there is plant water stress, irrigate from a reservoir, river with an aquifer backup
irr_str8_res_aqu20      4      3       3
var                   obj  obj_num    lim_var         lim_op     lim_const     alt1    alt2    alt3
w_stress              hru        0       null              -       0.80000        <       <       <       !water stress < this value
vol                   res        1       pvol              *       0.05000        >       <       <       !reservoir volume > this fraction of principle volume
cha_flo               cha       69       null              -       0.05000        -       >       >       !cha_flo > this fraction of flow
aqu_dep               aqu       37       null              -      50.00000        -       -       <       !aquifer depth < this many meters below surface
act_typ               obj  obj_num       name         option        const      const2                  fp  outcome
irrigate              res        1   sprinkler   sprinkler_med     50.00000   100.00000                null  y   n   n
irrigate              res       69   sprinkler   sprinkler_med     50.00000   100.00000                null  n   y   n
irrigate              aqu       37   sprinkler   sprinkler_med     50.00000   100.00000                null  n   n   y
```

cond is the number of conditions set for irrigation to occur, **alts** irrigation source alternatives, **acts** is the number of actions (action in the case of this study is irrigation), **var** means variables, **obj are** objects such HRU to be irrigated and irrigation source (0 for HRU means all HRUs under particular crop land usr type must be irrigated), **obj_num** is object number (e.g. channel, reservoir or equifer to irrigate from), **lim_var** is a limit variable, **lim_op**=limit operator, **lim_const**=limit constant (e.g. water stress threshold, threshold set for the model to stop irrigating from a particular source), **pvol**=principal volume of reservoir, **option** in the action option, **const** is the amount that can be applied when irrigation is needed, **fp**=pointer for option, **outcome**=action outcomes.

Appendix 5: Simulated irrigation for Apples for each year between 2012 and 2015



Appendix 6: Simulated irrigation for Nectarines for each year between 2012 and 2015



Appendix 7: Simulated irrigation for Citrus for each year between 2012 and 2015