DEVELOPMENT AND ASSESSMENT OF AN INTEGRATED WATER RESOURCES ACCOUNTING METHODOLOGY FOR SOUTH AFRICA: PHASE 2

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by

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EXECUTIVE SUMMARY

RATIONALE

Water plays a key role in the social and economic wellbeing of a country (Colvin et al., 2008). Globally, there is an increasing demand for water due to population and economic growth. This increase in demand, together with the pollution of water resources and climate change, has resulted in increased water scarcity in many catchments. Molden et al. (2007) state that, globally, 1.2 billion people live in catchments where the utilisation of water resources is no longer sustainable, resulting in physical water scarcity. A further 1.6 billion people live under conditions of economic water scarcity, where lack of infrastructure limits access to available water. Both physical and economic water scarcity are prevalent in South Africa. The National Water Resources Strategy (DWAF, 2004b; DWA, 2013) indicates that there are many key catchments in South Africa where demand equals or exceeds supply. Water storage infrastructure is already highly developed and there are limited additional economically feasible sites for dams and inter-catchment transfer schemes (DWA, 2013; DWS, 2015).

The current status of water resources in South Africa thus requires a change in emphasis from infrastructure development to better water management, resulting in more effective and efficient use and allocation of water resources. It is widely recognised that good water management is strongly dependent on the availability of good data and information. This is also true for successful cooperative governance and stakeholder participation (Lemos et al., 2010). Difficulties in describing complex water resource systems in a simple yet sufficiently comprehensive manner are also a constraint (Karimi et al., 2013a). In summary, the Food and Agriculture Organisation (FAO) and the World Water Council (WWC) (FAO and WWC, 2018) state that good water governance will require “a clear understanding of hydrological processes, more and better-quality data, and a means of interpreting it for a wide range of professionals across the water and water-using sectors, to provide a common understanding and agreement on the means of improving water management.”

OBJECTIVES AND AIMS

The intention was for this study (WRC Project K5/2512) to build on the work completed in an earlier project (WRC Project K5/2205). In addition to reviewing water accounting frameworks, these projects had two general objectives. The first was to demonstrate the use of a water resource accounting framework in order to help understand water availability and use at a catchment scale. The second was to develop an integrated and internally consistent methodology and system to estimate the water availability and sectoral water use components of the water resource accounts. The more specific objectives of this follow-up study are as follows:

- Refine the water use quantification and accounting methodology through the identification of better or more recent datasets and improved data processing and model algorithms.
- Extend the methodology, making it more useful, by widening its scope to include accounts that show details of managed water use and the extent to which river flows are altered by land use, water infrastructure, abstractions and return flows.
- Apply and evaluate the refined methodology more widely in selected catchments in two water management areas (WMAs), which represent two different climate regions.
- Engage with catchment management agencies (CMAs) and other potential users of the water resource accounts.

FURTHER DEVELOPMENT OF THE METHODOLOGY

In this study, the water use quantification and accounting methodology was refined to help improve the accuracy of the accounts. The accuracy of water resource accounts is highly dependent on good climate data. Thus, there was a focus in this study on assessing the accuracy of and improving the spatial estimates of rainfall and total evaporation at a catchment scale. In addition to investigations related to improving estimates of catchment-scale rainfall and evaporation, the methodology was developed further to include the subdivision of quaternary catchments, the application of the National Land Cover (NLC) 2013-2014 land cover/use dataset, a better representation of dams and the suitability of data in the Water Authorisation Registration and Management System (WARMS) database of the Department of Water and Sanitation (DWS).

Rainfall is typically measured by a spatially sparse network of rain gauges, and rainfall data is not always freely available. This led to an investigation of the potential application of satellite remotely sensed rainfall datasets. Several suitable daily remotely sensed rainfall datasets were evaluated and it was found that the Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations (TAMSAT) and Global Precipitation Mission (GPM) datasets did not perform any better than the Tropical Rainfall Measuring Mission (TRMM) 3B42, Famine Early Warning Systems African Rainfall Climatology (FEWS ARC) 2.0 or Famine Early Warning Systems Rainfall Estimator (FEWS RFE) 2.0 datasets that were evaluated in the preceding project. However, it was concluded that it was necessary to use rain gauge data to adjust the remotely sensed rainfall estimates to reduce localised bias in these datasets. A few methods for adjusting the remotely sensed datasets to reduce localised bias were investigated and a suitable method, using cumulative frequency distributions of the remotely sensed and rain gauge data, was identified as being the most suitable based on a case study in the upper uMngeni catchment, resulting in acceptably accurate streamflow simulations.

The discontinuation of the production of a reference potential evaporation (ET_0) dataset produced by the Satellite Applications Hydrology Group (SAHG) at the University of KwaZulu-Natal required the investigation of alternative ET_0 datasets for use in the methodology. Several datasets were investigated and compared with ET_0 estimates based on the Penman-Monteith approach of the FAO, together with measured meteorological variables. The Land Surface Analysis Satellite Application Facility (LSA-SAF) ET_0 dataset was identified as a suitable alternative to the SAHG ET_0 dataset, although the dataset only included data from August 2016 onwards, overlapping the SAHG dataset by a few months.

Land cover and land use are key characteristics of a catchment in terms of water use, especially with regard to evaporation and other hydrological processes such as runoff and groundwater recharge. In the earlier project, the most recent and most comprehensive national dataset of actual land cover/use was the NLC 2000 dataset (ARC and CSIR, 2005; Van den Berg et al., 2008). Thus, more recent provincial land cover/use datasets were used in the case studies. In this project, the more recent NLC 2013-2014 dataset of actual land cover/use for the period 2013/14 (DEA and GTI, 2015) was applied. The land cover/use hierarchy and class dataset developed in the earlier project made it easy to apply this dataset as part of the methodology. The NLC 2013-2014 dataset was applied “as is” in this project, but could potentially be enhanced by overlaying other datasets to create classes that specifically identify dams, irrigated areas (in addition to centre-pivot irrigated areas), areas of degraded natural vegetation, wetlands and alien vegetation.

In some catchments, the presence of a large number of farm dams can have a significant impact on the hydrology of the catchment, especially early in the rainy season when they are only partially full and intercept runoff from upstream.

In this project, several improvements were made to the representation of farm dams, including better estimates of the surface area and storage volume of these dams and a determination of the portion of a catchment that contributes runoff to these dams. The Agricultural Catchments Research Unit (ACRU) model was also further developed to enable the modelling of linked dams such as the linked Brandvlei and Kwaggaskloof dams, which are in separate secondary catchments.

The WARMS database was investigated as a potential source of information for use in configuring the model, including information on specific crop types, irrigation system types, dam sizes and irrigation water source types. In the Breede catchment, a significant portion of the water used for irrigation is from groundwater, and the WARMS database made it possible to estimate the proportion of irrigation in each catchment from surface water and groundwater. This information was used in the configuration of the hydrological model and was thus represented in the water resource accounts.

In the earlier project, the Resource Base Sheet and Evapotranspiration Sheet of the Water Accounting Plus (WA+) Framework were combined to form a modified Resource Base Sheet. The modified Resource Base Sheet provides a useful summary of the inflows, outflows and changes of storage within a catchment. However, in this sheet, the managed water use component can be overshadowed by the much larger volumes associated with catchment-scale rainfall and evaporation. In this project, a modified version of the WA+ Withdrawal Sheet was applied to provide an overview of managed flows in a catchment, including abstractions, consumption and return flows. In addition, a means of showing the impact of water infrastructure on river flows was investigated as a starting point towards the potential development of a new water resource accounting sheet that shows the extent to which flows have been altered from natural conditions.

ENGAGEMENT WITH POTENTIAL USERS

As part of this study, engagement with potential users and other interested parties took place in the form of three formal workshops, but also more informally in discussions with individuals. Two workshops were held near the beginning of the project: one in the Breede catchment and one in the uMngeni catchment. The third workshop was held in Pretoria with the aim of including personnel from DWS's head office.

The objectives of the formal workshops were as follows:

- Build capacity by introducing delegates to the concept of water accounting, the different water accounting frameworks in use internationally and their scope of application.
- Inform delegates of the research completed in WRC Project K5/2205, including examples of water resource accounts from the case study catchments.
- Inform delegates of the further development of the water use quantification and accounting methodology used in this study.
- Initiate discussions with delegates, asking the following:
  - Would these water resource accounts be useful to you?
  - How would you use them?
  - How could they be further developed to be more useful to you?

The feedback provided by the delegates at the workshops was valuable in providing insight into how water professionals from a wide range of organisations perceived the water resource accounts. The delegates were interested in the concept of water resource accounting and were supportive of the water resource accounting initiative. An unexpected outcome of the workshops was the interest by delegates in the possibility of having a hydrological model, configured for a catchment, which could be used in a planning context to test different scenarios, and in an operational context with climate forecasts to assist in making water management decisions. This confirmed that the decision to use a modelling approach to compile water resource accounts, which enabled forecasts and what-if scenarios to be tested, was correct and indicated that there was a need for such a tool.

APPLICATION OF THE METHODOLOGY

The methodology was applied in three case study catchments: the uMngeni and the upper uThukela catchments in KwaZulu-Natal and the upper and central Breede catchment in the Western Cape. These case studies demonstrated the use of available datasets, data processing tools, hydrological model configurations and the compilation of water accounts. The accuracy of the water resource accounts was evaluated by verifying simulated streamflow against measured streamflow at several gauges in each case study catchment. The results of these verifications were not good, but served to highlight areas where the methodology required further development, including catchment rainfall estimates and the modelling of urban areas.

DISCUSSION AND CONCLUSIONS

The objectives of this project were achieved in that several refinements were made to the methodology, the methodology was extended to include accounting sheets showing additional water resource information, the methodology was applied in three case study catchments, highlighting areas where further development is required, and three workshops were held to inform potential users of the accounts and obtain their suggestions for further development. The verifications demonstrated that there was still some work to be done to refine the methodology. The accurate estimation of catchment rainfall was possibly the most critical for the production of accurate accounts. The compilation of water accounts is data intensive, and the non-availability of suitable data is a potential stumbling block to the production of water accounts. However, these accounts can be useful for highlighting areas where further monitoring is required, where better quality control of data is required, and where better data management and archiving is required.

A vision, which has directed the development of the water use quantification and accounting methodology, has been to eventually produce annual water resource accounts at quaternary catchment scale for the whole country every year. These water resource accounts would have significant potential applications in catchment-scale water management, as a source of information for use in the System of Environmental-Economic Accounting for Water (SEEA-Water) environmental economic accounts, to inform reporting on water-related Sustainable Development Goals (SDGs) and to inform reconciliation strategies, catchment management strategies and national water resources strategies. It is recommended that, in the short term, it is important to start producing water resource accounts operationally for the whole country, while in the longer term, working on refining the accuracy and detail of the accounts in selected priority catchments is a priority.

Water is a scarce and limiting resource in South Africa. A better understanding of water resource systems and the impact of water on society and the economy is required to manage the country's water resources efficiently and sustainably. Significant progress has been made in identifying suitable datasets and in the development of a methodology for compiling catchment-scale water resource accounts, which show sectoral water use with a strong land cover/use focus.

In conclusion, despite the challenges associated with producing accurate and detailed water resource accounts at a catchment level, the objective of being able to produce these accounts annually for the whole country to build an understanding of our country's water resources is still valid and needs to be urgently pursued.

RECOMMENDATIONS FOR FUTURE RESEARCH

Recommendations for further research relating to the operational application of the methodology to produce water resource accounts for the whole country include the following:

- Developing a set of simplifying assumptions for the estimation of water quantities used for irrigation, urban use, mining and power generation, and the representation of related flow networks.
- Selecting a hierarchical set of sectors and subsectors to be used in reporting sectoral water use.
- Developing a dataset of sub-quaternary catchment boundaries for South Africa, taking significant river tributaries, large dams, streamflow gauges, significant inter-catchment transfers and other significant abstraction and return flow nodes into consideration.
- Evaluating and implementing a data workflow, management and archiving system, such as Delft-FEWS or Kepler.
- Investigating and implementing a means of spatially displaying annual water resource accounts and their individual components for nested sets of catchments, ranging from quaternary to primary catchments.

Some recommendations for further research in selected priority catchments to improve the accuracy of the accounts and to extend the methodology include the following:

- Bias correction and downscaling remotely sensed rainfall data needs to be investigated further to improve the accuracy of catchment rainfall estimates.
- Additional datasets need to be sourced to enable the modelling of more specific agricultural crop types and – if possible – the representation of land management practices. Additional datasets need to be sourced to identify and enable the modelling of different irrigation systems and scheduling methods. A further investigation of the WARMS database is required as one of the potential sources of this information.
- The more recent and more detailed Mucina and Rutherford (2006) map of natural vegetation types offers better spatial representation and should be investigated further when the current WRC Project K5/2437, "Resetting the baseline land cover against which streamflow reduction activities and the hydrological impacts of land use change are assessed" has developed a set of hydrological modelling parameters for the Mucina and Rutherford (2006) natural vegetation types.
- Include the modelling of water use by alien vegetation to estimate its impact on the water balance in a catchment.
- The uMngeni catchment case study indicated the need to better represent the runoff from urban areas, possibly through better estimates of the area of impervious surfaces in urban areas.
- Although urban areas may not be high net users of water, they require a large supply of water at a high assurance of supply, and thus often have a significant localised effect on streamflow. Additional datasets on domestic and industrial water use and return flows, or the modelling of water use and return flows, are required to improve estimates of gross and net water use from these sectors.
- A common problem when modelling water resources over short time spans is the initialisation of water stores at the start of a simulation. Sources of information to initialise dam storage volumes and soil moisture at the start of a simulation period need to be investigated further.
- Accounts are for a specific temporal domain, but it would be useful to develop accounts that show how components of other accounts, such as streamflow or dam levels, relate to long-term historical values such as on a cumulative frequency distribution.
- The further development of accounts that show the impact of dams, water abstractions and return flows on river flows, which may have an effect on the condition of river ecosystems.
- The development of accounts that show the productivity of water in producing crops.
- The investigation of the feasibility of using climate forecasts to produce forecast water resource accounts.

Further work needs to be done to engage with water managers, especially at CMA level, to understand how the accounts might be useful to them and how the water accounts might need to be adjusted and further developed to meet their needs.

CAPACITY BUILDING

Several forms of capacity building took place as a result of the project, including postgraduate students, staff development, institutional development the (Centre for Water Resources Research at the University of KwaZulu-Natal), three workshops organised as part of the project, a conference presentation and a presentation on water accounting to two government delegations from South Sudan. Six postgraduate students contributed to the project: two MSc (Hydrology) and two BSc Honours (Hydrology) students completed their degrees, and two PhD students are busy completing their degrees. A paper titled "An integrated water resources accounting methodology for South Africa – initial development and application in the upper uMngeni catchment" was presented at the 2016 South African National Hydrology Symposium to inform delegates of the water accounting work that was completed in WRC Project K5/2205.

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ACRU	Agricultural Catchments Research Unit
ARC	Agricultural Research Council
AWAS	Australian Water Accounting Standard
AWS	Automatic Weather Station
BOM	Bureau of Meteorology (Australian)
CMA	Catchment Management Agency
CSIR	Council for Scientific and Industrial Research
CWRR	Centre for Water Resources Research
DBSA	Development Bank of South Africa
DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
DSO	Dam Safety Office
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
DWAF	Department of Water Affairs and Forestry (former)
ECMWF	European Centre for Medium-range Weather Forecasts
ET	Total Evaporation
ET_0	Reference Potential Evaporation
ETDI	Evapotranspiration Deficit Index
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organisation
FEWS	Famine Early Warning Systems
FEWS ARC	Famine Early Warning Systems African Rainfall Climatology
FEWS NET	Famine Early Warnings System Network
FEWS RFE	Famine Early Warning Systems Rainfall Estimator
FLDAS	FEWS NET Land Data Assimilation System
GCM	Global Climate Models
GDAL	Geospatial Data Abstraction Library
GDAS	Global Data Assimilation System
GEF	Global Environment Facility
GIS	Geographic Information System
GMAO	Global Modelling and Assimilation Office
GTI	GeoTerraImage (Pty) Ltd
GPM	Global Precipitation Mission
GPWA	General Purpose Water Accounting
HRU	Hydrological Response Unit

HYLARSMET	Hydrologically Consistent Land Surface Model for Soil Moisture and Evapotranspiration Modelling Over Southern Africa Using Remote Sensing and Meteorological Data
ICMA	Inkomati Catchment Management Agency
IHA	Indicators of Hydrological Alteration
ISD	Integrated Surface Data
ISIC	International Standard Industrial Classification
ISO	International Standards Organisation
IWMI	International Water Management Institute
LCA	Life Cycle Assessment
LCU	Land Cover/Use
LSA-SAF	Land Surface Analysis Satellite Application Facility
LSM	Land Surface Model
LST	Land Surface Temperature
MAP	Mean Annual Precipitation
MODIS	Moderate Resolution Imaging Spectroradiometer
MOY	Month of Year
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NFEPA	National Freshwater Ecosystem Priority Areas
NIWIS	National Integrated Water Information System
NLC	National Land Cover
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
NWRS	National Water Resources Strategy
PAW	Plant Available Water
PCA	Principal Components Analysis
R^2	Coefficient of Determination
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
RVE	Relative Volume Error
SAHG	Satellite Applications Hydrology Group
SANBI	South African National Biodiversity Institute
SASRI	South African Sugarcane Research Institute
SAWS	South African Weather Service
SDG	Sustainable Development Goals
SEEA	System of Environmental-Economic Accounting
SEEA-Water	System of Environmental-Economic Accounting for Water
SEVIRI	Spinning Enhanced Visible and Infrared Imager

SNA	System of National Accounts
SRTM	Shuttle Radar Topography Mission
StatsSA	Statistics South Africa
TAMSAT	Tropical Applications of Meteorology Using Satellite Data and Ground-Based Observations
TOPKAPI	TOPographic Kinematic APproximation and Integration
TPI	Topographic Position Index
TRI	Terrain Roughness Index
TRMM	Tropical Rainfall Measuring Mission
UM	Unified Model
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WA	Water Accounting
WA+	Water Accounting Plus
WARMS	Water Authorisation Registration and Management System
WFN	Water Footprinting Network
WMA	Water Management Area
WRC	Water Research Commission
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WSAM	Water Situation Assessment Model
WUA	Water User Association
WWC	World Water Council

CHAPTER 1: INTRODUCTION AND OBJECTIVES

DJ Clark

Water plays a key role in the social and economic wellbeing of a country (Colvin et al., 2008). Globally, there is an increasing demand for water due to population and economic growth. This increase in demand, together with the pollution of water resources and climate change, has resulted in increased water scarcity in many catchments. Molden et al. (2007) state that, globally, 1.2 billion people live in catchments where the utilisation of water resources is no longer sustainable, resulting in physical water scarcity. A further 1.6 billion people live under conditions of economic water scarcity, where lack of infrastructure limits access to available water.

Both physical and economic water scarcity are prevalent in South Africa. South Africa has an average annual rainfall of 490 mm compared to the global average of 814 mm, with 21% of the country receiving less than 200 mm rainfall per year (WWF-SA, 2017). The average potential evaporation is 1,800 mm per year. The spatial distribution of water resources is such that the main water source areas, consisting of just 8% of the country, contribute 50% of the runoff. The inter- and intra-annual variability in rainfall and the resulting runoff is such that approximately only 20% of the 49 billion m^3 of mean annual runoff is available at a high assurance (98%) (DWA, 2013). The National Water Resources Strategy (DWAF, 2004b; DWA, 2013) indicates that there are many key catchments in South Africa where demand equals or exceeds supply. As early as 2000 (although South Africa had a national surplus of water), demand exceeded supply in 10 of the former 19 WMAs, and all – except one – of the former 19 WMAs were linked by inter-catchment transfers to supply highly developed areas with high demand (DWAF, 2004b). Water storage infrastructure is already highly developed and there are limited additional economically feasible sites for dams and inter-catchment transfer schemes (DWA, 2013; DWS, 2015).

The current status of water resources in South Africa thus requires a change in emphasis from infrastructure development to better water management, resulting in the more effective and efficient use and allocation of water resources. It is widely recognised that good water management is strongly dependent on the availability of good data and information. This is also true for successful cooperative governance and stakeholder participation (Lemos et al., 2010). Water resource systems, which consist of both natural and engineered components, are spatially extensive and inherently complex, making them difficult to measure, understand and describe. There is growing recognition of the urgent need for all water stakeholders (including policy makers, catchment managers, scientists and water users) to communicate and cooperate to develop implementable and relevant objectives for sustainable and integrated water management in South Africa. However, this type of communication and consensus among various stakeholders, who often have conflicting social, economic and political interests, is also complex (Liu and Stewart, 2004). Difficulties in describing complex water resource systems in a simple yet sufficiently comprehensive manner are also a constraint (Karimi et al., 2013a). In summary, FAO and WWC (2018) state that good water governance will require "a clear understanding of hydrological processes, more and better-quality data, and a means of interpreting it for a wide range of professionals across the water and water-using sectors to provide common understanding and agreement on the means of improving water management."

1.1 WHAT IS WATER ACCOUNTING?

Water accounting is a field of water resource management that has developed rapidly in the past few years to help address the need to quantify, describe, understand, compare and communicate the status of water resource systems.

Water accounts are one of the tools that can be used to help describe and understand water resource systems and facilitate communication between stakeholders by providing a standardised summary of water stocks, flows, fluxes and consumption for a specified spatial and temporal domain. A more comprehensive overview of water accounting and water accounting frameworks can be found in Clark (2015a).

Water accounting is intended to enable water resource managers and policy makers to clearly view the options available to them, together with the required scientific information, and to make decisions based on knowledge of actual water availability and an understanding of the potential impacts on all water users (IWMI, 2013). Karimi et al*.* (2013a) explain that water accounting enables hydrological flows to be associated with water use sectors and the benefits that can be derived from these flows. Water accounting can help indicate where more comprehensive studies or monitoring are required (Molden and Sakthivadivel, 1999). Water accounts have many similarities to financial accounts, and there are several water accounting approaches (or frameworks) that specify the structure of the accounts and the prescribed or recommended procedures for compiling them. International recognition of the importance of water accounting has led to the development of standard water accounting frameworks by institutions such as the Food and Agriculture Organisation, the International Water Management Institute and the United Nations Bureau of Statistics. These water accounting frameworks, each with a different purpose and typically applied at different spatial and temporal domains, include the following:

- The SEEA-Water framework (UN, 2012) is a United Nations (UN) standard for compiling national water accounts and has a strong economics emphasis. It aims to measure the use of water resources by the economy and the impact of the economy on water resources.
- Aquastat is the FAO's global information system, which contains country and regional water and agriculture statistics (Eliasson et al*.*, 2003; FAO, 2003).
- The Water Accounting Plus (WA+) Framework, based on the Water Accounting (WA) system of the International Water Management Institute (IWMI), is a standardised method of providing spatial information on water depletion and withdrawal processes in complex river basins to describe the overall land and water management situation in these river basins in a simple and understandable manner (Karimi et al*.*, 2013a).
- The Australian Water Accounting Standard (AWAS) of the Australian Bureau of Meteorology (BOM) provides a guideline for compiling General Purpose Water Accounting (GPWA) accounts of water stocks and flows (BOM, 2012). The AWAS is based on financial accounting procedures and has a role in water auditing.
- The water footprinting concept of the Water Footprinting Network (WFN) describes the direct and indirect volume of freshwater used to produce a specified product, measured over the full supply chain from raw materials through production to end use, consumption or disposal (Hoekstra et al*.*, 2011). These water footprints can also be compiled at a country level to represent actual and virtual water flows between countries as a result of imports and exports.
- The life cycle assessment (LCA) approach is a technique to assess the environmental impacts, including water use, associated with a product over its life, including raw materials, manufacture, use and disposal. Life cycle assessment is part of the International Standards Organisation (ISO) 14000 environmental management standards [http://www.iso.org/iso/iso14000].

South Africa has recently been building capacity in developing water economic accounts at a national and WMA scale (Maila et al*.*, 2018) and catchment-scale water resource accounts (Clark, 2015a). The context for this current study, which follows the study of Clark (2015a), is water accounting at a catchment scale for application in water resources management, in contrast to the broader, more economically focused SEEA-Water accounts described in Maila et al. (2018). Hence, the term "water resource accounting" is used in this study, along with the following definition:

> "Water resource accounts describe the water resources within a specified spatial and temporal water accounting domain, including opening and closing storages, the source and quantity of water inflows, water use by different sectors within the domain, and the destination and quantity of water outflows."

1.2 WATER ACCOUNTING-RELATED INITIATIVES IN SOUTH AFRICA

Over the years, a number of water accounting-related water resource assessment initiatives have been undertaken in South Africa. A few of the more recent initiatives are summarised briefly in this section.

1.2.1 National water accounts

The Environmental Economic Accounts section of Statistics SA (StatsSA) compiled a national water account for 2000 using the SEEA-Water framework at WMA scale (StatsSA, 2009). These accounts, referred to here as the national water accounts, included estimates of water use and production by different economic sectors, such as agriculture, mining, electricity, commercial and industrial, and the domestic sector. The recently completed WRC Project K5/2419, "National water accounts for South Africa: systems, methods and initial results" (Maila et al, 2018), developed a methodological framework for use by StatsSA to compile SEEA-Water physical (water) and hybrid (water and economics) accounts at national and WMA scale. These accounts are intended for application at a national policy level. The poor availability and quality of physical and monetary data related to water was highlighted in the project.

1.2.2 Water resource assessment studies

The WRC has funded a series of water resource assessment studies, culminating in the most recent WR2012 study (Bailey and Pitman, 2015) [http://www.waterresourceswr2012.co.za]. These studies, referred to here as the water resource assessment studies, are a broad national assessment of the water resources of South Africa at a quaternary catchment scale. The main products of these studies are modelled monthly estimates of actual and naturalised streamflow per catchment since 1920. These estimates are used by the DWS in its Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM) for the long-term planning of water resources in South Africa.

1.2.3 Water resource accounts

WRC Project K5/2205, "Development and assessment of an integrated water use quantification methodology for South Africa" (Clark, 2015a), aimed to develop a methodology to quantify water use and availability, and to represent this information using the WA+ Framework. These accounts will be referred to here as water resource accounts. A hydrological modelling approach was used as it enabled the estimation of components of the hydrological cycle that cannot be easily measured, and would enable the evaluation of "what-if"-type scenarios. The aim was to produce annual accounts at quaternary catchment scale, but modelling was done at a daily time step at sub-quaternary catchment scale and results were aggregated up. The methodology has a strong land cover/use focus, and a hierarchical system of land cover/use classes was developed to accommodate land cover datasets with different levels of detail and different classification systems. This hierarchy enables sectoral water use to be reported at different levels of detail. The further development of this methodology was the objective of this study (WRC Project K5/2512).

1.2.4 Quantification of irrigation water use

WRC Project TT 745/17, "An earth observation approach towards mapping irrigated area and quantifying water use by irrigated crops in South Africa" (Van Niekerk et al., 2018), aimed to estimate the total area used for irrigated agriculture, estimate water use by irrigated agriculture, quantify water use by selected irrigated crops, and demonstrate the use of water accounting to determine water use and availability in large catchments.

The WA+ water accounts were compiled for seven secondary catchments for a year (August 2014 to July 2015). This project demonstrated the potential use of remote sensing to estimate the evapotranspiration components of water accounts and highlighted the difficulties in accurately determining rainfall and other components of the accounts that are difficult to measure *in situ* or remotely at a catchment scale. Two challenges related to the information required to compile water accounts were the unavailability of high-quality rainfall data, especially in mountainous areas, and accurate land use and crop maps.

1.2.5 Comparison of assessments

These various water assessment initiatives should not be seen as competing with each other. Rather, they complement each other and have the potential to support each other, where appropriate, through the sharing of datasets. Each of the assessments has a different purpose and emphasis. Table 1-1 compares national water accounts, water resource assessments and water resource accounts as a means of understanding their context. The quantification of irrigation water use in WRC Project TT 745/17 was not included in the comparison due to the scope of the assessment being focused primarily on irrigation water use and for just for one specific year.

Table 1-1: Comparison of three water resource assessment initiatives currently applied in South Africa

	National water accounts	Water resource assessments	Water resource accounts
Decision level	Policy at national level	Long-term planning at national and catchment level	Short-term planning and management at catchment level
Spatial scale	National and WMA	National to quaternary catchment	Primary catchment to sub-quaternary catchment
Assessment interval	Not yet produced on a regular basis, but StatsSA is working towards doing more regular assessments, possibly even annually.	Currently assessments are extended every five to 10 years through funding from the WRC.	Not yet produced on a regular basis, but could potentially be partially automated for annual and possibly monthly assessment. The potential exists for producing forward-looking assessments based on climate forecasts.
Water focus	Water requirements, net water use and quality of return flow for economically important water uses.	Naturalised and actual streamflow quantities, taking into account primary blue water abstractions.	Catchment water balance, including inflows, outflows and sectoral water use and depletion, with a strong land cover/use focus.
Acceptability	United Nations standard, well documented, very prescriptive, only recently becoming more widely applied.	Long history of consistent application of methodology in South Africa, thus widely accepted in South Africa by both consultants and DWS.	New methodology, so not widely known or accepted, but intended to be flexible to users' requirements and easy to understand.

	National water accounts	Water resource assessments	Water resource accounts
Ease of application of methodology	Well documented, but best suited for application by experts within government statistical institutions.	Several consultants in the water resources field in South Africa have experience in assessments, but they are largely driven by a small number of experts.	Intended to be easy to apply through the use of readily available datasets and shared data processing scripts.
Ease of interpretation of output	Moderate to complex	Easy	Easy

The national water accounts, based on the SEEA-Water accounts, have a strong economics focus for the purpose of informing national policy, but will require information from the water resource assessments and water resource accounts for estimates of variables for use in the physical supply and use of water. The water resources assessment studies have a long history in South Africa and are widely used and accepted. The datasets collected as part of the assessments are also useful secondary products. However, it is unfortunate that these assessments are only updated every few years. The water resource accounts have made a contribution through the investigation of new sources of data, especially remote sensing, and the methodology can be applied to produce catchment-scale water accounts in near real-time, permit the investigation of water resources management scenarios and could potentially be applied in hydrological forecasting. If the quantification of irrigation water use in WRC Project TT 745/17 were to be repeated on a regular basis, it would be invaluable for identifying the spatial extent of irrigation and providing estimates of irrigated water use.

1.3 OVERVIEW OF WRC PROJECT K5/2205

To provide the context for the current study, it is necessary to provide an overview of the earllier project (WRC Project K5/2205). For this purpose, the Executive Summary of that project, which is included in the final report by Clark (2015a), has been reproduced in this section.

1.3.1 Objectives and aims

The objectives of the project were to review existing water accounting frameworks and their application internationally, to demonstrate the use of a water resource accounting framework to help understand water availability and use at a catchment scale, and to develop an integrated and internally consistent methodology and system to estimate the water availability and sectoral water use components of the water resource accounts. Such an integrated system ideally needs to be able to compute the water balance, quantifying all water fluxes in the hydrological cycle. It also needs to distinguish between use by different sectors, different hydrological components (i.e. green and blue water), beneficial and non-beneficial water use, and consumptive and non-consumptive use.

1.3.2 Review of water accounting frameworks

Several water resource accounting frameworks exist. Each is developed by different organisations for a different purpose. A review of these existing water resource accounting frameworks provided an understanding of each framework to inform the decision regarding which framework would be most suitable for application for the purposes of the project and also for water resources planning and management in South Africa.

The objective of the review was to describe the concept of water accounting and to review four existing water accounting frameworks that could be applied in South Africa: the IWMI's water accounting system, the WA+ Framework, the UN's SEEA-Water and the AWAS. The IWMI's WA framework and the conceptually similar WA+ Framework both have a strong land use focus. The SEEA-Water has a strong economic focus, and the AWAS is closely related to financial accounting. Based on this review, the WA+ Framework was selected for use due its suitability for catchment-scale water accounts, its strong land cover/use focus and its simple format that makes it suitable for use as a communication tool.

1.3.3 Review of datasets and water use quantification methodologies

An investigation into the water resource-related datasets available in South Africa, and a review of water use quantification methodologies previously applied in South Africa and other African countries provided further insight and helped guide the development of a methodology for estimating water availability and use at a catchment scale. The data sources and methodologies that were investigated included the following:

- Catchment boundaries and altitude
- Rainfall, evaporation and air temperature
- Land cover/use
- Soil moisture and soil hydrological characteristics
- Surface and groundwater storage
- River flow networks and measured streamflow
- Abstractions, return flows and transfers
- Reserved flows

1.3.4 Design criteria

The following key design criteria were used to guide the development of the methodology:

- The water resource accounts should be based on the WA+ water resource accounting framework as it is the most suitable framework for application at a catchment scale to promote communication between water managers and water users within CMAs. The successful application of the WA+ water resource accounting framework would provide a sound basis for the application of the SEEA-Water framework.
- Quantification of water use would be based on a hydrological modelling approach, using the ACRU agrohydrological model, but the use of remotely sensed data products should be investigated as a potential source of data inputs for hydrological modelling. The hydrological modelling approach was selected as there are many components of the water resource accounts that cannot be easily measured, either directly or by remote sensing. A daily physical conceptual model, such as ACRU, enables the natural daily fluctuations in the water balance of the climate-plant-soil continuum to be represented and ensures internal consistency through the modelled feed-forwards and feedbacks between the various components of the hydrological system.
- The focus should initially be on the Resource Base Sheet component of the WA+ Framework, which deals with water availability and depletions, as this information is likely to be most useful for catchment-scale water management. The water abstractions and return flows that are represented in the WA+ Withdrawals Sheet are also important for catchment management, but should be a secondary focus.
- The initial aim should be to produce annual water resource accounts at a quaternary catchment scale, although the hydrological modelling should be done at a suitable spatial scale to represent variations in climate and sectoral water use within a quaternary catchment. The methodology should make it possible to aggregate up from finer to coarser spatial and temporal scales.

- The most effort should be concentrated on the components of the water accounts that are likely to be most sensitive. These are expected to be rainfall and total evaporation estimates at a catchment scale.
- Although the focus of the project is on quantifying water availability and use, the methodology should anticipate that water quality and economic aspects of water resources would be important additional components of the accounts in the future.

1.3.5 Development of the methodology

The development of the methodology was, to some extent, an iterative process with four main components: the processing of datasets, the compilation of a project database spreadsheet containing catchment configuration information, the configuration of the ACRU model using the project database and associated datasets, and the hydrological simulation and compilation of water resource accounts.

The WA+ Resource Base Sheet was modified to suit the purpose of the project by including inter-catchment transfers into and out of the accounting domain, replacing the four land water management categories with five broad water use sectors, including the interception, transpiration, soil water evaporation and open water partitions of total evaporation, and other minor changes. A land and water use summary table was developed to accompany the Resource Base Sheet in the form of a pivot table summarising areal extent, water availability and water use by land cover/use class.

As already stated, the methodology was intended to have a strong land cover/use focus. There are various land cover/use datasets available for different regions and points in time. These all use different land cover/use classifications. This situation led to the recognition that some means was required to provide consistency in the application of these various datasets and enable water resource accounts that are compiled using different datasets to be compared. An important component and achievement of this project was the development of a standard hierarchy of land cover/use classes and an associated database of land cover/use classes containing information that describes the hydrological characteristics of these classes. The methodology developed for determining hydrological response units (HRUs) for use in modelling using catchment boundaries, land cover/use, natural vegetation and soils datasets was also a useful development.

The poor spatial representation and poor availability of rain gauge data led to the investigation of remotely sensed rainfall datasets. Four remotely sensed daily rainfall datasets (CMORPH, FEWS ARC 2.0, FEWS RFE 2.0 and TRMM) were compared with rain gauge data, and the simulated streamflow resulting from the use of these rainfall datasets was compared with measured streamflow. The results of these evaluations were not conclusive. The remotely sensed datasets compared favourably with rain gauge data in the uMngeni catchment, but performed poorly in the Sabie-Sand catchment. Although remotely sensed rainfall offers advantages in spatial representation and availability, the coarse resolution and bias in rainfall quantities may be a problem in accurately estimating rainfall at sub-quaternary scale for use in water resource accounts.

This project focused on the quantification of water use by natural, cultivated and water body land cover/use classes as – together – these typically cover the largest portion of a catchment and are the easiest to represent in a hydrological model for a large number of catchments. Datasets for and representation of the urban and mining classes require further research. In this project, urban residential water use was estimated in a simple manner based on population. Industrial and commercial water use was not included in the water use estimates for the case study catchments.

The project database spreadsheet, in which the spatial configuration of catchments, subcatchments, HRUs, river flow networks, dams and other water infrastructure is specified, acts as a useful source of information from which the ACRU model, and potentially other hydrological models, can be configured.

This project database makes catchment configuration more transparent, editable and reproducible, although implementation by individual models will require different model specific assumptions. A library of Python scripts was developed to process datasets and populate the project database spreadsheet. A Java code was also developed to use the information contained in the project database spreadsheet and associated datasets to configure the ACRU hydrological model. The ACRU model was further developed to compile the modified WA+ resource base sheets and store the information required to populate the land and water use summary table.

The modified WA+ resource base sheets and the land and water use summary table that were developed to accompany these sheets provide a very clear and useful summary of water resource inflows, use and outflows for a catchment. The WA+ Withdrawal Sheet needs to be implemented to provide information on abstractions, return flows and water stocks.

1.3.6 Application of the methodology

The methodology was applied in two case study catchments: the uMngeni catchment in KwaZulu-Natal and the Sabie-Sand catchment in Mpumalanga. These case studies demonstrated the use of available datasets, data processing tools, the hydrological model configuration and the compilation of water accounts. These case studies highlighted many areas where the methodology requires further development.

1.3.7 Discussion and conclusions

In conclusion, this project has successfully reviewed existing water accounting frameworks, demonstrated the application of a water resource accounting framework to help understand water availability and use at a catchment scale, and developed an integrated and internally consistent water use quantification and accounting methodology to estimate the water availability and sectoral water use components of the water resource accounts, including the water balance and all water fluxes in the hydrological cycle. The methodology focused on quantifying actual water use rather than gross withdrawals. The methodology is suitable for use at a variety of catchment scales and temporal domains, and the accounting framework enables the aggregation of results from finer to coarser spatial and temporal scales, and at different levels of land cover/use detail.

1.3.8 Recommendations for future research

The eventual goal for the water use quantification and accounting methodology developed in this project is to be able to compile annual water accounts for each quaternary catchment for the whole country every year. Although a good foundation has been set for the development of such a water use quantification and accounting methodology, there is still much work to be done to refine the methodology. Some of the recommendations arising from this project include the following:

- Rainfall is a critical input for water resource assessments, and the use of remotely sensed rainfall datasets need to be investigated further.
- It is desirable to model water accounts at sub-quaternary catchment scale due to variations in climate, soil, topography and land cover/use within a quaternary catchment. Methods of subdividing catchments into subcatchments and homogeneous response regions need to be investigated further.
- The new 2013/2014 national land cover dataset of the Department of Environmental Affairs was only made available towards the end of WRC Project K5/2205 and should be evaluated for use in the methodology.
- Additional datasets need to be sourced to enable the modelling of more specific agricultural crop types and, if possible, the representation of land management practices. Additional datasets need to be sourced to identify and enable the modelling of different irrigation systems and scheduling methods.

- The more recent and more detailed Mucina and Rutherford (2006) map of natural vegetation types offers better spatial representation and should be investigated further when the current WRC Project K5/2437, "Resetting the baseline land cover against which streamflow reduction activities and the hydrological impacts of land use change are assessed", has developed a set of hydrological modelling parameters for the Mucina and Rutherford (2006) natural vegetation types.
- In this project, only surface water use was assumed. Additional datasets need to be sourced to identify where groundwater is used and to model this.
- Although urban areas may not be high net users of water, they require a large supply of water at a high assurance of supply, and thus often have a significant localised effect on streamflow. Additional datasets on domestic and industrial water use and return flows, or the modelling of water use and return flows, are required to improve estimates of gross and net water use from these sectors.
- A common problem when modelling water resources over short time spans is the initialisation of water stores at the start of a simulation. Sources of information to initialise dam storage volumes and soil moisture at the start of a simulation period need to be investigated further.
- The water accounts, in the form of modified WA+ resource base sheets, provide an easy-to-read, common platform for water resource managers and users to interact on. Further sheets that show information about water abstractions, return flows and water stocks should be considered.
- In this project, the methodology was applied in two case study catchments in the summer rainfall region of South Africa. The methodology needs to be tested in catchments in the winter rainfall region in terms of rainfall and ET_0 estimates, and parameterisation of the hydrological model.
- Further work needs to be done to engage with water managers, especially at CMA level, to understand how the accounts might be useful to them and how the water accounts might need to be adjusted and further developed to meet their needs.

1.4 PROJECT OBJECTIVES

The intention was for this study (WRC Project K5/2512) to build on the work completed in the earlier project (WRC Project K5/2205). In addition to a review of water accounting frameworks, the general objectives of these two projects were to demonstrate the use of a water resource accounting framework to help understand water availability and use at a catchment scale, and to develop an integrated and internally consistent methodology and system to estimate the water availability and sectoral water use components of the water resource accounts.

The more specific objectives of this follow-up study were to do the following:

- Refine the methodology through identification of better or more recent datasets and improved data processing and model algorithms.
- Extend the methodology, making it more useful, by widening its scope to include accounts showing details of managed water use and the extent to which river flows are altered by land use, water infrastructure, abstractions and return flows.
- Apply and evaluate the refined methodology more widely in selected catchments in two WMAs representing two different climate regions.
- Engage with CMAs and other potential users of the water resource accounts.

The water use quantification and accounting methodology was developed using the following broad guidelines:

- The accounts should be focused on providing information suitable for water management at a catchment level.
- The accounts need to be developed for application at an appropriate spatial scale so that the impact by and on specific water use sectors can be assessed.

- The methodology needs to be developed so that it can eventually be applied in a consistent manner for the whole country.
- As far as possible, freely available datasets should be used so that the methodology can be easily applied by anyone.

1.5 DOCUMENT OUTLINE

This chapter has provided a brief introduction to water accounting and an overview of the work that was done in the earlier project. It then set out the objectives of this project. Chapter 2 describes the refinements made to the water use quantification and accounting methodology during this project. Chapter 3 describes the modified WA+ Resource Base Sheet from the earlier project, and the modification of the WA+ Withdrawal Sheet within this project. Chapter 4 describes an initial investigation into developing accounts that indicate the extent to which flows are altered by land use, water infrastructure, abstractions and return flows. Chapter 5 provides an overview of the various workshops held during the project to inform delegates about water accounting and obtain their suggestions regarding the further development of the accounts. Chapter 6 describes the datasets identified and the methodology used in the application of these datasets to configure the ACRU hydrological model to provide the variables required to produce the water resource accounts. Chapter 7 includes a description of the uMngeni case study catchment and the water accounts compiled for the catchment. Chapter 8 includes a description of the upper uThukela case study catchment and the water accounts compiled for this catchment. Chapter 9 includes a description of the upper and central Breede case study catchment and the water accounts compiled for this catchment. Chapter 10 includes a discussion on the general results of the project and the further development of the methodology. Chapter 11 includes some conclusions about the methodology and its application, and makes recommendations for further application and research. Chapter 12 summarises the capacity building that has taken place during the project.

CHAPTER 2: REFINEMENTS TO THE METHODOLOGY

DJ Clark, S Suleman, M Mahomed

The work components that resulted in refinements to the methodology are discussed in this chapter. The variability of climate, both spatially and temporally, results in variability in the availability and use of water resources, and water resource accounts can help to understand and manage this variability. The accuracy of water resource accounts is highly dependent on good climate data. Thus, Clark (2015a) proposed that, when developing the water use quantification and accounting methodology, the most effort should be focused on spatial estimates of rainfall and total evaporation (ET), which are likely to be the two dominant components of water resource accounts at a catchment scale. In addition to investigations related to improving estimates of catchment-scale rainfall and evaporation, further development was done relating to the subdivision of quaternary catchments, the application of the NLC 2013-2014 land cover/use dataset, better representation of dams and the suitability of data in the WARMS database for use in the methodology.

2.1 SPATIAL RAINFALL ESTIMATES

Accurate estimation of areal rainfall is important as it is one of the key inputs required for hydrological modelling, and thus also an important component of water resource accounts.

However, accurate estimates of areal rainfall are difficult due to its high spatial variability, a relatively sparse rain gauge network and poor accessibility to recent, quality controlled and infilled rain gauge datasets. Rain gauge networks are crucial, yet expensive to establish and maintain, and there has been a general decline in the number of rain gauges in South Africa (Pegram et al., 2016). In WRC Project K5/2241, Pegram et al. (2016) updated and infilled the national database of rain gauge measurements from the original database developed by Lynch (2004) up to 2010 using rain gauge data provided by the South African Weather Service (SAWS). However, as useful as this database is, the data is not freely available. It includes a relatively sparse rain gauge network, only SAWS rain gauges are included, and it only contains data up to 2010.

Typically, when configuring the ACRU model, driver rain gauges are selected for each catchment. An adjustment factor (the ACRU variable CORPPT) is then applied for each catchment to the daily driver rain gauge data to provide an estimate of daily catchment rainfall values. The 12 adjustment factors, one for each month of the year (MOY), are calculated using the ratio of the median MOY rainfall at the driver rain gauge to the area-weighted median MOY rainfall for the catchment (Lynch, 2004; Schulze and Lynch, 2008b). This requires a suitable spatial distribution of driver rain gauges, each with a full record for the simulation time period.

Clark (2015a) reported on an initial investigation into four remotely sensed rainfall datasets: CMORPH (Joyce et al., 2004), FEWS RFE 2.0 (Novella and Thiaw, 2012), FEWS ARC 2.0 (Novella and Thiaw, 2012) and TRMM 3B42 (Kummerow et al., 2000). The evaluation included a comparison of individual pixels with rain gauge data, as well as a comparison of the measured streamflow data with modelled streamflow using these datasets as input to the ACRU model. The requirement for some form of adjustment to account for localised bias was evident, but an initial attempt to do a simple adjustment to reduce localised biases using median MOY values to calculate an adjustment ratio was unsuccessful. Clark (2015a) concluded that further investigation was required into methods for downscaling and adjusting to reduce localised bias.

In this study, the application of satellite remotely sensed rainfall data for use in hydrological modelling was investigated further. There were two components to this investigation: an investigation by Suleman (2017) into additional satellite remotely sensed rainfall datasets, without bias correction, and an investigation into simple methods to adjust the remotely sensed rainfall estimates to reduce localised bias.

2.1.1 Investigation of satellite remotely sensed rainfall datasets

An investigation into the use of additional satellite remotely sensed rainfall datasets was the subject of an MSc (Hydrology) dissertation by Suleman (2017). A summary of the findings is presented in this section.

The investigation aimed to do the following:

- Select appropriate satellite remotely sensed rainfall datasets with a daily temporal resolution based on characteristics such as spatiality, latency and availability.
- Compare satellite remotely sensed rainfall estimates with *in-situ* rain gauge measurements within the study catchments.
- To use both rain gauge data and satellite remotely sensed rainfall estimates as input to a hydrological model and compare modelled streamflow with streamflow measurements.

The case study sites for the investigation coincided with the three case study catchments used in the bigger water resource accounting study: the upper uMngeni and upper uThukela catchments in the summer rainfall region and the upper and central Breede catchment in the winter rainfall region.

The satellite remotely sensed rainfall datasets selected were TRMM 3B42, GPM, TAMSAT version 3, FEWS RFE 2.0 and FEWS ARC 2.0. The FEWS and TAMSAT products have specific coverage over Africa, while TRMM 3B42 and GPM are global products. The spatial resolution and data availability for each of the datasets are shown in Table 2-. In addition to the TRMM 3B42, FEWS RFE 2.0 and FEWS ARC 2.0 datasets evaluated by Clark (2015a), the GPM dataset was also evaluated as it is a newer dataset that is expected to replace TRMM. The TAMSAT dataset was evaluated due to its finer spatial resolution. Time series of rainfall values were extracted from these datasets for individual pixels corresponding to selected rain gauges and for the area-weighted catchment rainfall values for each individual catchment. In this investigation, the satellite remotely sensed rainfall datasets were applied without any adjustments being made to reduce localised biases in the datasets. Daily rain gauge measurements were obtained from DWS and SAWS.

Table 2-1: Details of the satellite rainfall products used

	TRMM 3B42 V7	FEWS ARC 2.0	FEWS RFE 2.0	TAMSAT V3	GPM (IMERGV4)
Spatial resolution	0.25° x 0.25°	0.10° x 0.10°	0.10° x 0.10°	0.0375° x 0.0375°	0.10° x 0.10°
Data availability	1998 to present	1983 to present	2001 to present	1983 to present	2014 to present

Comparing coarse pixel-based satellite remotely sensed rainfall estimates with rain gauge measurements is not ideal, due to the difference in scales, but it does provide an indication of the accuracy of the estimates and a means of comparing the different remotely sensed rainfall datasets.

2.1.1.1 Comparison of remotely sensed and *in-situ* rain gauge rainfall

Satellite remotely sensed rainfall estimates were compared with *in-situ* rain gauge measurements at the rain gauges listed in Table 2- within the uMngeni and uThukela catchments in the summer rainfall region. The coefficients of determination (R^2) are shown in Figure 2-1 and the relative volume error (RVE) values are shown in Figure 2-2. The R^2 values for the two FEWS datasets were better than for the other three datasets at all except one rain gauge. In some cases, the R^2 values for the GPM were better than those for the TRMM 3B42, but performance was mixed. The R^2 values for the TAMSAT dataset were poor. There were no clear trends in the RVE values, representing the overall accuracy of estimates of rainfall depth, with different datasets performing differently at different gauges.

Table 2-2: Rain gauges used in the uMngeni and uThukela catchments

Rain gauge ID	Station name	Latitude	Longitude
V3E002	Chelmsford at Chelmsford Dam (DWS)	29,94974	-27,95460
U3E004	Cotton Lands at Hazelmere Dam (DWS)	31,04144	-29,61701
U2E002	Driefontein at Cedara (DWS)	30,28308	-29,53368
V1E008	Eendracht at Driel Barrage (DWS)	29,28722	-28,76705
U2E010	Inanda Dam (DWS)	30,87227	-29,72506
V2E002	Rietvlei at Craigie Burn Dam (DWS)	30,28308	-29,16703
0268883 6	Mooi River (SAWS)	30,00200	-29,21800
0239698 5	Pietermaritzburg (SAWS)	30,40200	-29,62700

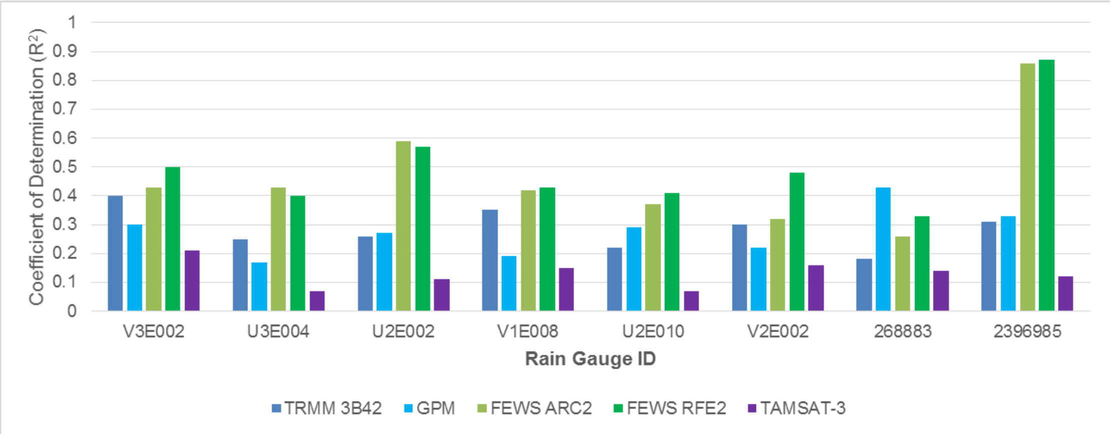

Figure 2-1: Comparison of rainfall datasets – coefficient of determination

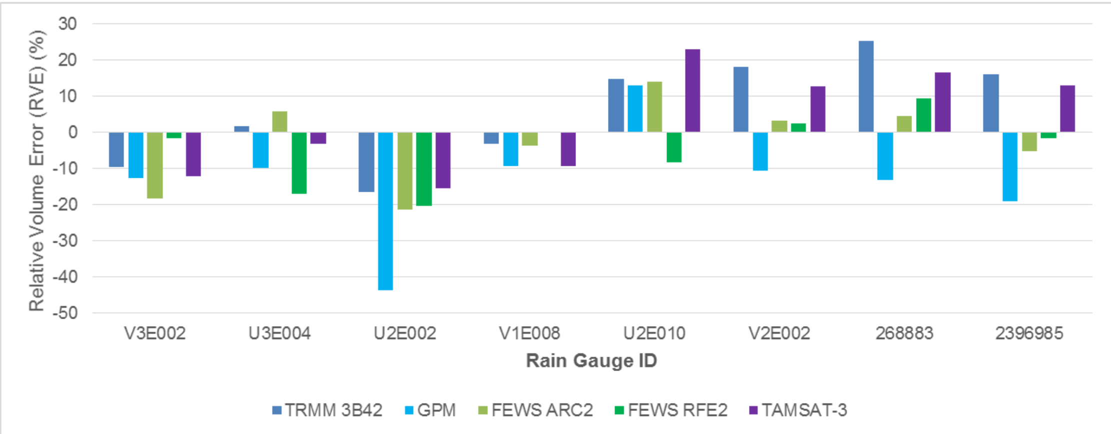

Figure 2-2: Comparison of rainfall datasets – relative volume error

Similarly, satellite remotely sensed rainfall estimates were compared with *in-situ* rain gauge measurements at the rain gauges listed in
Table 2- in the Breede catchment in the winter rainfall region. The R^2 values are shown in Figure 2-3 and the RVE values are shown in Figure 2-4. Again, the R^2 values were best for the two FEWS datasets and worst for the TAMSAT dataset. The RVE values indicated that, at most rain gauges, the satellite remotely sensed rainfall estimates were underestimating rainfall.

Table 2-3: Rain gauges used in the Breede catchment

Rain gauge ID	Station name	Latitude	Longitude
0022729 X	Worcester (SAWS)	19,41800	-33,66300
H1E007	Doorn at Kwaggaskloof Dam	19,25083	-33,83472
H9E002	Krantzkloof at Korinte-Vet Dam	21,16250	-34,00638
H6E001	The Waters Kloof at Theewaterskloof Dam	19,29189	-34,07591
H4E007	Haweqwas Stateforest at Stettynskloof Dam	19,47412	-33,76092
H3E002	Montagu	20,12747	-33,79537
H2E003	Lakenvlei at Lakenvallei Dam	19,58274	-33,36261

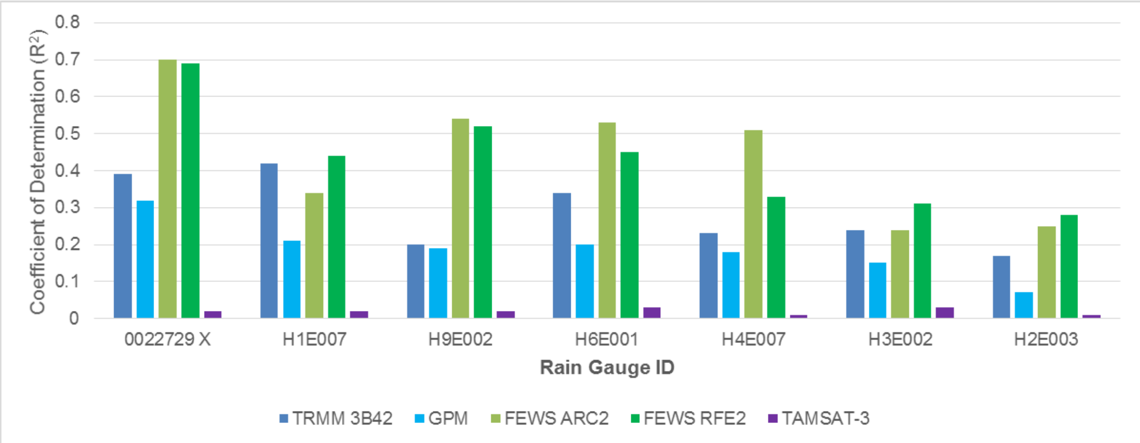

Figure 2-3: Comparison of rainfall datasets – coefficient of determination

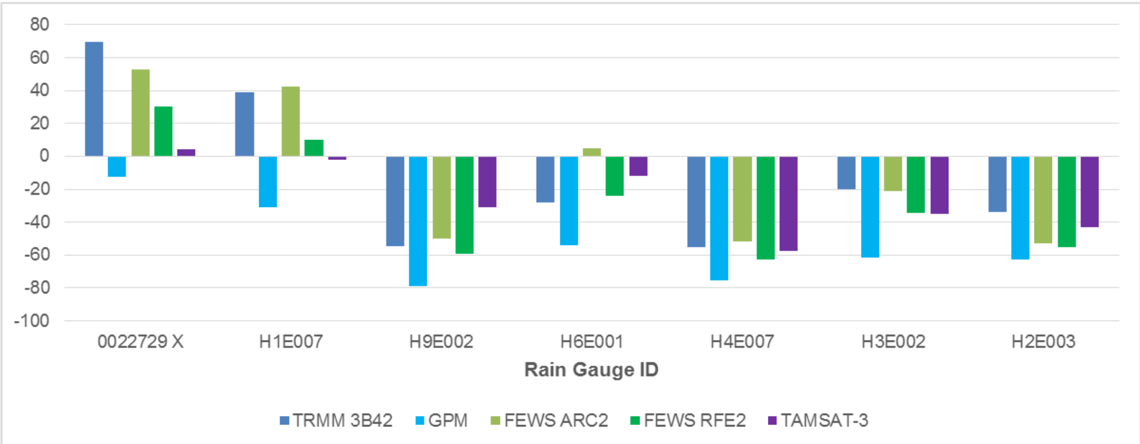

Figure 2-4: Comparison of rainfall datasets – relative volume error

2.1.1.2 Comparison of streamflow based on remotely sensed and rain gauge rainfall

Time series of rainfall values were created per individual catchment for each of the satellite remotely sensed rainfall datasets and also for the rain gauge measurement. For each rainfall dataset, the time series of rainfall values were used as input to the ACRU hydrological model configured for each of the three case study catchments. The simulated streamflow estimates were compared with streamflow measurements at the weirs listed in Table 2- within the uMngeni and uThukela catchments in the summer rainfall region.

The R^2 values are shown in Figure 2-5 and the RVE values are shown in Figure 2-6. The R^2 values for the streamflow estimated using rain gauge data and the TRMM 3B42 dataset were typically better than for the other four datasets, but the R^2 values for all datasets were poor. The RVE values, representing the overall accuracy of estimates of streamflow volume, indicate that, in most cases, streamflow was substantially underestimated, with different datasets performing differently at different gauges.

Table 2-4: Streamflow measurement weirs used in the uMngeni and uThukela catchments

Upper uMngeni catchment			
Weir ID	**Name**	**Latitude**	**Longitude**
U2H006	Karkloof at Shafton	-29.38175	30.27775
U2H007	Lions River (Mpofana River at Weltervreden	-29.44258	30.14852
U2H013	Mgeni River at Petrus Stroom	-29.51261	30.09441
Upper uThukela catchment			
Weir ID	**Name**	**Latitude**	**Longitude**
V6H004	Sondags River at Kleinfontein	-28.40458	30.01280
V7H017	Boesmans River at Drakensberg Loc 1	-29.18516	29.63708
V2H006	Little Mooi River at Dartington	-29.26619	29.86800

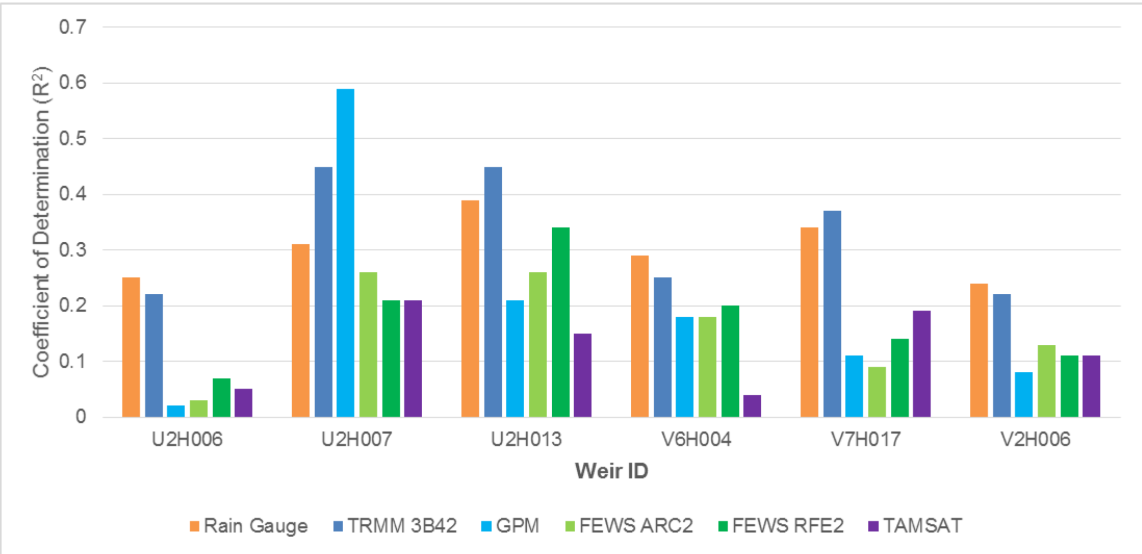

Figure 2-5: Comparison of streamflow – coefficient of determination

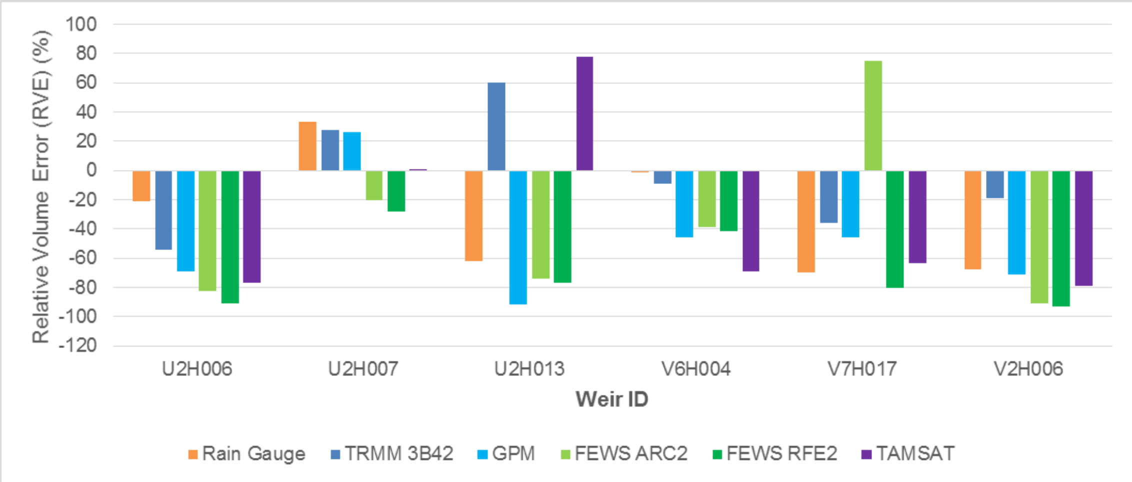

Figure 2-6: Comparison of streamflow – relative volume error

The simulated streamflow estimates were compared with streamflow measurements at the weirs listed in Table 2- within the Breede catchment in the winter rainfall region. The R^2 values are shown in Figure 2-7 and the RVE values are shown in Figure 2-8. Again, the R^2 values were generally poor with different datasets performing differently at different gauges. There were no clear trends in the RVE values, with streamflow being substantially over- and underestimated in many instances.

Table 2-5: Streamflow measurement weirs used in the Breede catchment

Upper and Central Breede catchment			
Weir ID	**Name**	**Latitude**	**Longitude**
H1H013	Koekedou River at Ceres	-33.35972	19.29833
H4H016	Keisers at Mc Gregor Toeken Geb	-33.93944	19.84055
H4H018	Poesjenels at Le Chasseur	-33.86777	19.71611

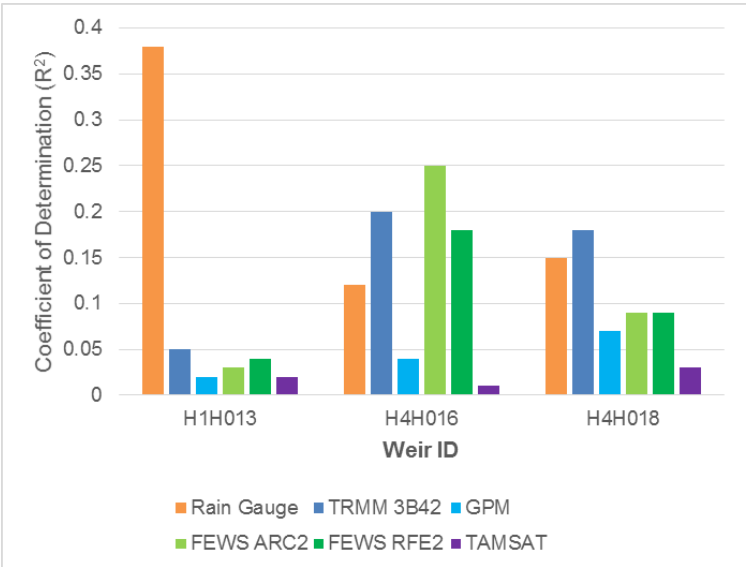

Figure 2-7: Comparison of streamflow – coefficient of determination

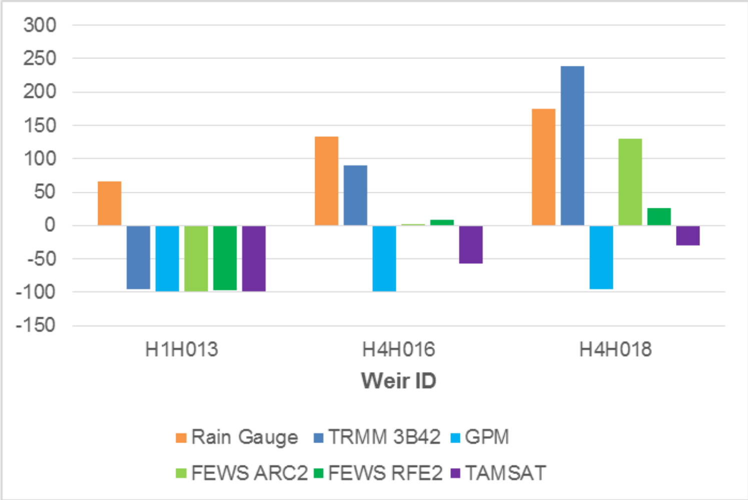

Figure 2-8: Comparison of streamflow – relative volume error

2.1.1.3 Outcome

Based on the results of this investigation, the following conclusions were drawn:

- The results seem to confirm that some adjustment of the satellite remotely sensed rainfall estimates is required to reduce localised bias.
- The use of rain gauge data did not result in consistently better streamflow estimates than for the satellite remotely sensed rainfall data. It is thus worth further investigating the use of satellite remotely sensed rainfall.
- Despite the finer resolution of the TAMSAT dataset, it did not perform better than any of the other coarser datasets and, in particular, the poor R^2 values were of concern. Further investigation of the TAMSAT dataset could thus not be justified.
- The GPM dataset did not perform particularly well either, compared to the other datasets. Thus, considering that the dataset only starts in 2014, further investigation of the GPM dataset could not be justified at this stage.

2.1.2 Investigation of methods for reducing localised bias in rainfall estimates

The investigation into the adjustment of satellite remotely sensed rainfall datasets to reduce bias formed part of a case study in the upper uMngeni catchment as part of a PhD thesis by Clark (2018), and is summarised here. The investigation reported in this section aimed to test and compare several simple methods for adjusting the remotely sensed rainfall estimates to reduce localised bias. The investigation had two main components: an initial comparison of methods to adjust the remotely sensed rainfall values for a single pixel corresponding to a driver rain gauge, and a comparison of methods to adjust the remotely sensed rainfall values for a catchment using a driver rain gauge selected to represent the catchment.

The relationship between catchments, pixels and rain gauges is shown in Figure 2-9 to help describe the different bias correction methods. The investigation reported in this section was done for the upper uMngeni catchment (upstream of Albert Falls Dam) and a map showing the catchment, rain gauges and streamflow gauges is given in Figure 2-10.

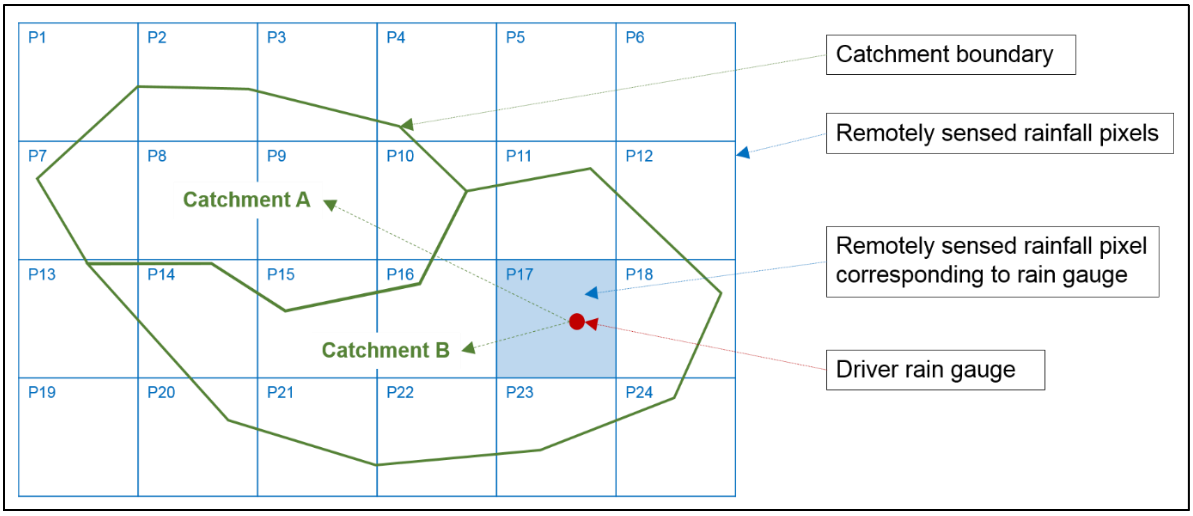

Figure 2-9: Relationship between catchments, pixels and rain gauges

Eleven rain gauges were used in the investigation, as shown in Figure 2-10. Six of these gauges (shown in green) were operational, and five (shown in orange) were no longer operational, but had relatively recent data until the end of 2010 or later. The rain gauge data was obtained from the DWS's website [http://www.dwa.gov.za/hydrology/] and from the Agricultural Research Council (ARC) on request. The details of these rain gauges are given in Table 2-.

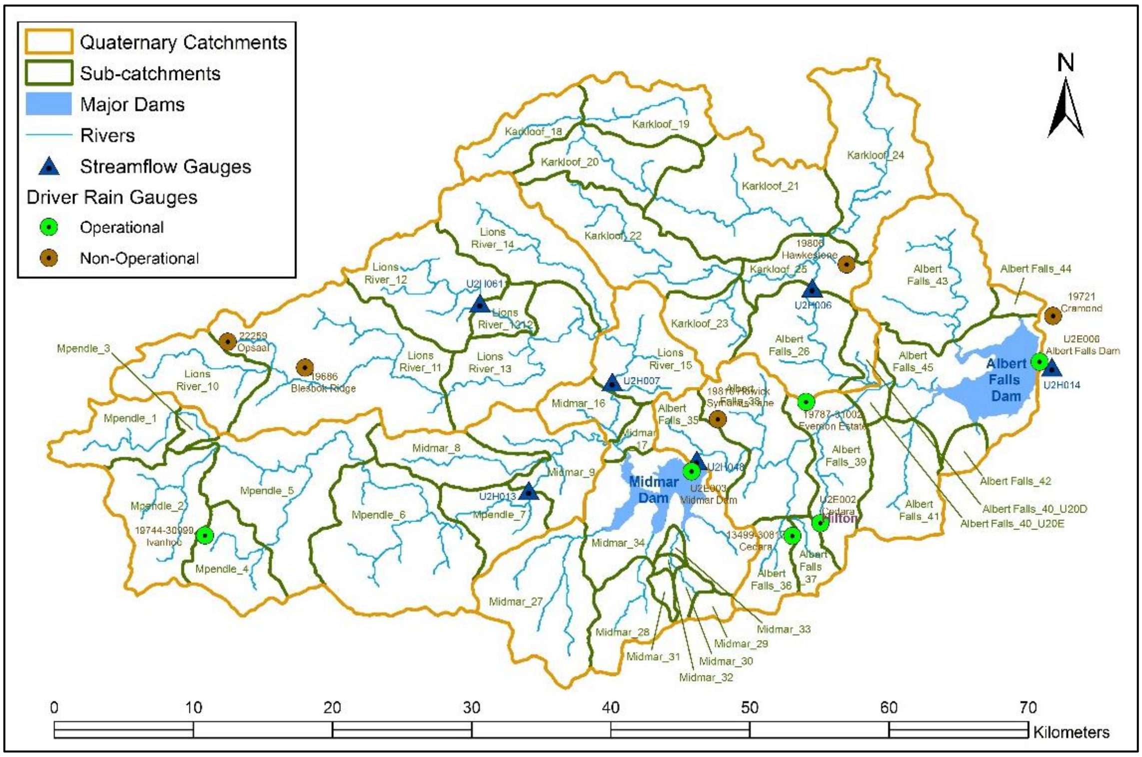

Figure 2-10: Location of rain gauges and streamflow gauges in the upper uMngeni catchment

Table 2-6: Rain gauges used in the investigation

Rain gauge ID	Source	Start date	End date	Operational
22259_OpsaalFortNott	ARC	1989/01/01	2013/08/31	No
19686_BlesbokRidgeNottRoad	ARC	1979/12/01	2010/12/31	No

19744-30999_IvanhoeImpendhle	ARC	1971/01/01	-	Yes
U2E003_MidmarDam	DWS	1964/10/01	-	Yes
19810_SymondsLaneHowick	ARC	1970/01/01	2013/05/31	No
13499-30817_Cedara	ARC	1920/01/01	-	Yes
U2E002_DriefonteinCedara	DWS	1952/07/01	-	Yes
19787-31002_EverdonEstateHowick	ARC	1972/01/01	-	Yes
19806_HawkestoneHowick	ARC	1921/01/01	2011/05/31	No
U2E006_AlbertFallsDam	DWS	1974/01/01	-	Yes
19721_CramondAlbertFalls	ARC	1919/01/01	2013/06/30	No

2.1.2.1 Comparison of methods for reducing bias in rainfall estimates for rain gauge pixels

It is difficult to evaluate methods for reducing bias in estimates of catchment areal rainfall, as rainfall is measured at a point using rain gauges, and these gauges may not even be within the study catchment. For this reason, the methods for reducing bias in rainfall estimates were initially tested for hypothetical catchments, each representing a single pixel in the relevant remotely sensed dataset within which a rain gauge existed. These tests were based on the broad assumption that the point rainfall measured at a rain gauge would be representative of the rainfall on the associated pixel and would thus enable some degree of comparison between point rain gauge measurements and estimated rainfall values for the pixel to be compared, although the area of a pixel is approximately 100 km^2 for the FEWS datasets and 625 km^2 for the TRMM dataset.

In this investigation three rain gauges in the upper uMngeni catchment were used for which daily rainfall data was available from the DWS's website [https://www.dwaf.gov.za/hydrology.hymain/aspx]. These rain gauges were U2E002 at Cedara (data starts on 1 July 1952), U2E003 at Midmar Dam (data starts on 1 October 1964) and U2E006 at Albert Falls Dam (data starts on 1 January 1974). For each of these rain gauges, measured rain gauge data was compared with the adjusted rainfall estimates calculated using the adjustment methods described in Table 2- for the corresponding remotely sensed rainfall pixel for each of the remotely sensed rainfall datasets. The three remotely sensed rainfall datasets were evaluated for the following time periods for which data was available:

- TRMM 3B42 – January 1998 to September 2015
- FEWS RFE 2.0 – January 2001 to September 2015
- FEWS ARC 2.0 – January 1983 to September 2015

Table 2-7: Methods for adjusting remotely sensed rainfall for a rain gauge pixel

Method	Description
RS_Orig	Unadjusted remotely sensed satellite rainfall estimates.
RS_MeanMOY	Adjusted remotely sensed satellite rainfall estimates using ratio of MOY (calendar month) monthly means for rain gauge to MOY monthly means for remotely sensed data to correct daily remotely sensed values.
RS_MedianMOY	Adjusted remotely sensed satellite rainfall estimates using ratio of MOY (calendar month) monthly medians for rain gauge to MOY monthly medians for remotely sensed data to correct daily remotely sensed values.
RS_FDWhole	Adjusted remotely sensed satellite rainfall estimates using whole common daily time series to calculate a cumulative frequency distribution curve for both the rain gauge and remotely sensed datasets and using the ratios between points on these curves to correct daily remotely sensed values.

Method	Description
RS_FDSeason	Adjusted remotely sensed satellite rainfall estimates using common daily time series to calculate a cumulative frequency distribution curve for each of four seasons (1 = October to December; 2 = January to March; 3 = April to June; 4 = July to September) for both the rain gauge and remotely sensed datasets and using the ratios between points on these curves for the relevant season to correct daily remotely sensed values.
RS_FDMOY	Adjusted remotely sensed satellite rainfall estimates using common daily time series to calculate a cumulative frequency distribution curve for each MOY for both the rain gauge and remotely sensed datasets and using the ratios between points on these curves for the relevant MOY to correct daily remotely sensed values.

An initial analysis of the results indicated a potential problem with the FEWS ARC2 dataset. The bias corrected FEWS ARC2 estimates compared well with rain gauge measurements for some statistics (sum, max, mean, counts), but the correlation and regression statistics were relatively poor. A plot of the cumulative error between the FEWS ARC2 estimates and the rain gauge measurements showed a marked change in slope at approximately 30 September 1997. The FEWS ARC2 raster images seem to be incorrectly dated one day later than they should be for the period prior to 30 September 1997. On the assumption that there was an error in the dating of the FEWS ARC2 raster images, the values in the time series up to 30 September 1997 were moved one day earlier and a zero value was added for 30 September 1997.

For the purpose of this comparison, two comparative statistics were selected, although other statistics were also calculated:

- *Percentage difference in means:* This is the percentage difference between the mean of the daily remotely sensed rainfall and the mean of the daily rain gauge rainfall. This gives an indication of how closely the total remotely sensed rainfall depth matches the total rain gauge rainfall depth over the full comparison period.
- *Coefficient of determination:* This is the R^2 between the daily remotely sensed rainfall and the daily rain gauge rainfall. It is the square of Pearson's correlation coefficient (r) and is an indicator of the linearity of the relationship between the daily remotely sensed rainfall values relative to the daily rain gauge rainfall values.

The comparison of the percentage difference, shown in Table 2-, indicates that there is a bias in the original unadjusted remotely sensed rainfall estimates and that all the adjustment methods are successful in reducing this bias, albeit to varying degrees. The two FEWS datasets tend to underestimate rainfall volumes and the TRMM 3B42 dataset tends to overestimate rainfall. The bias correction method using the cumulative frequency distribution of all the values (RS_FDWhole) seems to give the best and most consistent results in reducing bias, although it seemed to work better for the two FEWS datasets than for the TRMM 3B42 dataset. The similar RS_FDSeason and RS_FDMOY methods did not seem to perform significantly better. Thus, the additional data processing associated with these two methods does not appear to be justified. The correlations of the rain gauge measurements with the remotely sensed estimates, shown in Table 2-, give an indication of how well the magnitude of the individual daily rainfall values is represented. The two FEWS datasets are more closely correlated to the rain gauge data than the TRMM 3B42 dataset. Two possible reasons for the poorer correlation of the TRMM 3B42 dataset are the coarser resolution and a six-hour phase difference between the TRMM 3B42 (the day starts at 00h00 UTC) and the rain gauge data (the day starts at 06h00 UTC). The various adjustment methods do not seem to improve the correlations much compared to the uncorrected remotely sensed estimates.

Table 2-8: Comparison of rainfall estimate adjustment methods – percentage difference in means

Rain gauge	Dataset	Adjustment method					
		RS_Orig	RS_Median	RS_Mean	RS_FDWhole	RS_FDMOY	RS_FDSeason
U2E002_DriefonteinCedara	FEWS ARC 2.0	-8.971	-2.147	1.463	-0.182	1.165	0.280
	FEWS RFE 2.0	-10.681	-0.288	0.052	-0.087	0.356	0.166
	TRMM 3B42	1.180	1.896	0.206	2.714	8.022	4.991
U2E003_MidmarDam	FEWS ARC 2.0	-3.594	-2.639	1.142	-0.613	0.028	-0.376
	FEWS RFE 2.0	-9.828	-2.543	-0.170	-0.440	-0.463	-0.834
	TRMM 3B42	6.243	-3.104	-0.102	0.071	3.413	2.280
U2E006_AlbertFallsDam	FEWS ARC 2.0	2.091	-2.286	1.459	-0.195	-0.569	-0.806
	FEWS RFE 2.0	-4.674	-0.117	-0.433	-0.756	-0.032	-0.425
	TRMM 3B42	5.904	-0.682	-0.224	-0.594	2.707	3.477

Table 2-9: Comparison of rainfall estimate adjustment methods – coefficient of determination

Rain gauge	Dataset	Adjustment method					
		RS_Orig	RS_Median	RS_Mean	RS_FDWhole	RS_FDMOY	RS_FDSeason
U2E002_DriefonteinCedara	FEWS ARC 2.0	0.771	0.753	0.764	0.782	0.785	0.784
	FEWS RFE 2.0	0.774	0.768	0.781	0.769	0.789	0.785
	TRMM 3B42	0.219	0.219	0.225	0.226	0.250	0.254
U2E003_MidmarDam	FEWS ARC 2.0	0.529	0.525	0.524	0.538	0.550	0.543
	FEWS RFE 2.0	0.621	0.603	0.627	0.634	0.624	0.619
	TRMM 3B42	0.278	0.279	0.281	0.280	0.267	0.278
U2E006_AlbertFallsDam	FEWS ARC 2.0	0.441	0.433	0.433	0.443	0.462	0.450
	FEWS RFE 2.0	0.719	0.714	0.724	0.711	0.702	0.697
	TRMM 3B42	0.282	0.281	0.287	0.278	0.302	0.294

This investigation was extended later in the project by applying the *RS_FDWhole* adjustment method to a larger number of gauges with an additional year of data and including the CMORPH dataset. The four remotely sensed datasets had a common data period for the years 2001 to 2016 and were evaluated for this common time period for as long a period as the measured rainfall data permitted as some rain gauges were no longer operational. For each of the rain gauges listed in Table 2- the time series of measured rainfall are compared with the time series of satellite remotely sensed rainfall at the pixel coincident with the rain gauge. Both the unadjusted (original) remotely sensed rainfall values and the values adjusted using the *RS_FDWhole* method described in Table 2-, were included in the comparison. The comparisons are shown in Table 2-2. For each rain gauge, the period evaluated is specified together with the number of records included in the comparison. Days with missing data were excluded from the comparison.

Table 2-2 Comparison of satellite remotely sensed rainfall data with rain gauge data

Gauge	Dataset	Percentage difference in means		Coefficient of determination	
		Original	Adjusted	Original	Adjusted
22259_OpsaalFortNott	CMORPH	-28.8	1.9	0.32	0.32
	FEWS ARC2	-37	4.1	0.21	0.32
Period: 1 January 2001 to 31 August 2013 Records: 4,595	FEWS RFE2	-39.6	1.2	0.37	0.37
	TRMM 3B42	-13.3	1.2	0.33	0.34
19686_BlesbokRidgeNottRoad	CMORPH	6	6.1	0.16	0.15
	FEWS ARC2	-11	9.2	0.18	0.18
Period: 1 January 2001 to 31 December 2010 Records: 3,583	FEWS RFE2	-8.7	2.6	0.21	0.2
	TRMM 3B42	30.3	5.3	0.18	0.17
19744-30999_IvanhoeImpendhle	CMORPH	-17.4	0.7	0.31	0.29
	FEWS ARC2	-26.7	-4	0.25	0.26
Period: 1 January 2001 to 31 December 2016 Records: 5,768	FEWS RFE2	-26.1	0	0.37	0.35
	TRMM 3B42	0.3	-1.2	0.27	0.26
U2E003_MidmarDam	CMORPH	-4.8	-0.2	0.34	0.32
	FEWS ARC2	-6.3	-2.6	0.55	0.54
Period: 1 January 2001 to 31 December 2016 Records: 5,661	FEWS RFE2	-10.7	0.5	0.62	0.63
	TRMM 3B42	5.5	-1.2	0.28	0.28
19810_SymondsLaneHowick	CMORPH	-11.2	-1.6	0.24	0.23
	FEWS ARC2	-14	-1.8	0.44	0.43
Period: 1 January 2001 to 31 May 2013 Records: 4,383	FEWS RFE2	-18.2	-0.2	0.49	0.49
	TRMM 3B42	-3.1	-1.4	0.24	0.24
13499-30817_Cedara	CMORPH	-8.9	4.3	0.34	0.33
	FEWS ARC2	-5.5	3.9	0.86	0.85
Period: 1 January 2001 to 31 December 2016 Records: 5,829	FEWS RFE2	-5	8.8	0.85	0.84
	TRMM 3B42	4	3.3	0.26	0.28
U2E002_DriefonteinCedara	CMORPH	-14.8	-2.4	0.28	0.27
	FEWS ARC2	-12.3	-3.3	0.76	0.76
Period: 1 January 2001 to 31 December 2016 Records: 5,814	FEWS RFE2	-11.8	0.3	0.75	0.74
	TRMM 3B42	-2	-2.7	0.25	0.26
19787-31002_EverdonEstateHowick	CMORPH	-31.2	-2.9	0.33	0.33
	FEWS ARC2	-32.6	-4.3	0.58	0.57
Period: 1 January 2001 to 31 December 2016 Records: 5,723	FEWS RFE2	-32.3	0.1	0.57	0.6
	TRMM 3B42	-26.8	-3	0.28	0.29
19806_HawkestoneHowick	CMORPH	-35.6	1.1	0.26	0.28
	FEWS ARC2	-35.6	-5.1	0.39	0.39
Period: 1 January 2001 to 31 May 2011 Records: 3,714	FEWS RFE2	-39	0.3	0.47	0.47
	TRMM 3B42	-32.8	0.8	0.25	0.27
U2E006_AlbertFallsDam	CMORPH	-3.7	-2.7	0.32	0.31
	FEWS ARC2	-1.2	-3.6	0.42	0.4
Period: 1 January 2001 to 31 December 2016 Records: 5,696	FEWS RFE2	-6.4	0.2	0.51	0.5
	TRMM 3B42	2.6	-1.8	0.31	0.3

Gauge	Dataset	Percentage difference in means		Coefficient of determination	
		Original	Adjusted	Original	Adjusted
19721_CramondAlbertFalls	CMORPH	-14.9	-0.2	0.27	0.26
Period: 1 January 2001 to 30 June 2013 Records: 4,506	FEWS ARC2	-15.8	0.2	0.36	0.36
	FEWS RFE2	-18.7	3.3	0.41	0.4
	TRMM 3B42	-10.1	0	0.24	0.24

In an initial analysis of the rain gauge data, phase errors were observed when comparing individual events at a rain gauge with the same events at nearby rain gauges and the remotely sensed datasets. The 22259_OpsaalFortNott, 19686_BlesbokRidgeNottRoad, 19806_HawkestoneHowick and 19721_CramondAlbertFalls gauges were all found to have a one-day phase error during the comparison period 2001 to 2016. Adjusting these datasets resulted in substantial improvements to the correlations of gauge versus remotely sensed data.

The following observations were made from the comparative statistics given in Table 2-2:

- All four remotely sensed rainfall products, in their original form, mostly underestimate the total volume of rainfall during the comparison period, although the TRMM 3B42 product overestimated rainfall at some gauges.
- At most rain gauges, the R^2 statistics do not indicate a particularly strong relationship between remotely sensed and rain gauge data, although there is a stronger relationship at the operational gauges with a longer comparison period. The strongest relationship is for the two FEWS products at the two Cedara gauges.
- In almost all cases, the percentage difference in mean statistics indicates that adjustments to the remotely sensed data results in datasets that are more similar to the rain gauge data than the unadjusted remotely sensed datasets. However, the adjustment did not make much difference to the R^2 statistics, and in some cases, resulted in slightly lower R^2 values.
- Although the bias in the two FEWS datasets was generally greater than the other two datasets, the bias in the adjusted FEWS datasets, especially the FEWS RFE2 dataset, was smaller than for the other two datasets.

A comparison of remotely sensed rainfall with rain gauge data, such as that presented above, has two main weaknesses that need to be considered when evaluating the results:

- The different daily time periods used for the different datasets is a weakness. The operational rain gauges are part of automatic weather stations and the daily rainfall values may be for a day that extends from 12h00 to 12h00 (midday to midday), although this could not be confirmed. The non-operational rain gauges for which data was sourced from the ARC were most likely manually read rain gauges and the daily rainfall values are for a day that extends from 08h00 to 08h00. The DWS's *U2E002_DriefonteinCedara* gauge is possibly also manually read with a day that extends from 08h00 to 08h00. The two FEWS products have daily rainfall values for a day that extends from 08h00 to 08h00 for South Africa. The CMORPH and TRMM 3B42 products have daily rainfall values for a day that extends from 02h00 to 02h00 for South Africa.
- Even if possible errors in the remotely sensed rainfall estimates are ignored, the statistics for point rainfall measurements from a rain gauge should be expected to be different to the statistics for averaged rainfall over a pixel that is tens or hundreds of square kilometres in extent. Due to the spatial variability of rainfall within a pixel, it is expected that the average pixel rainfall will be dampened relative to point rain gauge values, resulting in lower total volumes, means and standard deviations. This expectation was confirmed in the comparison shown in Table 2-2.

However, given the smaller pixel size of the two FEWS products relative to the CMORPH and TRMM 3B42 products, greater similarity was expected between the statistics for the FEWS estimates and the measured rainfall values, but this was not the case. The remotely sensed products could be expected to have a greater number of rain days. This was confirmed to be the case.

A comparison with measured rain gauge values at a pixel level provides a means of comparing different remotely sensed rainfall products with each other using rain gauge data as a common baseline. However, such a comparison does not indicate how well the remotely sensed rainfall products represent areal rainfall over a catchment. As there is no direct means of measuring catchment rainfall for comparison with remotely sensed rainfall products, the comparison of simulated streamflow from a hydrological model with measured streamflow is one means of evaluating the accuracy of these remotely sensed rainfall products.

2.1.2.2 Comparison of rainfall bias correction methods for catchments

Five different methods for estimating catchment rainfall were included in this investigation. These are described in Table 2-3. For the measured rainfall data, two datasets were used: the original unadjusted rain gauge data (*Gauge_Orig*) and the rain gauge data adjusted by monthly medians (*Gauge_Med)*. For each remotely sensed rainfall product, three datasets were used: the original unadjusted remotely sensed estimate (*RS_Orig*), the remotely sensed estimate adjusted using all available rain gauges and using accumulative frequency distributions (*RS_GaugeFDBias*), and the remotely sensed estimate adjusted using only operational rain gauges and using accumulative frequency distributions (*RS_GaugeFDBias* method). Initially, the *RS_GaugeFD* method (Table 2-3) for adjusting remotely sensed rainfall data was used as this was similar to the *RS_FDWhole* method used for the rain gauge pixels in Section 0. However, this was later modified to create the *RS_GaugeFDBias* method, which first makes an adjustment at the driver rain gauge pixel and then translates this adjustment to the catchment rainfall.

Table 2-3: Different estimates of catchment rainfall evaluated using ACRU

Method	**Description**
Gauge_Orig	The measured driver rain gauge data values for the driver gauge assigned to a catchment (only rain gauges with a full record for the simulation time period can be used as driver rain gauges).
Gauge_Med	Catchment rainfall estimates calculated using the ratio of the median MOY rainfall at the driver rain gauge to the area-weighted median MOY rainfall for the catchment (from Schulze et al*.,* 2008b) are used to adjust the daily driver rain gauge data (i.e. standard ACRU CORPPT method).
RS_Orig	The catchment areal means of the original remotely sensed satellite rainfall estimates without any adjustment to reduce bias.
RS_GaugeFD	Adjusted remotely sensed satellite rainfall estimates using common daily time series to calculate a cumulative frequency distribution curve for both the driver rain gauge time series and the remotely sensed catchment time series, and using the ratios between points on these curves to correct daily remotely sensed catchment values.

Method	Description
RS_GaugeFDBias	Adjusted remotely sensed satellite rainfall estimates using common daily time series to calculate a cumulative frequency distribution curve for both the driver rain gauge time series and the remotely sensed driver rain gauge pixel time series, and using the ratios between points on these curves to correct the daily remotely sensed catchment values based on a cumulative frequency distribution curve of the daily remotely sensed catchment values. This method effectively calculates an adjustment at the rain gauges and then translates this adjustment to the catchment.

A critical part of using rain gauge data for hydrological modelling is the allocation of a driver rain gauge to each catchment being modelled. The allocation of driver rain gauges was done manually based on the proximity of the catchment to the driver rain gauge, altitude and mean annual precipitation (MAP). When using rain gauge data directly, only rain gauges that are operational for the required simulation period can be used, although nearby non-operational gauges may still be useful for patching missing data in the datasets at the operational gauges. When using rain gauge data to adjust the remotely sensed estimates using accumulative frequency distributions, the gauges do not necessarily need to be operational during the simulation period as long as there is sufficient overlap between the rainfall datasets to generate suitable accumulative frequency distributions. In some cases, potential driver rain gauges were excluded due to long periods of missing data or the availability of operational rain gauges nearby.

The ACRU model was configured for the upper uMngeni catchment as described in Clark (2018). For each rainfall dataset, the ACRU model was run for the period 1 October 2007 to 30 September 2016 (a total of nine hydrological years). The simulated streamflow results using each rainfall dataset were compared to measured streamflow at the six streamflow gauges listed in Table 2-4. The measured streamflow data was obtained from the DWS's website [http://www.dwa.gov.za/hydrology/]. The first year of simulated streamflow was regarded as a warmup period for the model and was excluded from the statistical analysis. Any periods where there was missing data in each measured streamflow dataset were also excluded from the statistical analysis. At streamflow gauge U2H061, only three hydrological years (starting in October 2013) were included in the comparison as measurements only started in 2013. For each rainfall dataset, the simulated streamflow was compared with measured daily streamflow datasets based on a day that extended from 08h00 to 08h00 to fit better with daily rainfall datasets with the same 24-hour period.

Table 2-4: Streamflow gauges used for verification

Gauge ID	Gauge description	Upstream area (km^2)	Located in catchment
U2H006	Karkloof River at Shafton	334.48	Karkloof_25
U2H007	Lions River (Mpofana River) at Weltevreden	363.39	Lions River_15
U2H013	Mgeni River at Petrus Stroom	297.61	Mpendle_7
U2H014	Mgeni River at Albert Falls	1652.90	Albert Falls_45
U2H048	Mgeni River at Midmar	926.85	Midmar_34
U2H061	Mpofana River	50.61	Lions River_12

For the purpose of comparing results, the following three comparative statistics were selected, although other statistics were also calculated:

- *Mean percentage difference:* This is the percentage difference between the mean of the simulated daily streamflow and the mean of the measured daily streamflow. It gives an indication of how closely the total simulated streamflow volume matches the total measured streamflow volume over the full comparison period.

- *Coefficient of determination:* This is the R^2 between the simulated daily streamflow and the measured daily streamflow. It is the square of Pearson's correlation coefficient (r) and is an indicator of the linearity of the relationship between the simulated daily streamflow values relative to the measured daily streamflow values.
- *Nash-Sutcliffe efficiency:* The Nash-Sutcliffe efficiency (NSE) value (Nash and Sutcliffe, 1970) provides a relative index of the degree of association between measured and simulated streamflow values.

A comparison of measured and simulated total streamflow volumes for the whole eight-year comparison period, using the percentage difference between the mean daily measured streamflow and the mean daily simulated streamflow, is shown in Table 2-5. In this table, small differences between measured and simulated streamflow are highlighted in the darkest shade of blue, with bigger differences shown in increasingly lighter shades of blue. In the evaluation of the results, greater emphasis has been placed on the comparisons at the upstream streamflow gauges (U2H006, U2H007 and U2H013) as gauges U2H014 and U2H048 are located immediately downstream of large dams and thus have additional uncertainties associated with them, such as errors in upstream flow estimates, abstractions and releases, and U2H061 is just downstream of the inter-catchment transfer from Mearns Weir and Spring Grove Dam with the transfer flows being substantially greater than just the runoff from the catchment.

The following observations were made:

- Neither the original (unadjusted) rain gauge data nor the median adjusted rain gauge data gave good estimates of streamflow volume, substantially overestimating flows, except at U2H061. This indicates that, in this investigation, the point rain gauge measurements were not a good representation of areal rainfall quantities in the catchments in the upper uMngeni catchment. The adjustment of the measured values using monthly median values resulted in poorer streamflow volume estimates in all catchments.
- In general, the original (unadjusted) remotely sensed rainfall datasets did not give good results. Streamflow was generally underestimated by CMORPH, FEWS ARC 2.0 and FEWS RFE 2.0, but overestimated by TRMM 3B42. The two FEWS datasets had a larger bias.
- For the FEWS ARC 2.0 and FEWS RFE 2.0 products, the adjusted rainfall datasets generally gave better estimates of streamflow volume than the unadjusted datasets. For these two products, the adjustment using both operational and non-operational gauges generally resulted in better estimates of streamflow volume than for adjustment using only the operational rain gauges.
- For the CMORPH and TRMM 3B42 products, the adjusted rainfall datasets gave better estimates of streamflow volume than the unadjusted datasets at some gauges, but not at others. For these two products, the adjustment using only the operational rain gauges generally resulted in better estimates of streamflow volume than for adjustment using both operational and non-operational gauges.
- Observing the estimated streamflow volume at the upstream streamflow gauges (U2H006, U2H007 and U2H013), the rainfall dataset that results in the best estimation of streamflow volumes over the full comparison period is the FEWS RFE 2.0 dataset, which has been adjusted using both operational and non-operational rain gauges. The corresponding FEWS ARC 2.0 dataset also resulted in relatively good streamflow volume estimates.
- In general, streamflow was poorly estimated at gauge U2H048 just downstream of Midmar Dam, even when estimates at the upstream gauges (U2H007 and U2H0013) were relatively good. The best streamflow estimates at U2H048 occur when the flow at the upstream gauges is substantially overestimated. The reason for these poor estimates at U2H048 is not immediately apparent, but appears to be due to poor estimation of runoff in the subcatchments surrounding Midmar Dam, although this would be surprising for rainfall data scenarios that result in good streamflow volume estimates upstream. The connectivity of flows from upstream catchments was checked and no errors were found. The flow releases and the bulk water abstraction from the dam were also checked and, as far as can be determined, using the data supplied, these values are correct, and would have to be changed substantially to make up the deficit in flow volumes.

- The results at U2H014 were varied and were possibly impacted on by the poor results at U2H048 upstream, so no clear conclusions can be made regarding the estimates at this gauge.

Table 2-5: Comparison of measured and simulated daily streamflow data using percentage difference in the means

Dataset	Method	Gauges	U2H006	U2H007	U2H013	U2H014	U2H048	U2H061
Rain gauge	Original	Operational	39.80	30.82	24.63	38.96	11.44	4.82
	Median adjusted	Operational	73.21	64.61	65.70	94.53	82.22	9.25
CMORPH	Original	-	-64.88	7.35	-27.36	-16.17	-28.38	-0.49
	Frequency adjusted	All	53.86	26.43	13.77	57.92	7.16	1.10
		Operational	11.12	26.43	13.77	31.07	7.16	1.10
FEWS ARC 2.0	Original	-	-82.44	-16.78	-54.83	-50.12	-63.10	-0.75
	Frequency adjusted	All	-3.98	5.22	-12.33	-2.67	-40.31	3.52
		Operational	-20.03	5.22	-12.33	-13.70	-40.31	3.52
FEWS RFE 2.0	Original	-	-90.25	-25.60	-55.61	-54.59	-64.80	-3.52
	Frequency adjusted	All	1.90	-0.44	6.52	-3.64	-43.72	-1.30
		Operational	-27.37	-0.44	6.52	-17.52	-43.72	-1.30
TRMM 3B42	Original	-	-53.67	33.17	21.12	6.91	23.87	-0.43
	Frequency adjusted	All	73.63	18.46	10.83	54.07	-0.37	-1.74
		Operational	21.02	18.46	10.83	27.64	-0.39	-1.74

The R^2 and NSE statistics were used as an indication of the goodness of fit between the simulated streamflow time series and the measured streamflow time series. The R^2 and NSE statistics for the time series of daily flow volumes are shown in Table 2-6 and Table 2-7. In these tables, values indicating a good degree of association between datasets are highlighted in the darkest shade of blue, with poorer degrees of association shown in increasingly lighter shades of blue.

The following observations were made:

- In general, the statistics indicate a poor degree of association between the simulated and the measured streamflow time series, except at gauge U2H061. Gauge U2H061 has a relatively small catchment area (50 km^2) and flows are often dominated by the measured inter-catchment transfer from Mearns Weir and Spring Grove Dam. The daily streamflow time series were plotted as graphs and it was observed that, when significant runoff that produced daily rainfall occurred, the simulated daily streamflow values peaked on the same day as the day on which the rainfall event occurred (as expected from the ACRU runoff algorithms), but the measured daily streamflow values usually peaked the following day with lower flow values. The poor degree of association between the simulated and the measured streamflow is likely to be due to differences in actual and estimated rainfall volumes, and the mismatch in the timing of flows. The mismatch in the timing of flows is possibly partly due to the ACRU model not lagging and attenuating flows as they proceed down river reaches and through dams.
- The NSE values at gauge U2H013 are mostly positive, indicating that the simulated streamflow is a better representation of the measured streamflow than simply using the mean of the measured streamflow. However, the negative NSE values at gauges U2H006 and U2H007 indicate a poor degree of association.

- The slightly higher R^2 values for the rain gauge and TRMM 3B42 rainfall data scenarios typically correspond to the overestimation of streamflow volumes by these scenarios, which possibly mitigates the problem with the timing of daily flows to some extent.

Table 2-6: Comparison of measured and simulated daily streamflow data using the coefficient of determination

Dataset	Method	Gauges	U2H006	U2H007	U2H013	U2H014	U2H048	U2H061
Rain gauge	Original	Operational	0.20	0.28	0.64	0.29	0.32	0.89
	Median adjusted	Operational	0.20	0.24	0.65	0.23	0.25	0.85
CMORPH	Original	-	0.17	0.46	0.42	0.60	0.38	0.94
	Frequency adjusted	All	0.37	0.44	0.45	0.28	0.60	0.96
		Operational	0.33	0.44	0.45	0.33	0.36	0.93
FEWS ARC 2.0	Original	-	0.03	0.30	0.20	0.25	0.00	0.88
	Frequency adjusted	All	0.09	0.23	0.25	0.08	0.18	0.79
		Operational	0.08	0.23	0.25	0.14	0.03	0.63
FEWS RFE 2.0	Original	-	0.10	0.22	0.31	0.27	0.00	0.95
	Frequency adjusted	All	0.26	0.27	0.27	0.18	0.29	0.97
		Operational	0.25	0.27	0.27	0.21	0.08	0.95
TRMM 3B42	Original	-	0.25	0.48	0.40	0.26	0.26	0.94
	Frequency adjusted	All	0.40	0.48	0.38	0.24	0.51	0.98
		Operational	0.40	0.48	0.38	0.26	0.26	0.95

Table 2-7: Comparison of measured and simulated daily streamflow data using Nash-Sutcliffe efficiency

Dataset	Method	Gauges	U2H006	U2H007	U2H013	U2H014	U2H048	U2H061
Rain gauge	Original	Operational	-1.53	-1.30	0.54	-0.89	0.13	0.86
	Median adjusted	Operational	-2.61	-3.63	0.13	-3.93	-0.78	0.79
CMORPH	Original	-	-0.11	-0.21	0.38	0.63	0.34	0.93
	Frequency adjusted	All	-0.99	-1.34	-0.02	-2.76	-0.24	0.91
		Operational	-0.20	-1.34	-0.02	-1.49	-0.24	0.91
FEWS ARC 2.0	Original	-	-0.33	0.07	0.08	0.19	-0.05	0.84
	Frequency adjusted	All	-1.35	-1.07	0.22	-0.09	-0.41	0.32
		Operational	-0.89	-1.07	0.22	0.17	-0.41	0.32
FEWS RFE 2.0	Original	-	-0.22	0.05	0.11	0.17	-0.05	0.95
	Frequency adjusted	All	-0.08	-0.16	0.15	0.02	0.03	0.94
		Operational	0.15	-0.16	0.15	0.24	0.03	0.94
TRMM 3B42	Original	-	0.10	-0.72	0.21	-0.34	-0.12	0.93
	Frequency adjusted	All	-0.83	-0.16	0.24	-1.30	0.08	0.94
		Operational	0.08	-0.16	0.24	-0.56	0.08	0.94

The R^2 and NSE statistics for the time series of monthly flow volumes are shown in Table 2-16 and Table 2-9. These statistics on the monthly flows are useful in giving an indication as to whether the poor degree of association between the simulated and the measured daily streamflow time series was due to differences in actual and estimated rainfall volumes or to the mismatch in the timing of flows. There was a substantial improvement in both the R^2 and NSE statistics at most gauges and for most rainfall data scenarios. This seems to indicate that the mismatch in the timing of flows is one of the sources of poor association between the measured and simulated streamflow time series. However, poor agreement for both of the unadjusted FEWS datasets indicates that poor estimation of rainfall volumes may also be a significant source of poor association with the measured values. Rainfall occurrence was not changed in the method used to adjust the remotely sensed rainfall estimates, just rainfall volume, for the purpose of reducing perceived localised biases.

Table 2-8 Comparison of measured and simulated monthly streamflow data using the coefficient of determination

Dataset	Method	Gauges	U2H006	U2H007	U2H013	U2H014	U2H048	U2H061
Rain gauge	Original	Operational	0.51	0.62	0.83	0.54	0.80	0.96
	Median adjusted	Operational	0.52	0.60	0.84	0.48	0.62	0.95
CMORPH	Original	-	0.51	0.75	0.57	0.65	0.66	0.97
	Frequency adjusted	All	0.78	0.78	0.67	0.53	0.71	0.97
		Operational	0.73	0.78	0.67	0.61	0.71	0.97
FEWS ARC 2.0	Original	-	0.06	0.48	0.43	0.37	0.00	0.95
	Frequency adjusted	All	0.23	0.55	0.45	0.44	0.30	0.89
		Operational	0.31	0.55	0.45	0.59	0.30	0.89
FEWS RFE 2.0	Original	-	0.26	0.30	0.53	0.38	0.00	0.97
	Frequency adjusted	All	0.67	0.43	0.50	0.57	0.36	0.96
		Operational	0.65	0.43	0.50	0.48	0.36	0.96
TRMM 3B42	Original	-	0.71	0.79	0.59	0.47	0.47	0.97
	Frequency adjusted	All	0.85	0.76	0.58	0.44	0.46	0.97
		Operational	0.83	0.76	0.58	0.48	0.46	0.97

Table 2-9: Comparison of measured and simulated monthly streamflow data using Nash-Sutcliffe efficiency

Dataset	Method	Gauges	U2H006	U2H007	U2H013	U2H014	U2H048	U2H061
Rain gauge	Original	Operational	0.13	0.39	0.78	0.09	0.77	0.95
	Median adjusted	Operational	-0.32	-0.34	0.40	-1.89	0.39	0.93
CMORPH	Original	-	0.25	0.65	0.53	0.73	0.64	0.98
	Frequency adjusted	All	0.24	0.38	0.47	-1.43	0.62	0.97
		Operational	0.68	0.38	0.47	-0.38	0.62	0.97
FEWS ARC 2.0	Original	-	-0.31	0.42	0.10	0.28	-0.08	0.95
	Frequency adjusted	All	0.16	0.39	0.44	0.60	0.26	0.87
		Operational	0.31	0.39	0.44	0.64	0.26	0.87
FEWS RFE 2.0	Original	-	-0.33	0.15	0.10	0.23	-0.09	0.97
	Frequency adjusted	All	0.70	0.33	0.50	0.70	0.24	0.96
		Operational	0.58	0.33	0.50	0.58	0.24	0.96
TRMM 3B42	Original	-	0.47	0.35	0.44	0.20	0.31	0.97
	Frequency adjusted	All	0.24	0.58	0.50	-0.80	0.42	0.97
		Operational	0.79	0.58	0.50	-0.02	0.42	0.97

2.1.2.3 Outcome

The comparison of measured rain gauge data with remotely sensed rainfall estimates at the coincident pixel showed that there was a varying degree of bias at the gauges evaluated for the comparison period. The adjustment method, based on the accumulative frequency distributions of the datasets, was effective in reducing the differences between the mean and the standard deviation of the measured and estimated datasets, and moving the slope of the best-fit regression line closer to 1.0, but it was not effective in improving the goodness of fit indicated by the R^2 values.

This type of comparison provides an indication of the relative performance of the different remotely sensed rainfall products in the study catchment.

This investigation showed that, in the upper uMngeni catchment, neither rain gauge data nor unadjusted satellite remotely sensed rainfall estimates were good sources of catchment rainfall data on their own for use in hydrological modelling at catchment scale. The use of rain gauge data for the localised adjustment of remotely sensed rainfall data in individual catchments showed some potential, but results for the different products were mixed, and also varied between catchments. The localised adjustments to the remotely sensed rainfall estimates seemed to have a greater benefit in improving the estimated rainfall and streamflow volumes for the FEWS ARC 2.0 and FEWS RFE 2.0 products than for the other two products. The adjustment method based on accumulative frequency distributions enables measured rainfall data from non-operational rain gauges to be used, although, in this investigation, only one of the five non-operational gauges was found to be useful in improving rainfall and streamflow estimates. The timing of the modelled streamflow was identified as one cause of the generally poor goodness of fit between measured and simulated daily streamflow time series. This timing problem is partly due to the lack of flow routing down the main river reaches within the ACRU model. The intended use of the output from the hydrological simulations needs to be considered. Good estimates of volumes are sufficient for producing annual water catchment accounts, but both volume and timing are important for use in making operational water management decisions. Downscaling of the relatively coarse resolution that is remotely sensed may help to improve the rainfall estimates, especially in smaller catchments. This investigation, for just one case study catchment, did not result in a clear recommendation regarding which rainfall dataset was best, although the adjustment method, based on accumulative frequency distributions, seemed to be effective in reducing the localised bias of remotely sensed rainfall datasets.

2.2 SPATIAL REFERENCE POTENTIAL EVAPORATION ESTIMATES

Accurate estimation of evaporative demand is important as it is one of the key inputs required for hydrological modelling. It is also an important component of water resource accounts. The accurate estimation of ET for different land uses within a catchment is an important component of water resource accounting and for understanding sectoral water use. The partitioning of ET into its components is useful for differentiating between beneficial and non-beneficial water use. Evaporative demand can vary significantly in space and time. In addition, different types of land cover and land management result in different responses to this demand.

As discussed in Clark (2015a), numerous potential approaches are available for estimating ET. Ground-based measurements can be done using techniques such as the Bowen ratio, eddy covariance, scintillometry, surface renewal and weighing lysimeter. However, these techniques are mostly only applied at research sites for specific types of land cover. The use of ground-based measurements of ET is not feasible at a catchment scale. Techniques to estimate ET at fine spatial scales (10 to 30 m) using a surface energy balance approach and satellite remotely sensed data inputs, together with ground-based meteorological data, are well advanced. However, there are not many “off-the-shelf” ET products available and those that are available are at a relatively coarse spatial and temporal resolution.

The Moderate Resolution Imaging Spectroradiometer (MODIS)-derived MOD16 ET product from the National Aeronautics and Space Administration (NASA) [https://modis.gsfc.nasa.gov/data/dataprod/mod16.php] has a spatial resolution of 1 km and is produced at eight-day intervals. The Meteosat Second Generation (MSG)-derived ET product [https://landsaf.meteo.pt/] from the LSA-SAF is used daily and has a spatial resolution of approximately 3 to 4 km. The processing of ET estimates from scratch is time consuming and requires a certain degree of knowledge and skill. There are several surface energy balance models, such as SEBAL, SEBS, TSEB, METRIC, Alexi and ETLook, but not all are publicly available. These models rely on suitable cloud-free satellite remote sensing images being available, as well as ground-based meteorological data. Infilling techniques are used to produce daily time series. Karimi et al. (2013b) and Van Niekerk et al. (2018) compiled water accounts by using surface energy balance methods to estimate ET for specific catchments.

An alternative approach to estimating ET is to use measurements or estimates of ET_0, together with land cover-related crop coefficients and estimates of soil water availability. As described by Clark (2015a), a modelling approach was adopted for the water use quantification and accounting methodology. Hence, Clark (2015a) decided that it would be best to use ET_0 as input to the ACRU model and to model ET, rather than to use remote sensing-based estimates of ET. This approach was similar to that of Sinclair and Pegram (2010; 2013b), where the TOPographic Kinematic APproximation and Integration (TOPKAPI) model is used to estimate soil moisture at a three-hour time step for a 0.125° spatial grid over South Africa. Sinclair and Pegram (2013b) estimate ET dynamically from ET_0 using a crop factor and water availability. This approach is more flexible as it is easier to estimate continuous daily time series and it would enable land cover/use scenarios to be run. The spatial resolution of ET_0 estimates is also possibly less critical than for ET as the spatial variability of land cover/use does not have to be considered for the ET_0 estimates.

Direct measurements of A-pan or S-tank ET_0 are available, but generally have a sparse spatial distribution and are point measurements. An alternative to relying on direct measurements of ET_0 is to use one of several empirical equations together with measured meteorological data. The simpler equations, such as those of Blaney and Criddle (1950), Hargreaves and Samani (1982; 1985), Linacre (1977) and Thornthwaite (1948), primarily require air temperature data. The FAO's 56 Penman-Monteith method (Allen et al., 1998) of estimating ET_0 is widely used and accepted as a standard, but requires measurements of solar radiation, air temperature, air humidity and wind speed. As an alternative to relying on measured meteorological data, remotely sensed land surface temperature (LST) and solar radiation datasets are increasingly being used, together with empirical equations for estimating ET_0 (Gavilán et al., 2006; Aguilar and Polo, 2011; Maeda et al., 2011; Cammalleri and Ciraolo, 2013). There are also a number of weather reanalysis datasets available, which combine meteorological modelling and ground-based meteorological measurements that could be used to provide estimates of ET_0 using modelled meteorological variables. Such reanalysis datasets include NASA's MERRA-2 and the ERA Interim dataset of the European Centre for Medium-range Weather Forecasts (ECWMF). These are described briefly in Section 0 and Section 0, respectively.

The earlier study (Clark, 2015a) used the Penman-Monteith ET_0 dataset (described in Section 0), which was originally produced by the SAHG. However, this dataset is no longer being produced. In this section, other ET_0 datasets and datasets of meteorological variables that could be used to estimate ET_0 are investigated. The requirements relating to ET_0 data for use in the ACRU model are discussed in Section 0. Several datasets that could potentially be used are described and compared in Section 2.2.3. The methodology and initial results of the development of an ET_0 dataset using daily temperature data from the MODIS LST dataset and the MERRA-2 reanalysis dataset are presented in Section 0 and Section 0, respectively. The datasets are compared in Section 0.

2.2.1 The Satellite Applications Hydrology Group's ET_0 dataset

Sinclair and Pegram (2010) of the SAHG describe the development of an ET_0 dataset for South Africa using a modification of the FAO's 56 Penman-Monteith method (Allen et al., 1998), which uses forecasts of meteorological variables from the Unified Model (UM) run by SAWS. Estimates of solar radiation were based on Meteosat data products obtained from the LSA-SAF of the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) under a research agreement. Sinclair and Pegram (2010) validated the ET_0 estimates by comparing them with ET_0 estimates that were calculated using observed meteorological data (temperature, relative humidity and wind speed) from a network of weather stations, and found that estimates based on the FAO's 56 Penman-Monteith method were unbiased and relatively highly correlated. The hourly soil moisture and ET_0 estimates described in Sinclair and Pegram (2013b) are freely available on the SAHG's website [http://sahg.ukzn.ac.za/soil_moisture]. The dataset starts in September 2007 and runs up to early April 2017. Some information on the SAHG's ET_0 dataset is given in Table 2-10.

Table 2-10: Information on the SAHG's ET_0 dataset

Attribute	Information
Spatial extent	14.915° (W), 34.055° (E), -21.9445° (N), -36.0245° (S)
Spatial resolution	0.11° × 0.11°
Length of record	September 2007 to April 2017
Temporal resolution	Hourly (0Z-23Z)
File formats	ASCII, GeoTiff
Availability	Freely available
Source	ftp://sahg.ukzn.ac.za/ET0/

Starting in 2017, the ARC intended taking over responsibility for updating the Hydrologically Consistent Land Surface Model for Soil Moisture and Evapotranspiration Modelling Over Southern Africa Using Remote Sensing and Meteorological Data (HYLARSMET) soil moisture dataset. One of the input datasets – the ET_0 dataset – would also have been calculated. However, Weepener (2018) confirmed that the ARC subsequently took a decision to rather use ET_0 as calculated from its weather stations to produce an ET_0 dataset for the country and that there would be a cost associated with providing the dataset to users. This decision to not continue to update the SAHG's ET_0 dataset resulted from the meteorological data from SAWS's UM only being available up to July 2017 as, at that point, SAWS had started using a new, higher-resolution version of the UM that was incompatible, and there was a problem with EUMETSAT's remotely sensed radiation data, which was used in the calculations, not being available for a period starting from October 2017.

It is unfortunate that this dataset will not continue to be updated and made freely available, as it was a valuable dataset for South Africa. However, this eventuality had partly been anticipated at the beginning of the project because of the infrequent intervals at which the dataset was updated. In addition, there was a need to investigate alternative sources of ET_0 data or methods to estimate ET_0 to enable the modelling of historical water resource accounts prior to 2007.

2.2.2 Requirements for ET_0 datasets

Before investigating any alternative spatial ET_0 datasets or developing an ET_0 dataset using other spatial datasets of meteorological variables, it is worth considering the requirements for ET_0 datasets for use in water use quantification and accounting methodology.

Spatial extent: The spatial extent of the dataset needs to include the transboundary catchments on South Africa's borders with the neighbouring countries of Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe.

Spatial resolution: The spatial resolution needs to be sufficiently fine to enable the spatial variability of ET_0 to be represented adequately, especially in catchments where there is a large altitude range. Given the size of the quaternary catchments, and that – in this project – the catchments are typically modelled at sub-quaternary scale, it is estimated that the resolution of the ET_0 data should not be greater than approximately 0.1° x 0.1°.

Length of record: Typically, water resource accounts would be compiled for the previous month, season or year to summarise the water resource situation in that period. However, individual water resource accounts may provide greater insight into the water resource situation if considered in relation to a historical time series of accounts. A record length of at least 10 years would be preferable.

Temporal resolution: The ET_0 data is required as input for daily hydrological modelling, and thus the ET_0 data needs to be at least at a daily time step. However, the ET_0 data needs to be compatible with the daily rainfall inputs to the model, where rainfall is traditionally measured for a day ranging from 08h00 to 08h00. Thus, there may be some advantage to using an hourly ET_0 dataset to enable the data to be aggregated up to a day period that is compatible with the rainfall data.

Data format: The data should be in a raster file format that is easy to work with and preferably for which a subset of the data can be downloaded for Southern Africa alone to reduce the size of the files that are downloaded and stored locally.

Availability: The dataset should ideally be continuous with no missing time steps. The dataset should be readily available and accessible for research and public use at a cost that is not prohibitive to the dataset being purchased annually for the full spatial extent of the catchments of South Africa. The data should ideally be available with a latency of less than two months to enable water resource accounts to be compiled as soon after the accounting period as possible.

2.2.3 Description of potentially suitable datasets

An initial investigation into datasets was conducted and a few datasets were identified. These include datasets of ET_0 and of meteorological forcing variables that could be used to calculate ET_0 using one of the empirical equations mentioned in the introduction to Section 0. The datasets that were initially identified are briefly described in this section.

2.2.3.1 The LSA-SAF's METREF ET_0

The LSA-SAF is part of the EUMETSAT [http:\\landsaf.ipma.pt]. The LSA-SAF has an operational near real-time daily ET_0 dataset called METREF. The METREF dataset consists of daily estimates of the FAO's Penman-Monteith ET_0 (mm/day) using daily radiation data from the MSG satellite's Spinning Enhanced Visible and Infrared Imager (SEVIRI) platform (De Bruin et al., 2016). Further information about the dataset can be found in Trigo et al*.* (2011) and De Bruin et al*.* (2016), and on the product's webpage [https://landsaf.ipma.pt/en/products/evapotranspiration/metref/]. Some information on the METREF ET_0 dataset is given in Table 2-11. The relatively fine spatial resolution of this dataset would seem to be well suited to the purpose of producing catchment-scale water resource accounts. The short length of record means that it is only suitable for use in water resource accounts from the 2016/17 hydrological year onwards. However, it may be suitable to append to ET_0 time series produced from SAHG's ET_0 dataset.

Table 2-11: Information on LSA-SAF's ET_0 dataset

Attribute	Information
Spatial extent	MSG disk (Europe and Africa)
Spatial resolution	± 3-4 km depending on location
Length of record	August 2016 to the present
Temporal resolution	Daily

Attribute	Information
File formats	HDF5
Availability	Freely available
Source	http:\\landsaf.ipma.pt

2.2.3.2 The FEWS NET PET ET_0

The Famine Early Warnings System Network (FEWS NET) provides a daily global FAO Penman-Monteith ET_0 dataset called PET. Some information on the METREF ET_0 dataset is given in Table 2-12. Further information about the dataset can be found on the product's webpage [https://earlywarning.usgs.gov/fews/product/81]. The webpage explains that the ET_0 dataset is calculated using six-hourly climate parameter data (including air temperature, atmospheric pressure, wind speed, relative humidity and solar radiation) extracted from the Global Data Assimilation System (GDAS) of the National Oceanic and Atmospheric Administration (NOAA).

The dataset is intended to provide early warning for drought- or flood-induced famine conditions. The course 1° × 1° spatial resolution of this dataset is unfortunately not well suited to the purpose of producing catchment-scale water resource accounts.

Table 2-12: Information on the FEWS NET PET ET_0 dataset

Attribute	Information
Spatial extent	Global [-180° (W), 180° (E), 90° (N), -90° (S)]
Spatial resolution	1° × 1°
Length of record	January 2001 to present
Temporal resolution	Daily (0Z-23Z)
File formats	BIL
Availability	Freely available
Source	https://earlywarning.usgs.gov/fews/datadownloads/Global/PET

2.2.3.3 NASA's MERRA-2 reanalysis

The MERRA-2 is an atmospheric reanalysis of the modern satellite era produced by NASA's Global Modelling and Assimilation Office (GMAO) (Gelaro et al., 2017). Gelaro et al*.* (2017) describe reanalysis as a process in which a data assimilation system is used to process meteorological observations using an underlying forecast model to combine disparate observations in a consistent manner to create gridded meteorological datasets. Sen Gupta and Tarboton (2016) describe the downscaling of MERRA data to produce sub-daily raster datasets at a resolution suitable for application in hydrological modelling. Based on the approach of Sen Gupta and Tarboton (2016), there are two MERRA-2 datasets that could potentially be used to estimate ET_0. The MERRA-2 M2SDNXSLV dataset is a daily dataset that includes daily maximum, minimum and mean air temperature data that could be used in one of the temperature-based empirical equations for estimating ET_0. The details of this daily dataset are shown in Table 2-13. The MERRA-2 M2T1NXSLV dataset is an hourly dataset that includes air temperature, humidity, radiation and wind speed variables that could be used in the Penman-Monteith equation to estimate ET_0. The details of this daily dataset are shown in Table 2-22. The relatively coarse spatial resolution of the MERRA-2 datasets means that downscaling would be necessary to be suitable for use in the hydrological modelling in this project on a sub-quaternary scale.

Table 2-13: Information on the MERRA-2 M2SDNXSLV dataset

Attribute	Information
Spatial extent	Global [-180° (W), 180° (E), 90° (N), -90° (S)] – can be subset
Spatial resolution	0.5° latitude × 0.65° longitude
Length of record	January 1980 to present

Attribute	Information
Temporal resolution	Daily (0Z-23Z)
File formats	ASCII, HDF, NETCDF
Availability	Freely available
Source	https://disc.gsfc.nasa.gov/datasets/M2SDNXSLV_V5.12.4/summary

Table 2-14: Information on the MERRA-2 M2T1NXSLV dataset

Attribute	Information
Spatial extent	Global [-180° (W), 180° (E), 90° (N), -90° (S)] – can be subset
Spatial resolution	0.5° latitude × 0.65° longitude
Length of record	January 1980 to present
Temporal resolution	Hourly
File formats	ASCII, HDF, NETCDF
Availability	Freely available
Source	https://disc.gsfc.nasa.gov/datasets/M2T1NXSLV_V5.12.4/summary

2.2.3.4 The ECMWF's ERA-Interim reanalysis

The ERA-Interim is a global atmospheric reanalysis dataset produced by the European Centre for Medium-range Weather Forecasts (ECMWF). The ERA-Interim dataset is described in Berrisford et al. (2009) and Dee et al. (2011. The details of this daily dataset are given in Table 2-15. The ERA-Interim dataset includes surface-level variables such as air temperature, radiation and wind speed that could be used in the Penman-Monteith equation to estimate ET_0. The relatively coarse spatial resolution of the ERA-Interim dataset means that downscaling would be necessary to be suitable for use in the sub-quaternary hydrological modelling of this project.

Table 2-15: Information on the ECMWF ERA-Interim dataset

Attribute	Information
Spatial extent	Global [-180° (W), 180° (E), 90° (N), -90° (S)] – can be subset
Spatial resolution	±80 km
Length of record	1979 to present
Temporal resolution	Three-hourly
File formats	GRIB, NETCDF
Availability	Freely available
Source	http://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/

2.2.3.5 The FEWS NET FLDAS

The FEWS NET Land Data Assimilation System (FLDAS) uses rainfall and other meteorological inputs such as temperature, humidity, radiation and wind speed to produce modelled estimates of hydro-climate conditions such as soil moisture, evapotranspiration, surface runoff and baseflow (McNally et al., 2017). There are several FLDAS datasets available, produced at different spatial and temporal scales using different input datasets and different models. The dataset referred to here is the daily dataset with a spatial resolution of 0.1° × 0.1° produced using the Noah Land Surface Model (LSM) described in Ek et al. (2003). McNally et al. (2017) describe the Noah LSM as a four soil-layer water and energy balance LSM that is used as the operational LSM in the weather, climate and data assimilation systems by NOAA's National Centers for Environmental Prediction (NCEP). The details of this daily dataset are given in Table 2-16. The dataset includes both the meteorological variables used as input to the model and the modelled output variables. The meteorological model input variables could be used in the Penman-Monteith equation to estimate ET_0.

It would be interesting to investigate the accuracy of the modelled surface runoff and baseflow at quaternary catchment level for use in a simple water resource account, excluding sectoral water use.

Table 2-16: Information on the FEWS NET FLDAS dataset

Attribute	**Information**
Spatial extent	Southern Africa [6° (W), 54.6° (E), 6.4° (N), -37.8° (S)] – can be subset
Spatial resolution	0.1° × 0.1°
Length of record	January 2001 to present
Temporal resolution	Daily (0Z-23Z)
File formats	NETCDF
Availability	Freely available
Source	https://disc.gsfc.nasa.gov/datasets/FLDAS_NOAH01_A_SA_D_V001/summary

2.2.4 Calculating ET_0 from MODIS land surface temperature data

Spatial estimates of ET_0 were required as part of the research for an MSc (Hydrology) dissertation by Mahomed (2017) relating to the calculation of the Evapotranspiration Deficit Index (ETDI). An investigation into the calculation of ET_0 from MODIS land surface temperature data formed part of this research and a summary of the findings is presented in this section. Mahomed (2017) applied the approach used by Maeda et al. (2011) to estimate ET_0 using the remotely sensed LST in the equation of Hargreaves and Samani (1985). The MODIS Aqua/Terra eight-day LST product, called MOD11A2-Version 6 [http://modis-land.gsfc.nasa.gov/temp.htm], with a spatial resolution of 1 km, was used. The calibration of Hargreaves and Samani's equation was performed using ET_0 calculated using the FAO Penman-Monteith equation (Allen et al., 1998) with ground-based measurements of meteorological data obtained from the ARC.

The results, comparing the Penman-Monteith ET_o estimates from ground-based measurements of meteorological variables with the estimates based on LST for the period 2011 to 2016, are shown in Figure 2-11 for selected quaternary catchments within the uMngeni catchment and in Figure 2-12 for the upper uThukela catchment. These results show the importance of the localised calibration of the empirical equation of Hargreaves and Samani (1985). They also show that, once calibrated, the Hargreaves and Samani equation can be used with LST data to produce estimates of ET_0 that are comparable with the Penman-Monteith ET_0 estimates based on ground-based measurements. Furthermore, they show that there is substantial bias in the uncalibrated ET_0 estimates during the warmer summer months. These results indicate that the approach of using remotely sensed LST data is worth further investigation, especially given the relatively fine spatial resolution of the MODIS LST data. However, the main obstacle to this approach may be in obtaining access to the ground-based measurements of the meteorological variables that are required for the localised calibration of the equation of Hargreaves and Samani (1985). Another potential problem with the LST approach is that the remotely sensed estimates of LST depend on cloud-free days.

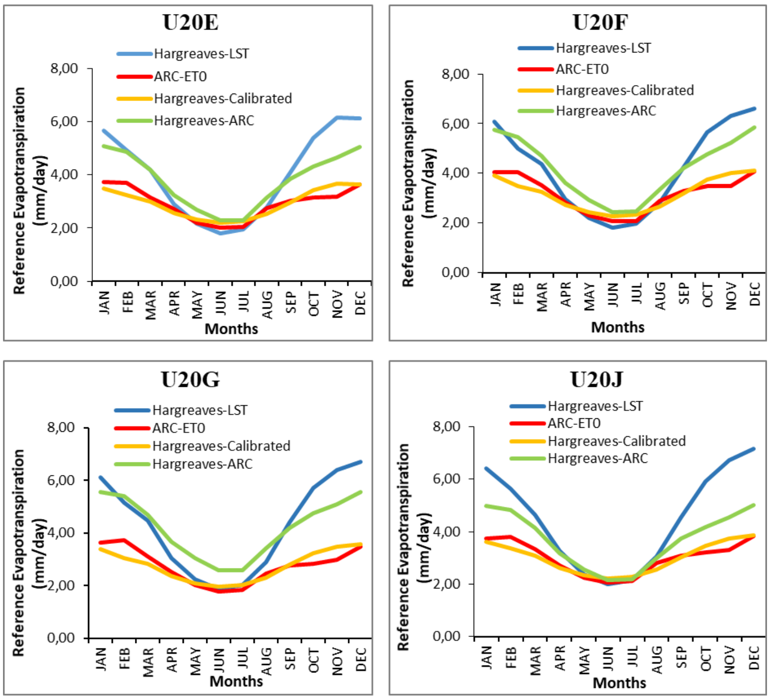

Figure 2-11: Comparison of the monthly average distribution of ET_0 estimates in the uMngeni catchment (2011-2016) (Mahomed, 2017)

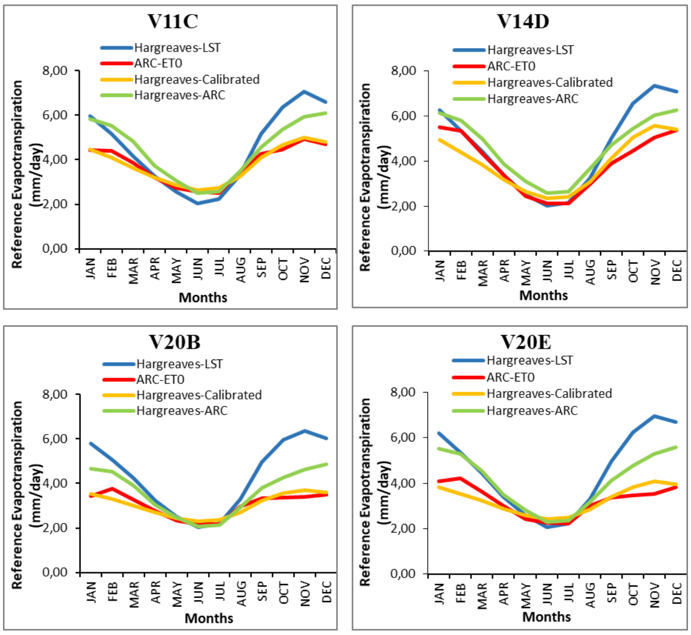

Figure 2-12: Comparison of the monthly average distribution of ET_0 estimates in the upper uThukela catchment (2011-2016) (Mahomed, 2017)

2.2.5 Calculating ET_0 from MERRA-2 air temperature data

A comparison of the data products described in Section 2.2.3, with spatial resolution and length of record as the main criteria, resulted in a decision to investigate the MERRA-2 reanalysis dataset further. Sen Gupta and Tarboton (2016) successfully demonstrated the feasibility of downscaling MERRA data to produce sub-daily raster datasets at a resolution suitable for application in hydrological modelling. This section describes the methodology used in an initial investigation into the use of the MERRA data to estimate ET_0.

Use of the MERRA M2T1NXSLV hourly raster dataset, together with the Penman-Monteith equation, would require the spatial downscaling of several meteorological variables. Thus, for this initial investigation, it was proposed that the MERRA-2 M2SDNXSLV (GMAO, 2015b) dataset of daily maximum, minimum and mean air temperature be used together with the equation of Hargreaves and Samani (1985) to estimate ET_0.

As described in Sen Gupta and Tarboton (2016), the three daily temperature datasets were first resampled to a finer resolution using bilinear interpolation. A resampled resolution of 0.025° x 0.025° was selected as 0.025° is a multiple of both the original 0.5° latitude and 0.625° longitude pixel size. The MERRA-2 dataset of geopotential heights (GMAO, 2015a) and the 90 m Digital Elevation Model (DEM) (Weepener et al., 2011e) for South Africa were both resampled to the same resolution using bilinear interpolation. For each resampled pixel, the difference in elevation between the DEM elevation and the geopotential height was calculated. In order to downscale the resampled temperature rasters, lapse rates describing the change in temperature with altitude were required.

Schulze (1997) defined 12 lapse rate regions and associated air temperature lapse rates for South Africa, with regions 8 and 9 later being combined. In a subsequent study by Schulze and Maharaj (2004), the lapse rates for maximum and minimum temperatures for each month of the year in each region were revised. However, in some of the regions, more than one set of lapse rates was specified for different altitude or topographic index zones within the lapse rate region. For the purpose of downscaling Global Climate Model (GCM) temperature predictions, a single set of simplified MOY lapse rates – one for maximum temperatures and one for minimum temperatures – was assigned to each of the lapse rate regions (Schulze et al., 2014). These simplified lapse rate values were applied in this investigation to downscale the MERRA-2 temperature data.

The downscaled temperature rasters were then used in the equation of Hargreaves and Samani (1985) to calculate a raster containing estimated ET_0 values for each day. An initial verification of the estimated ET_0 values, calculated using MERRA-2 temperature estimates (both at the original scale and downscaled), was done using the Penman-Monteith ET_0 estimates (SASRI, 2018) based on freely available automatic weather station (AWS) measurements, which were made available by the South African Sugarcane Research Institute (SASRI) and Mondi, and accessible on the SASRI WeatherWeb portal [http://portal.sasa.org.za/weatherweb/]. For comparison purposes, the SAHG's ET_0 estimates were also included in the verification. Six AWSs at a range of altitudes in the uMngeni catchment were selected.

At most of the stations, the downscaling of the MERRA-2 data did not substantially change the magnitude of the ET_0 estimates compared to the estimates using the temperature data at the original scale. The verifications of both the MERRA-2 ET_0 estimates were poor at five of the six weather stations, which almost always substantially overestimated ET_0. The MERRA-2 ET_0 estimates were generally better in the cooler winter months, with large differences in the hotter summer months. This observation concurs with the uncalibrated Hargreaves and Samani ET_0 estimates of Mahomed (2017), shown in Figure 2-11. The SAHG's estimates were generally better than the MERRA-2 estimates, but also generally overestimated ET_0 and gave better estimates in the summer months than in the winter months. The SAHG's estimates showed a peak in March 2016, which was not evident in the estimates based on measured meteorological data. These results indicated that either the MERRA-2 modelled temperature estimates were poor in the uMngeni catchment, or a localised calibration of the equation of Hargreaves and Samani (1985) was required. Given these poor results, it was decided that some of the other datasets described in Section 2.2.3 should be investigated before proceeding with a further investigation of the MERRA datasets.

2.2.6 Comparison of ET_0 datasets

The datasets listed in Table 2-25 were investigated. For the FLDAS dataset, ET_0 was estimated using the FAO's Penman-Monteith equation (Allen et al., 1998). The MERRA-2 estimates from Section 2.2.5 were included in the comparison.

For each of these datasets, estimated ET_0 value were extracted at pixels corresponding to selected AWSs to create a daily time series of ET_0 values for each weather station. For each weather station, a daily time series of ET_0 values was created with ET_0 being estimated with the FAO's Penman-Monteith equation (Allen et al., 1998) using measured meteorological data. In this investigation, weather stations in all three the case study catchments used in the bigger water resource accounting study were used: the uMngeni catchment, the upper uThukela catchment and the upper and central Breede catchment. There were several SASRI weather stations in the uMngeni catchment for which ET_0 estimates were already freely available for use in the study. In the uThukela and Breede catchments, it was necessary to use weather station data made available by NOAA for research purposes to calculate the ET_0 using the FAO's Penman-Monteith equation (Allen et al., 1998). This NOAA integrated surface data (ISD) [https://www.ncei.noaa.gov/data/global-hourly/access] is an invaluable additional source of measured meteorological data. The availability of variables required for the Penman-Monteith equation varies between stations, and thus the FAO's guidelines (Allen et al., 1998) for estimating the missing variables were applied. Solar radiation data was not available for any of the stations used in this investigation. The various spatial ET_0 datasets and the weather station datasets all had different start and end dates, and there was not a single suitably long time period for which all the datasets overlapped. Thus, although not ideal for comparison purposes, the verification for each dataset at each weather station was done for the time period for which there was data available in each instance.

Table 2-17: Details of datasets compared

Dataset	Spatial resolution	Start date	End date	Variables
SAHG ET_0	0.11° × 0.11°	September 2007	February 2017	ET_0
LSASAF METREF	± 3-4 km	August 2016	present	ET_0
FEWS NET FLDAS	0.1° × 0.1°	January 2001	present	Net shortwave radiation Net longwave radiation Soil heat flux density Mean air temperature Surface pressure Specific humidity Relative humidity Wind speed
MERRA-2 M2SDNXSLV	0.5° × 0.65°	January 1980	present	Maximum air temperature Minimum air temperature Mean air temperature

The weather stations used for verification in the uMngeni catchment are listed in Table 2-18. Three graphs, comparing the ET_0 datasets using three comparative statistics between each ET_0 dataset and the ET_0 estimates based on measured meteorological variables, are shown in Figure 2-13, Figure 2-14 and Figure 2-15 for the uMngeni catchment. The LSA-SAF METREF and FLDAS datasets typically underestimate the ET_0, while the SAHG's ET_0 and MERRA datasets often overestimate ET_0. The SAHG's ET_0 and LSA-SAF METREF datasets have a smaller bias than the other two datasets.

The R^2 and NSE statistics indicate that the SAHG's ET_0 and the LSA-SAF METREF datasets have a close agreement with the measurement-based station ET_0 estimates. The R^2 and NSE statistics indicate that the FLDAS and MERRA datasets have a reasonable agreement with the measurement-based station ET_0 estimates at some stations, but perform poorly at others.

Table 2-18: Weather stations in the uMngeni catchment used for the verification of ET_0 estimates

ID	Station name	Source	Altitude(m)	Start date	End date
1.	685800 – Cedara	NOAA-ISD	1,071	2000/01/01	2018/12/02
2.	685810 – Pietermaritzburg	NOAA-ISD	673	2000/01/01	2018/12/02
3.	685820 – Oribi Airport	NOAA-ISD	739	2013/12/11	2018/12/03
4.	685830 – Mount Edgecombe	NOAA-ISD	94	2000/01/01	2018/12/03
5.	685930 – Virginia	NOAA-ISD	6	2000/01/01	2018/12/03
6.	Greytown – Gilboa M [544 – AWS]	Mondi	1,523	2016/07/28	2018/08/22
7.	Greytown – Ravensworth M [538 – AWS]	Mondi	1,021	2016/07/28	2018/12/05
8.	Greytown – Seele Office M [543 – AWS]	Mondi	884	2016/07/28	2018/12/05
9.	Mt Edgecombe – Rainshelter [462 – AWS]	SASRI	96	2007/07/23	2018/12/06
10.	New Hanover – Torwoodlea [503 – AWS]	SASRI	822	2008/12/09	2018/12/05
11.	Pietermaritzburg – Faulklands [483 – AWS]	SASRI	740	2000/01/01	2016/04/06
12.	Pietermaritzburg – Ukulinga [492 – AWS]	SASRI	809	2008/03/13	2016/04/06
13.	Umkhomazi – Mt Home M [520 – AWS]	Mondi	1,151	2016/04/30	2018/12/06
14.	Wartburg – Bruyns Hill [455 – AWS]	SASRI	990	2000/01/01	2018/12/06
15.	Wartburg – Fountain Hill [512 – AWS]	SASRI	853	2015/08/13	2018/12/06

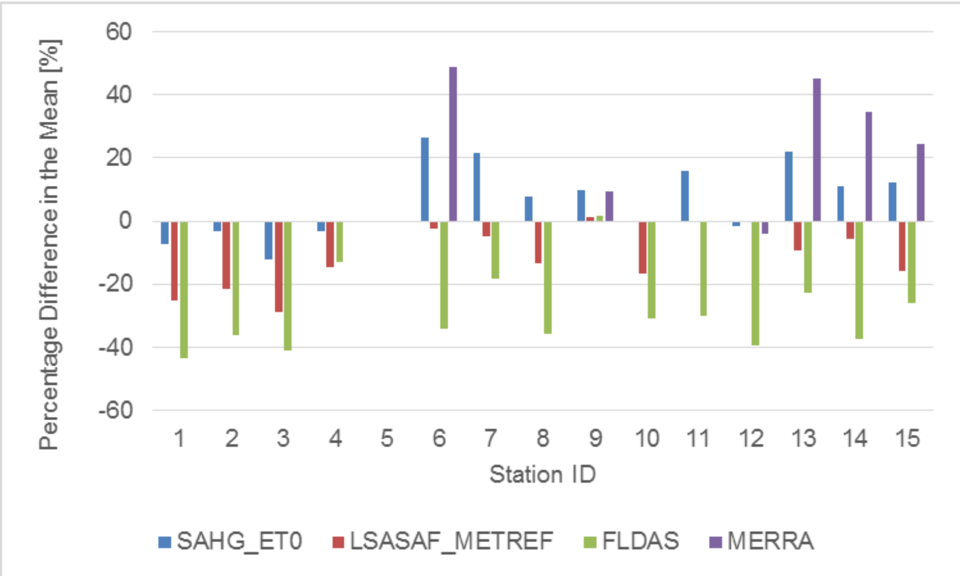

Figure 2-13: Comparison of the ET_0 datasets in the uMngeni catchment – percentage difference in means

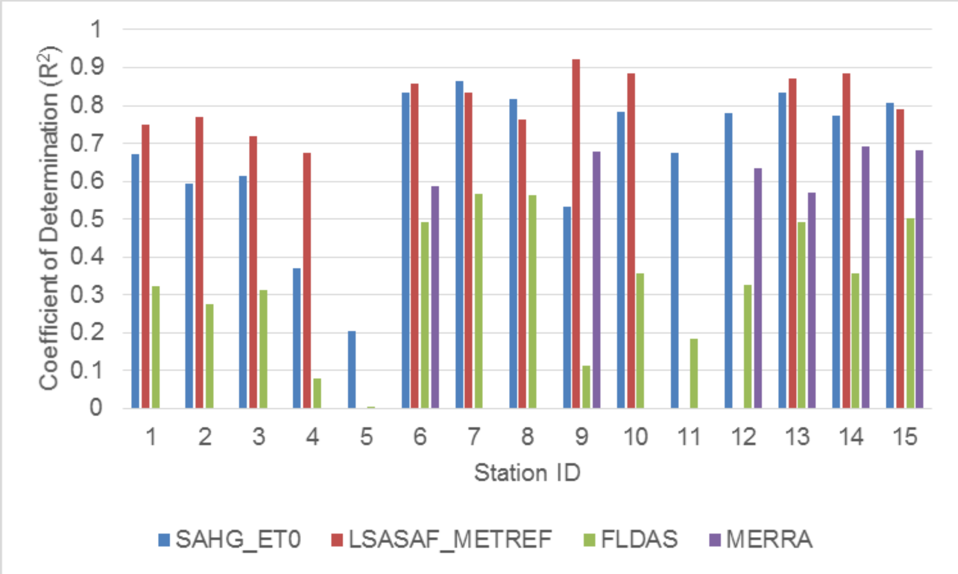

Figure 2-14: Comparison of the ET_0 datasets in the uMngeni catchment – coefficient of determination

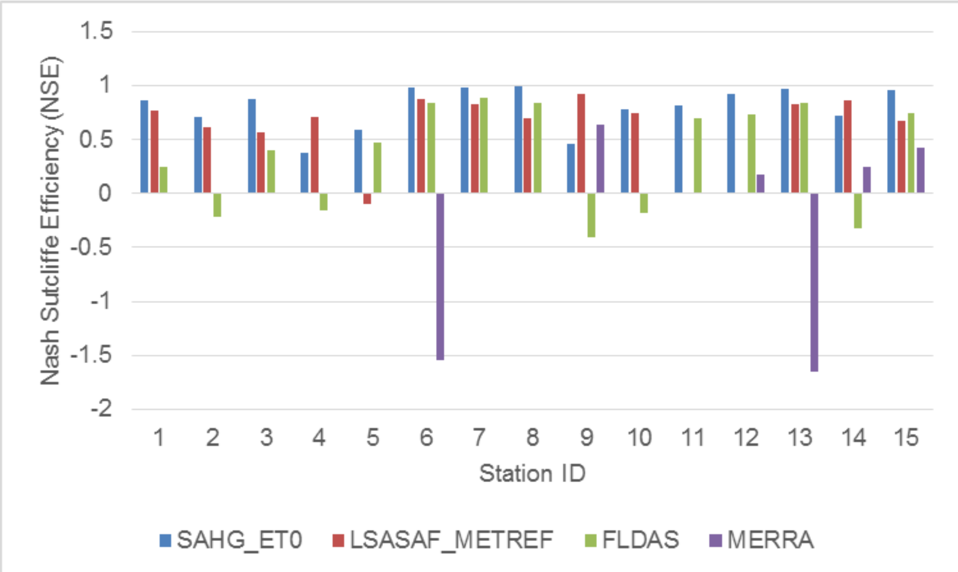

Figure 2-15: Comparison of the ET_0 datasets in the uMngeni catchment – Nash-Sutcliffe efficiency

The weather stations used for verification in the upper uThukela catchment are listed in Table 2-19. Three graphs comparing the ET_0 datasets using three comparative statistics between each ET_0 dataset and the ET_0 estimates based on measured meteorological variables for the upper uThukela catchment are shown in Figure 2-16, Figure 2-17 and Figure 2-18. The SAHG's ET_0, LSA-SAF METREF and FLDAS datasets typically underestimate the ET_0. The SAHG's ET_0 dataset has a smaller bias than the LSA-SAF METREF and FLDAS datasets. The R^2 and NSE statistics indicate that the SAHG's ET_0 and LSA-SAF METREF datasets have a close agreement with the measurement-based station ET_0 estimates, with a poorer agreement by the FLDAS datasets. Together with the stations in the uMngeni catchment, it was noted that the underestimation of ET_0 seemed to be worse at NOAA's ISD, which may be related to the station estimates of ET_0 for which solar radiation data measurements were not available.

Table 2-19: Weather stations in the uThukela catchment used for the verification of ET_0 estimates

ID	Station name	Source	Altitude(m)	Start date	End date
1.	684710 – Van Reenen	NOAA-ISD	1,680	2000/01/01	2018/12/03
2.	684740 – Royal Natal National Park	NOAA-ISD	1,392	2000/01/01	2018/12/03
3.	684780 – Estcourt	NOAA-ISD	1,144	2000/01/01	2018/12/03
4.	684790 – Ladysmith	NOAA-ISD	1,069	2000/06/14	2018/12/03
5.	684850 – Mooi River	NOAA-ISD	1,393	2013/12/11	2018/12/03
6.	685890 – Giants Castle	NOAA-ISD	1,763	2000/01/01	2018/12/03
7.	Muden – Ivala [481 – AWS]	SASRI	793	2000/01/01	2016/04/06

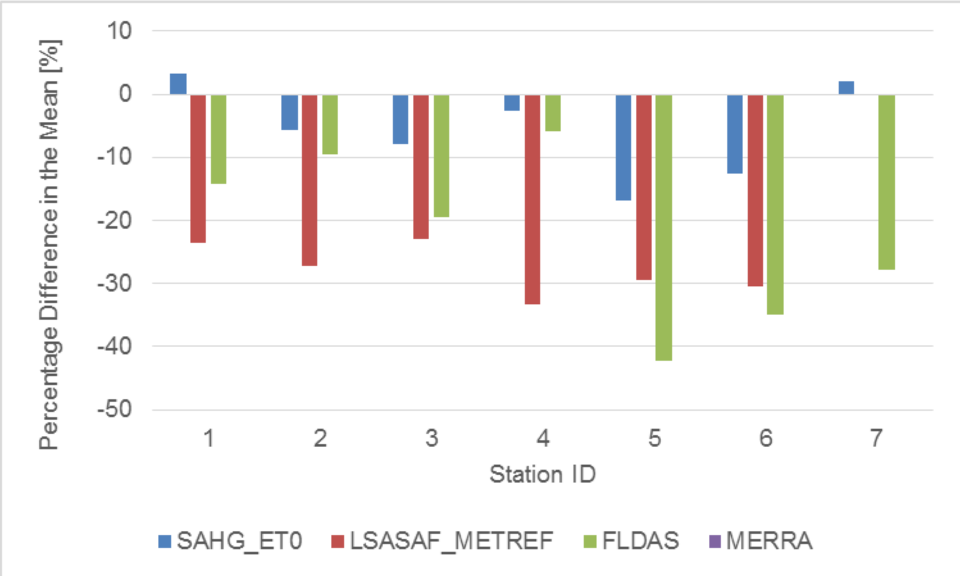

Figure 2-16: Comparison of the ET_0 datasets in the uThukela catchment – percentage difference in means

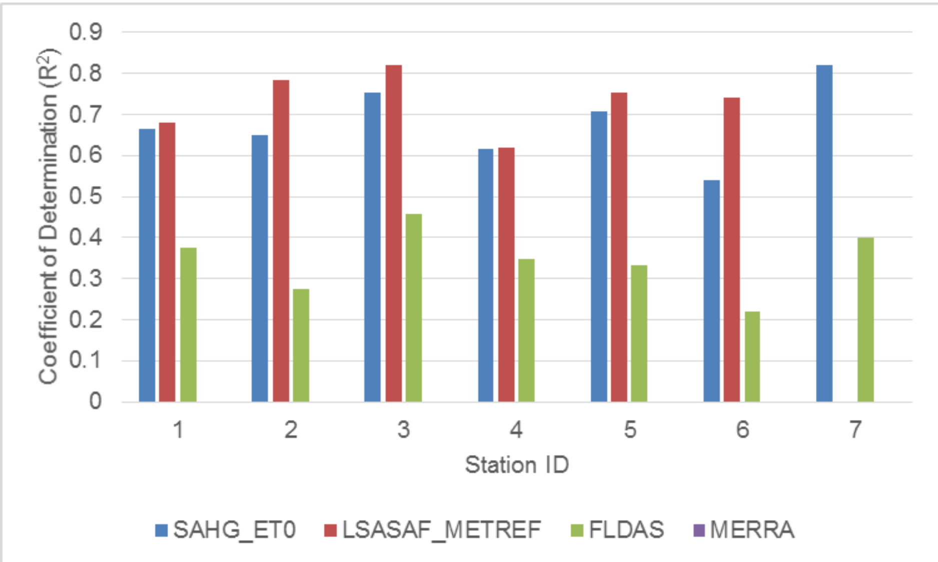

Figure 2-17: Comparison of the ET_0 datasets in the uThukela catchment – coefficient of determination

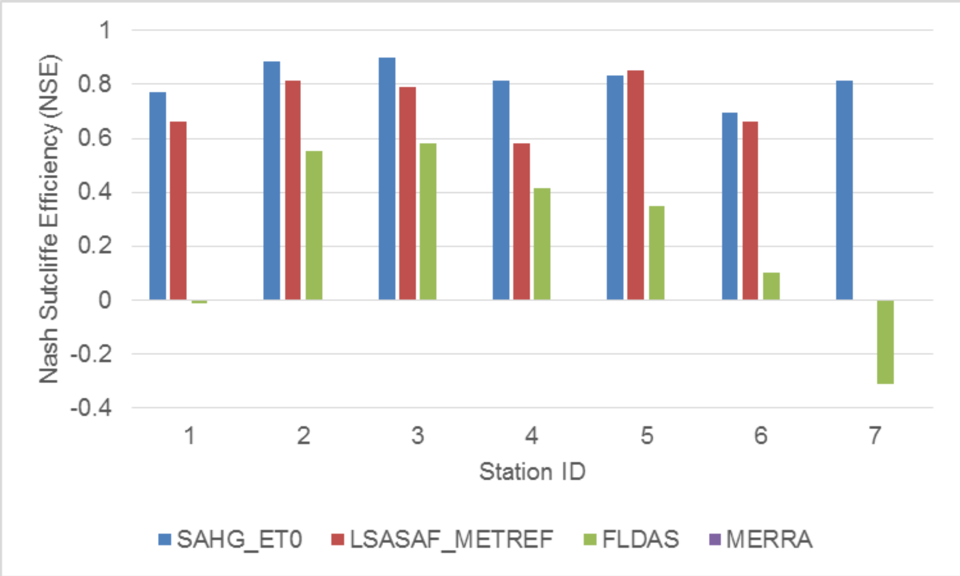

Figure 2-18: Comparison of the ET_0 datasets in the uThukela catchment – Nash-Sutcliffe efficiency

The weather stations used for verification in the upper and central Breede catchment are listed in Table 2-20. Three graphs comparing the ET_0 datasets using three comparative statistics between each ET_0 dataset and the ET_0 estimates based on measured meteorological variables are shown in Figure 2-19, Figure 2-20 and Figure 2-21 for the Breede catchment. The SAHG's ET_0, LSA-SAF METREF and FLDAS datasets all underestimate ET_0, with the SAHG's ET_0 dataset having a smaller bias than the LSA-SAF METREF and FLDAS datasets. The R^2 and NSE statistics indicate that all three datasets have a close agreement with the measurement-based station ET_0 estimates.

Table 2-20: Weather stations in the Breede catchment used for the verification of ET_0 estimates

ID	Station name	Source	Altitude(m)	Start date	End date
1.	687180 – Robertson	NOAA-ISD	204	2000/01/01	2018/12/02
2.	688210 – Worcester	NOAA-ISD	270	2000/01/01	2018/12/02

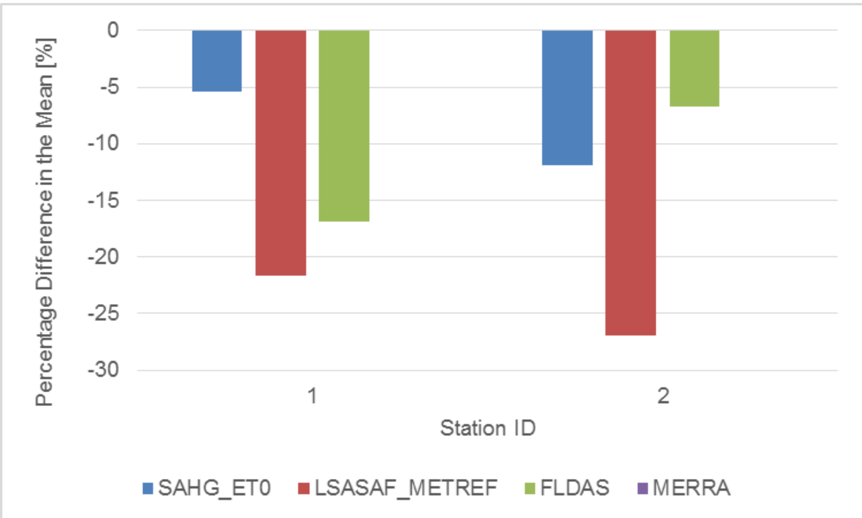

Figure 2-19: Comparison of the ET_0 datasets in the Breede catchment – percentage difference in means

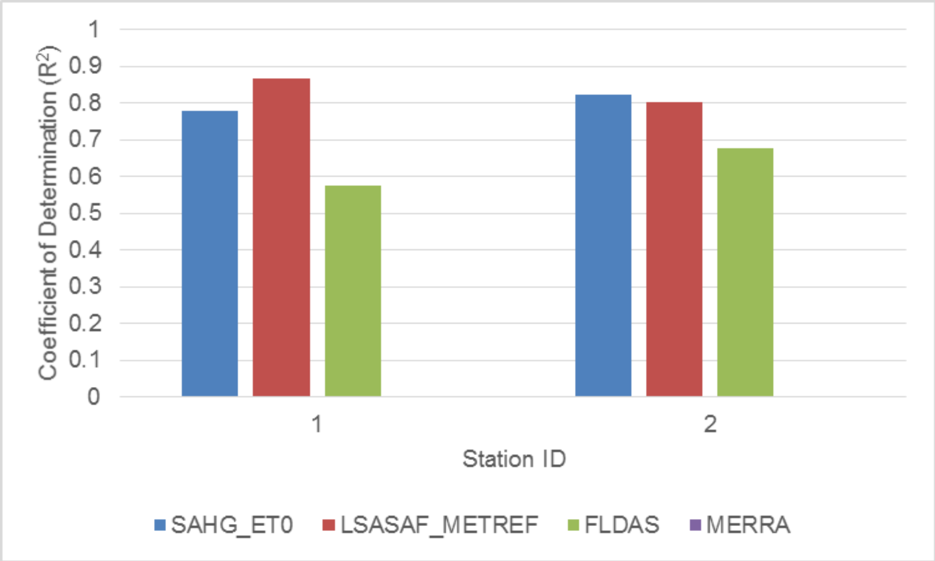

Figure 2-20: Comparison of the ET_0 datasets in the Breede catchment – coefficient of determination

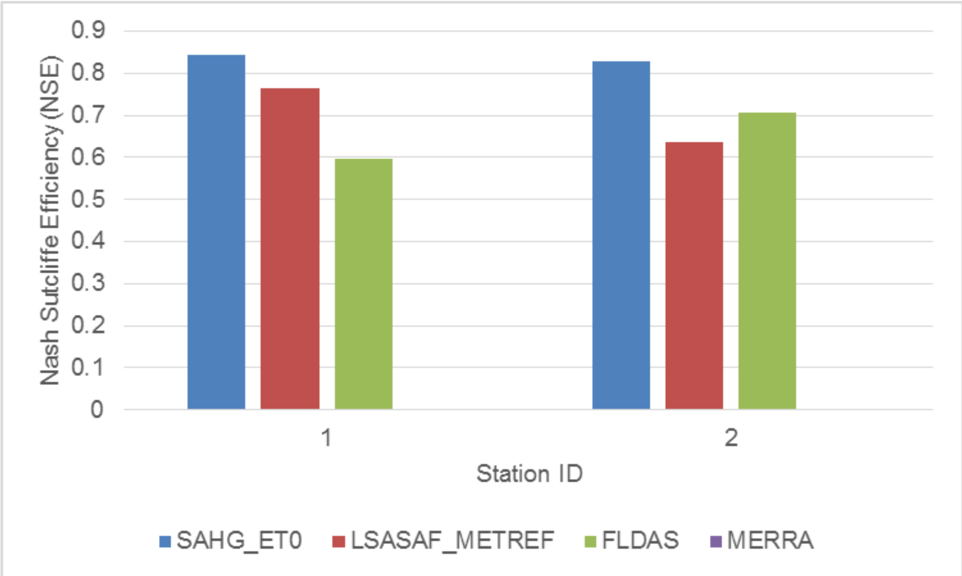

Figure 2-21: Comparison of the ET_0 datasets in the Breede catchment – Nash-Sutcliffe efficiency

2.2.7 Outcome

The relatively poor performance of the FLDAS and MERRA-2 was disappointing as both datasets are current and have datasets that cover the period 2013-2018 for which water resource accounts are to be compiled in this study. The performance of the LSA-SAF METREF dataset was relatively good, although there is often a substantial bias in the estimates. However, the LSA-SAF METREF dataset only starts in 2016. Thus, it will be necessary to append estimates from the LSA-SAF METREF dataset to the SAHG's ET_0 dataset for each catchment to provide a full time series for the period 2013-2018.

2.3 SUB-QUATERNARY CATCHMENTS AND RESPONSE REGIONS

Natural capital accounts are compiled for a specified spatial domain and a specified temporal domain, which may be a point in time or a time period. The natural systems in which ecosystems exist and in which water processes occur can be divided into spatial units based on watersheds, climate regions, ecosystem types and other biophysical criteria. However, land and water are generally managed within administrative units such as countries, provinces and municipal districts, which seldom match well with natural spatial units. A common nested set of spatial boundaries will be required to enable the investigation of linkages between water resource accounts and other natural capital accounts, and the aggregation of water resource accounts for reporting at different levels, although this does not preclude different types of natural capital accounts being compiled at finer spatial resolutions within the common spatial boundaries. A means of translating between natural biophysical boundaries and administrative boundaries may be required if reporting at administrative boundaries is necessary, although for this study, the water resource accounts are catchment based.

The DWS uses a hierarchical system of catchments, which is composed of 22 primary catchments containing secondary, tertiary and quaternary catchments, It is useful as a standardised national set of nested catchment boundaries. The revised sets of primary, secondary, tertiary and quaternary catchment boundaries developed by Weepener et al*.* (2011a) were selected for use in this study. The quaternary catchments (SLIM, 2014b) are the smallest standard national set of catchment boundaries recognised by DWS. However, it is often desirable to do hydrological modelling at sub-quaternary catchment scale due to variations in climate, soil, topography and land cover/use within a quaternary catchment and to represent large dams and important water abstraction and return flow points within a quaternary catchment. A dataset of sub-quaternary catchment boundaries was available from Umgeni Water for the uMngeni catchment, but no sub-quaternary catchment dataset could be found for the uThukela or the Breede catchments.

Clark (2015a) investigated two potential sub-quaternary catchment datasets: the National Freshwater Ecosystem Priority Areas (NFEPA) (Nel et al., 2011a) catchment boundaries (Nel et al*.*, 2011c) and the River Network Quinary Catchments dataset (Maherry et al*.*, 2013). Some advantages of using the NFEPA catchments dataset are that it is an existing dataset, it is based on the 1:500,000 rivers dataset for South Africa (DWS, 2012) and it would facilitate links to the river ecosystem accounts. Some potential difficulties with using the NFEPA catchments dataset (Nel et al., 2011c) are that the boundaries do not match the quaternary catchment boundaries exactly; due to spatial variations in the density of the 1:500,000 rivers dataset, some NFEPA catchments are very small, while others are the size of a whole quaternary catchment; the catchment boundaries do not take large dams into consideration and thus catchment boundaries may intersect dams; there are some errors in the location of the catchment boundaries; and it may still be necessary to subdivide some NFEPA catchments to represent catchments for features such as new large dams and streamflow monitoring points. The River Network Quinary Catchments boundaries developed by Maherry et al. (2013) was developed using a similar approach to that used for the NFEPA catchments dataset. The River Network Quinary Catchments was developed using the Shuttle Radar Topography Mission (SRTM) 90 m DEM, thus the boundaries match the new Quaternary Catchment (SLIM, 2014b) boundaries fairly well, but do not match exactly and would need to be adjusted. Unfortunately, the River Network Quinary Catchments does not take large dams into account and – more importantly – a superficial investigation showed that it was not topologically “clean” from a geographic information system (GIS) point of view. It was thus not fit for use in this study. Geographic information system tools exist to delineate catchments using a DEM and user-defined pour points. However, this can be difficult to automate over large areas.

In this study, a brief investigation was conducted into some potential methods of subdividing catchments into smaller homogeneous subregions that are not hydrological subcatchments using the upper uThukela catchment as an example. Variability in land cover/use is already taken into account in the methodology through land cover/use-based HRUs. Variability in soils is also considered to some extent by determining the dominant soil type per HRU. The main source of concern is to try and represent variability in climate drivers such as rainfall, evaporative demand and air temperature in cases where these vary significantly within a catchment. These subdivisions could be used as an alternative to sub-quaternary catchments or, where necessary, to further subdivide sub-quaternary catchments, such as along the Drakensberg Escarpment where the altitude can change by 1,000 m within a few kilometres. A few approaches are briefly discussed in the following sections. The objective would be for the subdivisions to create more biophysically homogeneous regions, and for the regions to be well defined contiguous regions within a catchment, avoiding too much fragmentation of the catchment. The outcome of this investigation is discussed in Section 0.

2.3.1 Köppen climate zones

The Köppen climate zones for South Africa, described in Schulze et al. (2008a) and shown in Figure 2-22, were briefly investigated. However, as can be seen in Figure 2-22, these climate zones are spatially quite coarse and thus not suitable for subdividing quaternary catchments.

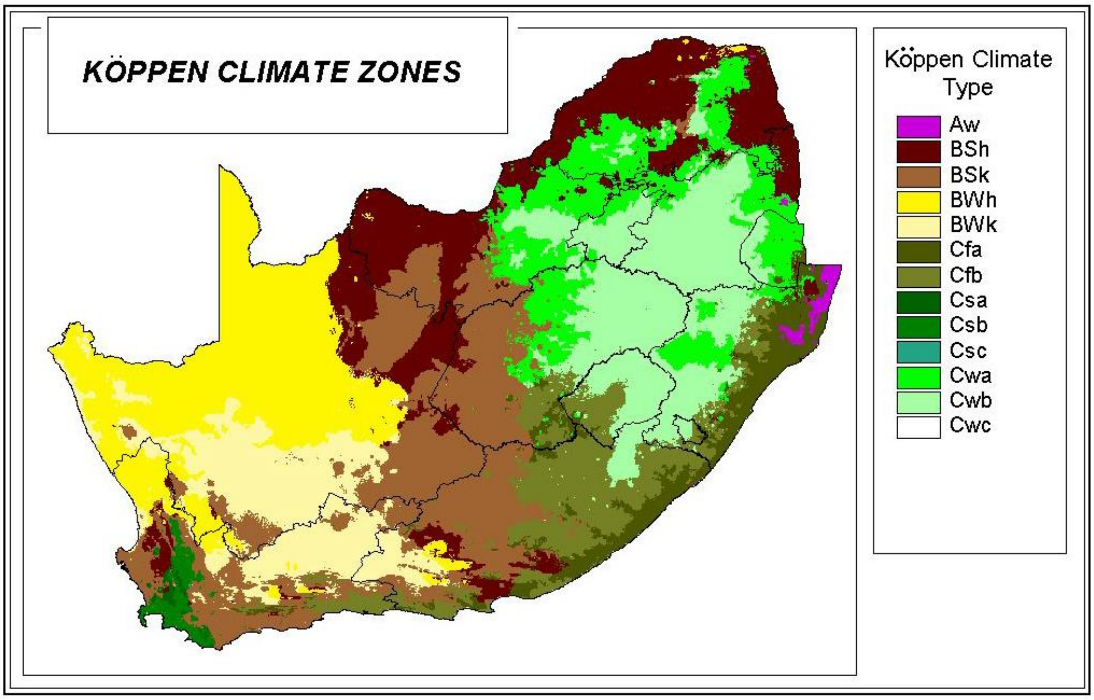

Figure 2-22: Köppen climate zones for South Africa (Schulze et al., 2008a)

2.3.2 Altitudinal breaks

A simple method of creating altitude-based regions within quaternary catchments would be to use a fixed altitude range, for example 200 m, as shown in Figure 2-23. Some advantages of this method are that it would be easy to apply, the number of altitude regions would vary between catchments depending on the range of altitudes within each quaternary catchment, and the altitude bands in adjacent quaternary catchments would be contiguous at the catchment boundaries. A disadvantage of this method is that the selected altitude range may be suitable for one part of a study catchment where there is a rapid change in altitude, but unsuitable for another part of a study catchment that is relatively flat, resulting in arbitrary regions being created purely because of the selected altitude range.

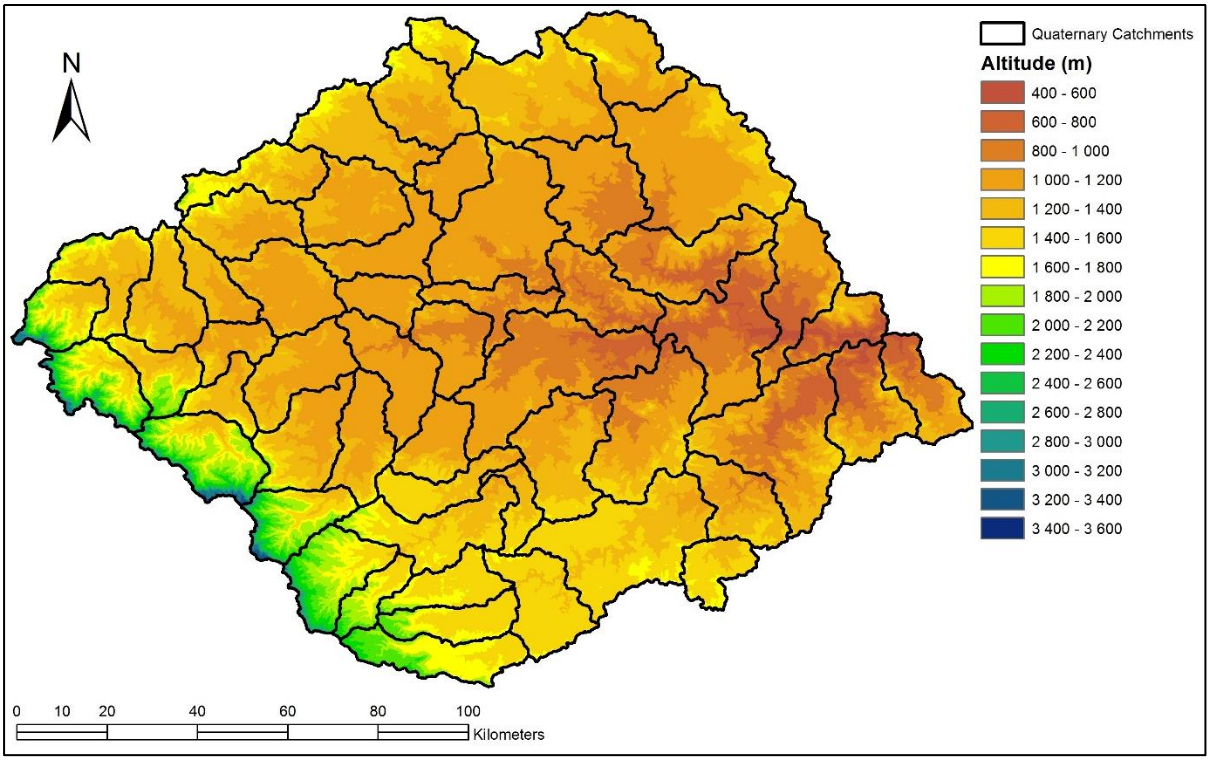

Figure 2-23: The DEM altitudes in 200 m bands for the upper uThukela catchment (after Weepener et al., 2011e)

A better approach is that described by Schulze and Horan (2010), in which each quaternary catchment is divided into three regions (upper, middle and lower) based on natural breaks in altitude using Jenks' optimisation, as shown for the upper uThukela catchment in Figure 2-24. These quaternary catchment subdivisions are referred to as "quinary catchments", although they are not strictly catchments, and will be referred to here as "altitude regions". It is important to note that, within each quaternary catchment, each altitude region may consist of more than one polygon, especially in the upper region. The general assumptions made with regard to surface flows are that, within a quaternary catchment, the upper region flows into the middle region, which flows into the lower region, which flows into the lower region of the downstream quaternary catchment. This approach makes sense based on the reasonable assumption that variability in climate within a catchment is closely related to altitude. This dataset, developed by Schulze and Horan (2010), is potentially useful for defining more homogeneous climate subregions. One potential disadvantage of this approach is that the altitude regions in adjacent quaternary catchments are not contiguous at the catchment boundaries. The polygon boundaries in this dataset are not compatible with the new quaternary catchment boundaries of the DWS, and so would need to be adjusted to fit these new catchment boundaries. This approach has some merit, although it is proposed that a variable number of altitudinal subdivisions be derived for each catchment, in terms of Jenks' optimisation of the number of subdivisions, so that catchments with a large altitudinal range have more subdivisions than catchments with a small altitudinal range, and the altitudinal subdivisions be used in a hydrological model configuration as subregions within a catchment, particularly as more homogeneous climatic regions, rather than as interlinked "subcatchments" – as is done in Schulze and Horan (2010).

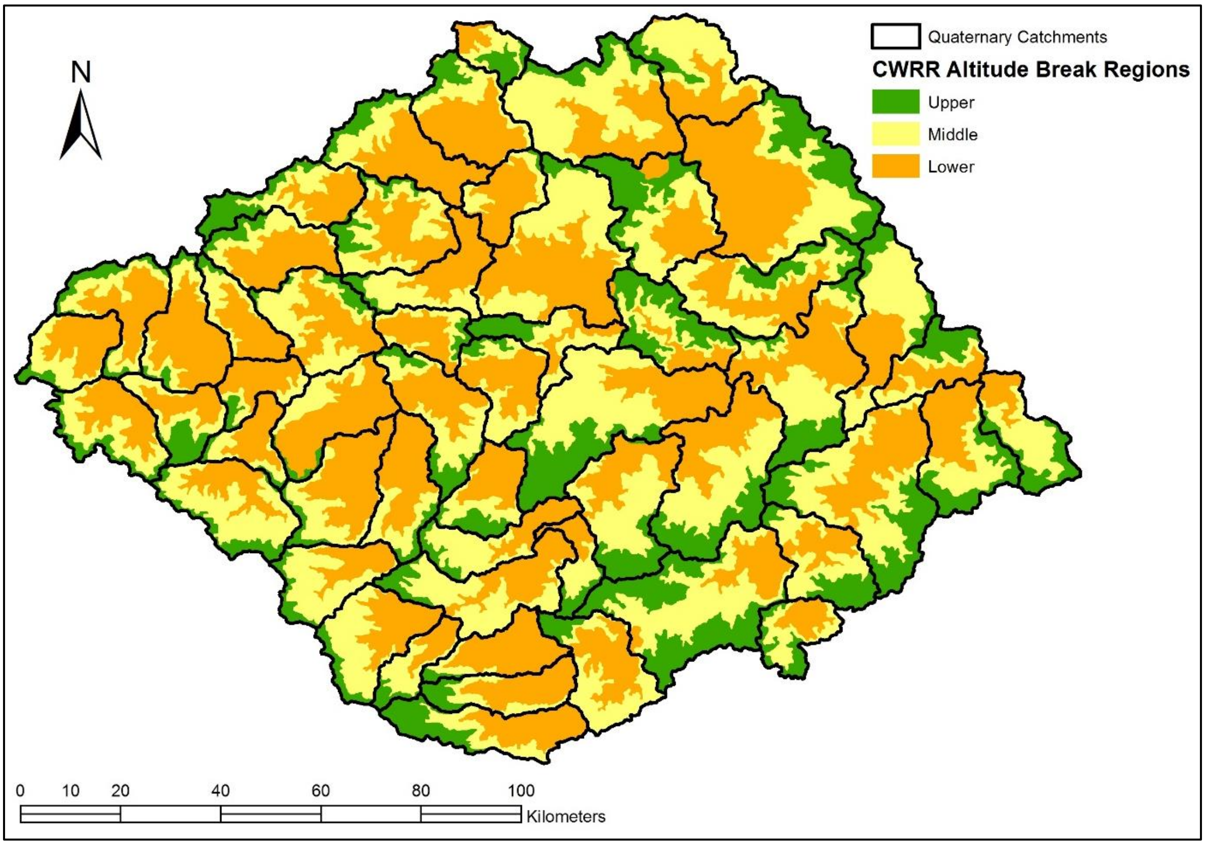

Figure 2-24: Sub-quaternary regions for the upper uThukela catchment based on natural breaks in altitude (after Schulze and Horan, 2010)

2.3.3 The DEM base indexes

Lastly, two indexes, calculated using altitude data from the 90 m DEM (Weepener et al., 2011e), were investigated. These indexes were calculated using the Geospatial Data Abstraction Library (GDAL) tool called *gdaldem* [http://www.gdal.org/gdaldem.html]. The Topographic Position Index (TPI) is defined as "the difference between a central pixel and the mean of its surrounding cells", and is shown in Figure 2-25. For the TPI, positive values indicate ridges, negative values indicate valleys, and values near zero indicate flat areas or areas with constant slope. The selection of thresholds within the continuous TPI values for a specific catchment enables landscapes to be divided into discrete slope position classes, such as the crest, upper slope, mid-slope, lower slope and valley bottom. In this investigation, just three classes were created, as the scale of the study catchment is relatively large. As can be seen in Figure 2-25, the quaternary catchments along the Drakensberg Escarpment in the southwest have a high concentration of blue and red pixels, representing prominent ridges and valley. The yellow pixels indicate regions that are flat or have a relatively constant slope. Unfortunately, the TPI does not seem to be suitable for defining subregions for hydrological modelling within the relatively coarse quaternary catchments.

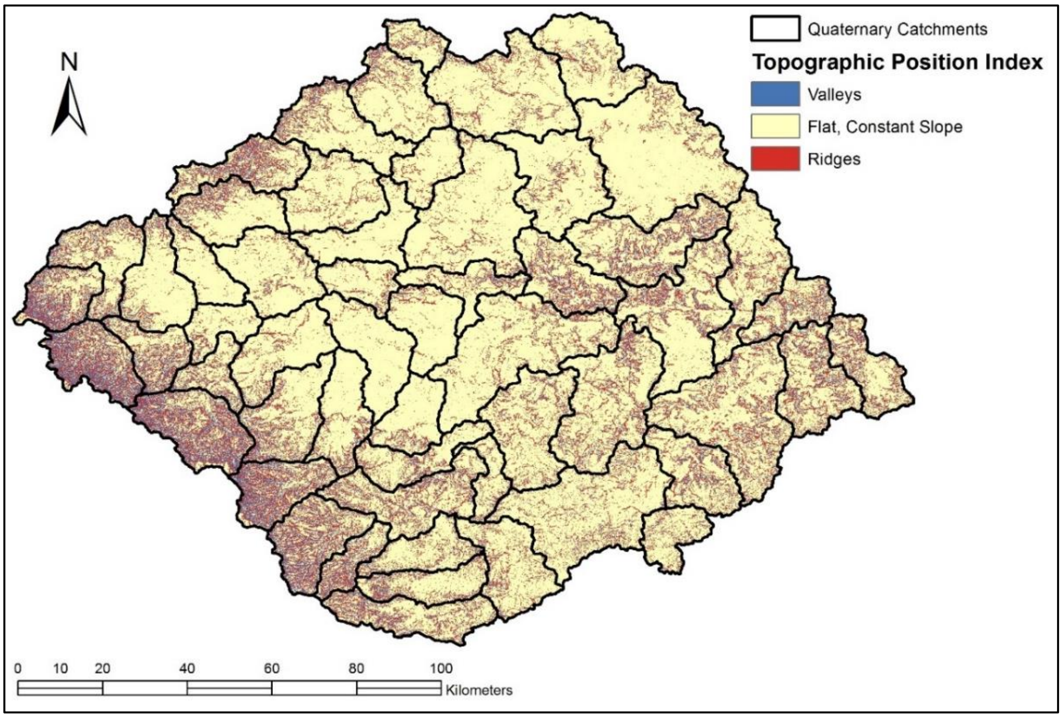

Figure 2-25: Topographic Position Index in the upper uThukela catchment

The Terrain Roughness Index (TRI) is defined as "the mean difference between a central pixel and its surrounding cells". It is shown in Figure 2-26. Again, for this investigation, just three TRI classes were created. The Jenks' optimisation option in the ArcMap software was used to determine the classes. As expected, high roughness values – shown in red – were calculated along the escarpment, with the yellow pixels showing less rough terrain in the foothills. The TRI seems to be slightly better suited to defining subregions within quaternary catchments than the TPI. However, the classes shown in Figure 2-26 still do not result in the type of well-defined contiguous regions required for the scale at which hydrological modelling is being done for this project.

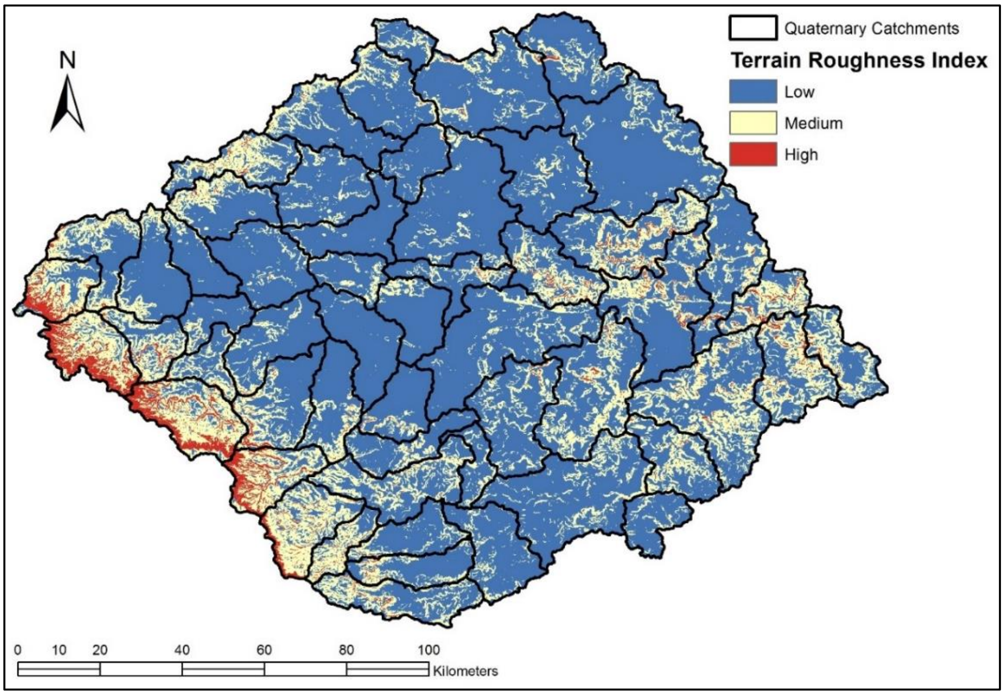

Figure 2-26: Terrain Roughness Index in the upper uThukela catchment

2.3.4 Vegetation types

Another approach would be to use a biophysical indicator such as natural vegetation as an indicator of suitable subregions in quaternary catchments, as the prevalence of natural vegetation types in different locations is often due to a combination of climatic, topographic, geological and other factors. The Acocks veld types (Acocks, 1988) are shown in Figure 2-27 and the more detailed veld types from the National Vegetation Map (SANBI, 2012) are shown in Figure 2-28. Both datasets show some clear visual relationships between veld types and altitude, for example, along the higher-altitude northwestern and southwestern sides of the upper uThukela catchment, and also in the lower-altitude central to eastern part of the catchment. There are fewer veld types in the Acocks dataset, which results in fewer polygons, representing larger and more contiguous regions, which would make it easier to use for the purpose of defining subregions, but may be less spatially accurate than the newer dataset of the South African National Biodiversity Institute (SANBI) (2012). In the SANBI (2012) dataset, some of the vegetation types cover relatively large regions, but these have internal polygons that represent vegetation types, such as Highveld alluvial vegetation, which exists in small scattered pockets across most of the study catchment. It would be necessary to merge these scattered vegetation types into the surrounding vegetation types to create more contiguous subregions.

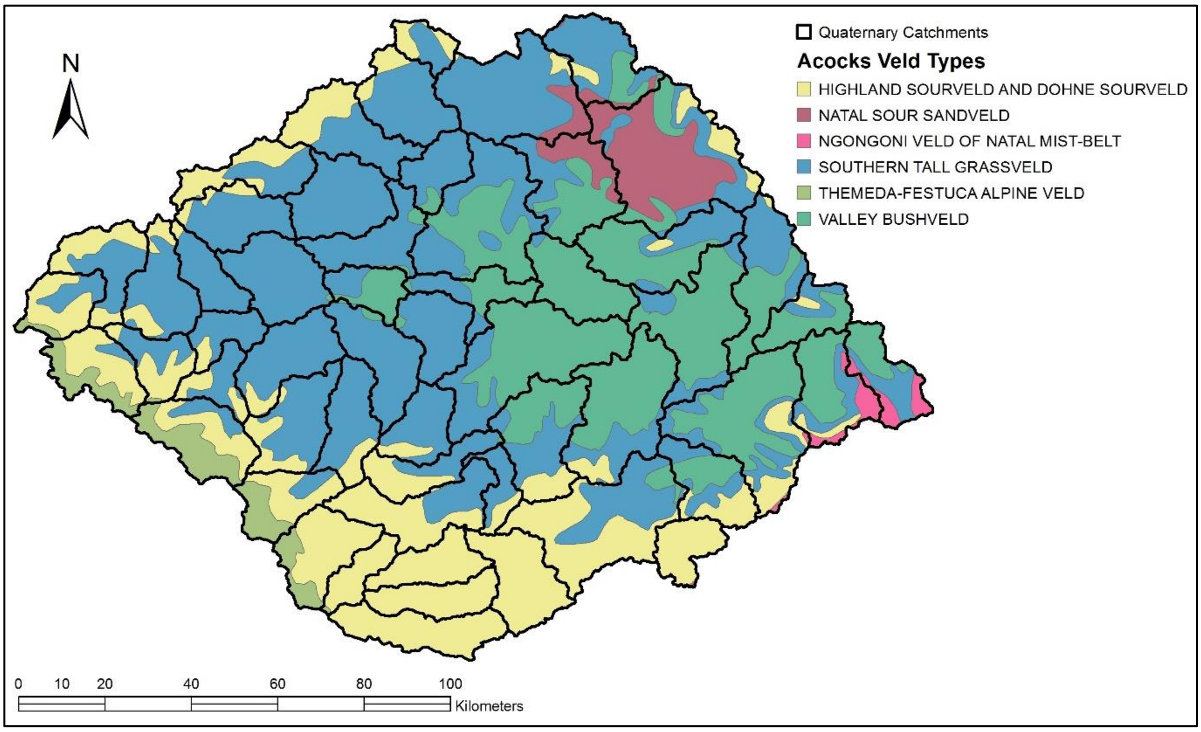

Figure 2-27: Acocks veld types in the upper uThukela catchment (after Acocks, 1988)

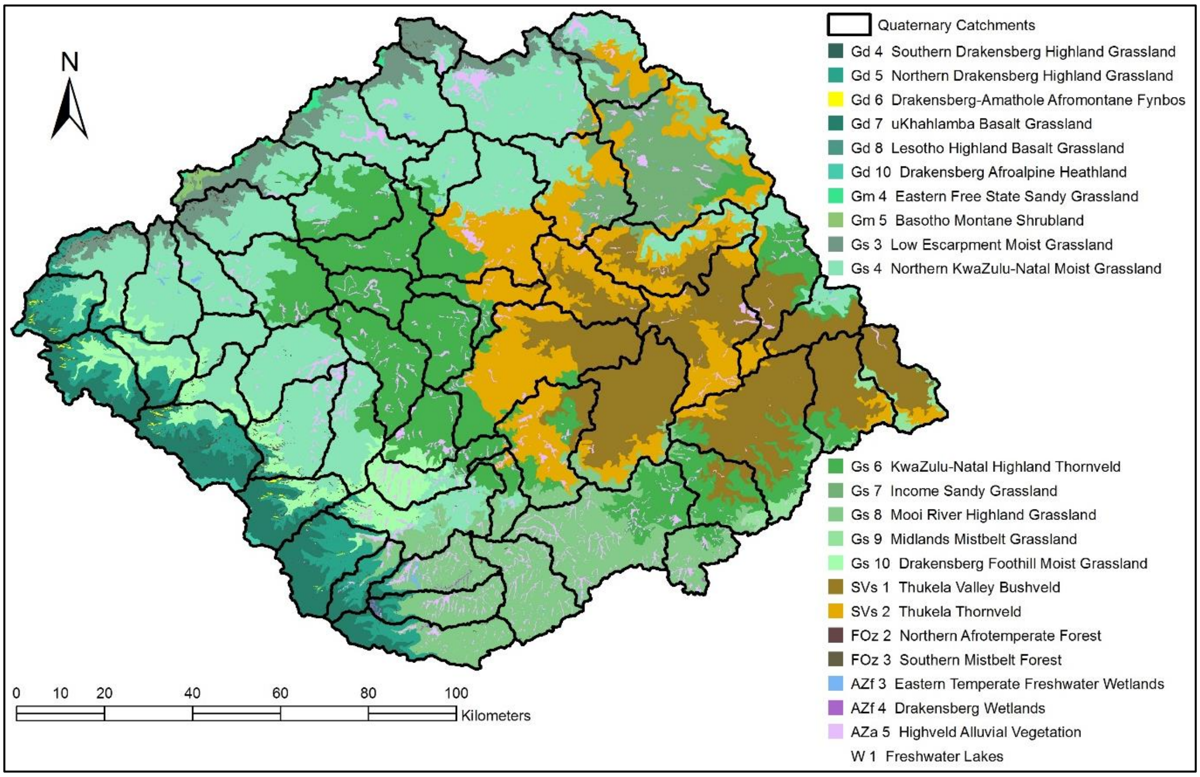

Figure 2-28: Natural vegetation types in the upper uThukela catchment (after SANBI, 2012)

2.3.5 Outcome

The division of quaternary catchments into subregions needs to carefully balanced between having smaller, more homogeneous regions and modelling at a spatial scale that matches the scale at which the data in the various datasets is available. Based on the investigation of potential methods for creating sub-quaternary catchments and response regions, as described briefly above, the following conclusions were made:

- For the purposes of this study, it was decided that the NFEPA catchments would be used, although some adjustments would be required, especially to take large dams and the new quaternary catchment boundaries into account. A potential advantage of using the NFEPA catchments could be that the water resource accounts would be compatible with the river ecosystem accounts described by Driver et al*.* (2015).
- Although there may be some merit in defining subregions within some sub-quaternary catchments in which there is a large range in altitude, based on natural breaks in altitude, the course resolution of the climatic data, especially rainfall, would mean that these subdivisions would not result in a better representation of the variability in climate. Finer-resolution climatic data, possibly through downscaling, would be required for the subregions to be meaningful.
- The use of natural vegetation types for defining subregions within sub-quaternary catchments has some merit due to the biophysical representation of climatic, topographic, geological and other factors. However, a disadvantage of this approach is that the spatial distribution of natural vegetation types changes over time due to climate change, for example.
- The TPI and TRI methods are not suitable for the scale at which hydrological modelling is being done for the purpose of producing catchment-scale water resource accounts in this study as the subregions are not well-defined contiguous regions, such as those based on natural breaks in altitude.

2.4 LAND COVER DATASETS AND CLASSES

Land cover and land use are key characteristics of a catchment with regard to water use, especially evaporation, and other hydrological processes, such as runoff and groundwater recharge. The land cover/use within even a sub-quaternary catchment is heterogeneous, dynamic and can have a significant effect on the hydrology within a catchment. Recent and detailed datasets of actual land cover are thus required to model sectoral water use. At the start of the earlier project, WRC Project K5/2205 (Clark, 2015a), the most recent and most comprehensive national dataset of actual land cover/use was the NLC 2000 dataset (ARC and CSIR, 2005; Van den Berg et al., 2008). It included 49 land cover/use classes. In WRC Project K5/2205, more recent local land cover/use datasets were available for the two case study catchments. For the uMngeni case study, the 2011 dataset (Ezemvelo KZN Wildlife and GeoTerraImage, 2013) was used, which had a resolution of 20 m and 47 land cover/use classes. For the Sabie-Sand case study, the 2.5 m resolution Inkomati Catchment Management Agency (ICMA) (2012a) cover/use dataset was used, in which specific crop types were identified. GeoTerraImage (Pty) Ltd (GTI) subsequently developed an updated national dataset of actual land cover for 2013/14 (NLC 2013-2014) for the Department of Environmental Affairs (DEA) (DEA and GTI, 2015; GTI, 2015). The NLC 2013-2014 dataset is a raster dataset with a 30 m resolution, which includes 72 land cover/use classes. This new NLC 2013-2014 dataset was only made available towards the end of WRC Project K5/2205 and was thus not evaluated. The NLC 2013-2014 dataset was applied in this study, as described in Section 0. Agricultural land use can have a significant influence on water resources in a catchment, but in most land cover/use datasets, it is represented by very broad classes such as "commercial dryland agriculture" and "commercial irrigated agriculture". For hydrological modelling purposes, this requires some assumptions to be made regarding the actual crop type. The impact of these assumptions was investigated, as briefly described in Section 0. Some changes and additions to the database of land cover/use classes used for the hydrological modelling are described in Section 0.

2.4.1 Application of the 2013/2014 national land cover/use dataset for South Africa

As discussed in Clark (2015a), land cover datasets are compiled for different purposes by different people and organisations. Thus, the classification system that is used varies. For this reason, some form of standard classification of land cover/use is required. A water use quantification and accounting methodology can then be applied to whichever land cover/use classification is used for the best available land cover/use dataset available for a study catchment. The use of a standard classification also makes it easier to compare results from studies for different time periods or for different catchments. For each land cover/use dataset, it would be necessary to map each of the dataset classes to one of the standard classes, but having done that, a consistent methodology for quantifying water use can be applied. The development of a hierarchical system of standard land cover/use classes, for use in water use quantification and accounting methodology, is described in Clark (2015a).

This system includes the following:

- A lookup file for the standard land cover/use class hierarchy
- A database of the standard land cover/use classes that contain a set of hydrological modelling variable values for each class
- A set of mapping files relating land cover/use dataset classes to the standard land cover/use classes

The 2013/14 national land cover/use raster dataset (NLC 2013-2014) for South Africa (DEA and GTI, 2015) was investigated for use as part of this water accounting methodology. The 72 classes used in the NLC 2013-2014 dataset are shown in Table 2-21. In this study, a mapping file relating the NLC 2013-2014 land cover/use dataset classes to the standard land cover/use classes was created as shown in Appendix A.

In NLC 2013-2014 (DEA and GTI, 2015), waterbodies are represented by two classes: water seasonal and water permanent. This provides more information than NLC 2000 (ARC and CSIR, 2005), which had a single class: waterbodies, but less information than the KwaZulu-Natal 2011 (Ezemvelo KZN Wildlife and GeoTerraImage, 2013) and ICMA 2010 (ICMA, 2012b) datasets, which have classes differentiating between artificial water bodies (i.e. dams) and one or more types of natural water bodies. For the purposes of this study, the water permanent class was assumed to be dams of various sizes, and the water seasonal class was assumed to be associated with river reaches and wetlands, such as that just north of Brandvlei Dam, and was modelled as a very shallow dam.

The NLC 2013-2014 classes that represent natural vegetation are similar to the few broad classes used in the other land cover/use datasets. As described in Clark (2015a), the natural vegetation classes are mapped to a single standard vegetation class and the ACRU model is configured using the relevant Acocks veld type (Acocks, 1988) for the catchment. However, unlike the NLC 2000 and KwaZulu-Natal 2011 datasets, the NLC 2013-2014 does not include any classes that represent degraded natural vegetation. This means that the effect of land cover degradation cannot be represented in the hydrological modelling or in the water accounts.

Table 2-21: Classes of the 2013/14 national land cover/use raster dataset for South Africa (DEA and GTI, 2015)

ID	Description
0.	Missing data
1.	Water seasonal
2.	Water permanent
3.	Wetlands
4.	Indigenous forest
5.	Thicket/dense bush
6.	Woodland/open bush
7.	Grassland
8.	Shrubland fynbos
9.	Low shrubland
10.	Cultivated commercial fields (high)
11.	Cultivated commercial fields (medium)
12.	Cultivated commercial fields (low)
13.	Cultivated commercial pivots (high)
14.	Cultivated commercial pivots (medium)
15.	Cultivated commercial pivots (low)
16.	Cultivated orchards (high)
17.	Cultivated orchards (medium)
18.	Cultivated orchards (low)
19.	Cultivated vines (high)
20.	Cultivated vines (medium)
21.	Cultivated vines (low)
22.	Cultivated permanent pineapple
23.	Cultivated subsistence (high)
24.	Cultivated subsistence (medium)
25.	Cultivated subsistence (low)
26.	Cultivated cane pivot – crop

ID	Description
37.	Mines water seasonal
38.	Mines water permanent
39.	Mine buildings
40.	Erosion (donga)
41.	Bare non-vegetated
42.	Urban commercial
43.	Urban industrial
44.	Urban informal (dense trees/bush)
45.	Urban informal (open trees/bush)
46.	Urban informal (low vegetation/grass)
47.	Urban informal (bare)
48.	Urban residential (dense trees/bush)
49.	Urban residential (open trees/bush)
50.	Urban residential (low vegetation/grass)
51.	Urban residential (bare)
52.	Urban school and sports ground
53.	Urban smallholding (dense trees/bush)
54.	Urban smallholding (open trees/bush)
55.	Urban smallholding (low vegetation/grass)
56.	Urban smallholding (bare)
57.	Urban sports and golf (dense tree/bush)
58.	Urban sports and golf (open tree/bush)
59.	Urban sports and golf (low vegetation/grass)
60.	Urban sports and golf (bare)
61.	Urban township (dense trees/bush)
62.	Urban township (open trees/bush)
63.	Urban township (low vegetation/grass)

ID	Description		ID	Description
27.	Cultivated cane pivot – fallow		64.	Urban township (bare)
28.	Cultivated cane commercial – crop		65.	Urban village (dense trees/bush)
29.	Cultivated cane commercial – fallow		66.	Urban village (open trees/bush)
30.	Cultivated cane emerging – crop		67.	Urban village (low vegetation/grass)
31.	Cultivated cane emerging – fallow		68.	Urban village (bare)
32.	Plantations/woodlots mature		69.	Urban built-up (dense trees/bush)
33.	Plantation/woodlots young		70.	Urban built-up (open trees/bush)
34.	Plantation/woodlots clearfelled		71.	Urban built-up (low vegetation/grass)
35.	Mines 1 bare		72.	Urban built-up (bare)
36.	Mines 2 semi-bare			

The classes that represent cultivated areas are similar to those used in the other datasets and are useful in differentiating between a number of broad categories of agricultural land uses that might have different hydrological characteristics and can be modelled accordingly. A few classes represent specific crop types, such as sugarcane, pineapples and vines. However, similar to the other datasets, with the exception of the ICMA 2010 dataset, many of the classes do not represent specific crops. Thus, as for the other datasets, annual dryland and irrigated field crops were assumed to be maize in the summer rainfall regions and wheat in the winter rainfall regions. A preliminary investigation by Reddy (2017) into the hydrological impact of this assumption was investigated, as briefly described in Section 0. Unlike the other datasets, the NLC 2013-2014 dataset subclassifies some of the cultivated classes into high, medium and low categories, related to biomass productivity, but the potential usefulness of these categories in determining crop seasonality or making better crop type assumptions needs to be investigated further. For the purpose of the upper and central Breede catchment case study, the three cultivated orchards classes were assumed to be deciduous fruit crops, but in other catchments, could potentially be other permanent crops such as citrus, stone fruit, nut trees, coffee, tea or even bananas. With regard to irrigation, the NLC 2013-2014 dataset seems to only identify cultivated areas under centre pivot-type irrigation and not cultivated areas under other types of irrigation. This means that all non-pivot-irrigated cultivated areas have to be assumed to be dryland, which could potentially mean that irrigation water use will be significantly underestimated in some regions. Other datasets that identify irrigated land are thus required. One such dataset is that developed by Van Niekerk et al. (2018). However, this dataset was only completed in 2018 and was thus unfortunately not available for application in the case studies described in chapters 0 to 0.

The classes that represent urban areas are similar to those used in the other datasets and are useful in differentiating between a number of broad categories of urban land use that might have different hydrological and water use characteristics and can be modelled accordingly. Unlike the other datasets, the NLC 2013-2014 dataset subclassifies many of the urban classes into dense trees/bush, open trees/bush, low vegetation grass and bare categories. For the other land cover/use datasets, in the absence of subclasses, each class was assigned an assumed proportion of pervious to impervious areas and the pervious areas were assumed to have natural vegetation to try and take typical vegetation types in different regions into account.

2.4.2 Irrigated crop types in the uMngeni catchment

An investigation into the use of spatial information on crop types in the DWS's WARMS database (Anderson et al., 2008) for use in hydrological modelling was the subject of a BSc (Hydrology) Honours project by Reddy (2017).

The national land cover datasets for South Africa include very broad classes that describe agricultural land cover and that differentiate between commercial and subsistence agriculture, dryland and irrigated agriculture, and annual and perennial crops. In the absence of information about which specific crop types exist within a catchment, assumptions are typically made based on these broad land cover/use classes. The study compared modelled hydrological variables such as evapotranspiration, surface runoff and baseflow for natural vegetation, and assumed irrigated crops and actual irrigated crops grown within a catchment. Information on actual irrigated crops grown in the uMngeni catchment was obtained from the WARMS database, although this database unfortunately only includes information for irrigated crops. The results showed that, in some instances, there was a significant difference between the modelled hydrological variables for natural vegetation and crops (assumed or actual), but that there was less difference between the modelled hydrological variables when comparing assumed and actual crop types. Further research needs to be done to identify other suitable sources of spatial crop type information.

2.4.3 Updates to the database of land cover/use classes

One of the most important components of the water use quantification and accounting methodology, described in Clark (2015a), was the development of a hierarchical system of land cover/use classes and an accompanying database of hydrological characteristics for each of these classes. The database of hydrological characteristics for land cover/use classes has been further developed in this study by adjusting the hydrological characteristics for a few classes, including soya beans, bananas, deciduous fruit and grapes, adding new classes for canola, sunflower, grain sorghum and lucerne, and assigning International Standard Industrial Classification (ISIC) codes to each relevant class in the dataset.

The SEEA-Water water accounting framework and the System of National Accounts (SNA) use the UN's ISIC system to classify economic activity (UN, 2012). The ISIC is described in detail in UN (2008). It is not a classification of industries, goods and services, but represents the type of production in which an industry engages (UN, 2012). A summary of the ISIC codes and economic activities that are relevant for water management is given in Table 2-22.

Table 2-22: Simplified ISIC codes and economic activities relevant to water management (after UN, 2011)

ISIC codes	Economic activity	Relevance for water policy and management
1-3	Agriculture, forestry and fishing	Most water is abstracted from inland water resources. It is important to distinguish "blue water", which is water abstracted from surface and groundwater sources, from "green water", which is abstracted from the soil.
5-33, 41-43 38, 39, 45-99	Manufacturing, mining and quarrying, construction and other industrial activities Service activities	These economic activities abstract water directly from inland water resources or through municipal water networks (ISIC-36). They are important contributors to waterborne emissions.
35	Electric power generation, transmission and distribution	These require large quantities of water and can be divided into non-consumptive use for hydroelectricity, and other types of generation where there is consumptive use for cooling.
36	Water collection, treatment and supply	This economic activity refers to water abstracted by public or private entities, possibly treated and supplied through mains to industries and households.
37	Sewerage, including the treatment of wastewater	This activity is often done in conjunction with ISIC 36. Sewage is collected through municipal networks, which may or may not treat the water in wastewater treatment facilities before returning it to the environment.

ISIC codes	Economic activity	Relevance for water policy and management
No code	Households as consumers	Households usually receive water from water utilities (ISIC-36) and return wastewater through sewerage utilities (ISIC 37).

An ISIC code has been assigned for each of the agricultural, forestry and mining classes in the database of hydrological characteristics for land cover/use classes. The relevant land cover/use classes and the ISIC codes assigned to each of them are shown in Appendix 0. This is a useful first step towards possibly implementing the SEEA-Water water accounting framework in parallel to the WA+ water accounts for water resource accounting. However, the ISIC classification has an industry and economics focus. A more general classification that is more inclusive of environmental-type assets and services would also be useful.

2.4.4 SANBI's 2012 natural vegetation dataset

In most of the land cover/use datasets, natural vegetation is classified as either natural vegetation or degraded natural vegetation with a few very general classes for each. In the earlier study (WRC Project K5/2205), the Acocks veld types (Acocks, 1988), together with hydrological modelling parameters assigned to these types by Schulze (2004), were used to model the spatial distribution and hydrology on naturally vegetated areas. The more recent and more detailed SANBI (2012) map of natural vegetation types offers better spatial representation, but a similar set of hydrological modelling parameters for these vegetation types is not available. The current WRC Project K5/2437, "Resetting the baseline land cover against which streamflow reduction activities and the hydrological impacts of land use change are assessed", will, as one of its outcomes, develop a set of hydrological modelling parameters for the SANBI (2012) natural vegetation types. As WRC Project K5/2437 is still in progress, it has not been possible to apply the SANBI (2012) map of natural vegetation types in this study as intended, and the Acocks veld types were thus used.

2.5 BETTER REPRESENTATION OF DAMS

Dams can have a significant effect on the hydrology within a catchment due to their regulatory effect on water flows and due to the evaporation from their open water surfaces. In addition to the large dams that are built to provide a secure water supply to urban areas, many catchments may also have a large number of smaller farm dams of various sizes that are used for irrigation, stock watering and recreational fishing. These smaller dams can also have a significant effect on the hydrology within a catchment (Maaren and Moolman, 1985; Tarboton and Schulze, 1990; Sawunyama et al., 2006), but are often overlooked as part of water resource systems (Sawunyama et al., 2006). However, the lack of good datasets characterising these dams, and the need to simplify the representation of these dams for modelling purposes, provided challenges for the configuration of the model and for the simulations. When configuring the ACRU hydrological model for the three case study catchments, it became increasingly apparent that a better representation of dams, and small farm dams in particular, was necessary. For this purpose, a comparison of datasets that contain information about the location and size of dams was performed as described in Section 0. Improvements made to the water use quantification and accounting methodology regarding the representation of dams in the hydrological model are then discussed in Section 0 to Section 0.

2.5.1 Comparison of dam datasets

In the two case studies described in Clark (2015a), the Database of Registered Dams (DSO, 2014), obtained from the DWS's Dam Safety Office (DSO), was used. For dams, the ACRU model requires the full surface area and storage capacity as inputs, as well as information describing the area-to-volume relationship for the dam basin.

A closer look at the DWS's DSO database of registered dams for use in the upper uMngeni catchment (quaternary catchments U20A, U20B, U20C, U20D and U20E) raised some concerns regarding the accuracy of the area and storage capacity data for some dams. For example, this database states that Surrey Dam (U201/94) in quaternary catchment U20B has a volume of 3,000,000 m^3, but a surface area of just 10 ha. These concerns led to a small investigation in which three datasets, containing information about dams, were compared: the DWS's DSO database (DSO, 2014), the DWS's WARMS database (Anderson et al., 2008) and the 1:50,000 topographic maps from the Surveyor-General. It should be noted that, for this comparison, a 2014 version of the DWS's DSO database and a 2014 version of the DWS's WARMS database were used, although, subsequent to this investigation, it was noted that a 2016 version of the DWS's DSO database was available. The project team is also aware that DWS has been busy with a validation and verification exercise to improve the integrity of the WARMS database. The version of the 1:50,000 topographic maps is not known, but it is estimated to be approximately 2003, so it may not include dams built in the last 15 years or more, and there may be a few dams that have been extended since the release of the version of the database used here. Unfortunately, all three datasets use a different system of identification numbers, which makes it difficult to compare dam records between datasets. The text names in the DSO and WARMS databases helped to some extent, but even then there were often differences in spelling.

The purpose of this investigation was not to try and identify the best dataset to use as the study area was small, but rather to get a better understanding of how similar or different these databases were and how they might potentially be used in conjunction with each other to identify individual dams for which the data in one database may not be correct. It is understood that both the DSO and WARMS databases initially relied, to a large extent, on the submission of information on dam sizing from land owners or managers that may be based on rough estimates and not actual measurements in the case of smaller farm dams.

The DWS's DSO database (DSO, 2014) contains a smaller subset of dams as it only includes dams that meet the requirements for registration, while the WARMS database, in addition, includes many more smaller dams that do not meet the requirements for registration. Both the DSO and WARMS databases include the position of each dam by means of a latitude and a longitude position. These latitude and longitude positions were used to create a shapefile for each dataset. All three datasets were opened simultaneously in ArcMap. For each of the DSO's registered dams in the catchment, an attempt was made to identify the corresponding dam in the WARMS database and 1:50,000 topographic map dataset. Google Earth [https://www.google.com/earth/] was also used to help verify the location of dams. In some cases, the position and names of the dams made it easy to identify the corresponding dams, but in other cases, no corresponding dam could be found. A summary of this investigation is given in Table 2-23. Based on this investigation, the main concern is that there are many dams for which the location recorded in the DSO and WARMS databases is incorrect. Incorrectly recorded locations for dams is a problem for hydrological modelling as these dams may incorrectly be modelled in the wrong catchment. Another concern is that, from the 1:50,000 topographic map datasets and Google Earth, there appear to be many dams with a large surface area that do not appear in either the DSO or WARMS databases, although the reason for this is not clear.

Table 2-23: Summary of corresponding dams in the upper uMngeni catchment

Description	Number of dams
Total number of DSO-registered dams in the upper uMngeni catchment	103
Number of corresponding dams found in the WARMS dataset	58
Number of corresponding dams found in the 1:50,000 topographic map dataset	63

Description	Number of dams
Number of corresponding dams found in both the WARMS database and in the 1:50,000 topographic map dataset	47
Number of DSO-registered dams for which no corresponding dam could be found in either the WARMS or 1:50,000 topographic map dataset.	29
Of these:	
- The number of dams for which a corresponding dam was found in Google Earth based on location	7
- The number of dams for which two or more possible corresponding dams were found in Google Earth based on location	7
- The number of dams for which no corresponding dam could be found in Google Earth based on location	15

The dam size attributes were compared for the 47 dams for which corresponding records could be found in all three datasets. The dams' full surface areas were compared for all three datasets, as shown in Figure 2-29, with the dams being sorted based on the surface area specified in the DSO dataset. There are a few instances where there appears to be an error in the recorded area of a DSO dam as the other two datasets show a much bigger or smaller area value. One error, that is not very clear in Figure 2-29, is for Midmar Dam (the second record from the right), where the area for both the WARMS and the 1:50,000 topographic map datasets is the old area before the dam wall was raised in about 2002. Dams' full storage volumes were compared for the DSO and WARMS datasets, as shown in Figure 2-30, with the dams being sorted based on the volume specified in the DSO dataset. The 1:50,000 topographic map dataset does not have a dam volume attribute. The comparison of volume values from the DSO and WARMS databases also highlights several records that should be investigated further. In the case of volume, there is not a third data value to indicate which dataset may contain the more correct value. An equation that represents a generic surface area-to-volume relationship, such as that of Maaren and Moolman (1985), could be used to help identify records for which the recorded volume may be incorrect, assuming that the recorded area is correct.

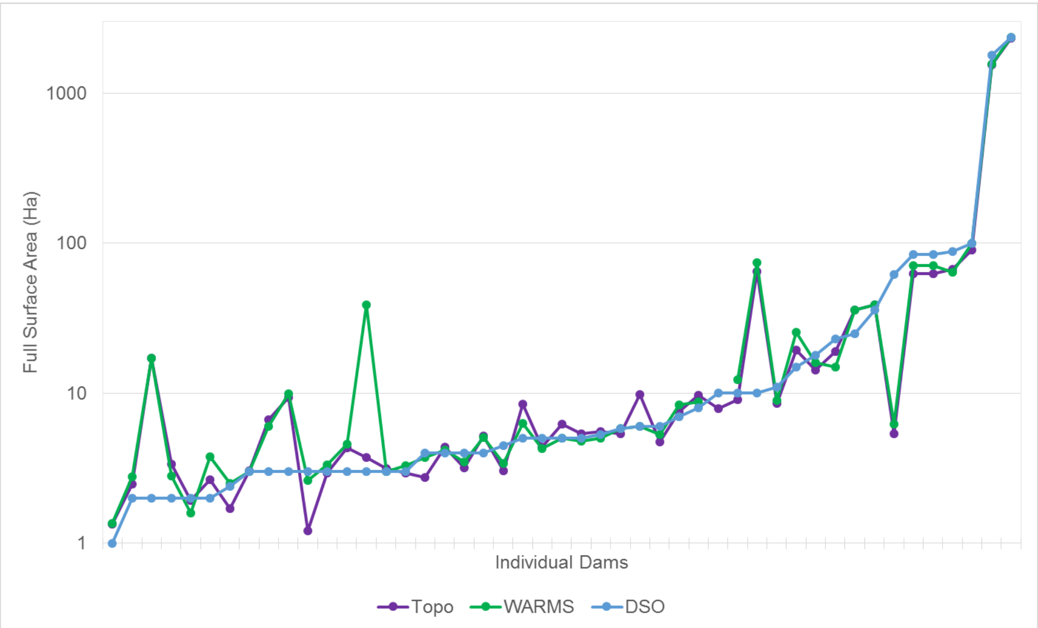

Figure 2-29: Comparison of dams' full surface areas (ha) for the DSO, WARMS and 1:50,000 topographic map datasets (in DSO dataset area order)

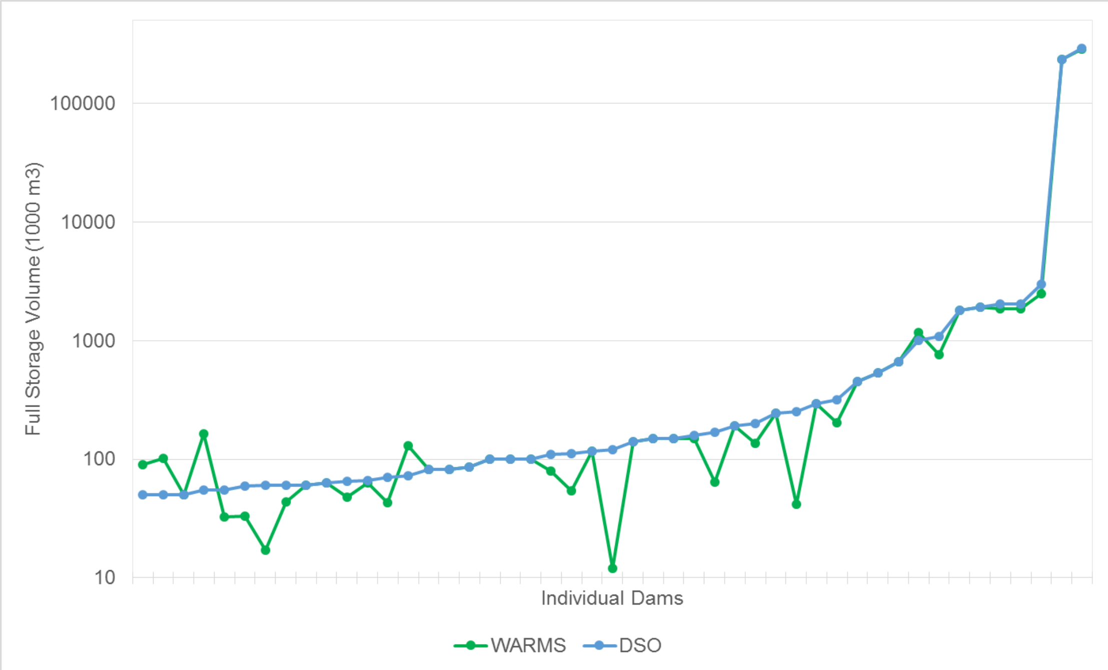

Figure 2-30: Comparison of dams' full storage volume (x 1,000 m^3) for the DSO and WARMS datasets (in DSO dataset volume order)

The results of this investigation indicate that both the DSO and WARMS datasets contain some incorrect records and should be checked and corrected before use. However, the lack of a reliable identifier of individual dams that is common to all three datasets makes cross-checking difficult. It is suggested that the dam areas be cross-checked using all three datasets. Once any incorrect areas have been corrected, the volumes can be cross-checked using the equation of Maaren and Moolman (1985).

2.5.2 Improved estimate of the volume and area of small farm dams

The land cover/use datasets usually include at least one class, which represents waterbodies and may even have a specific class representing dams, thus providing an estimate of the total surface area of dams within a catchment. As explained in Clark (2015a), a simple way to estimate the total dam volume is to use an equation, such as Equation 2.1 (Maaren and Moolman, 1985), which represents a generic surface area-to-volume relationship. As explained by Clark (2015a), some disadvantages of this method are that an accurate estimate of the surface area of small farm dams is difficult due to the relatively coarse resolution of the land cover/use datasets relative to the size of the dams; the water surface area of dams changes seasonally and the full surface area may not be accurately estimated depending on when the imagery used for the land cover/use dataset was captured; all dams are represented as one lumped dam per sub-quaternary catchment; and the generic surface area-to-volume relationship may not give an accurate estimate of total dam storage volume when applied to the combined total surface area of a number of smaller dams.

$$A = 7.2\,S_v^{\,0.77} \qquad \textbf{(2.1)}$$

where:

A = surface area (m^2)

S_v = storage volume (m^3)

In the earlier study (WRC Project K5/2205), a methodology was developed to estimate the volume and area of dams within a catchment as described in Clark (2015a). The DWS's DSO database of registered dams (DSO, 2014) was used in conjunction with the land cover/use datasets.

The DSO (2014) database was selected as it represents all dams of a significant size, including those with a storage capacity of more than 50,000 m^3, and excluding only very small dams. It includes surface area, volume and other useful information, seems to be updated regularly, and is freely available. However, the only spatial information associated with the dataset is the latitude and longitude of each dam. The location of the dams needs to be checked against other sources such as Google Earth [http://earth.google.com] and the 1:50,000 topological maps available from the Surveyor-General. The location of dams at the exit of catchments needs to be checked to make sure that the point feature that represents the dam is located in the correct sub-quaternary catchment and not in the downstream catchment. The volumes and surface areas were summed for all the registered dams within a catchment and a lumped registered dam was modelled at the exit of each catchment in which one or more registered dams existed. The surface area of the lumped registered dam in each catchment was compared to the estimated total dam area in each catchment from the land cover/use dataset, and if smaller than the total land cover/use area, the additional area was assumed to be the total area of small farm dams. The total volume of the small farm dams was then calculated using Equation 2.1. These lumped small farm dams were assumed to receive all the runoff from within a catchment, but not inflows from upstream catchments.

In this project, further evaluation of the simulated daily streamflows for the uMngeni catchment indicated that the volume of the small farm dams was potentially being overestimated, resulting in excessive attenuation of flows to downstream catchments. This led to an investigation into a method for estimating the individual areas and volumes of small farm dams (unregistered dams).

The following methodology was developed and tested:

- For each catchment, the land cover/use raster dataset was clipped to the boundary of the catchment.
- The clipped catchment land cover/use raster dataset was then masked to create a raster dataset of dams only.
- The clipped raster of catchment dams was then polygonised to create a vector dataset of dams for the catchment.
- For each dam polygon within the new polygonised vector dataset of catchment dams, the area and the corresponding dam volume were calculated using Equation 2.1.
- The lists of registered dams and the polygonised vector dataset of catchment dams were each sorted from largest to smallest.
- Then, assuming that the dams in the top portion of the list of the polygonised vector dataset of catchment dams corresponded to the list of registered dams, the lower portion of the list of the polygonised vector datasets of catchment dams was assumed to represent the list of small farm dams in the catchment.
- For each catchment, the surface areas and volumes of each dam in the list of small farm dams were summed to create a lumped small farm dam.

This methodology was applied in the upper uMngeni catchment. The catchment and registered dams for the upper uMngeni catchment are shown in Figure 2-31. A graph comparing the old and new estimates of the volumes of the lumped small farm dams is given in Figure 2-32. This graph shows the effect of Equation 2.1 to calculate the volume of small farm dams from the lumped area, compared to calculating the volumes of individual farm dams and then summing them.

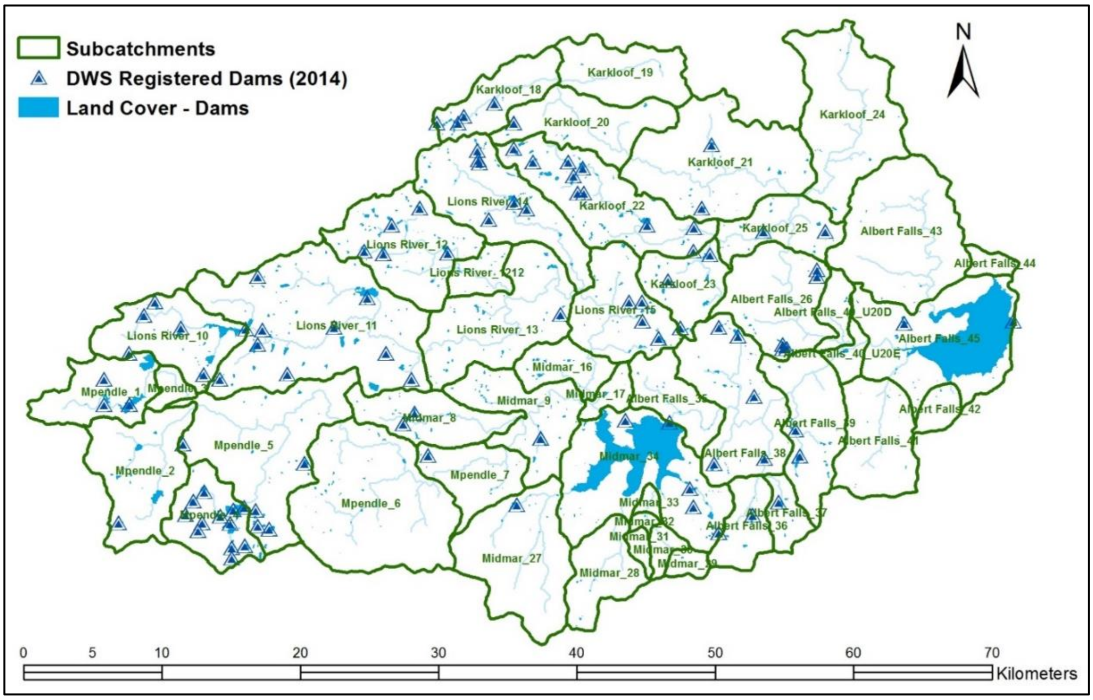

Figure 2-31: Location of dams in the upper uMngeni catchment

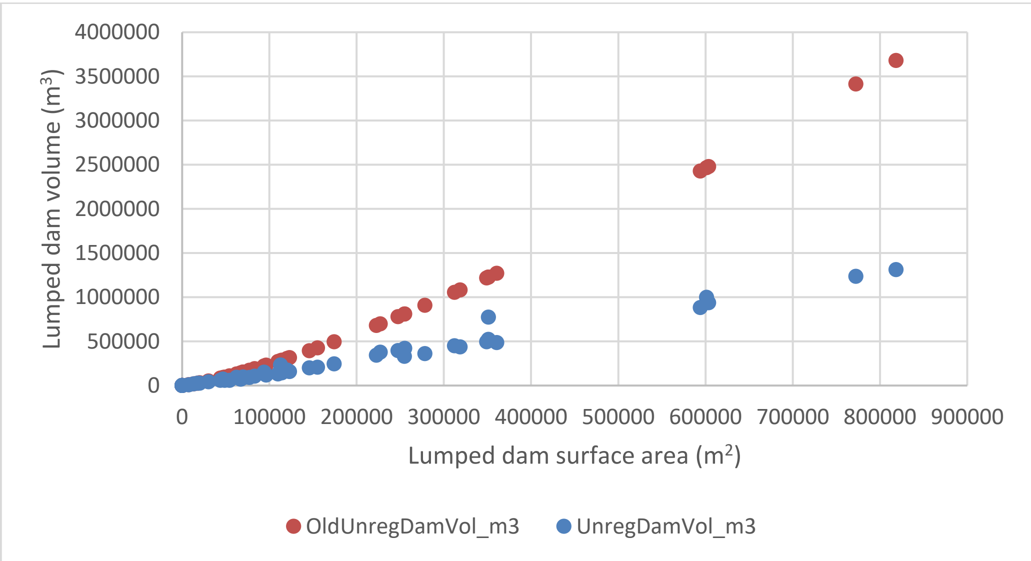

Figure 2-32: Comparison of old and new estimates of the volume of small farm dams

The ACRU model determines the surface area-to-volume relationship of dams using a power function of the form shown in $\boldsymbol{A_s = a'(S_v)^{b'}}$ (Schulze et al., 1995),

$$\boldsymbol{A_s = a'(S_v)^{b'}} \quad \textbf{(2.2)}$$

where:

A_s = surface area of water (m^2)
S_v = storage (volume of water (m^3)
a' = equation constant
b' = equation exponent

The constant and the exponent in $A_s = a'(S_v)^{b'}$ are determined using a survey of the dam basin. For large dams, the constant and the exponent can be derived from basin survey information available from DWS. For small dams, especially unregistered, small farm dams, this information is not available. It is often only the full surface area that is known. Even the full storage volume is not known. In this case, these model inputs are typically defaulted to the values derived by Maaren and Moolman (1985): a' = 7.2 and b' = 0.77. Full storage volume is then estimated using these values in $A_s = a'(S_v)^{b'}$, together with surface area. However, the DWS's database of registered dams, which is used as part of the methodology being developed in this project, contains estimates of both the full surface area and full storage volume of each dam. For these registered dams, the constant and exponent values in $A_s = a'(S_v)^{b'}$ were adjusted so that the area-to-volume curves fit through the full surface area and full storage volume of each dam.

2.5.3 Runoff contribution upstream and downstream of small farm dams

The quaternary catchments dataset generally has catchment boundaries that correspond to the downstream location of large dams. However, other relatively large dams, as well as new dams, may exist within the boundaries of quaternary catchments. When configuring ACRU and other hydrological models, sub-quaternary catchment boundaries would typically be created to correspond to these dams so that the runoff into them can be correctly estimated. However, in catchments such as the upper uMngeni catchment, there may be numerous small farm dams and it is not practical to represent and model the catchment areas of all these dams individually.

The following assumptions are made in modelling the dams in each catchment:

- Individual, large registered dams, above a user-specified threshold, are modelled as individual dams, which are assumed to be on the main river channel at the downstream exit of the catchment.
- All other registered dams are combined as a lumped registered dam by summing the individual surface areas and volumes, and are represented by a dam node that is assumed to be off the main river channel, unless specified as being on the main river channel.
- All the small farm dams (unregistered) are combined as a lumped farm dam by summing the individual surface areas and volumes. They are represented by a dam node that is assumed to be off the main river channel. These small farm dams impede runoff generated within a catchment, but are not assumed to be used for irrigation. These lumped small farm dams are assumed to flow into a lumped registered dam in their respective catchment, if there is one, or an individual large dam, if there is one; otherwise to a river node at the downstream exit of their respective catchments.
- For modelling purposes, these lumped small farm dams and the lumped registered dams that are not on the main channel were initially assumed to receive runoff from the whole catchment, but not flow from upstream catchments.
- All water users that abstract water within their catchment use the lumped registered dams on the main river channel in the same catchment as a water source, or if there are no registered dams, the water source is a river node immediately upstream of the downstream exit of the catchment.

In catchments such as the upper uMngeni, where there are numerous small farm dams, these dams are often widely distributed spatially within each subcatchment. The fourth assumption meant that the modelled lumped dam would receive more runoff and that the evaporation from the dam and its yield would be higher than it was in reality. If the dam is not full, it would impede all runoff from the catchment, affecting flows downstream. Thus, some means was required to estimate and represent the contributing catchment area for small farm dams within a catchment. For this purpose, some Python scripts were developed to estimate the contributing catchment area for small farm dams using a catchment boundary dataset, a land cover/use dataset and a DEM-based flow direction dataset.

This worked well for the land cover/use raster dataset for KwaZulu-Natal (Ezemvelo KZN Wildlife and GeoTerraImage, 2013), which has a class Water (dams). However, it did not work as well for the NLC 2013/14 national land cover/use raster dataset (DEA and GTI, 2015), which does not have a class specifically identifying dams. The NLC 2013/14 dataset has a more general class, Water permanent, which not only represents dams, but also sections of river reaches with well-defined permanent open water sections, for example. Thus, some manual processing was required to adjust the contributing catchment area in some catchments.

The value of applying these scripts is demonstrated in Figure 2-33 for the upper uMngeni catchment. In each catchment, the area shaded in light green is the area upstream of small dams, and the area shaded in olive green is the area downstream of small dams. Catchments that are mostly or completely shaded in light green would fit well with the fifth assumption. Catchments that have a large portion that is shaded olive green only have dams in the upper reaches of the catchment, and only intercept a portion of the runoff. The two large dams shown are Midmar Dam and Albert Falls Dam. These two dams were excluded from the analysis and are thus included in the area downstream of small farm dams. These upstream-to-downstream regions may be used in the process of determining land cover/use based on HRUs. For example, what would previously have been a single natural grassland HRU within a subcatchment will now be modelled as two natural grassland HRUs: one contributing runoff into the smaller farm dams and registered dams, and one contributing runoff downstream of these dams.

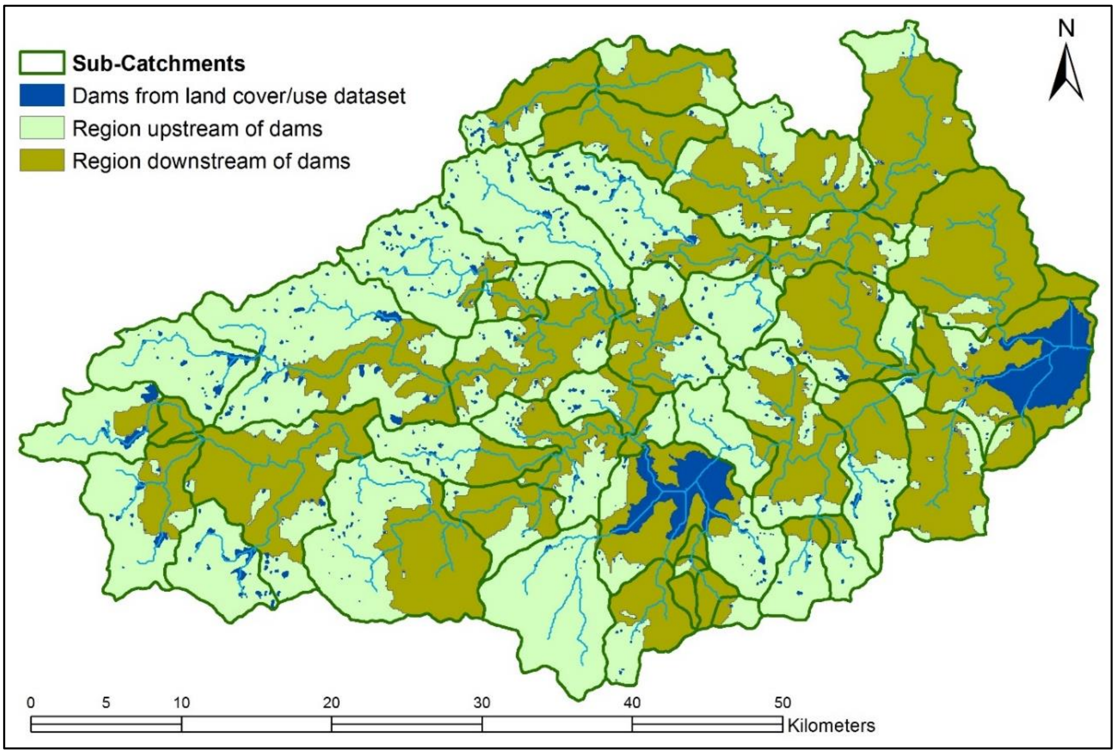

Figure 2-33: Areas upstream and downstream of dams in the upper uMngeni catchment

2.5.4 Modelling linked dams

The concept of primary, secondary, tertiary and quaternary catchments for South Africa, which is used by DWS, is very useful as a consistent, standardised set of catchment boundaries. However, there are a few instances where large dams have since been built and where the dam spans more than one catchment. This situation presents a problem when configuring a hydrological model, as runoff is typically calculated per catchment, but dams are represented as a single entity for the purpose of calculating variables such as surface area, stored volume, flow releases and spillway flows. The case study catchments selected for this project include two such cases.

In the upper uThukela catchment, the Woodstock Dam has its wall at the downstream exit of quaternary catchment V11D, but also floods up one of the tributaries into quaternary catchment V11E, as shown in Figure 2-34. In this instance, the problem was solved by simply merging the V11D and V11E quaternary catchments into a single catchment for modelling purposes, although this could potentially create a problem when aggregating catchment accounts for reporting purposes.

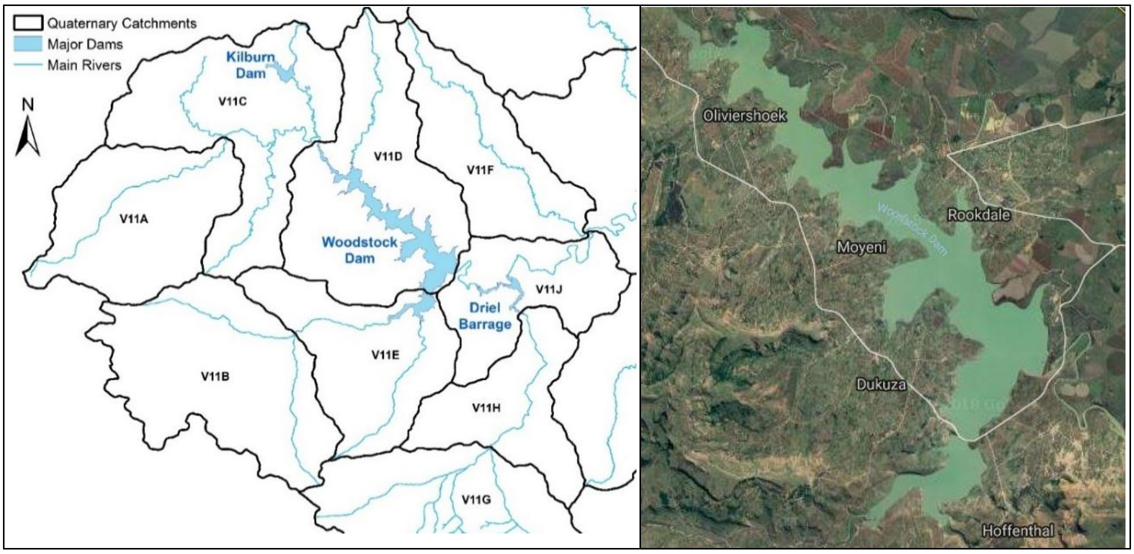

Figure 2-34: Woodstock Dam, spanning quaternary catchments V11D and V11E (Satellite image courtesy of Google Maps)

In the Breede catchment, the Greater Brandvlei Dam consists of two separate dams: Brandvlei Dam and Kwaggaskloof Dam, each with their own dam wall, in two separate secondary catchments, as shown in Figure 2-35. However, above a certain elevation, these dams are linked. This is a more complicated system to configure in the ACRU model than the situation with Woodstock Dam, as it is not practical to merge two secondary catchments for modelling purposes. The two dams need to be modelled as separate, yet related entities.

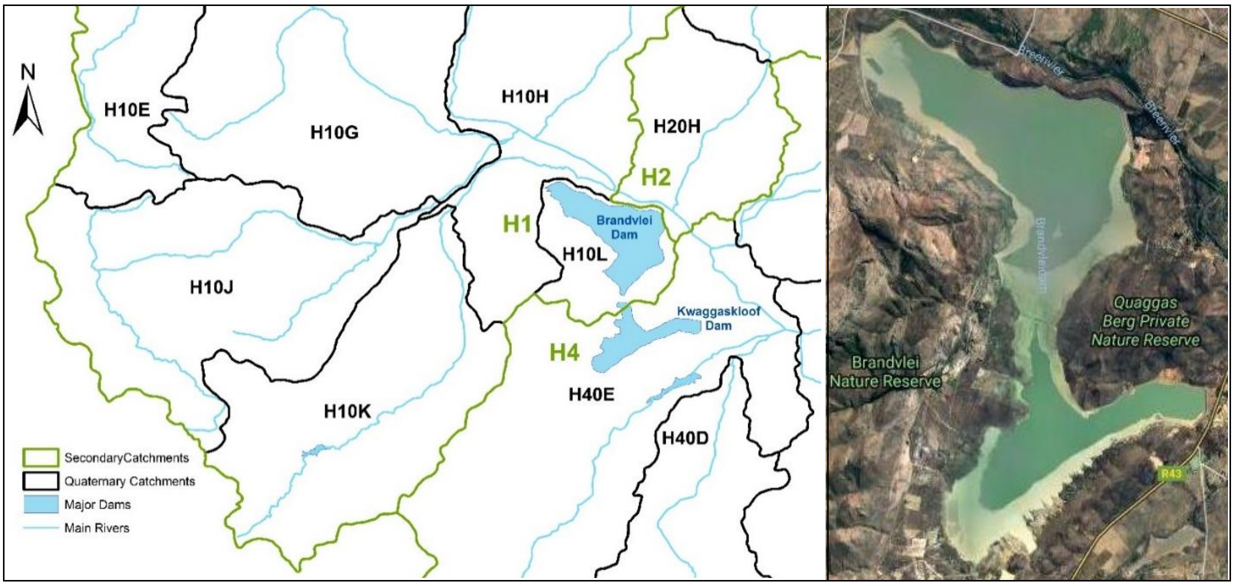

Figure 2-35: Linked Brandvlei and Kwaggaskloof dams in secondary catchments H1 and H4 (Satellite image courtesy of Google Maps)

This problem was resolved by developing a new process class called *PBalanceConnectedDams* for the ACRU model to exchange water between two connected dams to balance the upper water level. The ACRU model requires information specifying the area-to-volume (the surface area of the water for a given storage volume) relationship for each dam to be modelled. This enables evaporation from the dam, which is closely related to surface area, to be calculated. Water levels are not modelled and no model inputs that describe the level-to-volume relationship are required. However, to exchange water between connected dams, the levels need to be calculated and water transferred between dams until they have a common water level.

The levels were thus calculated by first deriving a level-to-volume relationship using the area-to-volume relationship. To derive the level-to-volume relationship, the surface area was calculated for a large number of small increments in volume, and the change in level was estimated for each increment by dividing the incremental volume by the average of the two surface areas before and after the increment in volume. At each daily time step in an ACRU model run, inflows and outflows of water (due to runoff, evaporation, abstractions, releases, etc.) occur for the separate dams, resulting in different dam levels. At the end of the time step, the levels are compared and water is transferred from the dam with the higher level to the dam with the lower level so that the dams end up with the same level. The conceptual diagrams, shown in Figure 2-36, describe how two dams may be linked. In the case of the Greater Brandvlei Dam, the situation is likely to be that shown in diagrams 1a and 1b, where a level will be reached when the direct flow of water from one dam will no longer occur, although there may be some seepage between the dams. In the case of Woodstock Dam, one of the dam basins will empty completely before direct flow between the sections of the dam ceases. For the purposes of the modelling, where the cut-off level between the dams may not be known, the situation shown in diagrams 2a and 2b, where one of the dam basins will empty completely before flow between the dams ceases, is used as a simplification.

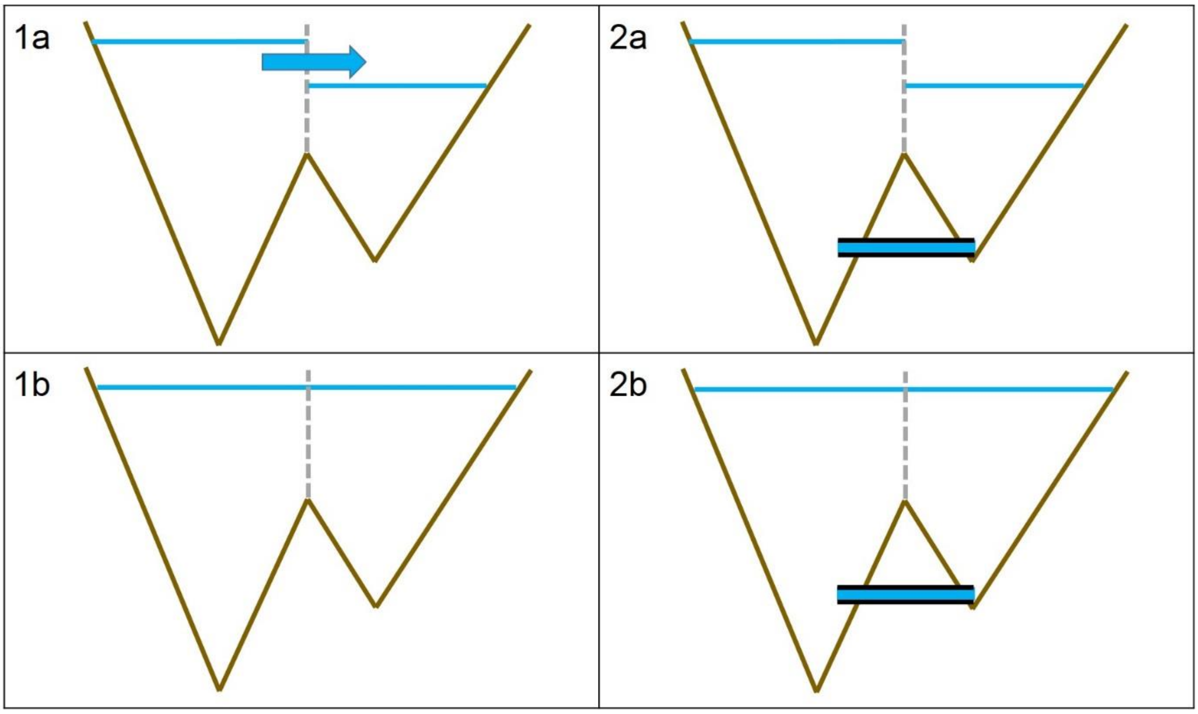

Figure 2-36: Conceptual diagrams of linked dams

2.6 WARMS DATABASE

The DWS's WARMS database (Anderson et al., 2008) is a potentially useful database of information that could be used in the methodology, including irrigated crop types, types of irrigation systems used, registered abstraction quantities, surface vs groundwater water sources, dam area and dam storage capacity. The WARMS database was briefly investigated in WRC Project K5/2205 (Clark, 2015a), but was not used based on concerns related to the spatial and factual integrity of the database. In this current study, it was proposed that the updated WARMS database be reinvestigated based on the understanding that DWS was undertaking verification exercises to improve the integrity of the database. In Section 0, the WARMS database was investigated as one source of data relating to the surface area and capacity of dams in a catchment, including unregistered dams.

In Section 0, the WARMS database was investigated as a source of information on irrigated crop types occurring within a catchment. In this section, information in the WARMS database for the upper and central Breede catchment was investigated for use in the methodology, including the spatial distribution of different water user, water source, irrigation crop and irrigation system types.

The Breede-Gouritz CMA provided a copy of the WARMS database for the Breede-Gouritz WMA once it had removed personal details of water users. The data for the upper and central Breede catchments was extracted and used in this investigation. The aim of this investigation was to determine what type of information was available in the database and whether any of the information could potentially be used to improve the configuration of the ACRU model for use in compiling catchment-scale water resource accounts. The data identified as being potentially useful is discussed in the sections below.

Most of the analysis was done per quaternary catchment as the drainage region code field provided an easy-to-use spatial context for the data, and it was not practical to show pie charts for the smaller sub-quaternary catchments used in the hydrological modelling. The latitude and longitude coordinates that provided a point location for each water user were used to show the spatial distribution of water users with catchments. Two main quantitative fields in the WARMS database may be useful: the registered volume field that contains the volume registered to the user, and the area field that contains the area of the irrigated fields for which there is a registered water user. The hydrological model and the water resource accounts require actual water abstractions, actual use and actual return flows. However, registered water use volumes may be useful as a guideline. It is anticipated that the areas of irrigated fields, together with crop-type information, will be useful in configuring the hydrological model.

2.6.1 Water use sector

The *WUSector* field indicates the sector to which a registered water resource belongs. This information could potentially be used to help identify catchments where water resources are being abstracted for use, and specifically the type of use, as this will impact on how the water use is modelled. These sectors are shown in Table 2-24, with the associated aggregated sector names used in the analysis.

Table 2-24: List of categories in the *WUSector* field and simplified categories used in the analysis

WUSector	WUSectorS
AGRICULTURE: AQUACULTURE	Aquaculture
AGRICULTURE: IRRIGATION	Irrigation
AGRICULTURE: WATERING LIVESTOCK	Livestock
INDUSTRY (NON-URBAN)	Urban/industrial
INDUSTRY (URBAN)	Urban/industrial

WUSector	WUSectorS
MINING	Mining
RECREATION	Other
SCHEDULE 1	Other
URBAN (EXCLUDING INDUSTRIAL AND/OR DOMESTIC)	Urban/industrial
WATER SUPPLY SERVICE	Urban/industrial

The proportions of registered water use per sector in each quaternary catchment are shown in Figure 2-37. Irrigation is the main water use sector in most catchments, followed by urban water use in some catchments where urban areas exist. The high proportion of urban use in Catchment H10K needs to be investigated further as there do not appear to be any substantial urban settlements in the catchment. In catchment H20D, the greatest proportion of water use is for aquaculture, which also needs to be investigated further. Aquaculture can have high water demands, but may not be a high net consumer of water as most of the abstracted water is returned to the river from which it was abstracted.

The spatial distribution of water users by sector and catchments with a high registered water volume are shown in Figure 2-38. It can be observed that there is a large number of irrigation water users, compared to other sectors, and that water users are not evenly distributed within and between the catchments. The total registered water use in each catchment was normalised by dividing it by the catchment area, effectively giving a depth of registered water use. The higher-use catchments H10C, H10H, H10L, H40J and H40G all contain or are close to urban areas.

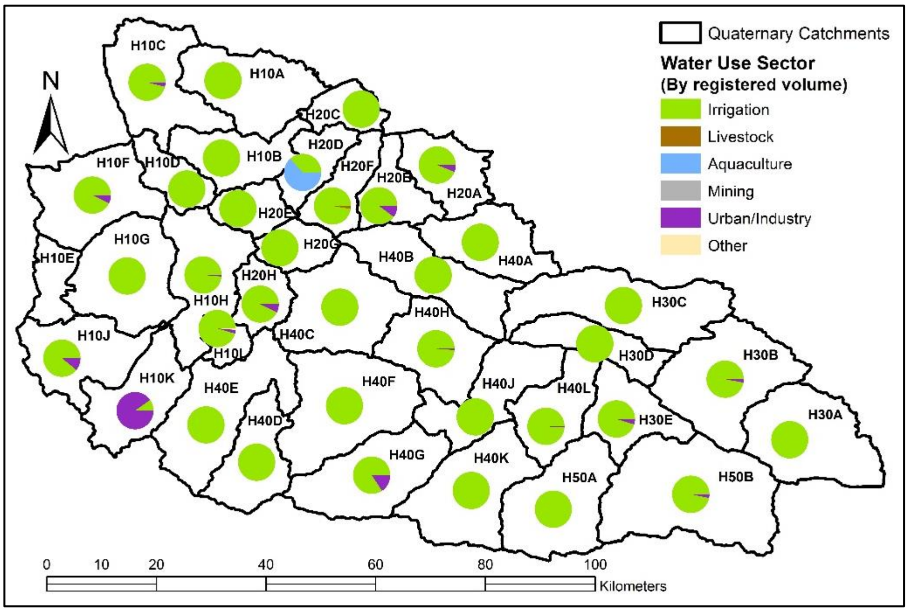

Figure 2-37: Proportions of registered water use per sector in each quaternary catchment

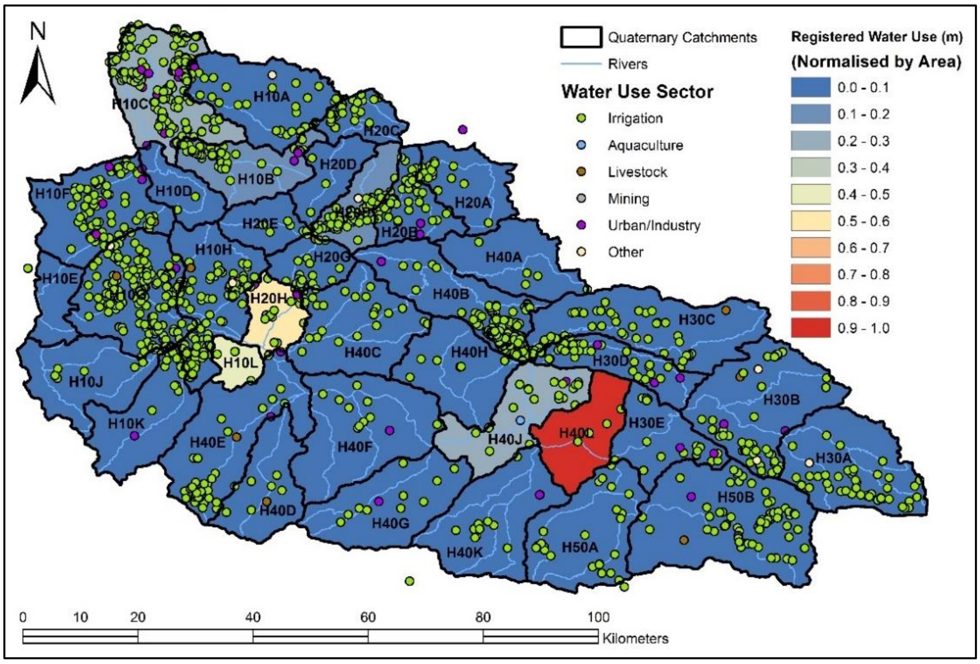

Figure 2-38: Spatial distribution of water users by sector and registered water use per catchment

2.6.2 Water source types

Information about water sources, such as whether surface water or groundwater is the primary water source, would be useful in configuring a hydrological model and compiling water resource accounts. In addition, it would be useful to determine whether surface water abstracted for irrigation or urban use comes from dams within a catchment or from run-of-river sources, and to represent this in the modelling. This is possibly one of the most important uses of the WARMS database in the context of the water use quantification and accounting methodology. In the initial configuration of the ACRU hydrological model for the upper and central Breede, it was noted that information was required regarding the spatial location and extent of groundwater use, especially for irrigation. The proportions of registered water use per water source type in each quaternary catchment for all water use sectors is shown in Figure 2-39. Many catchments have a high proportion of registered water use coming from run-of-river sources. There are also many catchments with a high proportion of registered water use coming from groundwater. This groundwater use needs to be taken into account in the configuration of the ACRU model as groundwater use is substantial in some catchments. It was surprising that there was not a higher proportion of water use from dams in the vicinity downstream of the Greater Brandvlei Dam, although this may be hidden by the scheme use in downstream catchments. The spatial distribution of water use from the different water source types is shown in Figure 2-40. Some catchments show predominantly run-of-river water sources, while other catchments seem to have highly concentrated, mixed river and groundwater sources.

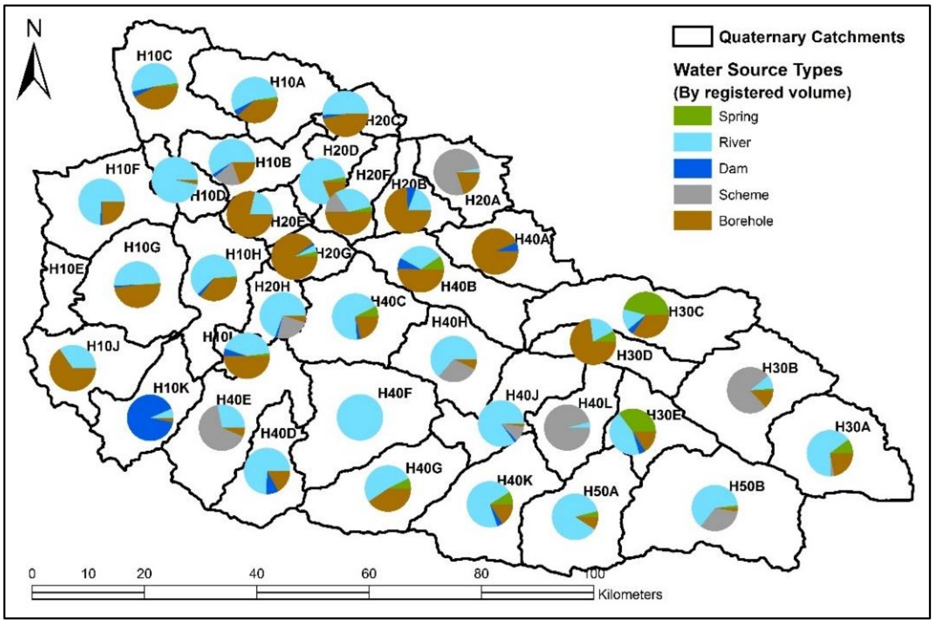

Figure 2-39: Proportions of registered water use per water source type in each quaternary catchment for all water use sectors

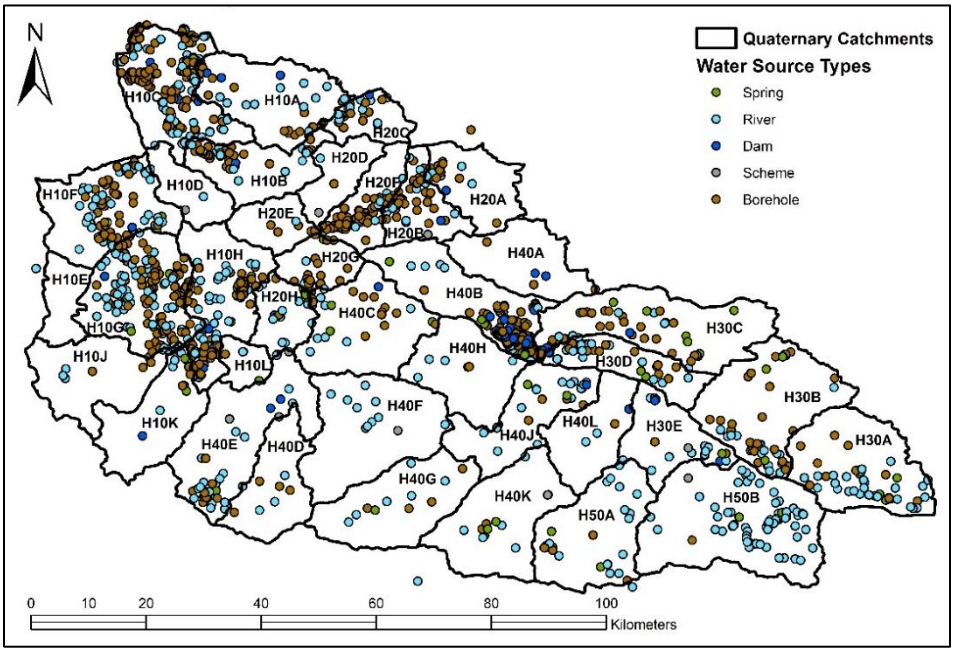

Figure 2-40: Spatial distribution of use from different water source types

Water sources by registered volume were analysed for irrigation users alone, as shown in Figure 2-41. Similarly, water sources by area irrigated were analysed for irrigation users alone, as shown in Figure 2-42. In most catchments, the proportions by registered volume and by area irrigated are similar, as would be expected. In catchments H40A and H40K, the proportion from dams based on area irrigated was noticeably greater than the proportion from dams based on registered volume.

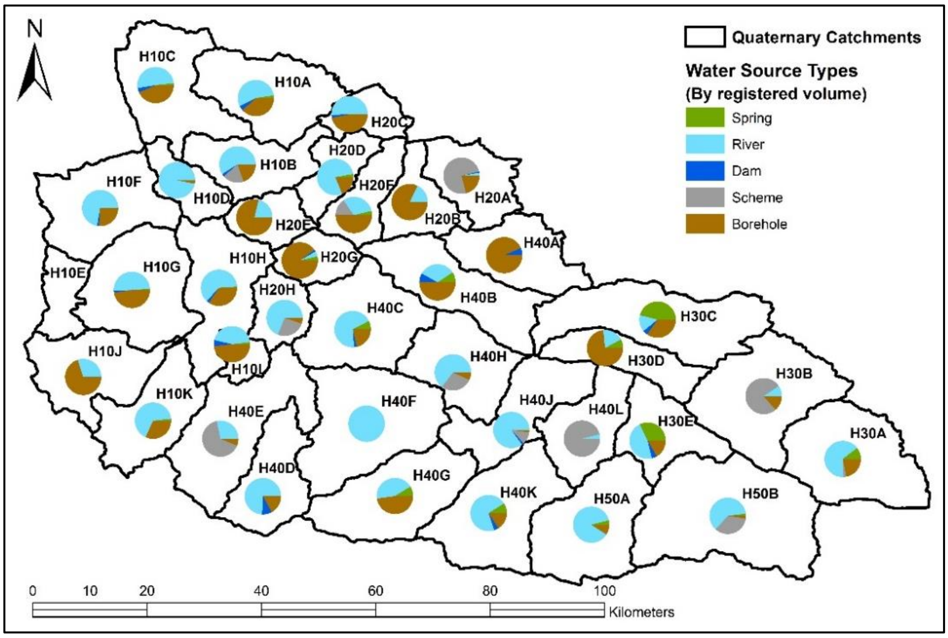

Figure 2-41: Proportions of registered water use per water source type in each quaternary catchment for irrigation use only

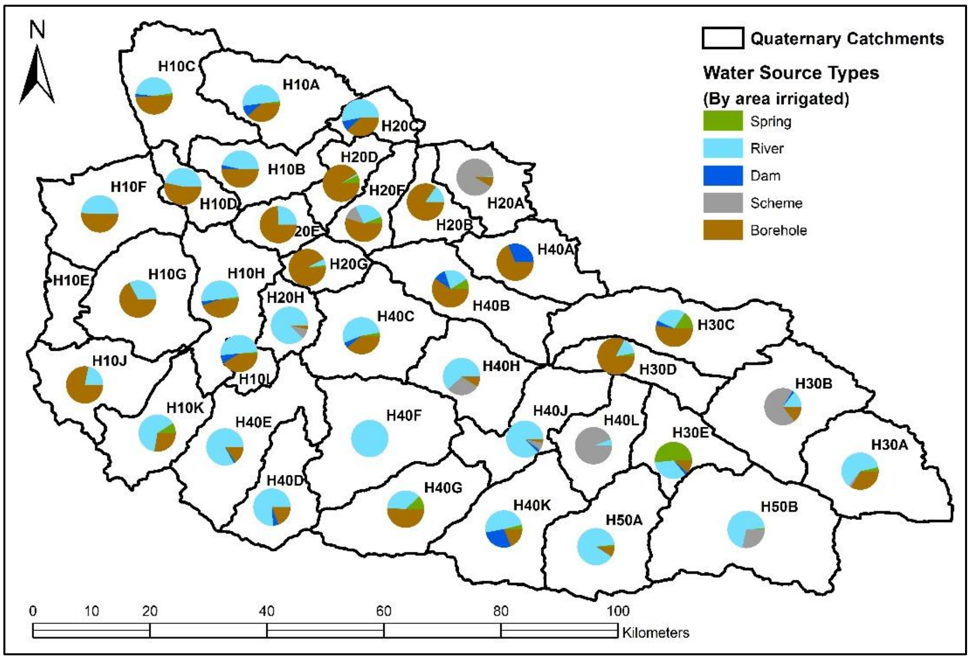

Figure 2-42: Proportions of water source types by area irrigated in each quaternary catchment for irrigation use only

2.6.3 Irrigation types

When modelling irrigation water requirements, knowledge of the type of irrigation system being used can be useful, as the different systems can have substantially different application efficiencies, which affects the quantity of water abstracted from water sources. The irrigation system field indicates the irrigation system type used by a registered water user. The irrigation system types are shown in Table 2-25, with the associated aggregated sector names used in the analysis.

The proportions of irrigation system type by registered water use in each quaternary catchment are shown in Figure 2-43. The proportions of irrigation system type by area in each quaternary catchment are shown in Figure 2-44. In most catchments, irrigation is predominantly done with micro and drip irrigation systems, with centre pivot and sprinkler systems being the predominant system type in catchments such as H20A, H20C and H10K.

Table 2-25: List of categories in the irrigation system field and simplified categories used in the analysis

Irrigation system	IrrigTypeS
CENTRE PIVOT	Centre pivot
DRIP	Drip
FLOOD: BASIN	Flood
FLOOD: BORDER	Flood
FLOOD: FURROW	Flood
LINEAR	Sprinkler
MICRO SPRAY	Micro
MICRO SPRINKLER	Micro
SPRINKLER: BIG GUN	Sprinkler
SPRINKLER: BOOM	Sprinkler
SPRINKLER: DRAGLINE	Sprinkler
SPRINKLER: HOP-ALONG	Sprinkler
SPRINKLER: PERMANENT	Sprinkler
SPRINKLER: QUICK-COUPLING	Sprinkler
SPRINKLER: TRAVELLING BOOM	Sprinkler
SPRINKLER: TRAVELLING GUN	Sprinkler
SUBSURFACE	Drip

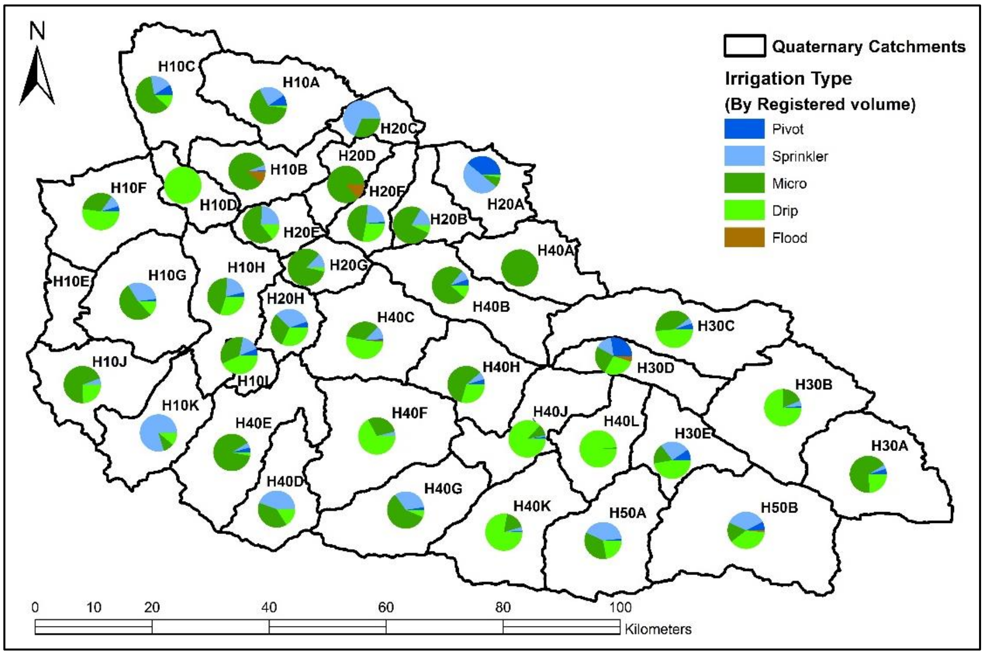

Figure 2-43: Proportions of irrigation system type by registered water use in each quaternary catchment

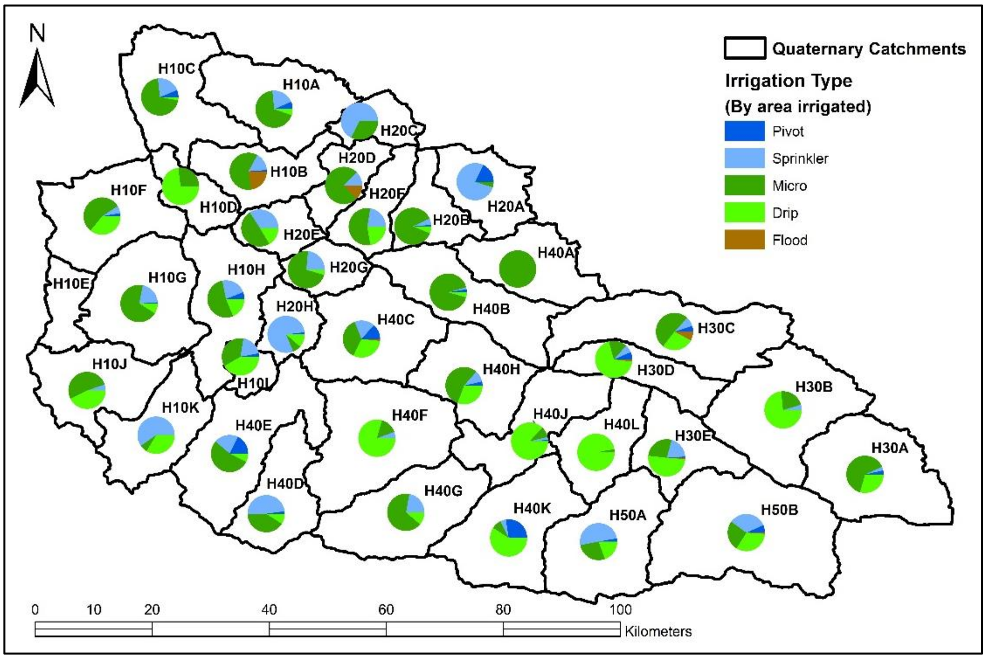

Figure 2-44: Proportions of irrigation system type by irrigated area in each quaternary catchment

2.6.4 Crop types

The national land cover datasets for South Africa include very broad classes that describe agricultural land cover, differentiating between commercial and subsistence agriculture, dryland and irrigated agriculture, and annual and perennial crops. More detailed information describing the spatial distribution of more specific crop types would enable better hydrological model parameterisation and the inclusion of more crop-specific water use estimates in the water resource accounts. Unfortunately, the WARMS database, due to its nature, only includes information on irrigated crops, whereas information on dryland crops would also be useful. The crop name field indicates the type of irrigated crop grown by a registered water user. The irrigation system types are shown in Table 2-26, with the associated aggregated sector names used in the analysis.

Table 2-26: List of categories in the crop name field and simplified categories used in the analysis

Crop name	CropTypeS	*Crop name*	CropTypeS
ALMONDS	Nut trees	MAIZE	Field crops
APPLES	Fruit trees	MANGOES	Fruit trees
APRICOTS	Fruit trees	NECTARINES	Fruit trees
AVOCADOS	Fruit trees	NURSERY	Other
BABALA	Forage/pasture	NUTS	Nut trees
BANANAS	Fruit trees	NUTS	Nut trees
BEANS – DRY	Vegetables	OATS	Field crops
BEETROOT	Vegetables	OLIVES	Fruit trees
BUTTERNUTS	Vegetables	ONIONS	Vegetables
CABBAGE	Vegetables	ORANGES	Fruit trees
CARROTS	Vegetables	PAPRIKA	Vegetables

CHERRIES	Fruit trees	PASTURES SUMMER AND WINTER	Forage/pasture
CITRUS	Fruit trees	PASTURES – PERENNIAL	Forage/pasture
CITRUS	Fruit trees	PASTURES – SUMMER	Forage/pasture
CUCURBITS	Vegetables	PEACHES	Fruit trees
CUT FLOWERS	Other	PEARS	Fruit trees
DATES	Fruit trees	PECAN NUTS	Nut trees
FESCUE – GRAZING	Forage/pasture	PLUMS	Fruit trees
FIGS	Fruit trees	POMEGRANATE	Fruit trees
GARDEN	Other	POTATOES	Vegetables
GOOSEBERRIES	Other	PRICKLEY PEARS	Other
GRAPES – TABLE	Grapes	PROTEAS	Other
GRAPES – TABLE	Grapes	PRUNES	Fruit trees
GRAPES – WINE	Grapes	PUMPKINS	Vegetables
GRAZING	Forage/pasture	QUINCE	Fruit trees
GREEN FEED	Forage/pasture	RYE GRASS	Forage/pasture
GUAVAS	Fruit trees	SCHEDULED WATER USE	Other
HAZEL NUTS	Nut Trees	STARFRUIT	Fruit trees
HERBS	Other	STONE FRUIT	Fruit trees
KIKUYU	Forage/pasture	TEA	Other
LAVENDER	Other	TEFF	Forage/pasture
LAWN	Other	TOMATOES	Vegetables
LEEKS	Vegetables	VEGETABLES – SUMMER	Vegetables
LEMON	Fruit trees	VEGETABLES – WINTER	Vegetables
LEMON	Fruit trees	WATERMELONS	Other
LUCERNE	Forage/pasture	WHEAT	Field crops
MACADAMIA NUTS	Nut trees		

The proportions of crop type by registered water use in each quaternary catchment are shown in Figure 2-43. The proportions of crop type by area irrigated in each quaternary catchment are shown in Figure 2-44. In the upper and central Breede catchment, the predominant crops are fruit trees, nut trees and grapes, with some forage and pasture crops.

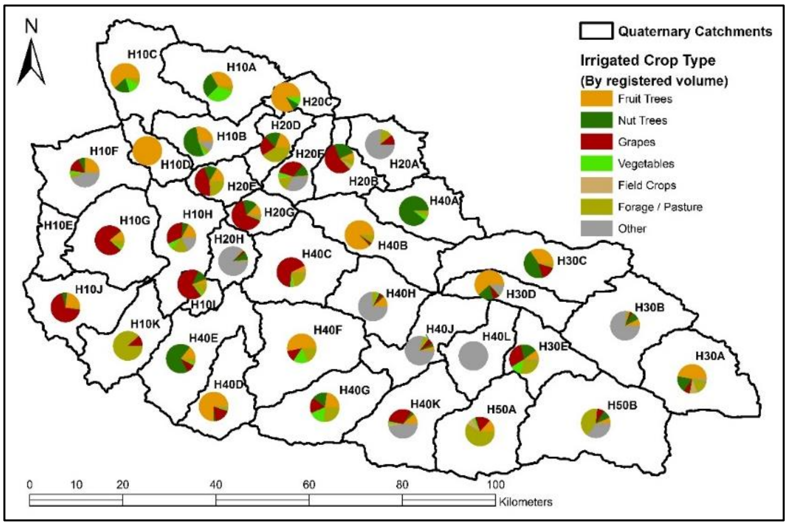

Figure 2-45: Proportions of irrigated crop type by registered water use in each quaternary catchment

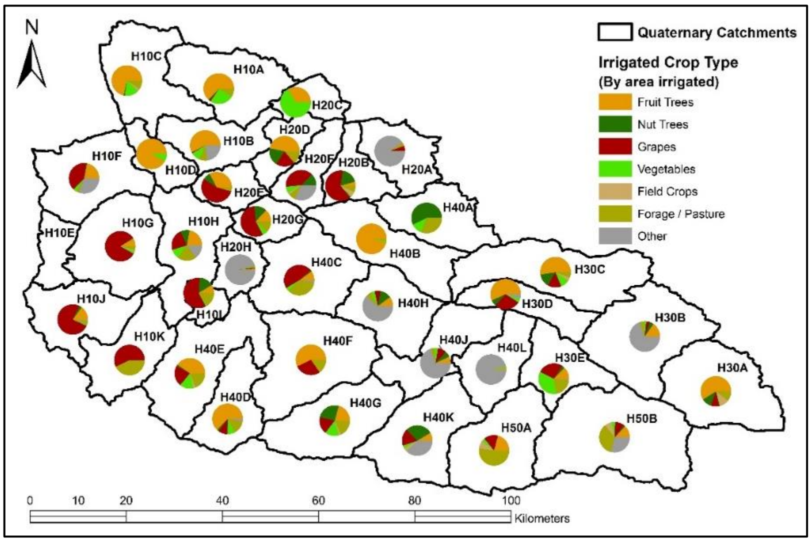

Figure 2-46: Proportions of irrigated crop type by irrigated area in each quaternary catchment

2.6.5 Discussion

Based on the investigations into the data available in the WARMS database, it is clear that the database contains some potentially useful data and information for use in the water use quantification and accounting methodology. However, there are some concerns about the accuracy of some of the data, although this is difficult to gauge without doing a detailed verification of the data. In addition, the database is not static. It represents the current point in time. For example, crop types may change with time. As DWS verifies the database, the database is expected to continue to be updated and improved. Thus, the WARMS data used to configure the ACRU model will need to be updated periodically.

The spatial information provided in the database needs to be investigated further to fully understand how it can be used. Each record in the database has a quaternary catchment ID, a latitude and longitude coordinate representing a point, and a Surveyor-General cadastral code. It was noted that there seemed to be some latitude and longitude points that were not within the associated quaternary catchment boundary. It is not clear whether this represents an error, or whether the water source and the water user were in different catchments.

The crop type information will be useful in the model configuration to improve on the very broad land cover use classes available in the national land cover datasets, and may help in identifying areas where irrigation is applied. A source of information on dryland crop types is still required, as the WARMS database only has data on irrigated crops.

A challenge relating to the application of the WARMS data in the hydrological modelling is to balance having very detailed representation of land and water use with the reality that uncertainties in some model inputs, such as rainfall, may outweigh the perceived benefits of the more detailed representation.

CHAPTER 3: APPLICATION OF THE WATER ACCOUNTING PLUS (WA+) SHEETS

DJ Clark

The WA+ Framework, based on IWMI's water accounting system, is a standardised method of providing spatial information on water depletion and withdrawal processes in complex river basins to describe the overall land and water management situation in complex river basins in a simple and understandable manner (Karimi et al., 2013a). Based on a review of water accounting frameworks by Clark et al. (2015), the WA+ Framework was selected for use due its suitability for catchment-scale water accounts, its strong land cover/use focus and the fact that its simple format makes it suitable for use as a communication tool.

Karimi et al. (2013a) describe four WA+ water accounting sheets:

- The Resource Base Sheet contains information about water volumes, including inflows, outflows and consumptive use.
- The Evapotranspiration Sheet contains more detailed information on consumptive use due to total evaporation and indicates whether the depletions are beneficial or not.
- The Withdrawal Sheet provides an overview of managed flows in a catchment, including abstractions, consumption and returns.
- The Productivity Sheet describes the biomass and crop yield productivity of water.

In the earlier project (WRC Project K5/2205), the WA+ Resource Base Sheet was modified, as described in Clark (2015a), to better suit the requirements of the project and to include the component of the Evapotranspiration Sheet that shows the partitioning of total evaporation into its various subcomponents. The modified Resource Base Sheet is shown in Figure 3-1. In this project, the code used to compile the modified Resource Base Sheet was developed further to enable the annual account to be compiled for both calendar and hydrological years (with a user-specified starting month) to suit the requirements of different users of the accounts.

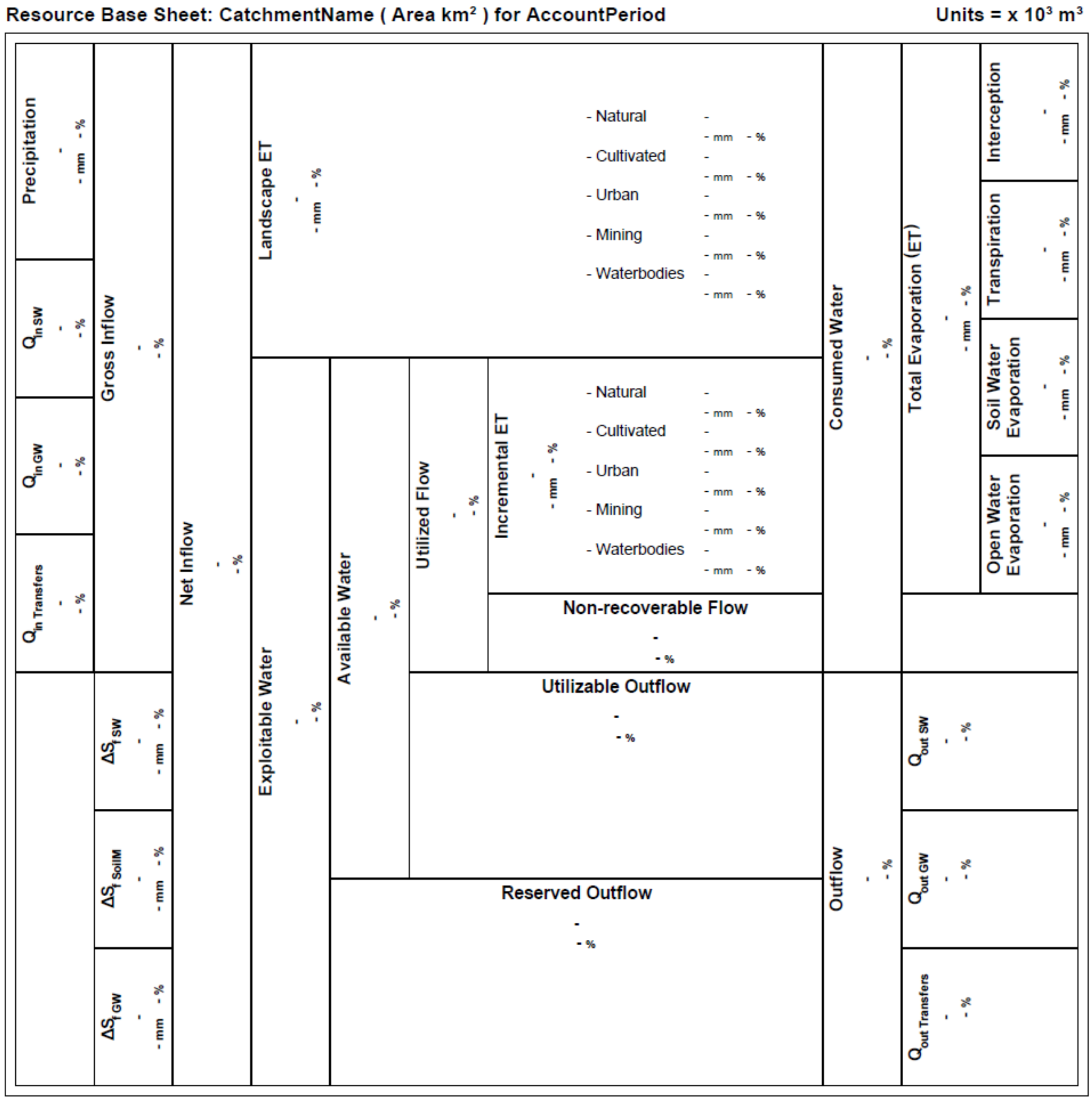

Figure 3-1: Schematic representation of the WA+ Resource Base Sheet, modified for the water use quantification and accounting system

The WA+ Withdrawal Sheet described by Karimi et al. (2013a) is shown in Figure 3-2. In this project, a prototype of a modified version of the WA+ Withdrawal Sheet was developed, as shown in Figure 3-3. The gross withdrawal from sources such as dams, rivers, groundwater and inter-transfers is shown on the left-hand side. The gross withdrawal is then partitioned into withdrawals from surface water, groundwater and transfers into the catchment. In the middle section of the sheet, the withdrawals are partitioned into the five broad water use sectors, and the proportion of each sector's withdrawal that is consumed or returned is indicated. The balance of withdrawals not consumed or returned includes losses and water storage. The natural withdrawals would, for example, be used to indicate environmental releases from a dam, and thus there would be no net consumption. The cultivated withdrawals would typically be for irrigation, for which it would be expected that a high proportion would be consumed, although, especially in the case of flood irrigation, there may be some returns. The urban withdrawals would be water for domestic, industrial and commercial use, of which varying portions may be consumed and returned. The mining withdrawals would be water used for mining processes.

The waterbodies' withdrawal is intended to indicate the volume of water that is lost due to evaporation from dams. The hydropower withdrawal represents water that may be released from a dam for hydropower generation. The return flow values do not indicate whether the returned water volumes are available for reuse within the catchment or downstream of the catchment. The right-hand side of the sheet shows total consumption and total returns, and also indicates whether the returns were to surface water, groundwater or to a transfer from the catchment. The water demand, withdrawal, consumption and return values are shown as volumes and as percentages, where the percentage values would be percentages of the relevant total value (usually in the column to the left).

Proposed enhancements to the modified Withdrawal Sheet include the following:

- Showing gross water demands
- Showing the demand deficit (the difference between demand and withdrawals)
- Showing supply system losses and the increase in water storage so that, for each water use sector, the consumption, return flows, losses and increased storage will sum to the withdrawal for that sector

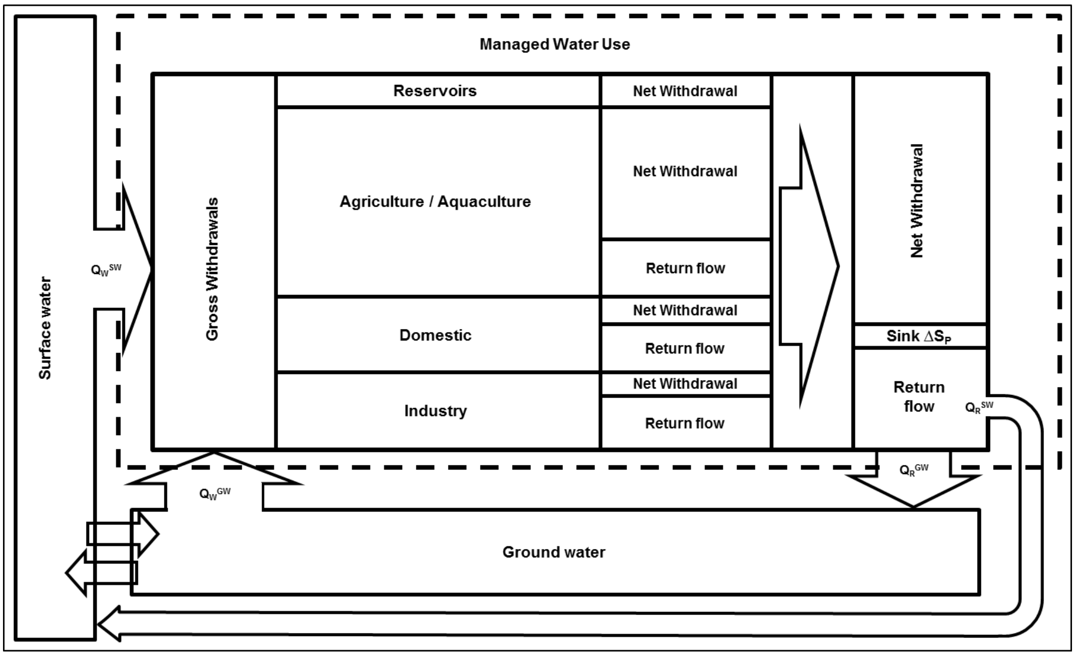

Figure 3-2: The WA+ Withdrawal Sheet (after Karimi et al., 2013a)

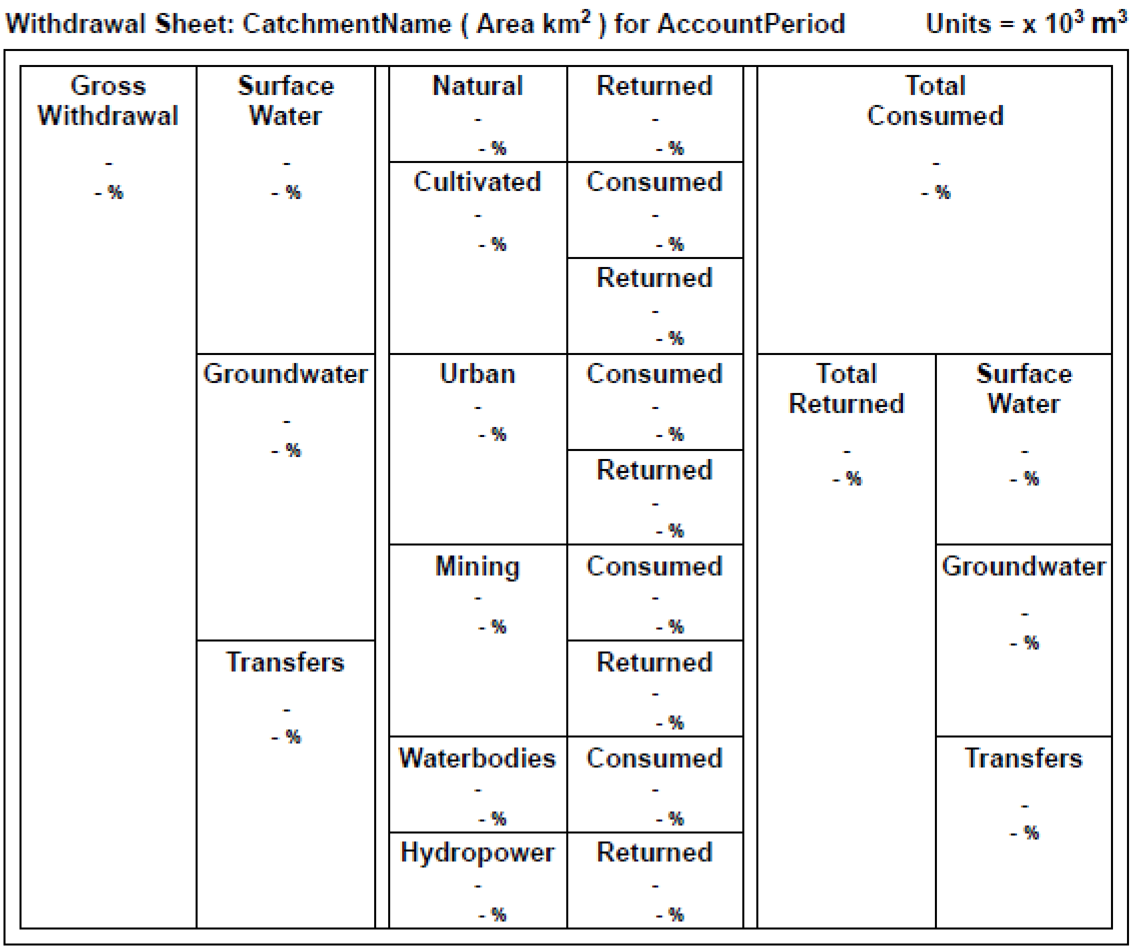

Figure 3-3: Schematic representation of the WA+ Withdrawal Sheet, modified for the water use quantification and accounting system

CHAPTER 4: ASSESSING CHANGES IN FLOWS WITHIN NATURAL VARIABILITY PATTERNS

N Rivers-Moore

Increasingly over the past two decades, the detrimental impacts of changes to flow regimes have been recognised. Changes to flows are typically reflected in biological responses (Jackson et al., 2007). Not only is too little flow deleterious to river health, but too much flow is also problematic. The Great Fish River in South Africa's Eastern Cape is cited as a classic example of a permanently altered system as a consequence of this (O'Keeffe and De Moor, 1988). This investigation aimed to develop prototype water accounts, showing the extent to which natural river flows are altered by water infrastructure, abstractions and return flows.

4.1 METHODOLOGY

Impacts on hydrographs were assessed using mean daily flow data for two quaternary catchments in each of the three study catchments (Table 4-1). Catchments were selected on the basis of the impacts of land use on reference median monthly flows ("natural") (Table 4-2). These were assessed by comparing modelled historical streamflow time series based on Acocks veld types (reference) and current observed streamflow data from gauging weirs. For the reference flow data, time series of daily flows for current (1950-1999) baseline conditions, from the database developed in earlier WRC projects (K5/1562 and K5/1843) for all 5,838 quinary catchments of South Africa, were used. The first two years of data was deleted, as per the recommendations of Taylor (2006), so that time series data spanned the period 1 October 1952 to 31 December 1999. For the observed flow data, reflecting current land use impacts, mean daily streamflow data was obtained for six gauging weirs (Table 4-1) from the DWS's hydrological information system [http://www.dwa.gov.za/Hydrology/] for the period 1 January 2000 to the present.

Table 4-1: Case study sites for the Breede, uMngeni and uThukela catchments

River	Quaternary	Gauge	Quinary
Breede	H10C	H1H003	2808
Breede	H10K	H1H009	2829
Mgeni	U20D	U2H006	4683
Mgeni	U20B	U2H007	4677
Thukela	V13C	V1H010	4887
Thukela	V20D	V2H002	4920

Table 4-2: Historical versus observed flow record lengths and rationale for catchment selection. All flow records were from 1 January 2000 to November 2018, with the exception of H1H009, which ran from 2008 to 2015.

Flow records	Rationale
H1H003	Downstream of the town of Ceres; crops and the Ceres Koekedouw Dam
H1H009	Impacted on by Stettynskloof Dam upstream
U2H006	Affected by land use and small farm dams
U2H007	Impacted on by the inter-catchment transfer from the Mooi River
V1H010	Settlement and irrigation
V2H002	Impacted on by Spring Grove Dam and Mearns Weir upstream, inter-catchment transfer to the uMngeni River, and the town of Mooi River

Data was formatted to be imported into the Indicators of Hydrological Alteration (IHA) software (Richter et al., 1996). Each flow data file was analysed using non-parametric statistics to derive metrics divided into five groups related to the magnitude, timing, duration and frequency of ecologically significant events (Table 4-3).

For the initial exploratory analyses, a principal components analysis (PCA) was run in PC-Ord (McCune and Mefford, 2011) using a correlation cross-products matrix. Variables that showed a high degree of collinearity were identified, and the variable with the highest eigenvalue from the PCA was selected for inclusion in the optimal variable matrix. Variables with high correlations, but lower eigenvalues, were deleted, as these did not add to the explanatory power of the PCA. The final PCA was run using the optimal matrix of variables.

Table 4-3: Flow metric groups defined by Richter et al. (1996)

Annual descriptive statistics		**Mean, standard deviation and coefficient of variation of annual flow, predictability**
Group 1	Monthly magnitudes	October to September median flows
Group 2	Magnitudes of annual extreme water flow conditions	1, 3, 7, 30 and 90-day flow minimums and maximums
Group 3	Timing – Julian date of flow event triggers	Date of longest mean, minimum and maximm exceedance sequence
Group 4	Frequency and duration (successive days of event above or below a threshold)	Mean, minimum and maximum flow threshold count and duration
Group 5	Rate and frequency of water condition changes	Rise and fall rates of hydrograph

To assess human impacts on flows, hydrographs of median monthly flows for reference and gauged flow data were plotted. Average monthly flows for the two most recent hydrological years were plotted on the same axes to illustrate inter-annual flow variability. Using the coefficients of dispersion for median monthly flows for the reference data, 95% confidence envelopes for upper and lower flows were derived. Impacts were also visually presented using radar plots based on percentage departure from reference flows.

4.2 RESULTS

Scree plots showed that the first two principal component axes accounted for the majority of the site variation. Many of the IHA metrics showed a high degree of correlation, which, after elimination based on correlations between variables and eigenvalues, provided the basis for the final PCA based on 35 variables. Based on flow metrics, each river system showed distinct differences, such as those plotted as non-overlapping sites in ordination space (Figure 4-1).

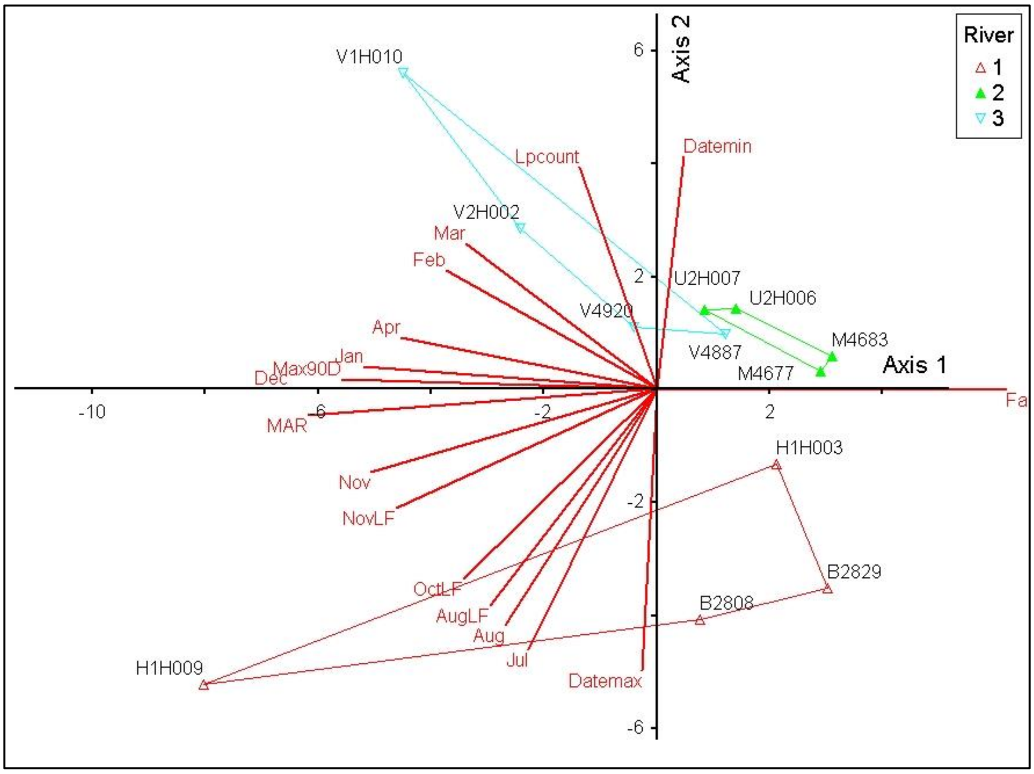

Figure 4-1: **Principal components analysis for six study sites, indicating flow metric vectors describing sites. Cumulative variance accounted for by axes 1 and 2 was 33.04 and 60.11% respectively. River codes are: 1 = Breede; 2 = uMngeni; 3 = uThukela. See Table 4-3 for vector code descriptions.**

Variation in PCA axis 1 was largely explained by median flow volumes, while parameters for extreme high and low flows (timing and count of low pulses; Julian dates of minimum and maximum flows) best described variation on PCA axis 2 (Table 4-4). The Breede catchment sites showed the greatest change between reference and observed flows, with particularly the flow volumes from Weir H1H009 impacted on by altered flows due to the Stettynskloof Dam upstream. Both sites in the uMngeni catchment show impacts on hydrographs, reflecting changes in volumes and timing, probably due to inter-basin transfers and changes in land use. Similarly, the gauged flows in the uThukela catchment showed changes in volumes and the timing of low flow events, again reflecting changes in land use and the impacts of inter-basin transfers from Spring Grove Dam.

Table 4-4: **Eigenvectors for the first two axes of a PCA based on IHA metrics for study sites in the Breede, uMngeni and uThukela catchments**

Variable	Parameter	PCA 1	PCA 2
MAR	Mean annual runoff	-0.2766	-0.0840
CV_ann	Annual coefficient of variation	0.1621	0.0496
Pred	Predictability	-0.0517	-0.1127
Const	Constancy	0.0547	-0.0333
Flood_pe	Percentage of floods in 60-day period	-0.1507	-0.1440
FFS	Flood-free season	-0.0314	0.1758
Nov	November median flow	-0.2505	-0.1494
Dec	December median flow	-0.2842	0.0101
Jan	January median flow	-0.2533	0.0769

Variable	Parameter	PCA 1	PCA 2
Feb	February median flow	-0.2152	0.1776
Mar	March median flow	-0.2045	0.1967
Apr	April median flow	-0.2366	0.1171
Jul	July median flow	-0.1681	-0.2640
Aug	August median flow	-0.1820	-0.2516
Max90D	90-day maximum	-0.2628	0.0493
Zero	Number of zero days	-0.1225	0.1858
BFI	Base Flow Index	0.0173	-0.1813
Datemin	Date of minimum	0.0769	0.2491
Datemax	Date of maximum	-0.0570	-0.2745
Lpcount	Low pulse count	-0.1302	0.2433
Lpdur	Low pulse duration	0.0957	-0.1876
Hpdur	High pulse duration	0.1046	-0.1589
Rise	Rise rate	0.0805	0.0555
Fall	Fall rate	0.2766	-0.0131
Rever	Number of reversals	-0.1685	0.1436
OctLF	October low flow	-0.2059	-0.2255
NovLF	November low flow	-0.2388	-0.1783
MarLF	March low flow	-0.1571	0.1877
AugLF	August low flow	-0.1910	-0.2405
OctCV	October coefficient of dispersal	-0.1472	0.2006
FebCV	February coefficient of dispersal	-0.0660	0.0647
JunCV	June coefficient of dispersal	0.0311	-0.0906
JulCV	July coefficient of dispersal	-0.1270	0.0174
AugCV	August coefficient of dispersal	-0.0873	0.1526
River	River (qualitative code)	-0.0368	0.2776

The general trends from the PCA results exhibited changes specific to each catchment:

- H1H003: This hydrograph showed reduced winter flows that were also outside the 95% confidence envelope, i.e. beyond acceptable ecological limits. However, the biggest proportional impacts were observed for the low-flow summer months of January and February (Figure 4-2).
- H1H009: Current flows were completely outside the 95% confidence envelope for the entire hydrological year, with median monthly flows elevated by 200 to 2,000% (Figure 4-3).
- U2H007: The current gauged flows fell within the 95% confidence envelope for the whole hydrological year, but with flows generally increased (or changes most pronounced) in the summer months of November and December (Figure 4-4).
- U2H006: Impacts for this site were similar to U2H007, but with the timing of impacts shifted to December and January (Figure 4-5).
- V1H010: Current observed flows were within the 95% reference envelope with the exception of February flows being elevated to beyond the natural range of variation. However, proportionally, the greatest impact is for September, where spring flows are reduced (Figure 4-6).
- V2H002: Median monthly flows showed a similar pattern of impacts to V1H010, but with changes in timing, i.e. January median flows were outside the 95% confidence envelope. Proportionally, this translated into reductions over the low-flow seasons (autumn to spring), and increased summer flows (Figure 4-7).

In each case, while median flows over a 20-year interval showed general seasonal trends of exceedance or compliance relative to the reference flow envelope, each site exhibited considerable inter-annual variability of flows.

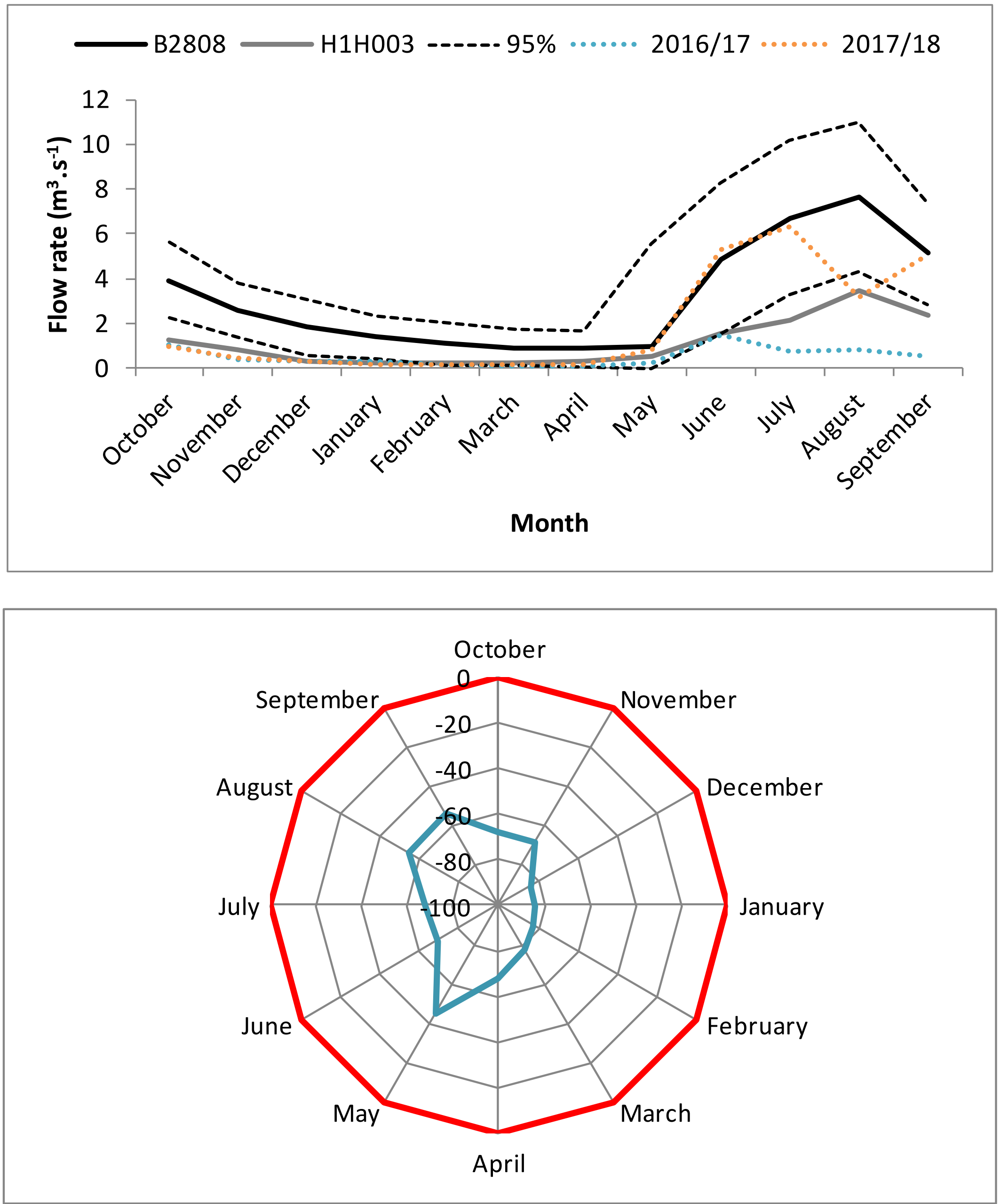

Figure 4-2: Hydrograph for gauging weir H1H003 in the Breede catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2016/17 and 2017/18 are shown for comparison against median flows from 1 January 2000 to October 2018. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).

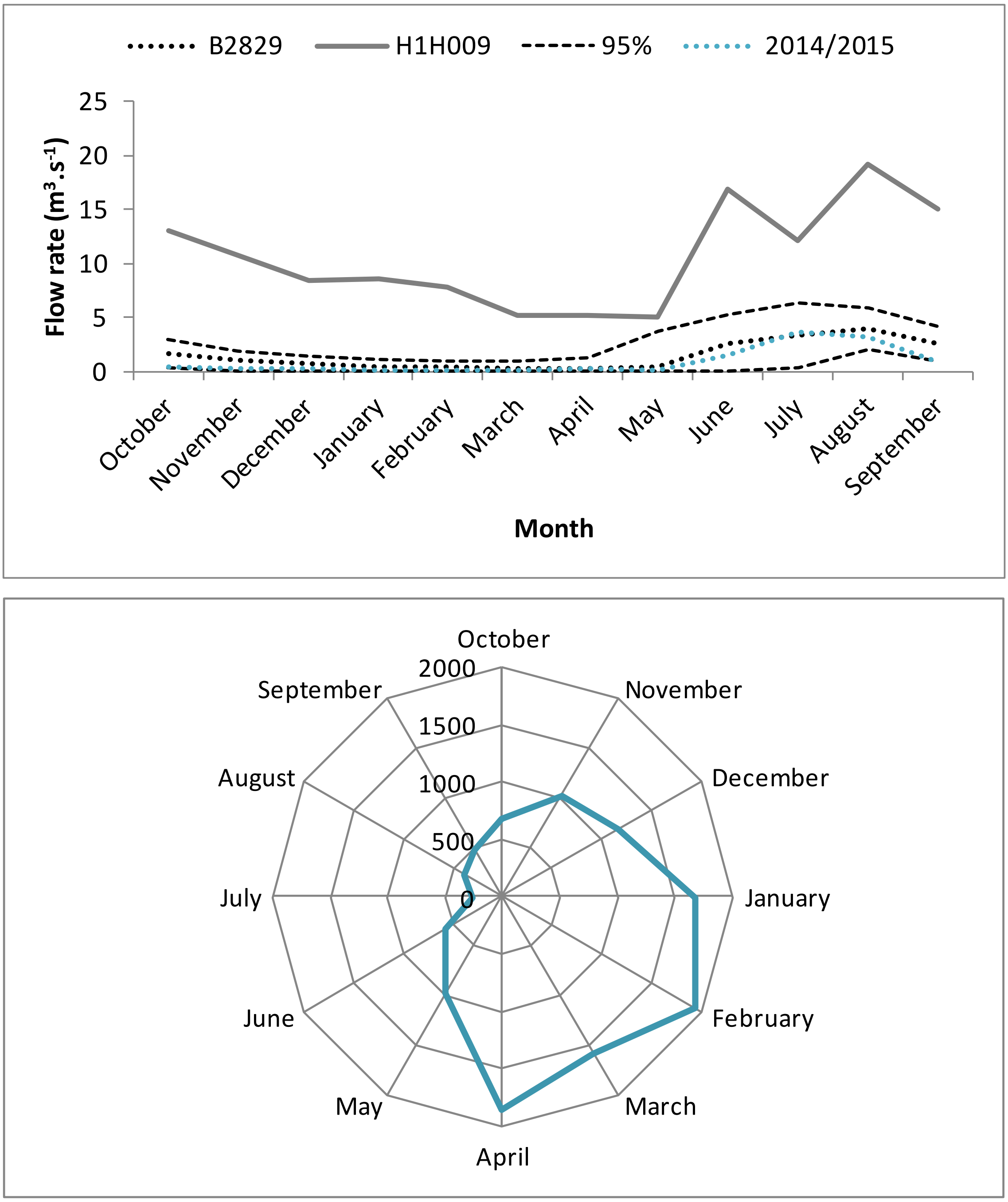

Figure 4-3: **Hydrograph for gauging weir H1H009 in the Breede catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2014/15 are shown for comparison against median flows from 1 January 2008 to October 2015. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).**

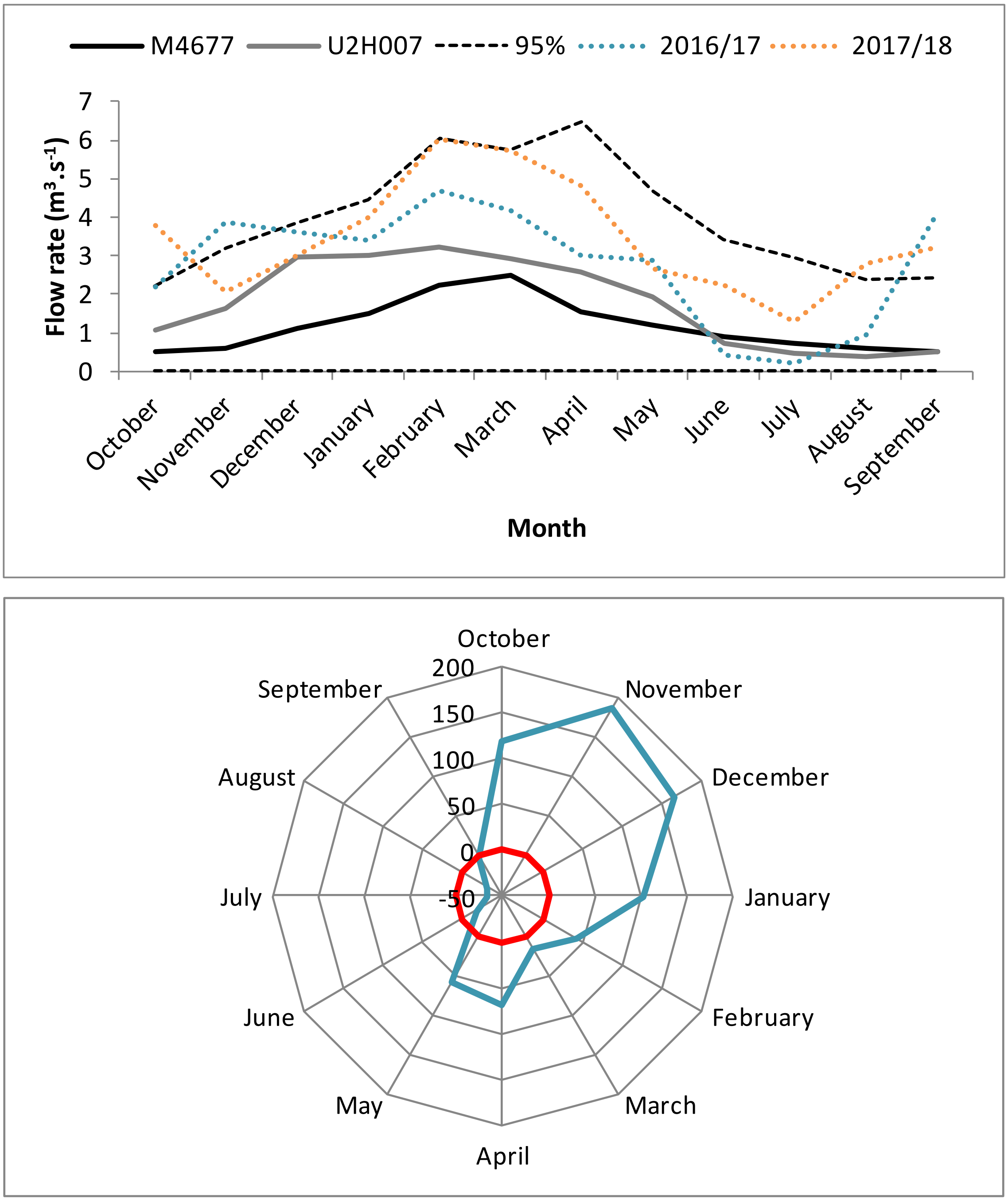

Figure 4-4: **Hydrograph for gauging weir U2H007 in the uMngeni catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2016/17 and 2017/18 are shown for comparison against median flows from 1 January 2000 to October 2018. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).**

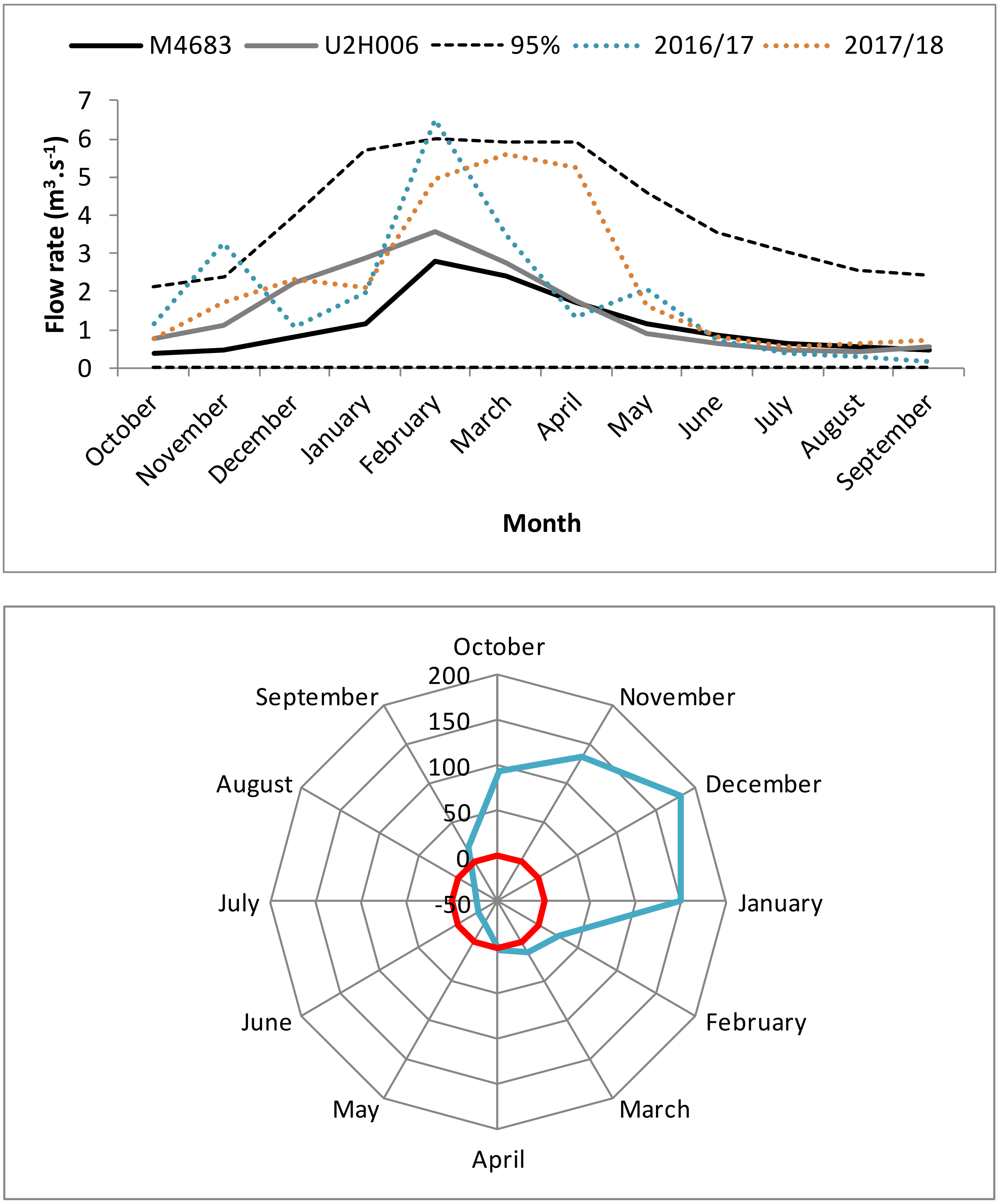

Figure 4-5: Hydrograph for gauging weir U2H006 in the uMngeni catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2016/17 and 2017/18 are shown for comparison against median flows from 1 January 2000 to October 2018. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).

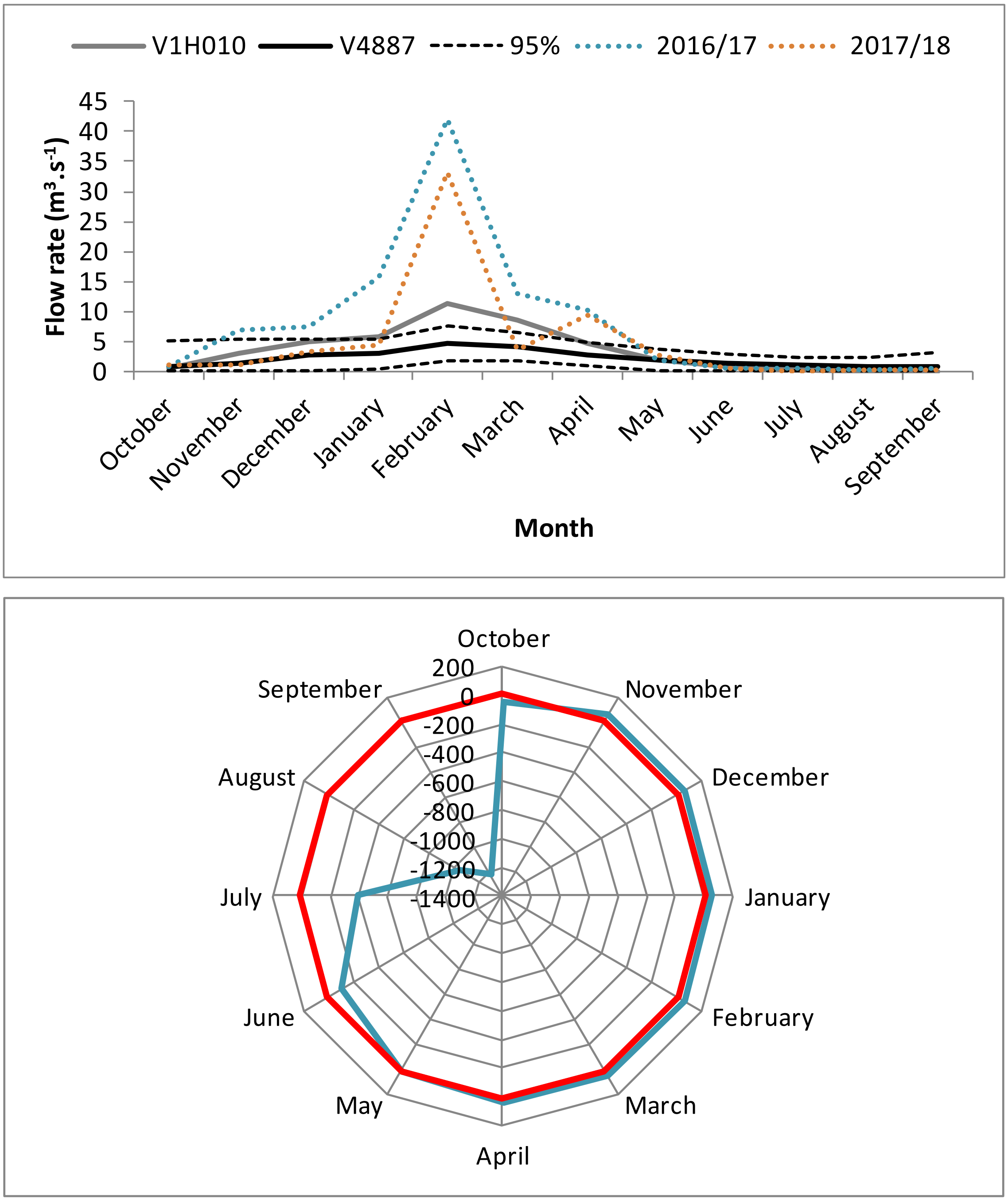

Figure 4-6: Hydrograph for gauging weir V1H010 in the uThukela catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2016/17 and 2017/18 are shown for comparison against median flows from 1 January 2000 to October 2018. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).

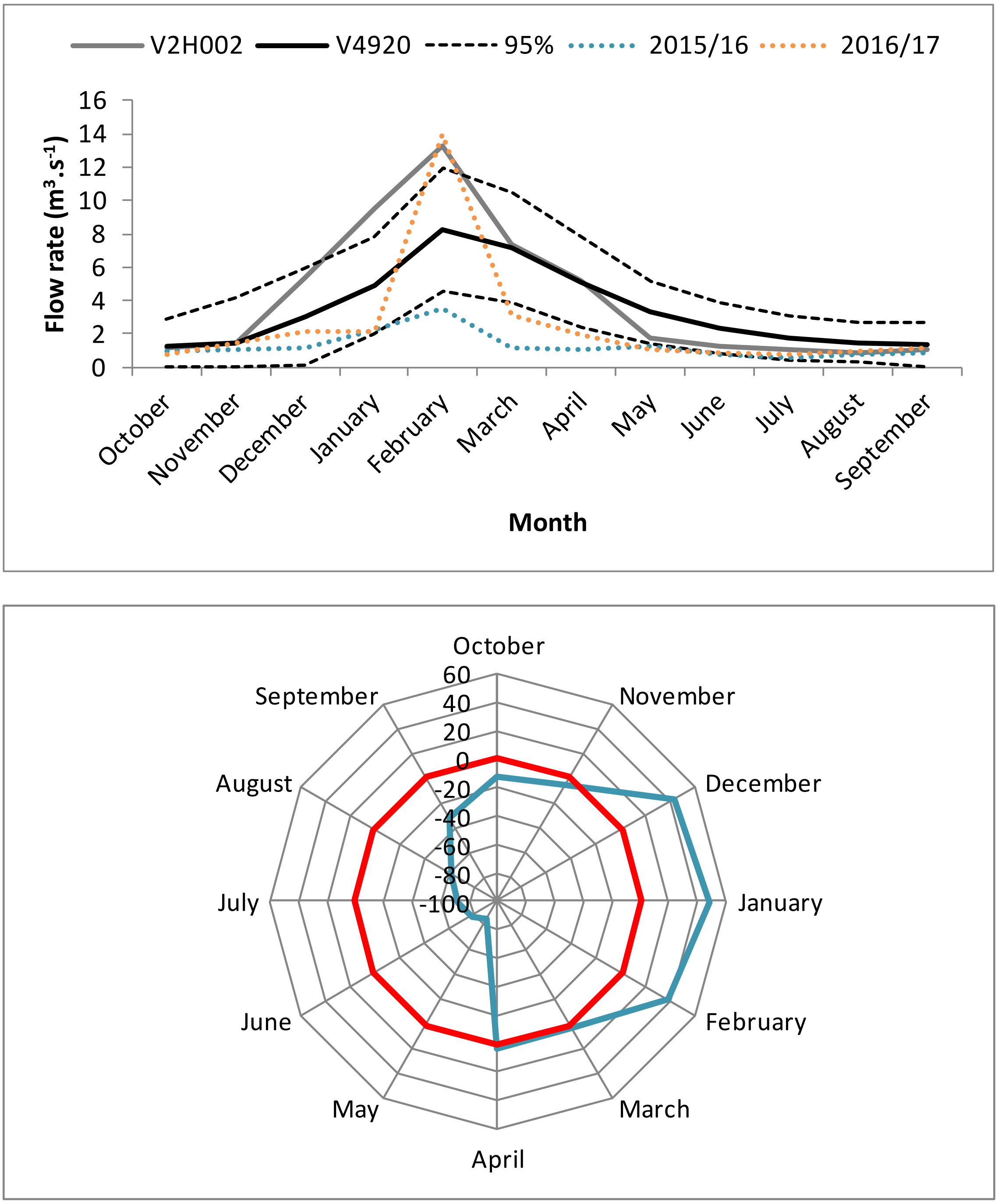

Figure 4-7: **Hydrograph for gauging weir V2H002 in the uThukela catchment, showing median monthly flows for historical and current observed flows, with a 95% confidence envelope for historical flows (top); mean flow rates for hydrological years 2015/16 and 2016/17 are shown for comparison against median flows from 1 January 2000 to October 2017. Radar plot of monthly percentage deviation from historical flows, relative to a baseline of 0% deviation (red line; bottom).**

4.3 DISCUSSION

Richter et al. (2012) recognise three basic approaches for setting environmental flow standards: minimum flow thresholds (how much water can be removed and still allow the ecosystem to function), statistically based standards (IHA, etc.) and percentage of flow. The last approach is viewed as being considerably more protective of flow variability than the minimum flow threshold, and relates explicitly to the sustainability boundary approach (Richter, 2010), which recognises that limits of flow alteration are set on the basis of allowable perturbations from the natural condition, expressed as percentage-based deviations from natural flows (Richter et al., 2012). In the absence of empirical data, Richter et al. (2012) regard flow alterations of ≤10% as affording a high level of ecological protection, 11-20% as affording a moderate level of ecological protection, and >20% most likely resulting in moderate to major changes in ecosystem functions.

The data reflected a mixture of either more or less flow than the reference monthly median flows, which variably exceeded the 10% threshold proposed by Richter et al. (2012) over a hydrological year. Furthermore, flow trends varied inter-annually, highlighting the need for annual water accounts.

Ecologically, all the changes described above are more likely to be stressful to the selected river systems over the low-flow periods. Changes in timing and frequency of high- or low-flow events could impact on life history cues of aquatic biota (spawning, migration, hatching). Ecologically, the Breede River system is likely to be the most altered of the three study regions. While it is difficult to describe specific ecological impacts without empirical data and biological response models, it is well known that flow patterns fundamentally impact on the types and distributions of aquatic species within river systems (Bunn and Arthington, 2002; De Moor, 2002; Poff and Zimmerman, 2010) with streamflow perceived as a “master variable”, which shapes many fundamental ecological characteristics of riverine ecosystems (Poff and Zimmerman, 2010). Flow alterations beyond the natural range of variability of a river system could differentially affect different components of aquatic biota, resulting in changes in community structure and trophic webs. These, in turn, could result in the dominance of particular pest species (such as blackfly and disease vectors) and/or reductions in the river system’s resilience and the river’s ability to provide ecosystem goods and services.

CHAPTER 5: ENGAGEMENT WITH POTENTIAL USERS OF THE WATER RESOURCE ACCOUNTS

DJ Clark, SI Stuart-Hill and KT Chetty

As part of this study, engagement with potential users and other interested parties took place in the form of three formal workshops, but also more informally in discussions with individuals associated with the Council for Scientific Research (CSIR), SANBI, Umgeni Water and the uMngeni Ecological Infrastructure Partnership. Presentations on water accounting were also given to two delegations from South Sudan.

Two workshops were held near the beginning of the project: one in the Breede catchment and one in the uMngeni catchment. The third workshop was held in Pretoria with the aim to include personnel from DWS's Head Office. The objectives of the formal workshops were to do the following:

- Build capacity by introducing delegates to the concept of water accounting, the main different water accounting frameworks in use internationally and their scope of application.
- Inform delegates of the research completed in WRC Project K5/2205, including examples of water resource accounts from the case study catchments for that project.
- Inform delegates of the further development of the water use quantification and accounting methodology in this study.
- Initiate discussions with delegates, asking the following questions:
  - Would these water resource accounts be useful to you?
  - How would you use them?
  - How could they be further developed to be more useful to you?

5.1 WORKSHOP 1: BREEDE CATCHMENT

The first workshop was held at the offices of the Breede-Gouritz CMA in Worcester on 1 July 2016. The 12 delegates at the workshop represented a variety of organisations, including DWS, the Department of Environmental Affairs and Development Planning of the Western Cape, the Breede-Gouritz CMA, the Central Breede Water User Association (WUA) and GreenCape. The workshop started with a presentation describing the concept of water accounting, the main water accounting frameworks in use internationally and their scope of application. The more general discussion during the course of the presentation was followed by a session of more focused discussion around the questions posed to the delegates. This section aims to summarise the main points of discussion.

5.1.1 General discussion

Water accounting frameworks

It was suggested that, from a water management perspective, the WA+ Framework was best suited to promoting understanding of water resources in a catchment and looking forward using climate forecasts, while the AWAS was best suited to looking back at actual water use and availability.

Spatial boundaries of accounts

There was some discussion about the feasibility of compiling water resource accounts for different spatial boundaries, other than catchments, for example water schemes, WMAs and municipal and provincial boundaries. It was suggested that water schemes would be a useful spatial domain for which to compile water resource accounts as water schemes constitute a spatial domain of interest within which water is managed and within which a particular set of operating rules would apply.

Water resource accounts for water schemes and catchments may coincide if there are common boundaries. Water resource accounts for WMAs are feasible as the boundaries of WMAs coincide with catchment boundaries. Water accounts for municipal and provincial boundaries are possible in the sense that a mass balance can be created for any spatial domain if the necessary data inputs are available. However, these administrative boundaries seldom coincide with catchment boundaries that represent natural water resource boundaries. The catchment scale accounts that are compiled using a hydrological modelling-based approach, such as that advocated in this study, could potentially be used as a source of information for some of the inputs that are required to compile accounts for municipal and provincial boundaries.

Reserve

The delegates agreed that it would be useful to include the reserve in the WA+ Resource Base Sheet accounts. However, this is not necessarily straightforward as the reserve is determined at a point on a river, and could be included in the accounts at that point, hence some means would be required to be able to translate the reserve to points upstream to provide an indication of whether individual upstream catchments were contributing a reasonable portion of the reserve.

Operating rules

The hydrological modelling case studies do not include the modelling of operating rules for dams as they used measured releases from dams and estimated urban and irrigation water use. However, if forecast accounts were to be compiled, it may be necessary to include operating rules for dams.

Operationalisation of the accounts

An important point that was made was that if the accounts are to be used operationally, i.e. compiled on a regular basis and used for operational water management decisions, then some means would be required to enable the model configurations to be easily updated with near real-time data.

Alien invasive vegetation

It would be useful to include alien invasive vegetation in the land cover/use classes for which water use was estimated for the water resource accounts. Alien invasive vegetation is not currently taken into account in the water resource accounts as the classification of the land cover datasets does not include alien invasive vegetation. However, alien invasive vegetation could be included in the accounts if a spatial dataset were available, which could be superimposed on the land cover datasets.

Forecast accounts

There was considerable interest in the potential ability to compile forecast water accounts based on climate forecasts, ranging from short-term to seasonal forecasts.

Water quality and economics

Currently, the development of the water accounting methodology has focused on water quantities. However, it is recognised that water quality and economics were also important for water management. Delegates recognised that water quantity was the correct starting point as quality and economics were often closely related to and dependent on water quantity. The point was made that water availability may, in some instances, be dependent on the quality of the water. In the Breede catchment, stored water is sometimes released for dilution downstream to ensure suitable water quality levels. Some delegates felt that water quality should take priority over economics for the future development of the accounting methodology, while others felt that the economics aspect could be developed in parallel as economic values or indices were derived from both quantity and quality data.

The delegates agreed that the methodology needed to be kept open to potentially include quality and economics. The quantity, quality and economic accounting sheets would need to be interlinked to provide a comprehensive water management tool.

Lawful water use and water restrictions

Delegates cautioned that unlawful use would need to be taken into account, and that even lawful use is sometimes underestimated as, in some townships, water use is not metered. Water-use restrictions also need to be considered in the modelling.

Application of the methodology outside the project

The application of the methodology for the whole of South Africa would require significant human and financial resources and would probably have to be driven by DWS. A smaller-scale application of the methodology could be done at CMA or possibly even WUA level. Some hydrological modelling expertise would be required, although data processing could be automated to some extent. Although the methodology was developed with ACRU as the selected hydrological model, other similar models could potentially be used. Capacity building would be required in the application of the methodology and the interpretation of the accounts.

5.1.2 Focused discussion

Would these water resource accounts be useful to you?

The delegates seemed to be interested in and supportive of the concept of water resource accounts, although there was not any clear preference for one of the three water accounting frameworks summarised in the presentation. However, beyond the interest in the water resource accounts themselves, there was possibly an even greater interest in the availability of a hydrological model setup for a catchment that could be used as a tool for water management. Water accounts would help in developing a better understanding of water resources in specific catchments. Water resource accounts could help build trust between water managers in water supply and water receiving catchments, and also between different levels of water management such as DWS, CMAs and WUAs. It was suggested that information on water quality and water transfers between catchments or regions may be of interest to the public.

How would you use these water resource accounts?

The delegates suggested several ways in which they could potentially use water resource accounts, including the following:

- Planning by institutions such as DWS and CMAs, and actual smaller-scale water management and operations by WUAs
- Considering an area of operation (for example the Greater Brandvlei Government Water Scheme) and see what can be changed to improve efficiency in the use of water resources
- Looking ahead using forecasts to help make operational decisions such as whether to use water from Brandvlei Dam late in the growing season or to save it for the next season
- Testing different catchment and water management scenarios to determine the effect on water availability and use, and the ability to meet the reserve
- Helping to motivate for physical locations where monitoring is required and to identify the key variables for monitoring
- Being a useful dataset for use in other social or economic studies
- Evaluating the effect of catchment water management strategies to meet the reserve

How could the water resource accounts be further developed to be more useful to you?

Suggestions for further developing the methodology and accounts included the following:

- Include water use by alien invasive vegetation
- Use climate forecasts to create short-term to seasonal forecast water accounts
- Accounts are for a specific temporal domain, but it would be useful to know how components of a particular account, such as streamflow or dam levels, relate to long-term historical values such as on a cumulative frequency distribution
- Include water quality and economic accounts

5.2 WORKSHOP 2: UMNGENI CATCHMENT

The second workshop was held at the University of KwaZulu-Natal in Pietermaritzburg on 21 July 2016. The 25 delegates at the workshop represented a variety of organisations including the WRC, DWS, Pongola to Umzimkulu Proto CMA, KwaZulu-Natal Department of Agriculture and Rural Development, Western Cape Department of Agriculture, StatsSA, eThekwini Water and Sanitation, Msunduzi Municipality, Umgeni Water, Umsunduzi Catchment Management Forum, Mooi River Irrigation Board, L&R Enterprises, the Institute for Natural Resources and the Centre for Water Resources Research. The workshop started with a presentation describing the concept of water accounting, the main water accounting frameworks in use internationally and their scope of application. The more general discussion during the course of the presentation was followed by a session of more focused discussion around the questions posed to the delegates. This section aims to summarise the main points of discussion and the results of a strengths, weaknesses, opportunities and threats (SWOT) analysis by delegates.

5.2.1 General discussion

Accounts useful to municipalities

There was some discussion regarding the use of water resource accounts by municipalities. The selection of a water accounting framework would depend on the purpose: AWAS for reporting water resources in a format with which managers with a financial background would be familiar, SEEA-Water for decision making around the economics of water and the WA+ Framework for understanding the hydrology of the water resource system. The mismatch between catchment and municipal boundaries would need to be considered. Municipalities are more than potential users of the water resource account. They have an important role to play in providing information and data about domestic and industrial water use and return flows for use in the accounts.

Authorised and unauthorised abstractions

The water resource accounts need to include water use by both authorised and unauthorised abstractions.

Data availability and measurement infrastructure

Delegates acknowledged that data availability was a critical requirement for accurate water resource accounts to be compiled and that lack of data in some regions may make it difficult to create water resource accounts for the whole country. The problem of many flow measurement weirs not being in working order was raised and that there would be a significant infrastructure cost associated with being able to produce accurate water resource accounts for the whole country. One of the outcomes from an initiative to produce water resource accounts for the whole country would be to highlight gaps in monitoring networks. The modelling approach to compiling the accounts was selected to help estimate components of the accounts that could not be easily measured or where measurements were spatially sparse, but models still require input data and data such as streamflow and dam levels for verification.

Uncertainty associated with input and modelled data

There was some discussion regarding the uncertainty associated with data and modelled estimates used in the water resource accounts. It is important that the accounts be accompanied by statements describing the source and accuracy of the data used and any assumptions made. Although models are based on many assumptions and can be a source of additional uncertainty, the modelling approach used ensures that the modelled water balance is in equilibrium and important feedback between components is represented.

Water quality, economics and environmental impacts

A point was made that a strength of the SEEA framework was that it provides an indication of the environmental impact as a result of the use of resources such as minerals and water. There was some discussion regarding the potential representation of water quality, economics and environmental impacts in the accounts. The importance of representing these aspects in accompanying accounts was acknowledged, but getting the estimates of water quantities correct was an important first step, as the other aspects all depended on an accurate estimation of quantities.

Estimation of agricultural water use

In the water use quantification methodology, agricultural water use was estimated in the hydrological model, based on the spatial extent of agricultural crops from land cover/use datasets, together with estimates of the hydrological characteristics of agricultural crops and irrigation efficiencies. Better spatial datasets, which contain more specific information about crop types and irrigation practices, would be useful for model configuration. Measured irrigation abstractions, if available, could be used directly in the accounts or to verify modelled irrigation abstractions.

Starting state of catchment

There was some discussion regarding the catchment state (i.e. water stocks in the soil, groundwater and dams) at the start of an accounting period. Currently, the hydrological model is initialised by running it for an initial "warm up" period and then simulating several years continuously, ensuring that the starting state of one account matches the end state of the previous account. The measurement or estimation of the state of the catchment water resources at the start of an accounting period is important for both historical and forecast accounts.

Water allocations and restrictions

Delegates cautioned that water use should not be confused with water allocations, for example, the water quantities in the WARMS database represent water allocations and not actual use. It was also suggested that water restrictions needed to be considered in the model as, during restrictions, actual water abstractions may be below estimated crop requirements.

National consistency of datasets

Based on the vision of producing water resource accounts for the whole of South Africa, there was some discussion regarding whether only national datasets, for example national land cover/use, should be used or whether the best available dataset for each catchment should be used. On one hand, it was argued that using only national datasets would ensure consistency between catchments. On the other hand, for a specific catchment, it makes sense to use the best information available. In the case of land cover/use, a hierarchy of land cover/use classes was developed as part of the methodology so that more specific classes could be aggregated up, thereby enabling comparison between catchment accounts based on different land cover/use datasets. It was suggested that the sensitivity of the accounts could be tested to determine whether there was any merit in using more detailed datasets in some catchments.

Degraded land cover and alien invasive vegetation

There was a question regarding whether all natural vegetation was treated as being in a pristine condition or whether different degrees of degradation were taken into account. In the methodology, the land cover/use hierarchy makes provision for “typical” and “degraded” classes of natural vegetation and different hydrological parameters were used for each class. However, degradation can only be taken into account if suitable spatial datasets are available that specify the degree of degradation. Alien vegetation is not currently taken into account, but this could be done if a spatial map of alien vegetation were available.

Utilisable outflow

There was some discussion regarding the “utilisable outflow” component of the WA+ Resource Base Sheet. Delegates indicated that this was a particularly useful component of the account as it gives an indication of the capacity for the further development of water resources within a catchment. The estimated utilisable outflow values are useful, but need to be considered in the correct perspective. It is for a specific accounting period and does not represent a long-term availability of “spare” water. If the reserve is not known, part or all of the utilisable outflow may be required to meet a downstream reserve. The utilisable outflow may represent flood flows that may not be feasible to use.

Long-term perspective for account components

The water resource accounts represent a specific temporal domain, for example a specific month, season or year, which takes some getting used to when one is accustomed to the long-term statistical values typically used in water resources planning. Delegates agreed that it would be useful to have some indication where various components of the Resource Base Sheet fit in relation to long-term statistical values, for example to show the annual rainfall or streamflow for a catchment in relation to a cumulative frequency distribution of values for the same catchment.

National application of the accounts

Delegates indicated that, in order to achieve the vision of applying the water resource accounts nationally, the DWS’s Planning Section would be an important stakeholder. The DWS would be the ideal implementer of a national water accounting system, but it may be possible for CMAs to create accounts for catchment areas within their jurisdiction.

5.2.2 Focused discussion

Would these water resource accounts be useful to you?

The delegates at this workshop, as in the case at the first workshop, seemed to be interested in and supportive of the concept of water resource accounts. However, there seemed to be an even greater interest in the possibility of having a hydrological model setup for a catchment that could be used as a planning and operational tool for water management. The historical accounts are both interesting and useful, but forecast accounts would be of even greater value.

How would you use these water resource accounts?

The delegates suggested several ways in which they could potentially use water resource accounts, including the following:

- Operationalise the resource-directed measures (RDM) by helping to set reserve and resource quality objectives, and as an indicator of reach resource classes A to D.
- Evaluate whether an existing reserve had been met, or a proposed reserve could be met, for a specific accounting period.

- Use the utilisable outflow as an indication of excess flow available for other purposes, although long-term availability would need to be considered.
- Evaluate if there are water resources available for allocation to historically disadvantaged individuals and for additional irrigation.
- Determine the availability of wastewater and return flows for reuse within a spatial domain.
- Use for planning by municipalities.
- Use for integrated water resources management, especially where there are conflicting uses.
- Use to inform individuals about water availability and use by showing water use and return flows.
- Assist in verifying the WARMS database.
- Use forecast accounts to manage releases from dams.
- Use the accounts, by linking land use and management to water, as a useful integrator between several government departments.
- Use as an indicator of where water management could be improved.
- Use as an indicator of where more monitoring is required.
- Use as an indicator of where water is available for allocation.
- Evaluate scenarios for planning.
- Use by municipalities to assess development proposals.
- Use by DWS to contribute to the State of Water Resources report.
- Use for policy making at the national level and to highlight where development could take place or where infrastructure is needed.
- Guide where investment in ecological infrastructure is required.
- Help in international water-sharing negotiations.
- Could contribute to the UN's World Water Assessment Programme.

How could the water resource accounts be further developed to be more useful to you?

Suggestions for further developing the methodology and accounts included the following:

- Use of climate forecasts to produce forecast water resource accounts.
- It would be useful to include an estimate of water use by alien invasive vegetation.
- Show values for a specific accounting period relative to long-term values, assuming land cover/use is static and using long-term historical climate data.
- Improve rainfall estimates, especially in mountain catchment areas where there are few, if any, rain gauges.
- Improve the initialisation of accounts at the start of an accounting period.
- Include associated water quality accounts.
- Include accounts showing the environmental impact of altered water resource systems.

5.2.3 SWOT analysis

At the end of the discussion session, delegates were asked to individually complete a SWOT analysis for the water use quantification and accounting methodology. The SWOT analysis has been summarised and interpreted in Table 5-1 from the perspective of the existing methodology and account format developed and applied in WRC Project K5/2205, considering the role of the water resource accounts in meeting the objective of better water management at a catchment scale. The following definitions of the four components of the analysis were used:

- *Strengths:* Internal characteristics of the methodology and accounts that are helpful in achieving the objective.
- *Weaknesses:* Internal characteristics of the methodology and accounts that are harmful to achieving the objective.

- *Opportunities:* Opportunities for the further development and application of the methodology and accounts to help in achieving the objective.
- *Threats:* External factors that are harmful to achieving the objective.

Table 5-1: Summary and interpretation of the SWOT analysis

Strengths • The accounts collate and summarise water resource information to provide a consistent overview in an appropriate format. • The accounts provide useful information in a systematic way that is comparable across different catchments. • The accounts provide information and build understanding. • The accounts are useful and meet a need. • The accounts have varied uses and broad applicability. • The accounts are integrative between water use sectors and different stakeholders. • The accounts promote informed decision making. • The catchment scale is appropriate for the accounts to be used as a water management tool. • The accounting approach and methodology are sound.
Weaknesses • Currently, historical accounts are created, which have some value, but real-time or forecast accounts would be especially useful for water management. • Allocations and curtailments are not currently considered in water use estimates. • The methodology and the accounts need further validation and verification. • The modelling assumptions and the uncertainty associated with the estimated values used in the accounts are not documented. • They do not use a nationally consistent land use classification.
Opportunities • Develop forecast accounts showing estimated future water availability and use. • Develop an account sheet showing the historical ranges of water availability and use as context for accounts that represent a specific time domain. • Improve estimates of groundwater availability and use. • Include water quality accounts. • Use accounts to report climate change impacts. • Improve estimates of losses, re-use and gross abstractions. • Apply in more catchments. • Deliver better parameter and variable measurements and estimates. • Improve modelling algorithms. • Bring accountability into the national water status, both locally and internationally. • Use accounts to motivate for investment in data collection and monitoring. • Use accounts to promote collaboration. • Use accounts as a source of data and information for other projects and assessments.
Threats • There are limited financial and human resources within the project for further development. • The accounts are data intensive. • Too many people see this as the panacea to all their dreams, which may result in losing sight of the real objectives. • Incorrect interpretation of accounts and misunderstanding of the limitations may result in the accounts being misused.

- Potential lack of confidence or support for the hydrological model currently used.
- Potential sensitivity to sectoral water use estimates may result in a lack of support from some sectors.
- Lack of involvement of DWS.
- Potential lack of support from DWS and other key stakeholders.
- Lack of data due to insufficient monitoring, data of a poor quality and access to data being blocked.
- Lack of data to verify modelled estimates used in the accounts.
- Difficult to operationalise and lack of political will to operationalise.
- Resources required to apply at a national scale.

5.3 WORKSHOP 3: PRETORIA

The third workshop was held at the WRC's offices in Pretoria on 30 October 2018. The delegates at the workshop represented a variety of organisations, including the CSIR, the DWS, the Inkomati Usuthu Catchment Management Agency, the SANBI and StatsSA. The workshop started with a presentation describing the concept of water accounting, the main water accounting frameworks in use internationally, an overview of the water use quantification and accounting methodology, including challenges and the status quo. The presentation was followed by a focused discussion around the questions posed to the delegates. This section aims to summarise the main points of discussion.

5.3.1 Who could use the information in these accounts?

The delegates indicated that the DWS's National Office and the CMAs were both potential users of the water resources accounts as they could potentially inform reconciliation strategies, reporting on the SDGs and development of catchment management and national water resources strategies. The accounts could be used by StatsSA as a source of information for use in the SEEA-Water environmental economic accounts if the relevant data quality standards can be met.

5.3.2 How could the information in these accounts be used?

In addition to the WRC-funded water resource studies, there are existing systems at DWS that include national water resource assessments. However, delegates indicated that the water resource accounts provided a greater level of detail and a different focus. This greater level of detail could be useful in the following:

- Promoting a better understanding of water resource systems in general.
- Promoting a better understanding of water resource systems at different scales, from source to sea, especially related to identifying subcatchments that are critical to maintaining the integrity of the system and situations in specific subcatchments that have a substantial negative impact on the catchment system downstream.
- Providing an understanding of the water balance beyond the engineering-dominated viewpoint associated with water resources planning.
- Promoting cross-disciplinary understanding of water resources, and thus making cooperation easier.
- Improving understanding of the effect of land and water use on groundwater recharge.
- Providing the information required to calculate indicators linking ecosystems and water with economics.
- Providing the water quantity information required for the economic analysis of water resources and thus strengthening the currently weak understanding of the links between water and the economy, including understanding the economic value of the reserve.
- Helping to inform decisions around the downstream impact of allocations and licencing, and the localised pricing of water.
- Prioritisation where monitoring is crucial to determine water volumes and system health.
- Identifying aspects of existing DWS water balance systems that can be changed or improved.

In particular, delegates were concerned that there may be some overlap between the water resource accounts and the reconciliation strategies that try to balance supply with demand. It was concluded that the reconciliation strategies are more operational and locally focused, while water resource accounts are at a broader catchment level, but provide a more detailed land cover/use-related water balance. It was suggested that the characteristics of the water resources accounts be compared with the contents of the reconciliation strategies to determine where there were overlaps or synergies.

The water resource accounts could also potentially be linked to the classification system that aims to take environmental, economic and social requirements related to setting resource quality objectives (RQOs) into account.

There are definite synergies between the water resource accounts and reporting for the SDGs, with both appearing to have very similar data requirements. The water resource accounts could provide the data components required to calculate the SDG indicators, for example SDG 6.4.2 and SDG 6.6.1.

Delegates suggested that the water resource accounts could inform the development of catchment management strategies.

Public awareness regarding various aspects of water resources is critical and delegates suggested that water resource accounts can possibly be used as a tool to increase awareness if the accounts are made easily accessible to the public in a form that can be easily understood. Similarly, the accounts can be used for communication, such as with the Green Drop system, and as a starting point in public participation processes. The accounts may also be a useful tool for training.

Water resource accounts provide information about the historical and current state of water resources in a catchment, which is useful, but ideally need to be linked to some sort of specification of what the desired state is to provide a means of prioritising areas for monitoring and intervention. Thus, the accounts could provide a measure of the health of a system and whether the rights and reserve set for the system are being met, including international rights to water.

5.3.3 The identification of areas for further development

The delegates agreed that the intention to produce water resource accounts at a quaternary catchment spatial scale and annual time scale was the appropriate objective. Although the vision of doing the accounts for the whole country to produce a national water balance was good, it may be best to start by identifying priority areas for application until the methodology is more widely accepted, especially within DWS.

Typically, catchment water balances consider only bulk water abstractions for urban use. The current effort to quantify urban water use by sector in the water resource accounts is useful for making links to economic accounts to hopefully provide a better economic understanding of water. However, the quantification of urban water use by sector was an area that was identified as requiring further development. The accurate representation of water transfers between catchments, generally for urban water provision, is also important.

Groundwater is a critical source of water in some parts of the country. The water resource accounts include the quantification of the changes in groundwater storage and use of groundwater. The accounts will help to understand the effect of land and water use on groundwater recharge. However, it was agreed that the quantification of groundwater availability and use was an area that still requires more work in South Africa.

There is scope to include the calculation of indicators, such as water stress indicators related to the SGDs, in the water resource accounts.

5.3.4 How does one get buy-in from key stakeholders and find a home for these accounts?

There was some discussion regarding the most appropriate home for the water resource accounts. However, it was unfortunate that the relatively small number of delegates did not include a wider representation of the different departments within DWS. Delegates suggested that a starting point would be to identify where similar methodologies were being applied in DWS to identify where there are overlaps and synergies with the accounts. The delegates suggested that, if the primary intended use of the water resource accounts were to be for catchment management, then the production of the accounts would possibly be best situated within the CMAs. As the CMAs would have resources and most of the data required to produce the accounts, they could be operationally responsible for producing the accounts, which could also feed into the development of the catchment management strategy. However, delegates also felt that there may need to be some form of oversight or coordination by DWS's National Office, possibly the Water Resources Planning Section, which could potentially make use of the accounts in developing the National Water Resources Strategy. A pilot study and cost analysis would be necessary to determine the value provided by the accounts.

5.3.5 Data for water resource accounting

The delegates recognised that sufficient and suitably accurate data was key to the successful production of the water resource accounts. The delegates confirmed that they shared similar frustrations regarding the relatively sparse monitoring network, the sometimes poor availability and accessibility of data, and the problems related to the poor quality of data.

Improved monitoring would be important for providing the adequate high-quality data required to produce the water resource accounts, but this would require significant investment. However, the accounts could help identify monitoring requirements and provide motivation for the monitoring. The DWS needs to at least maintain the current level of monitoring. Good control of data quality and accessible storage of the monitored data would also be key to the successful production of the accounts. If increased monitoring is not feasible, it will be important to identify which data and monitoring locations were most critical. Additional legal requirements to report water abstractions and return flows would also assist in providing data for water accounting.

Given the costs associated with monitoring and that it is not practical, or in some instances even possible, to monitor everything everywhere, some innovative and pragmatic solutions may need to be adopted. Technical advances, such as in remote sensing, need to be investigated. Remote sensing estimates will need to be verified where possible and can provide a better understanding of the spatial variability of data. Some data may need to be indirectly inferred from whatever related data is available.

Delegates noted that it is now a legal requirement for irrigators to report abstraction volumes for irrigation, which should make it easier to quantify water use for irrigation. It was also suggested that irrigation boards may be a good source of data on irrigation abstractions as abstractions are measured as users are charged for water abstracted.

It was suggested that the Directorate of National Water Resources Planning and the Directorate of Water Services may be able to provide some information on urban water use. The Reconciliation Strategy reports and the All Towns reports may also provide useful information on urban water use.

Better information is required about the rules related to dam operations and inter-catchments transfers.

5.4 OUTCOME

The objectives of the workshops were achieved in that the delegates were introduced to the concepts of water accounting, they were informed of the development of the water use quantification and accounting methodology, and they were given the opportunity to discuss how the water accounts and methodology could be useful and to make suggestions for further development. The feedback provided by the delegates at the workshops was valuable in that it was encouragingly reflective, critical and constructive, and also provided insight into how the water resource accounts were perceived by water professionals from a wide range of organisations. The delegates were interested in the concept of water resource accounting and were supportive of the water resource accounting initiative. An unexpected outcome of the workshops was the interest by delegates in the possibility of having a hydrological model configured for a catchment, which could be used in a planning context to test different scenarios, and in an operational context with climate forecasts to assist in making water management decisions. This confirmed that the decision to use a modelling approach to compiling the water resource accounts, enabling forecasts and "what-if" scenarios to be tested was correct and indicated that there is a need for such a tool. The creation of forecast accounts would depend on the availability of suitable climate forecasts and would require substantial further development of the methodology as catchment states need to be updated in near real-time and catchment water management operational decisions need to be predicted.

For the water use quantification and accounting methodology, and the water resource accounts to be accepted, it is important to build confidence in the accuracy of the accounts and to expand the methodology and accounts to meet the requirements of water managers. To build confidence in the accuracy of the accounts, further validation and verification is required, and application is required in more catchments.

The availability of data of a goodquality would be critical for the successful production of the water resource accounts. Lack of sufficient and suitable data and limited resources to further develop and apply the methodology are possibly the two main threats to the methodology, especially if the vision of eventually applying the methodology to create annual water resource accounts nationally is to be achieved. The support of the DWS, especially, but also other government departments and parastatals, with a mandate to measure and collect meteorological, water and environmental data, will be critical. There are possible synergies with existing initiatives at DWS. However, the water resource accounts were perceived as providing a greater level of detail and a different focus, which may be useful in developing a greater understanding of water resources and the links between water and the economy. The accounts may also play a role in building public awareness of water resources. The accounts could potentially provide data to support reconciliation strategies, report on SDGs and develop catchment management and national water resources strategies. Based on the catchment-scale focus of the water resource accounts, the operational production of the accounts could potentially be done by CMAs, but possibly with oversight by the DWS's National Office. It is expected that water management institutions such as CMAs and WUAs could apply the methodology for short-term planning and operational water management. The creation of annual water resource accounts for the whole country will require buy-in and resources from the DWS as the ideal implementer of such a national water accounting system. However, before implementing the water resource accounts for the whole country to produce a national water balance, it was recommended that it may be best to start by operationally producing water resource accounts in one or more selected catchments as a test case until the accounts are more widely accepted.

CHAPTER 6: DATASETS AND METHODOLOGIES

DJ Clark

The purpose of water resource accounts is to provide a clear view of the water resource states and flows in a domain for a specified time period. However, these accounts are highly dependent on the availability and accuracy of the data and information required to compile them. Many of the data parameters are highly variable in both space and time. Karimi et al*.* (2013b) point out that the availability of data on water use, flows and stocks is a major constraint for reliable water accounting worldwide. There are three main methods of quantifying water resource states and flows: direct measurement, remote sensing and modelling. Direct measurements of states and flows, such as precipitation, reference evaporation, soil moisture, streamflow and reservoir levels, are generally the most accurate, but are also often the most expensive and thus sparse, both spatially and temporally. Direct measurements are also usually point measurements, which may not adequately represent the spatial variability of climate, soils, land cover/use and streamflows within a catchment. The direct measurement of some quantities, such as precipitation, reference evaporation and soil moisture, are made at a point and are thus not spatially representative. The use of remote sensing using ground-based or satellite-based instruments has grown in recent years and has the advantage of providing more spatially representative estimates, and estimates in locations where direct measurements are either not available or not possible. However, direct measurements are often required to perform the localised calibration of remotely sensed measurements to reduce localised biases. This project focused on the use of pre-processed remote sensing data products for ease of application in the methodology. Some of the data requirements for water accounts, such as water withdrawals from rivers and groundwater, cannot be determined using remote sensing. Modelling using hydrological models can also be used to populate water accounts. This can be relatively inexpensive, but hydrological models also require some measured input data such as land cover/use, precipitation and reference or total evaporation. Direct measurements, such as streamflow, are required to validate hydrological model setups. One big advantage of hydrological modelling is that it enables “what-if” type scenarios, such as changes in land use, to be evaluated. A combination of direct measurement, remote sensing and modelling is required to provide the data that is necessary to compile water resource accounts. The accuracy of the various data sources used to compile an account and the associated uncertainties need to be considered.

The purpose of this chapter is to describe the datasets selected for use in configuring the hydrological model for the purpose of compiling catchment-scale water resource accounts for South Africa. Where relevant, the methodology applied to process the available data to ensure that it is suitable for the intended purpose is described. There was a deliberate focus on the use of freely available datasets so that anyone can easily apply the methodology outside of the case study catchments. Thus, the water use quantification and accounting methodology were, to a large extent, influenced by the availability and suitability of the available datasets.

6.1 CATCHMENT BOUNDARIES

A dataset of catchment boundaries at an appropriate scale is required to compile catchment-scale water accounts. These catchment boundaries should be based on key points in the river flow networks such as the intersection of tributaries with the main river, the walls of large dams, flow measurement weirs and major abstraction and return flow points.

6.1.1 Primary, secondary, tertiary and quaternary catchments

The DWS has divided the geographical region of Lesotho, South Africa and Swaziland into a hierarchical system of catchments, composed of 22 primary catchments with secondary, tertiary and quaternary catchments. The quaternary catchments are widely used for water resources assessments in South Africa.

One of the products from WRC Project K5/1908 by Weepener et al. (2011a) was an improved set of primary, secondary, tertiary and quaternary catchment boundaries. Weepener et al. (2011a) explain that hydrologists at the DWS defined pour points for each of the quaternary catchments, based on recognisable points such as the intersection of tributaries with the main river and the walls of large dams. These pour points were also selected so that they did not deviate too much from the previous quaternary catchment boundaries. The revised set of primary (SLIM, 2014a), secondary (SLIM, 2014c), tertiary (SLIM, 2014d) and quaternary (SLIM, 2014b) catchment boundary datasets were obtained from the DWS's Directorate of Spatial and Land Information Management.

6.1.2 Sub-quaternary catchments

A common nested set of spatial boundaries will be required to enable the investigation of linkages between water resource accounts and other natural capital accounts, and the aggregation of water resource accounts for reporting at different levels, although this does not preclude different types of natural capital accounts being compiled at finer spatial resolutions within the common spatial boundaries. The quaternary catchments (SLIM, 2014b) are the smallest standard national set of catchment boundaries recognised by DWS. However, it is often desirable to do hydrological modelling at sub-quaternary catchment scale due to variations in climate, soils, topography and land cover/use within a quaternary catchment and to represent large dams and important water abstraction and return flow points within a quaternary catchment.

For the purpose of this study, the NFEPA (Nel et al., 2011a) catchment boundaries (Nel et al., 2011c) were selected for use as a starting point for developing sub-quaternary catchment datasets. Some advantages of using the NFEPA catchments dataset are that it is an existing dataset, it is based on the 1:500,000 rivers dataset for South Africa (DWS, 2012), and it would facilitate links to the river ecosystem accounts. The catchment boundaries from the quaternary catchments dataset (SLIM, 2014b) were used as a template and each quaternary catchment was subdivided using the NFEPA boundaries as a guideline, with the following adjustments being required:

- Small adjustments were made to the NFEPA boundaries where they did not match the quaternary catchment boundaries exactly.
- Some very small NFEPA catchments, particularly in tertiary catchment V11G, were merged to create bigger catchments, where, due to spatial variations in the density of the 1:500,000 rivers dataset, some NFEPA catchments are very small.
- Some NFEPA catchments were merged in instances where the NFEPA catchments intersect large dams.
- Small adjustments were made to the NFEPA catchment boundaries in a few instances where they did not match the DEM-based flow direction dataset (Weepener et al., 2011c).
- Some NFEPA catchments were subdivided to represent catchments for features such as new large dams and streamflow monitoring points.

6.2 ALTITUDE

Good altitude data is important for determining catchment boundaries. Altitude is also a key factor in describing the spatial variability of climate. Weepener et al. (2011a) used the 90 m resolution SRTM (Farr et al., 2007) DEM to develop an improved 90 m DEM for South Africa and other DEM-related datasets.

These datasets included the following:

- Polygon shapefiles of primary, secondary, tertiary and quaternary catchment boundaries
- A gap-filled DEM
- A hydrologically improved DEM

- A vector dataset of flow paths
- A raster dataset of flow accumulations
- A raster dataset of flow directions
- A raster dataset of slope
- A raster dataset of aspect
- A hillshade raster

In this study, the hydrologically improved DEM (Weepener et al., 2011d) was used to determine the mean altitude and mean slope for each sub-quaternary catchment. The flow direction (Weepener et al., 2011c) and flow accumulation (Weepener et al., 2011b) datasets were used to assist in developing the sub-quaternary catchment boundary dataset. The hydrologically improved DEM (Weepener et al., 2011d) and flow direction (Weepener et al., 2011c) datasets was used to determine the portions of catchments contributing runoff to small farm dams.

6.3 CLIMATE

The variability of climate, both spatially and temporally, results in variability in the availability and use of water resources. The water resource accounts can help to understand and manage this variability. The accuracy of the water resource accounts is highly dependent on good climate data. The ACRU model requires daily rainfall time series for each sub-quaternary catchment as an input. The ACRU model also requires daily ET_0 time series, or other climate variables from which it can be calculated for each sub-quaternary catchment as an input. Air temperature data is used in ACRU to adjust crop coefficients following periods of water stress. Rainfall seasonality is used in the configuration of the ACRU model to set the coefficient of initial abstraction and assist in making deductions about dryland crop types in different regions of the country.

6.3.1 Rainfall

Rainfall is a critical variable for catchment-scale water accounts as it is often a primary source of water to a catchment. The accuracy of rainfall measurements or estimates will have a significant effect on the accuracy of water resource accounts. Rain gauge measurements, or radar or satellite-based estimates, are required as input to a water resource account and as an input to a hydrological model that may be used to estimate other components of water accounts. However, even if rain gauge measurements are available, they are subject to measurement and recording errors, generally have a sparse spatial distribution, and as they are point measurements, are not a good representation of areal average rainfall for a catchment or even a particular land use within a catchment. The measurement and areal estimation of rainfall is difficult due to high spatial and temporal variability, especially during convective rainfall events (Kummerow et al., 2000; De Coning and Poolman, 2011). Ground-based radar estimates of rainfall were not considered for the study as this data could not be accessed and is not available for the whole of South Africa.

Based on the investigation described in Section 0, FEWS RFE 2.0 (Novella and Thiaw, 2012) was selected for application in this study. This daily rainfall dataset has a spatial resolution of 0.10° and starts in 2001. In addition, the *RS_GaugeFDBias* method, described in Section 0, was applied to adjust the remotely sensed rainfall estimates using rain gauge measurements to reduce the bias and calculate an area-weighted mean rainfall estimate for each sub-catchment. In this method, the remotely sensed satellite rainfall estimates are adjusted using common daily time series to calculate a cumulative frequency distribution curve for both the driver rain gauge time series and the remotely sensed driver rain gauge pixel time series and using the ratios between points on these curves to correct the daily remotely sensed catchment values based on a cumulative frequency distribution curve of the daily remotely sensed catchment values.

This method effectively calculates an adjustment at the driver rain gauge and then translates this adjustment to the catchment. Driver rain gauges were selected for each catchment based primarily on their proximity to the catchment, but also on similarity in altitude and MAP. All rain gauges for which a suitably long rainfall record was available, overlapping the FEWS RFE 2.0 dataset, were used, not only operational rain gauges.

Daily rain gauge data for the driver stations was obtained from the following sources:

- Automatic weather station measurements, made available by SASRI and Mondi, and accessible from the SASRI WeatherWeb portal [http://portal.sasa.org.za/weatherweb/]
- Rain gauge measurements, made available on the DWS's Hydrological Services – Surface Water (Data, Dams, Floods and Flows) page of the DWS's website [http://www.dwa.gov.za/hydrology/]
- Weather station data in NOAA's ISD dataset, made available for research purposes and accessed from NOAA's website [https://www.ncei.noaa.gov/data/global-hourly/access]

6.3.2 Rainfall seasonality

In instances where detailed information regarding the specific types of dryland and irrigated crops grown in a catchment is not available from a land cover/use dataset, it is useful to be able to make some assumptions regarding the crop type based on whether the catchment is in the summer, winter or all-year rainfall region of South Africa. For example, wheat is a major crop that is typically grown in the winter and all-year rainfall regions, and maize is a major crop typically grown in the summer rainfall region. Rainfall seasonality is also used in the methodology to adjust the coefficient of initial abstraction values for different land cover types based on the recommendations in Schulze (2013). In this study, a map of rainfall seasonality developed by Schulze and Maharaj (2008a) as part of the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze et al., 2008b) was used.

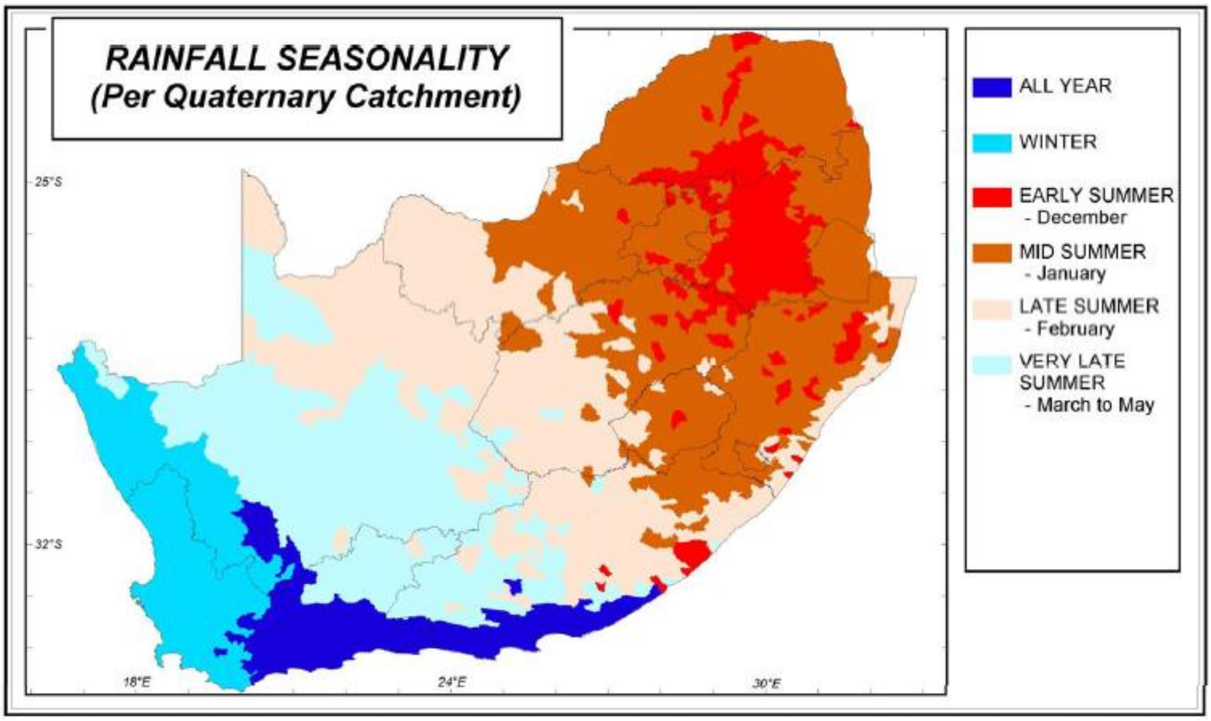

Figure 6-1: Map of rainfall seasonality (Schulze and Maharaj, 2008a)

6.3.3 Reference potential evaporation

The accurate estimation of ET for the different land uses within a catchment is an important component of water resource accounting and for understanding sectoral water use. The partitioning of ET into its components (evaporation of intercepted water, evaporation from the soil surface, transpiration by plants and evaporation from open water surfaces) will be useful for differentiating between beneficial and non-beneficial water use. In the methodology applied in this study, ET is estimated within the ACRU hydrological model as a function of an ET_0 demand, crop coefficients and soil water availability. Accurate special estimates of ET_0 are important as ET_0 is one of the key inputs required for hydrological modelling. The ET_0 can vary significantly in both space and time and, in addition, different types of land cover and land management result in different responses to this demand.

Based on the investigation described in Section 0, two ET_0 datasets were selected for use in this study:

- The SAHG's ET_0 dataset (Pegram et al., 2010; Sinclair and Pegram, 2010; Sinclair and Pegram, 2013a) of hourly estimates with a spatial resolution of 0.11° was developed using the Penman-Monteith equation (Allen et al., 1998), together with forecast climate data from the SAWS's UM version and remotely sensed radiation data. The SAHG's ET_0 dataset is available on the SAHG's website [http://sahg.ukzn.ac.za/soil_moisture/et] for the period October 2007 to February 2017.
- The LSA-SAF's METREF dataset (Trigo et al., 2011; De Bruin et al., 2016) of daily estimates with a spatial resolution of 3 to 4 km is an operational near real-time daily dataset using the FAO's Penman-Monteith equation for ET_0 and daily radiation data from the MSG satellite's SEVIRI platform (De Bruin et al., 2016). The METREF dataset is available on the LSA-SAF's website [https://landsaf.ipma.pt/en/products/evapotranspiration/metref/] since August 2016.

It was necessary to extend the SAHG's ET_0 dataset using the LSA-SAF's ET_0 as the SAHG's ET_0 dataset ends in February 2017, so does not cover the full accounting period for this study (2013 to 2018).

The ACRU model was originally developed to use A-pan ET_0, together with associated crop factors. Therefore, an adjustment factor of 1.2 (Shuttleworth, 2010) was applied to the ET_0 values in ACRU to estimate A-pan-equivalent daily ET_0 values.

6.3.4 Air temperature

Although air temperature is not directly required for water resource accounts, it is used in the ACRU model to adjust crop coefficients following periods of water stress and could potentially be used for crop yield modelling if water productivity were to be taken into account. As with rainfall and ET_0 data, ground-based measurements of air temperature are available from a sparse network of meteorological stations. As air temperature is not a critical variable for the hydrological modelling, and as crop yield modelling did not form part of the study, the datasets of long-term mean MOY maximum and minimum daily air temperature developed by Schulze and Maharaj (2008b; 2008c) were used in this case study. These datasets are part of the South African Atlas of Climatology and Agrohydrology (Schulze et al., 2008b) and give an indication of the spatial and temporal distribution of daily maximum and minimum air temperatures within a year.

6.4 LAND COVER/USE

The land cover within a catchment is typically heterogeneous, dynamic and can have a significant effect on the hydrology within a catchment. Water use within a catchment is closely linked to land cover and land use. In order to estimate sectoral water use within a catchment, the type, characteristics, extent and location of the land cover/use need to be determined.

Land cover and land use within a catchment are dynamic with natural seasonal variations and changes in agricultural crops, but also from year to year due to urban development, agricultural expansion, the invasion of alien plants, clear felling of plantations, burning and possibly even climate change. Land cover/use datasets that are derived from the classification of signatures from remotely sensed multispectral images are invaluable for estimating sectoral water use. Due to the dynamic nature of land cover/use, these datasets effectively represent the land cover/use at a point in time. However, for water accounts that are at a catchment scale and for relatively short time periods, it could be assumed that land cover/use stays relatively constant from one year to the next. Seasonal variations in the vegetated land cover are taken into account in the MOY hydrological characteristics of the vegetation used as input to the ACRU model. It is important that, as far as possible, the land cover/use maps that are used should represent the land use for the specific time domain of a water account.

As discussed in Clark (2015a), land cover/use datasets are compiled for different purposes by different people and organisations. Thus, the classification system used varies. For this reason, some form of standard classification of land cover/use is required so that the water use quantification and accounting methodology can be applied to different land cover/use classifications in a uniform and repeatable manner. The use of a standard classification also makes it easier to compare results from studies for different time periods or for different catchments. For each land cover/use dataset, it would be necessary to map each of the dataset classes to one of the standard classes, but having done that, a consistent methodology for quantifying water use can be applied. The development of a hierarchical system of standard land cover/use classes, for use in the water use quantification and accounting methodology, is described in Clark (2015a). This system includes the following:

- A lookup file for the standard land cover/use class hierarchy.
- A database of the standard land cover/use classes containing a set of hydrological modelling variable values for each class, including vegetation characteristics (canopy interception, crop coefficient, sensitivity to stress, root distribution), coefficient of initial abstraction, dryland or irrigated, annual or perennial, pervious and impervious area fractions.
- A set of mapping files relating land cover/use dataset classes to standard land cover/use classes.

The hierarchical structure provides a means of grouping similar land covers and uses so that they can be summarised with different degrees of detail in water accounts. The most specific categories are at the bottom of the hierarchy, within increasingly more general categories, ending with the most general categories at the top of the hierarchy. The following five categories form the top of the hierarchy:

- Natural: areas covered with natural vegetation or uncultivated bare ground
- Cultivated: areas covered with agricultural crops or production forest plantations
- Urban/built-up: urban and other built-up areas, including residential, commercial and industrial areas
- Mines and quarries: areas characterised by quarries, subsurface and surface mining features
- Waterbodies: open bodies of water and wetland areas with aquatic vegetation cover

As described in Clark (2015b), the methodology has a strong land cover/use emphasis and thus the determination of HRUs for modelling in ACRU are primarily based on land cover and use. The 2013/14 national land cover/use raster dataset (NLC 2013-2014) for South Africa (DEA and GTI, 2015), with a 30 m resolution and 72 classes, was used in this study and a mapping file relating the NLC 2013-2014 land cover/use dataset classes to the standard land cover/use classes was created, as shown in Appendix A.

The NLC 2013-2014 dataset uses six very broad classes to represent natural vegetation: indigenous forest, thicket/dense bush, woodland/open bush, grassland, shrubland fynbos and low shrubland. As described in Clark (2015a), the natural vegetation classes are mapped to a single standard vegetation class and the ACRU model is configured using the relevant Acocks veld type (Acocks, 1988) for the catchment.

The NLC 2013-2014 dataset does not include any classes that represent degraded natural vegetation, Thus, in this study, the effect of land cover degradation was not represented in the hydrological modelling or in the water accounts.

In NLC 2013-2014 (DEA and GTI, 2015), waterbodies are represented by two classes: water seasonal and water permanent. Thus there are no specific classes for artificial water bodies (i.e. dams) or one or more types of natural water bodies, such as rivers or inundated wetlands. For the purposes of this study, the water permanent class was assumed to be dams of various sizes, and the water seasonal class was assumed to be associated with river reaches and wetlands. However, it was noted that the water permanent class in some catchments also included open water in river reaches. Thus, the total area of dams in some catchments may be overestimated.

The classes that represent cultivated areas were useful in differentiating between a number of broad categories of agricultural land use that might have different hydrological characteristics and can be modelled accordingly. A few classes represent specific crop types such as sugarcane, pineapples and vines. However, many of the classes do not represent specific crops. Thus, as for the other datasets, annual dryland and irrigated field crops were assumed to be maize in the summer rainfall regions and wheat in the winter rainfall regions. For the purpose of the upper and central Breede catchment case study, the three cultivated orchards classes were assumed to be deciduous fruit crops, but in other catchments, they could potentially be other permanent crops such as citrus, stone fruit, nut trees, coffee, tea or even bananas. In Schulze (2013), different values are provided for vegetation variables for use in the ACRU model for four sugarcane-growing regions: KwaZulu-Natal South Coast, KwaZulu-Natal North Coast, Far North Coast and KwaZulu-Natal Inland. Using the methodology described in Clark (2015a), a shapefile of sugarcane-growing regions was created for the uMngeni catchment. This was used to determine the sugarcane-growing region, and could be determined for each HRU with sugarcane as a land cover/use.

With regard to irrigation, the NLC 2013-2014 dataset seems to only identify cultivated areas under centre pivot-type irrigation systems and not cultivated areas under other types of irrigation systems. This meant that all non-pivot-irrigated cultivated areas had to be assumed to be dryland, which could potentially mean that irrigation water use will be significantly underestimated in some regions. Water requirements for irrigation are estimated in the ACRU model, which was configured to use a soil water deficit scheduling method. The ACRU model was configured so that, in each sub-quaternary catchment, the lumped registered dam, if one exists, was assumed to be the water source for irrigation. Otherwise, irrigation was assumed to be from run-of-river sources on the main river reach within the catchment.

The classes in NLC 2013-2014, which represented urban areas, are useful in differentiating between a number of broad categories of urban areas that might have different hydrological and water use characteristics and can be modelled accordingly. The NLC 2013-2014 dataset includes a subclass for many of the urban classes, including the categories dense trees/bush, open trees/bush, low vegetation/ grass and bare. In this study, these subclasses were not taken into account as the pervious areas were assumed to have natural vegetation, based on Acocks's veld types (Acocks, 1988). Urban areas were represented in the ACRU model, as described in Clark (2015b), using a combination of pervious vegetated areas (irrigated in some instances), disjunct impervious areas (representing roofs) and adjunct impervious areas (representing roads and other infrastructure that are connected directly to some form of storm drainage). The proportion of these different areas varied for the different classes of urban areas. Residential water requirements, as described in Clark (2015b), were determined using population estimates from the functional typology population dataset of the CSIR (CSIR, 2013), based on the 2011 population census, and estimated daily water requirements for the different classes of urban area from the CSIR (2003).

For higher-density urban areas such as cities and towns, a large dam is typically assigned as the source of water for all residential water requirements, and return flows are assumed to occur in the catchments in which they were generated. For the low-density rural urban areas, the lumped registered dam in the local sub-quaternary catchment, if one exists, was assumed to be the water source, otherwise water from run-of-river sources on the main river reach within the catchment would be the water source. Industrial water use was not included, as no specific data, or a simple means of estimating it, was available.

6.5 SOIL CHARACTERISTICS AND SOIL MOISTURE STORAGE

The water stored in the soil profile of a catchment is one of the water stocks that needs to be estimated as part of a catchment water resource account. However, if the account is over a long period of time (i.e. a year), this may not be a critical input to the account. To determine the change in water stored in the soil profile during the accounting period, only the soil water storage at the start and end of the accounting period needs to be known. It is possible that direct point measurements of soil moisture could be available for irrigated fields or in small research catchments. However, this is not a feasible option when compiling water accounts for catchments. Satellite-based remote sensing estimates of soil moisture using radar backscatter, as discussed by Gibson et al. (2009) and Sinclair and Pegram (2010), offer good spatial representation, but only represent the moisture near the surface of the soil and not the whole soil profile.

The soils dataset developed and described by Schulze and Horan (2008) was used in this study. The soil hydrological properties that are included in the dataset are the depth, porosity, drained upper limit and wilting point for each of the A and B soil horizons, and also the saturated drainage rate from the A to the B soil horizon. Using the methodology described in Clark (2015a), the soils dataset is used as one of the region datasets used to generate the *LCURegions* spreadsheet. The dominant soil type for each land cover/use-based HRU within each sub-quaternary catchment was then used to determine the hydrological characteristics required by the ACRU hydrological model for each HRU. The soil moisture stores were initialised to 50% of plant available water (PAW). Tthe ACRU model was then run for a warm-up period of one full hydrological year prior to the start date of the required simulation period.

6.6 SURFACE WATER STORAGE

Surface water storage is understood to be water stored in lakes and dams and in snow and ice, although snow and ice can safely be ignored in South Africa for annual water accounts, as when snowfalls occur, these generally melt within a few days. Dams can have a significant effect on the hydrology within a catchment due to their regulatory effect on water flows and due to evaporation from their open water surfaces. In addition to the large dams built to provide a secure water supply to urban areas, many catchments may also have a large number of smaller farm dams of various sizes used for irrigation, stock watering and recreational fishing. The surface water storage of a catchment is one of the water stocks that needs to be estimated as part of a catchment water resource account, and may be important in catchments that contain a large lake or dam or numerous small farm dams.

For the large dams and other registered dams, the spatial location, full storage capacity and full surface area are specified in the DWS's database of registered dams (DSO, 2016). The large dams were modelled as individual dams and were assumed to be on the main river channel at the downstream exit of their respective catchments. The other registered dams in each sub-quaternary catchment were then lumped together by summing surface areas and storage capacities and calculating a composite area-to-capacity relationship to create a single lumped registered dam per catchment. These lumped registered dams were specified as being either on or off the main river channel and used as a water source for all water users in a sub-quaternary catchment. In sub-quaternary catchments where the NLC 2013-2014 land cover/use dataset (DEA and GTI, 2015) indicated a total surface area or dams greater than the total area of registered dams, a vector dataset of dam polygons derived from the NLC 2013-2014 land cover/use dataset was used in conjunction with the DSO (2016) database to identify unregistered dams.

For each unregistered dam, the estimated full surface area was used with the Maaren and Moolman (1985) equation to estimate the full storage capacity. The unregistered dams within each sub-quaternary catchment were then lumped together by summing surface areas and storage capacities and calculating a composite area-to-capacity relationship to create a single lumped unregistered dam per catchment. These small unregistered dams impede runoff generated within a sub-quaternary catchment, but were not assumed to be on the main river channel, and were not used as a source of water for irrigation. The area of the individual unregistered farms estimated from the land cover/use dataset was used together with the generalised empirical relationship $A = 7.2\ S_v^{0.77}$ (where: A = surface area [m^2]; S_v = surface area [m^3]), developed by Maaren and Moolman (1985), to estimate the individual dam volumes, and the areas and volumes were then summed.

In the uMngeni catchment and the upper uThukela catchment, the area-to-volume relationships of the large dams were provided by DWS's Durban regional office. In the Breede catchment, the area-to-volume relationships of the large dams were estimated using historical time series of measured depth-to-volume data. The area-to-volume relationships of the smaller, registered and unregistered farm dams were estimated by adjusting the generalised empirical relationship $A = 7.2\ S_v^{0.77}$ (where: A = surface area [m^2]; S_v = surface area [m^3]), developed by Maaren and Moolman (1985), to fit the full surface area and storage capacity for each dam.

The NLC 2013-2014 land cover/use dataset (DEA and GTI, 2015), the DEM dataset (Weepener et al., 2011d) and the flow direction dataset (Weepener et al., 2011c) were used to estimate the region within each sub-quaternary catchment that is upstream of farm dams. In each catchment, the runoff into dams and outflow from dams were configured as follows:

- HRUs within the region upstream of farm dams contribute runoff to the lumped unregistered dam, if it exists, otherwise to the lumped registered dam, if it exists.
- The lumped unregistered dam, if it exists, then flows into the lumped registered dam, if it exists.
- The lumped registered dam, if it exists, then flows to an individual large registered dam, if it exists, otherwise to the outlet of the catchment.
- HRUs within the region downstream of farm dams contribute runoff to an individual large registered dam, if it exists, otherwise to the outlet of the catchment.

The storage volumes of large dams at the start of the modelling warm-up period (1 October 2013) were initialised using measured values recorded by DWS and made available on the DWS's National Integrated Water Information System (NIWIS) Surface Water Storage webpage [http://niwis.dws.gov.za/niwis2/SurfaceWaterStorage]. The storage volumes of the smaller registered and unregistered farm dams were initialised to 50% of full storage capacity at the start of the simulation and the ACRU model was run for a warm-up period of one full hydrological year prior to the start date of the required simulation period.

As part of the hydrological modelling, it is necessary to take water released from large dams to meet ecological flow requirements and for abstraction by users downstream into account. These flow releases from large dams were estimated using measured flow data from the Hydrological Services – Surface Water (Data, Dams, Floods and Flows) page of the DWS's website [http://www.dwa.gov.za/hydrology/]. For the large dams, DWS measures flow over the spillway, and most of these dams have a flow measurement weir a short distance downstream of the dam. Thus, it was initially assumed that the flow releases could be estimated by subtracting any spillway flows from the flows at the downstream weir. However, for many of the large dams, it was found that when the dam was spilling flows, downstream weirs were spilling less than the spillway flows. The reason for this could not be determined. Thus, flow releases were estimated from daily flow volumes at the downstream weir, but during dam spill periods, the flow releases were estimated based on daily flow volumes just before and just after the spill period.

Seepage from large dams was assumed to be zero as, if there is any seepage, it would be accounted for in the estimation of flow releases described above. For the smaller registered and unregistered farm dams, a maximum seepage rate of 0.067% of the dam's full storage capacity per day was assumed, based on the recommendation in Smithers and Schulze (1995). The estimated area-to-capacity relationship for each dam is used in the ACRU model to estimate the current depth based on the current volume of water stored in the dam. The seepage rate is then varied with the depth of water, i.e. seepage reduces as the depth of water in the dam decreases.

As the water resource accounts were compiled for an annual time period, sub-daily flow routing of flows through dams and river reaches was not performed; hence, the hydraulic characteristics of the dam spillways are not required.

6.7 GROUNDWATER STORAGE

The groundwater storage of a catchment is another of the water stocks that needs to be estimated as part of a catchment water resource account. Changes in the groundwater stocks are expected to be relatively slow, but trends in decreasing groundwater stocks over several annual water accounts could help to identify unsustainable use of groundwater. Estimates of groundwater storage at the start and end of an accounting period would enable the change in groundwater storage over the time period to be determined. It is unlikely that direct measurements of groundwater storage and groundwater flows between catchments would be available for a whole study catchment (Karimi et al., 2013b), except possibly for some groundwater research catchments. In this study, the baseflow store in the ACRU model was initialised by running the model for a warm-up period of one full hydrological year prior to the start date of the required simulation period. The net change in the baseflow store during each annual accounting period was then used in the water accounts to indicate the change in groundwater storage within a catchment.

6.8 RIVER FLOW NETWORK

Knowledge of the river flow network, together with catchment boundaries, is required to be able to determine surface flows from one catchment to another and to enable the aggregation of accounts from sub-quaternary catchments to higher-level catchments. Knowledge of the river flow network is also required to be able to locate confluence nodes and nodes where abstractions, return flows, inter-catchment transfers and streamflow measurements occur. The NFEPA rivers shapefile (Nel et al., 2011b) was used in this case study to match the NFEPA catchment boundaries. This rivers dataset, together with the sub-quaternary catchment boundaries dataset, was used to create a point shapefile of river nodes. A river node was created where each sub-quaternary catchment boundary intersected a river segment at any points where there was a confluence of river reaches between these points and at points where river reaches flowed into large dams. For each node, attributes were set specifying the downstream node and indicating whether the node was at the exit of a sub-quaternary catchment. Typically, in the ACRU model, river reaches are modelled as simple conduits of water with no surface area within the catchment through which they flow. As the water resource accounts were compiled for an annual time period, sub-daily flow routing of flows through river reaches was not performed. Thus, hydraulic characteristics such as length, slope, friction and cross-sectional area were not required.

6.9 ABSTRACTIONS, RETURN FLOWS AND TRANSFERS

Water is abstracted from rivers, dams and groundwater for a range of different uses, including domestic use, use in industrial processes, hydropower generation and for the irrigation of agricultural crops. Some of these water users, especially irrigation users, deplete a large portion of the water abstracted, while others may return a large portion of the abstracted water, but may possibly return it to a different portion of the river flow network and possibly with a poorer quality of water.

As development in certain catchments reaches the point where demand exceeds the local supply, one solution is to transfer water from neighbouring catchments. Information on abstraction, return flows and transfers is an important part of water resource accounts as it quantifies the sectoral use of blue water and also represents the artificial movements of water within and between catchments. In principle, abstractions and transfers should be easy to quantify as they mostly require water to be pumped and because many of the users are required to pay for the water supplied, which is measured. Water supply systems are complicated, and are administered by a large number of different organisations. Thus, there is no single repository for this data, the amount of data is large, and it is difficult to gain access to this data.

6.9.1 Urban use and return flows

In this study, urban water use is understood to include residential, commercial and industrial water use in cities, towns and rural areas. The quantification of urban water use and return flows is important for water accounts as urban water use is not only significant in catchments with large urban areas, but this use often also involves transfers of water between catchments. Water for urban use is required at a high level of assurance. However, a large portion of water extracted for urban water use is often returned for further use within or downstream of the catchment in which it is used via waste water treatment works, except when used for irrigating sportsfields and gardens, filling swimming pools, used in evaporative cooling and incorporation into food and beverage products. Water for urban use may come from within the catchment in which it is situated or from a different catchment, as is often the case with cities supplied by large dams. In addition, water use and return flows by urban areas are often difficult to quantify spatially using catchment boundaries as census, municipal and cadastral boundaries often cross catchment boundaries.

In this study, the approach described in Clark (2015b) was applied to provide an estimate of residential (domestic household) water use. Population data was used, together with estimated per capita water use values for different classes of urban areas. The CSIR_SATypology_2013 dataset (CSIR, 2013), developed by the CSIR from the 2011 census data, was used. The CSIR (2013) dataset uses polygons based on the mesozones of the Functional Settlement Typology for South Africa, developed by the CSIR, which takes the amount and variety of functions provided by specific urban areas into account, as well as the population density and interconnectivity of these areas.

The first step was to determine which land cover/use classes existed within each mesozone polygon and the areal fraction of these land cover/use classes for each sub-quaternary catchment within each mesozone polygon. For each urban residential land cover/use class within a mesozone polygon, these fractional areas, together with a population density weighting for each class, was used to estimate the population of each urban residential land cover/use class. These population estimates were then aggregated for each catchment to estimate the population of each urban residential land cover/use class for each sub-quaternary catchment. For each urban residential land cover/use class, an average daily water use per capita and a return flow fraction were initially assigned based on the values in the user manual for the Water Situation Assessment Model (WSAM) (DWAF, 2005). However, the average daily water use per capita values from DWAF (2005) seemed to result in an overestimation of urban residential water abstractions, and so values from CSIR (2003) were used. These per capita population water use and return flow values were used to model urban water use in the ACRU model. Where the water source for a significant residential water user, such as a city or town, was known to be a specific dam, possibly even in a different catchment, the water source was specifically configured to supply that demand. Where the specific water source was not known, especially in rural areas, the water source was assumed to be from the registered dam in the same catchment or from run-of-river water. The uMngeni catchment is highly urbanised and the water infrastructure is highly developed, resulting is substantial transfers from dams in source catchments to the point of use.

Using water footprint information provided by Umgeni Water, a water source was assigned to each of the sub-quaternary catchments. However, the four large dams in the uMngeni catchment (Midmar Dam, Albert Falls Dam, Nagle Dam and Inanda Dam) also supply water to urban areas outside the catchment, so the residential water requirements for these areas was also estimated, and the relevant quantities of water were transferred from the catchment. Return flows from urban areas within the uMngeni catchment were assumed to occur within the same catchment in which the urban use took place. Industrial and commercial water use was not included in the water use estimates in the case study catchments.

The water use quantification methodology described in Clark (2015b) and in this study has focused mainly on water use by natural and cultivated land cover/use. Quantification of urban water use and return flows is a component of the methodology that requires further development.

6.9.2 Irrigation water use

Water use for irrigation is strongly linked to climate, soil type and the type of crop grown. If measurements of water abstracted for irrigation are not available, water use can be estimated using a crop yield or a hydrological model. In this study, water requirements for irrigation were modelled using the ACRU hydrological model. One potential problem with modelling water use for irrigation is that the NLC 2013-2014 land cover/use dataset (DEA and GTI, 2015) includes broad classes that distinguish between dryland and irrigated agriculture, but does not differentiate between type of irrigated crop, type of irrigation system or management practices. The DWS's WARMS database (Anderson et al., 2008) contains information on registered water use, but actual water use may differ from this amount due to climate variability and seasonal or annual changes in the area irrigated. However, the WARMS database does provide useful information on the type of irrigated crop and the type of irrigation system used, although the WARMS data only has point spatial reference, making it difficult to reconcile this information with the land cover/use datasets. As stated in Section 2.4.1, annual dryland and irrigated field crops were assumed to be maize in the summer rainfall regions and wheat in the winter rainfall regions. In the Breede catchment, perennial crops were assumed to be deciduous fruit trees.

6.9.3 Inter-catchment transfers

Large-scale inter-catchment transfers between major catchments are well documented, but depending on the catchment scale at which the water resource accounts are compiled, there may be many relatively small transfers between smaller catchments to supply water to cities and towns. The large-scale inter-catchment transfer flow quantities were estimated using measured flow data from the Hydrological Services – Surface Water (Data, Dams, Floods and Flows) page of the DWS's website [http://www.dwa.gov.za/hydrology/]. These large-scale inter-catchment transfers were included in the hydrological modelling and are described in more detail for each of the case study catchments in Chapter 0 to Chapter 0. The smaller-scale inter-catchment transfers that are related to urban water supply were estimated and represented as described in Section 0.

6.10 RESERVED FLOWS

Karimi et al*.* (2013a) explain that there may be a portion of blue water that, although not depleted in the domain of the account, is not available for use within the domain. A portion of the flow may be reserved to meet water requirements downstream, such as environmental flow requirements, navigational flow requirements and flows committed to downstream users. The reserve was not represented in the Resource Base Sheet accounts compiled for the case study catchments in this study, as further investigation is required on how to do this. The reserve is determined at a point on a river, and could be included in the accounts at that point. However, some means would be required to be able to translate the reserve to points upstream that represent individual smaller-scale catchments to provide an indication of whether individual upstream catchments were contributing a reasonable portion of the reserve.

6.11 MEASURED STREAMFLOW

The flow of surface water and groundwater from a catchment is the net result of all the other hydrological and artificial flows into, out of and within the catchment. In a mass balance water resource account, the surface water and groundwater flows from a catchment form the balance of the account after all inflows outflows and changes in storage have been accounted for. If measured, streamflow data is available, which can be used to verify the accuracy of the estimated surface water outflows. If parts of the account cannot be estimated, such as changes in storage, then the use of measured streamflow in the account may, in some instances, enable these missing parts of the account to be estimated, assuming that all the other parts of the account are correct. Measured streamflow data from the Hydrological Services – Surface Water (Data, Dams, Floods and Flows) page of the DWS's website [http://www.dwa.gov.za/hydrology/] was used for verification purposes for each of the case study catchments in Chapter 0 to Chapter 0.

CHAPTER 7: UMNGENI CATCHMENT CASE STUDY

DJ Clark

The uMngeni catchment forms part of the Pongola-Mtamvuna WMA, situated in the summer rainfall region of KwaZulu-Natal, South Africa, as shown in Figure 7-1. The catchment has an area of 4,455 km^2 and the altitude ranges from 1,913 m in the west to sea level in the east (Warburton, 2011). The MAP varies from 1,550 mm in the west to 700 mm in the drier middle part of the catchment (Warburton, 2011). The uMngeni River is the main source of water for the urban areas of Durban and Pietermaritzburg. The uMngeni River is regulated by four large dams (Midmar Dam, Albert Falls Dam, Nagle Dam and Inanda Dam) and is augmented with transfers from the Mooi River in the uThukela catchment. The National Water Resources Strategy (NWRS) (DWAF, 2004b) states that the Durban metropolitan area is the second-largest commercial and industrial area in South Africa and that strong population growth is projected for the uMngeni catchment due to urbanisation and economic growth in the Durban/Pietermaritzburg area. Rural areas include subsistence and commercial farming, with extensive irrigated agriculture, the cultivation of sugarcane and commercial forestry plantations (DWAF, 2004b). Streamflow in the catchment is largely perennial and there is little extraction of groundwater (DWAF, 2004b).

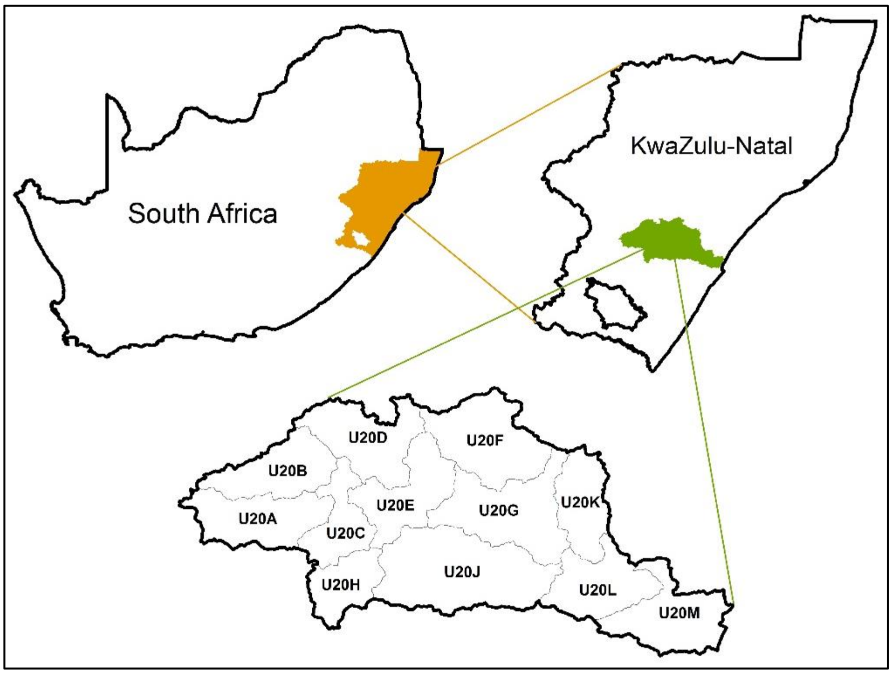

Figure 7-1: Locality map and quaternary catchments for the uMngeni catchment

The uMngeni catchment consists of the U20 tertiary catchment, which has the same boundary as the U2 secondary catchment. The U20 tertiary catchment contains 12 quaternary catchments. The areas of each of the secondary, tertiary and quaternary catchments are shown in **Error! Reference source not found.**. The quaternary catchment boundaries, rivers, registered dams, water transfers, streamflow gauges, driver rain gauges and driver evaporation stations are shown in Figure 7-2. The DEM altitudes are shown in Figure 7-3. The initial configuration of the ACRU model to produce water accounts for the uMngeni catchment, described in Clark (2015a), was completely revised in this study using the datasets and methodology described in Chapter 0, including new sub-quaternary catchment boundaries based on the NFEPA catchment boundaries (Nel et al., 2011c), use of the NLC 2013-2014 land cover/use dataset (DEA and GTI, 2015), improved modelling of dams, improved representation of transfers to urban areas within the catchment and representation of water transfers to urban areas outside the catchment.

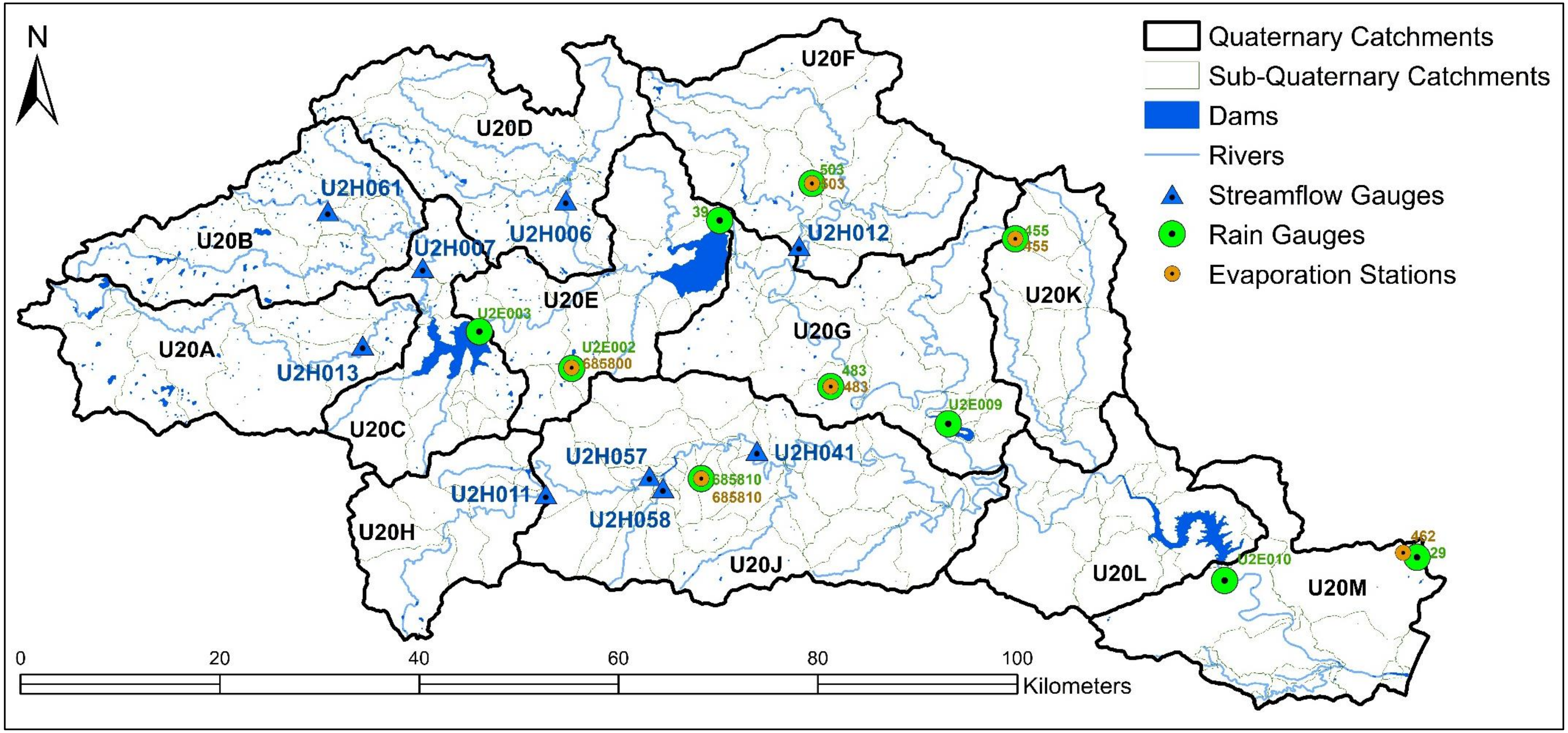

Figure 7-2: Catchments, rivers, dams, water transfers and measurement stations in the uMngeni catchment

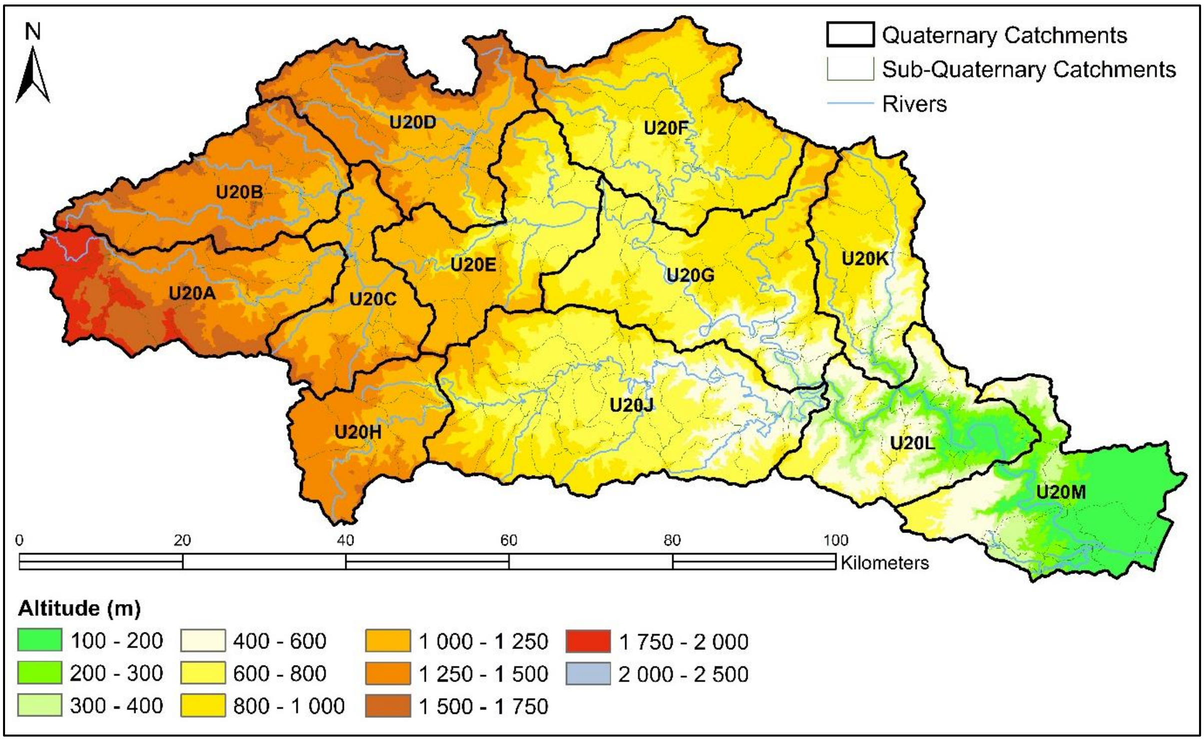

Figure 7-3: DEM altitudes for the uMngeni catchment (after Weepener et al., 2011e)

Table 7-1: Secondary, tertiary and quaternary catchment areas (km^2) (SLIM, 2014b)

Catchment areas (km^2)													
Secondary	**Tertiary**	**Quaternary**											
U2	U20	U20A	U20B	U20C	U20D	U20E	U20F	U20G	U20H	U20J	U20K	U20L	U20M
4456	4456	365	325	237	387	339	448	482	220	680	269	330	375

7.1 CLIMATE

The uMngeni catchment is located in the summer rainfall region of South Africa. Most of the catchment is classified as having mid-summer rainfall, while quaternary catchment U20M, near the coast, is classified as having late-summer rainfall (Schulze and Maharaj, 2008a). The MAP for the catchment is shown in Figure 7-4. Rainfall is highest in the Karkloof area in the north. The cooler western and northern parts of the catchment experience frost in winter, with only quaternary catchments U20L and U20M being largely frost free (Schulze and Maharaj, 2008d). The rain gauges that were used as driver stations to reduce the localised biases in the spatial rainfall estimates are shown in Figure 7-2.

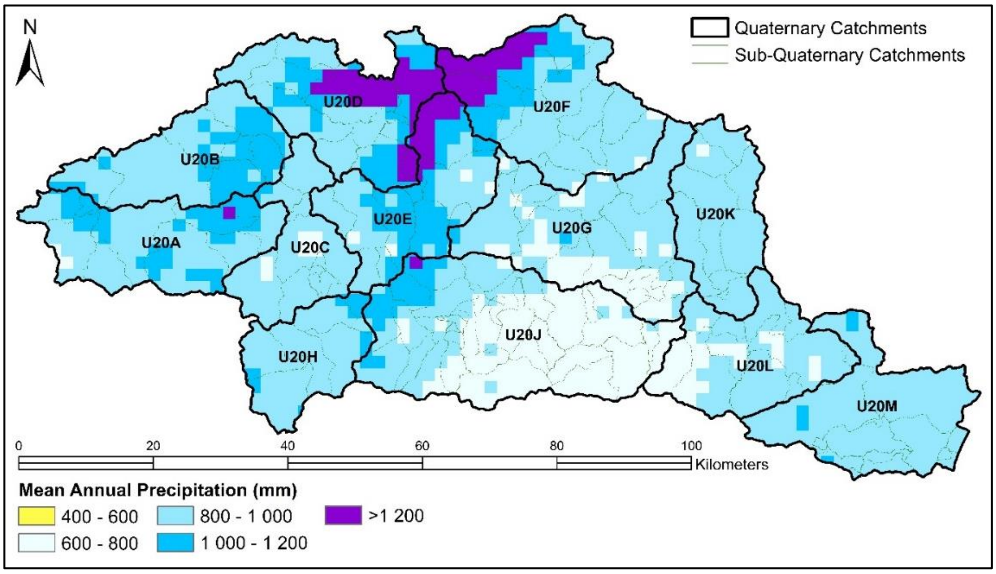

Figure 7-4: Mean annual precipitation in the uMngeni catchment (after Lynch, 2004; Schulze and Lynch, 2008a)

7.2 LAND COVER/USE

The spatial distribution of land cover/use for the uMngeni catchment is shown in Figure 7-5, based on the classification in the 2013/14 national land cover/use raster dataset (NLC 2013-2014) for South Africa (DEA and GTI, 2015). Natural vegetation in the catchment is predominantly grassland in the western part of the catchment and thicket/dense bush in the eastern part of the catchment, with some indigenous forest in the Karkloof area in the north. There is substantial urban land use in the catchment, which includes the urban areas of the greater Pietermaritzburg and Durban areas. Cultivated land use in the catchment includes substantial areas of forest plantations, sugarcane and other commercial crops, both dryland and irrigated. The catchment includes four large dams (Midmar Dam, Albert Falls Dam, Nagle Dam and Inanda Dam) and many small farm dams, especially in quaternary catchments U20A to U20E.

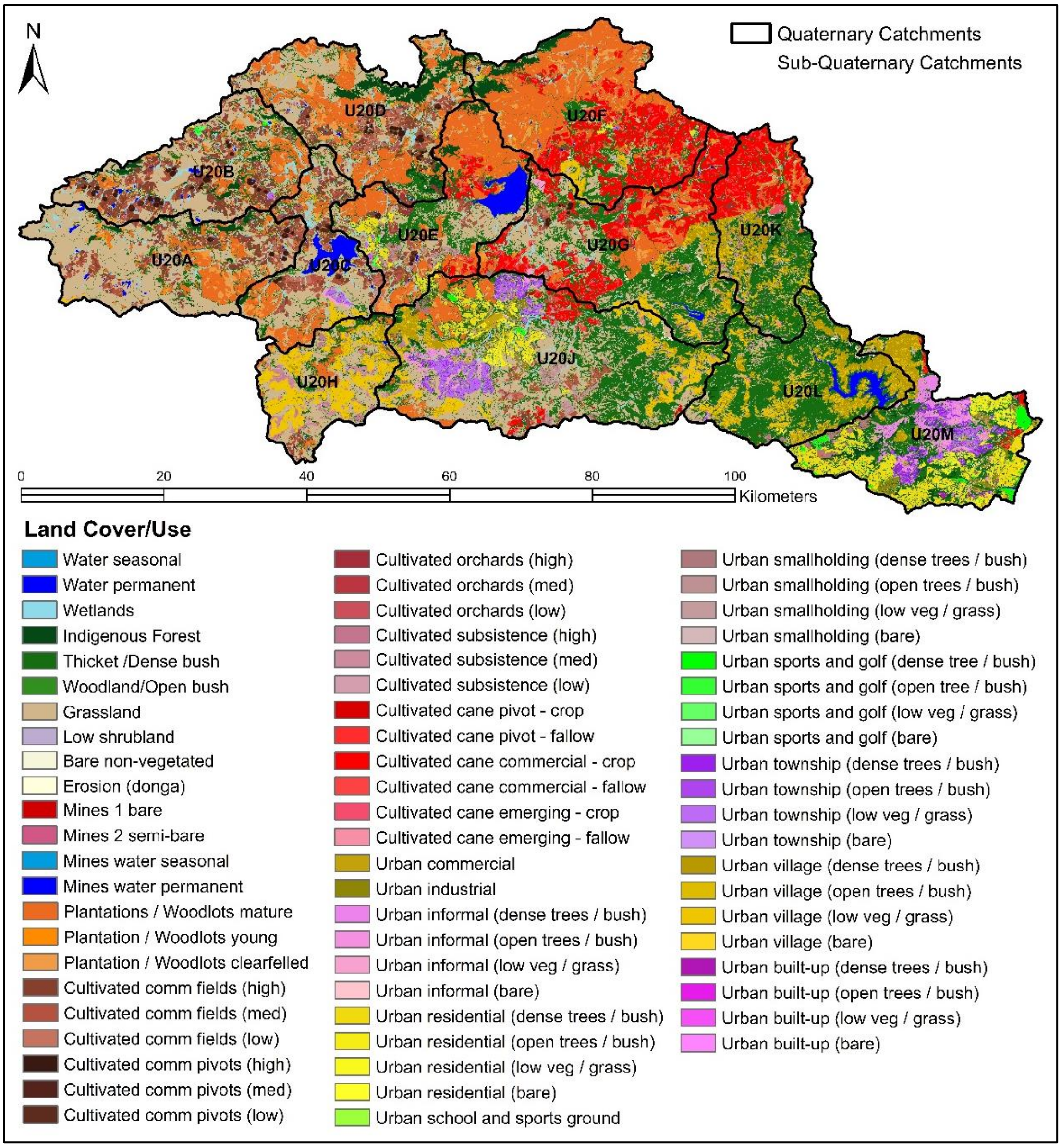

Figure 7-5: Land cover/use classes in the uMngeni catchment from the NLC 2013-2014 dataset (after DEA and GTI, 2015)

7.3 TRANSFERS, ABSTRACTIONS AND RETURN FLOWS

The only inter-catchment transfers into the uMngeni catchment are the transfers from Spring Grove Dam and Mearns Weir in the neighbouring uThukela catchment to the Mpofana River, a tributary of the Lions River in quaternary catchment U20B. Measured transfer flow values from Spring Grove Dam and Mearns Weir were included in the hydrological modelling and water resource accounts.

There are numerous transfers of water from major dams to urban areas in other catchments both within and outside the uMngeni catchment. Return flows from urban areas within the uMngeni catchment were assumed to occur within the same catchment in which the urban use took place. For the urban areas outside the uMngeni catchment, a daily water consumption figure was estimated from each of the three main supply dams (Midmar Dam, Nagle Dam and Inanda Dam), with water being released from Albert Falls Dam to supply Nagle Dam. These estimated transfers from the uMngeni catchment were abstracted from the relevant dams and were thus included in the hydrological modelling and water resource accounts.

7.4 RESULTS

The ACRU hydrological model was configured for the uMngeni catchment using the datasets and methodology described in Chapter 0 and in Section 0 to Section 0. The model was run for a five-year period from October 2013 to September 2018. The first hydrological year (2013/14) of the simulated period was regarded as a warm-up year to enable the initialisation of soil water and baseflow stores in the model. Where possible, it is useful to verify modelled water balance variables using measured data. For the purposes of this study, measured streamflow data was used to verify the modelled streamflow at several points in the catchment. The details of this verification exercise are included in Section 0. The verification showed that, although modelled streamflow was acceptable at a small number of gauges, the flow at most of the streamflow gauges was not simulated accurately, with the simulated streamflow volumes over the four-year period being undersimulated by more than 50% in several of the gauged catchments. The streamflow volumes were typically better modelled in the upper parts of the catchment. The results indicated that the urban areas, in particular, were not simulated well. This was noted as a key area where the methodology needed to be improved. The investigation, in Section 0, into methods of reducing localised bias in remotely sensed rainfall estimates, showed that an acceptable simulation of streamflow using remotely sensed rainfall data was possible. However, it is likely that poor rainfall estimates was one of the main causes of the poor simulation results. The verification in the uMngeni catchment highlighted the need for rain gauge measurements in, or close to, the catchments to be modelled, and the careful selection of driver rain gauges. The water infrastructure in the uMngeni catchment is highly developed and better information is required to describe the sources of water for each sub-quaternary catchment.

Using simulated catchment water balance variables, water resource accounts were compiled for each sub-quaternary catchment and for each month of the year. These water resource accounts were then spatially and temporally aggregated to compile annual accounts for each quaternary, tertiary and secondary catchment in the uMngeni catchment. The annual water inflows and outflows for the whole uMngeni catchment for each hydrological year are shown in Figure 7-6 to provide an overview of flows in the catchment for the four-year period. The annual Resource Base Sheet accounts for the whole uMngeni catchment are shown in Figure 7-7 for 2014/15, Figure 7-8 for 2015/16, Figure 7-9 for 2016/17 and Figure 7-10 for 201/18. An example of the Withdrawal Sheet account for 2017/18 is shown in Figure 7-11. The water volumes shown in the accounts are shown in thousands of cubic metres. The water depths, shown in millimetres, are the water volumes divided by the whole catchment area. Given the poor verification results, the values shown in the accounts should not be quoted as absolute values, but should rather be considered as indicative of the relative significance of the different components of the water balance.

Rainfall and evaporation are the two dominant flows, as clearly illustrated in Figure 7-6, highlighting the large proportion of rainfall that is lost as evaporation, and thus not available for managed water use. Apart from artificial transfers from Spring Grove Dam and Mearns Weir into quaternary catchment U20B, the only source of water to the catchment is rainfall as there is no flow into the uMngeni catchment from any upstream catchments. The volume of water transferred into the catchment was substantially higher in the period starting in 2015/16 than in the previous years to maintain water levels in the Midmar Dam amid uncertainty regarding how long the drought would continue. In both 2015/16 and 2017/18, there was a net increase in all the water stores, and the inter-catchment transfer was a key source of water, enabling this increase in storage. Looking at the *Landscape ET* section of the accounts, the majority of total evaporation occurs in the natural and cultivated categories, but with significant contributions from the urban and waterbodies categories. Irrigated agriculture represents only about 4% of the catchment area and the *Incremental ET* section of the account shows a small portion of total evaporation being contributed by irrigation.

Looking at the evaporation processes, the greatest portion of total evaporation occurs through transpiration, followed by soil water evaporation and then interception evaporation. There are substantial water transfers from the catchment to urban areas outside the catchment, which are included in the *Reserved Outflow* section. Information about reserved environmental flows was not included in the accounts. In the Withdrawals Sheet (Figure 7-11), urban water use is shown to be the primary user of water abstracted from dams and rivers in the catchment. However, a substantial portion of the water abstracted for urban water use is returned for potential reuse within the catchment.

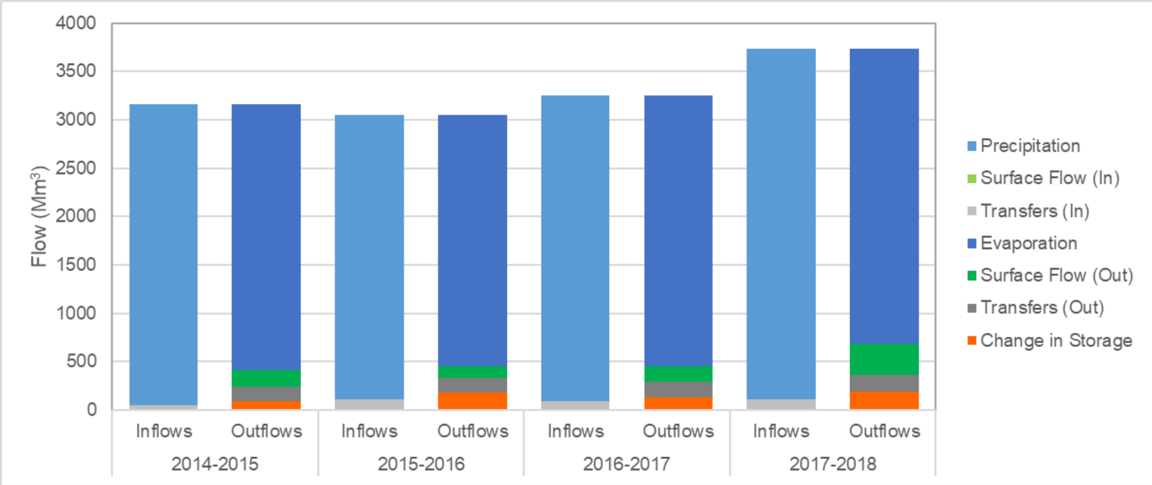

Figure 7-6: Summary of inflows and outflows for the uMngeni catchment

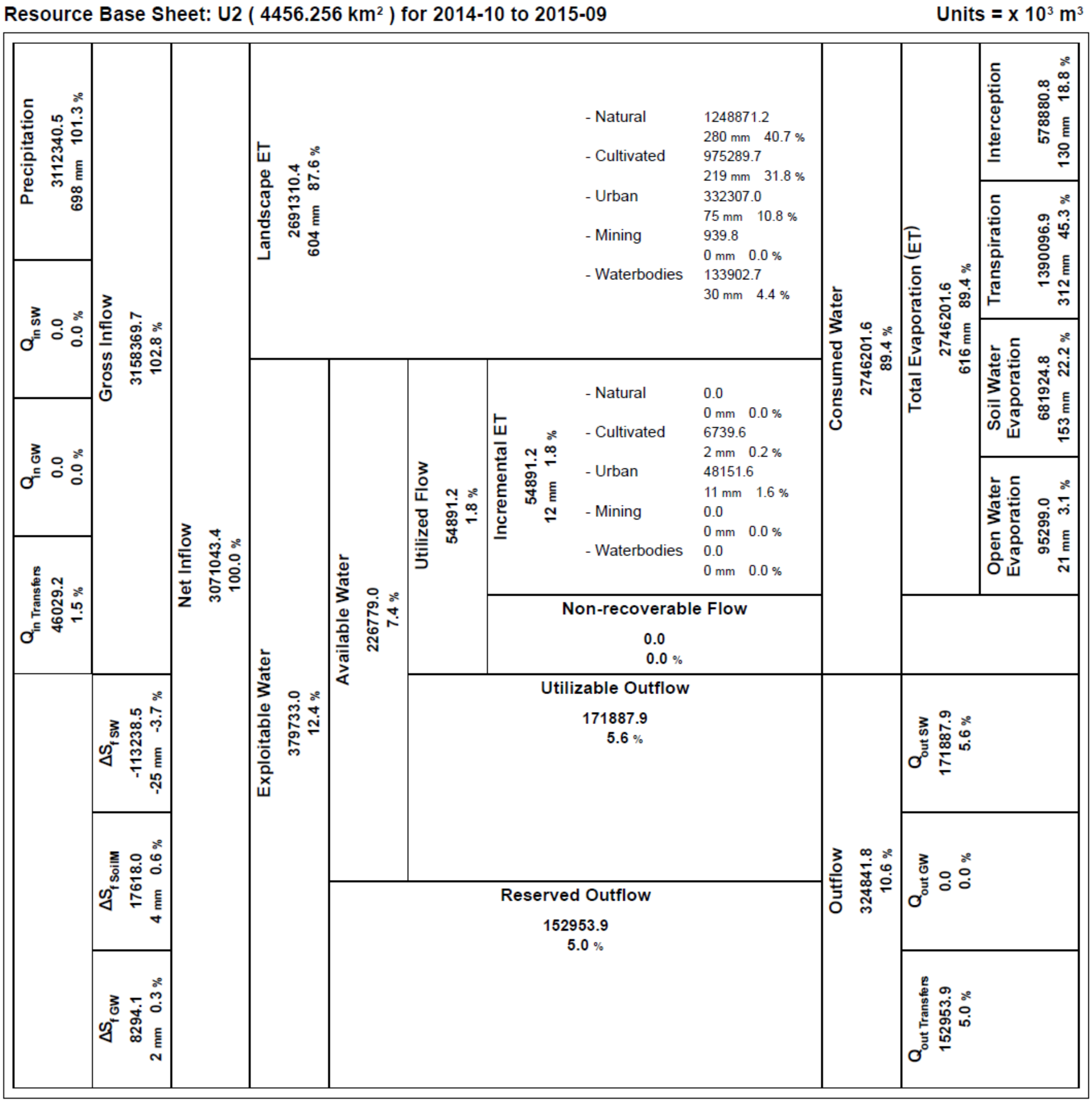

Figure 7-7: Resource Base Sheet for the uMngeni catchment (2014/15)

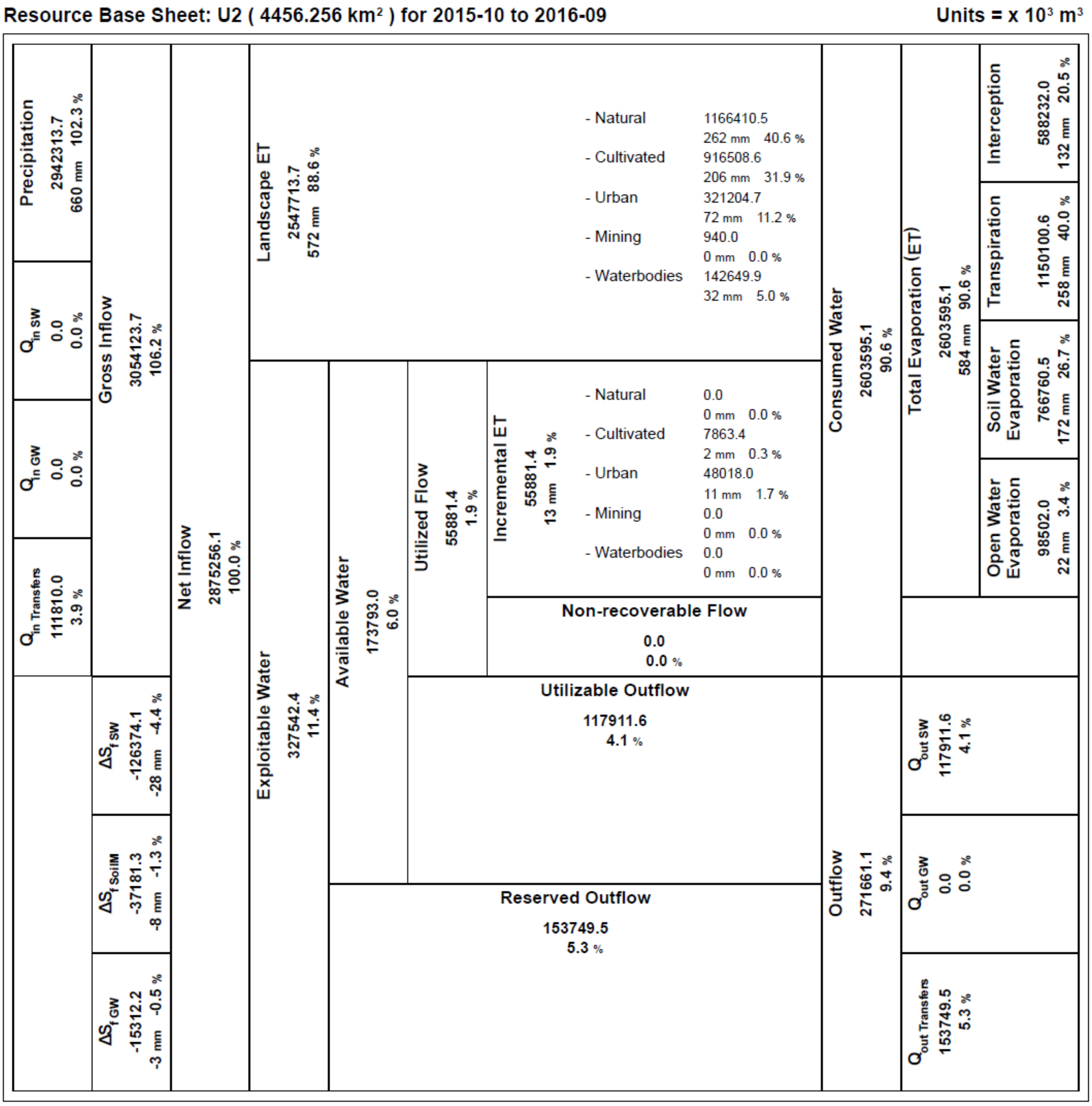

Figure 7-8: Resource Base Sheet for the uMngeni catchment (2015/16)

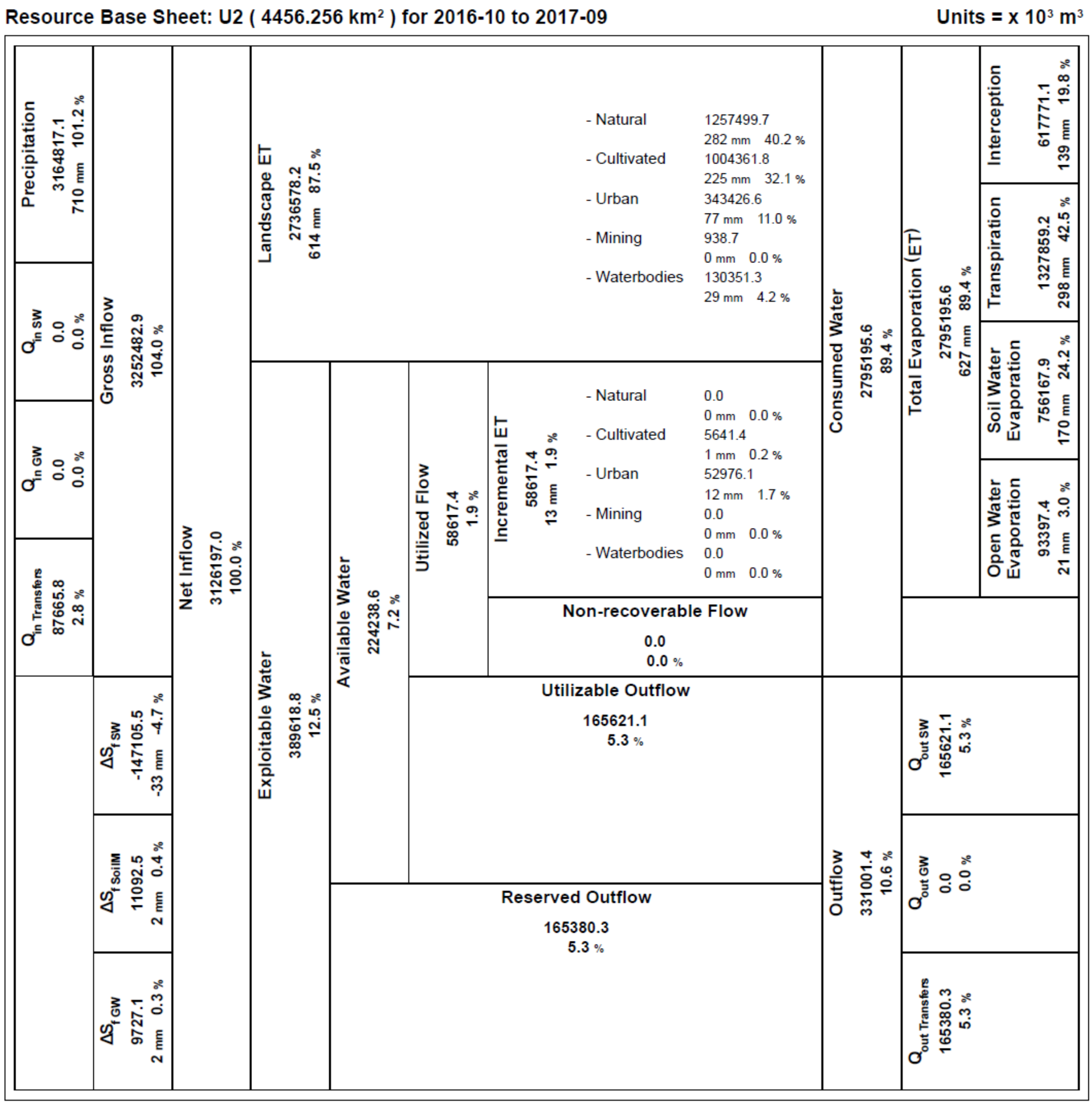

Figure 7-9: Resource Base Sheet for the uMngeni catchment (2016/17)

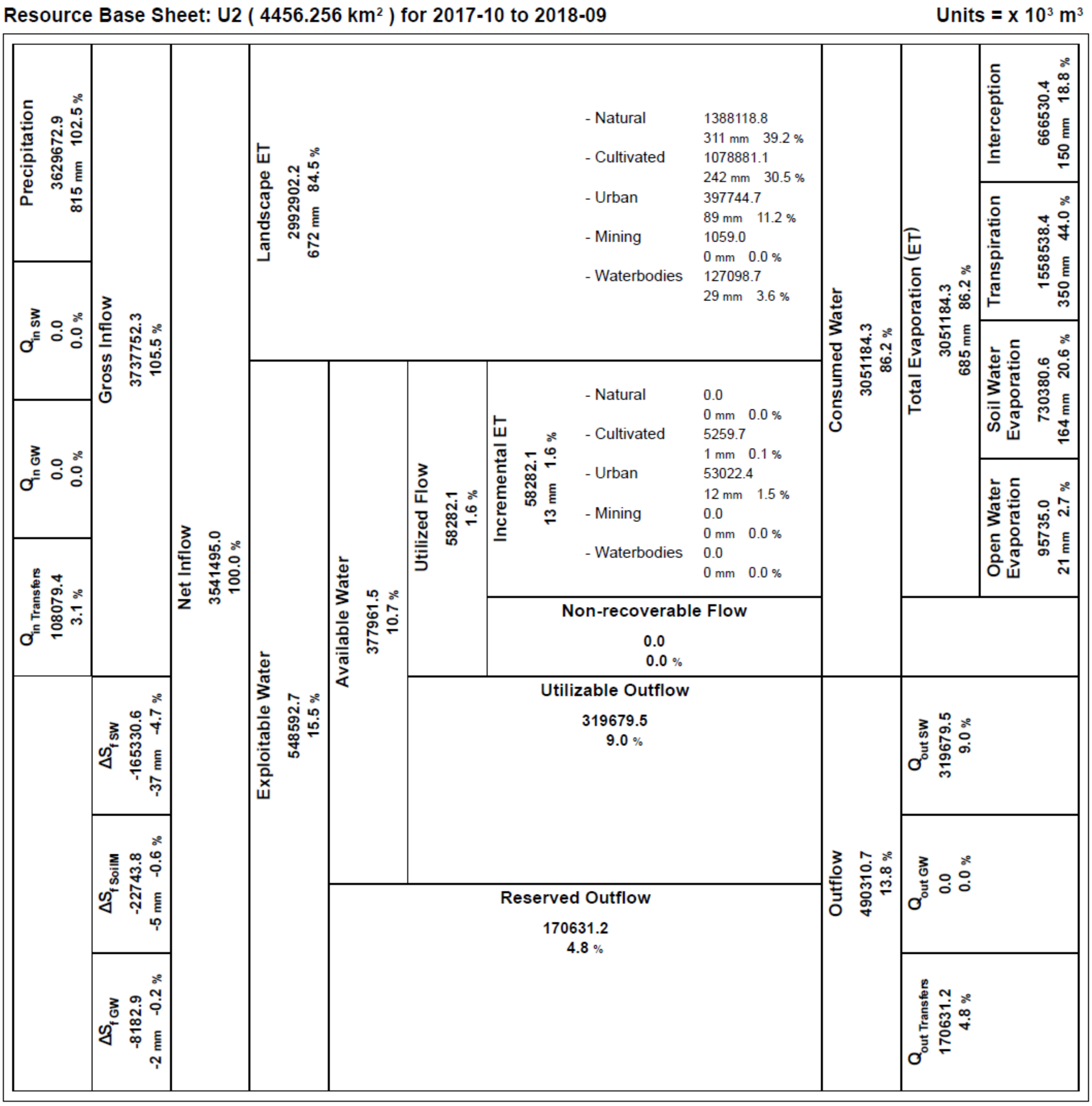

Figure 7-10: Resource Base Sheet for the uMngeni catchment (2017/18)

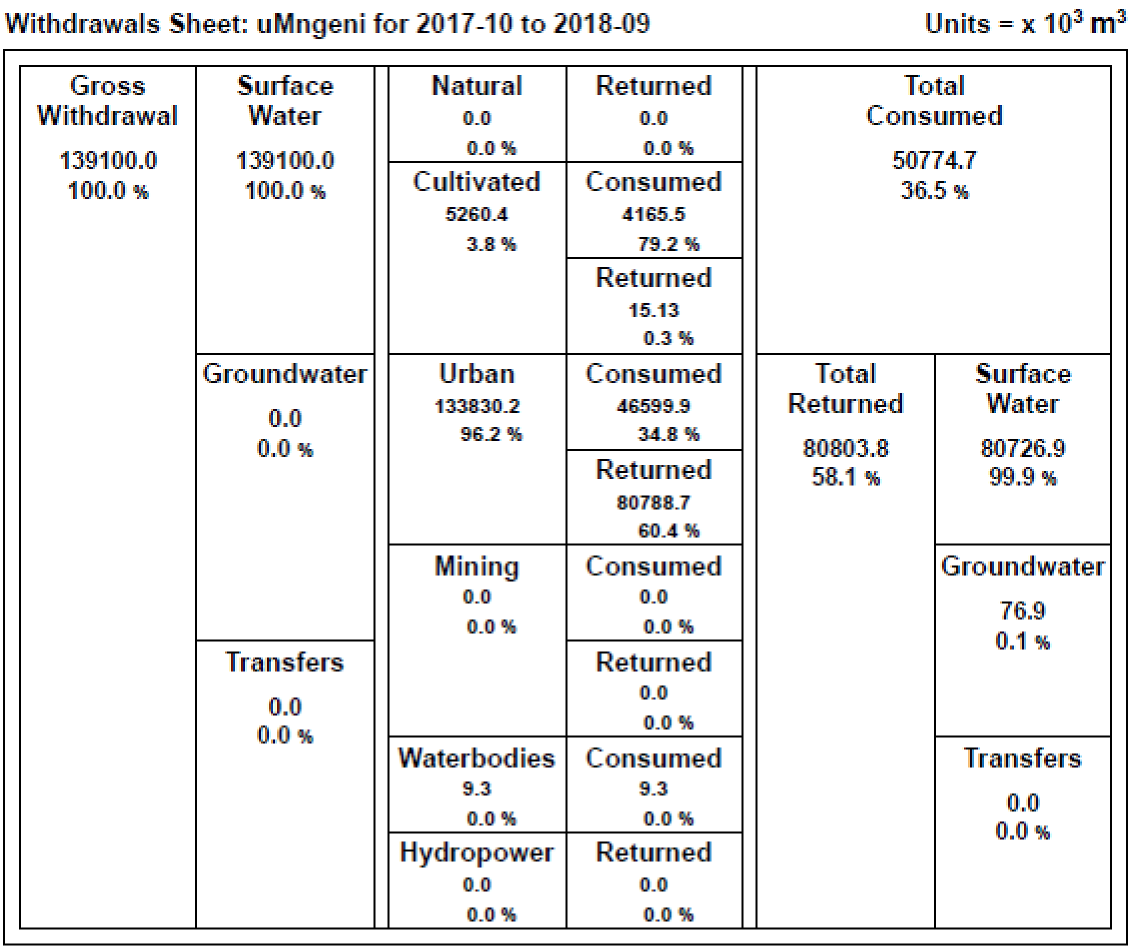

Figure 7-11: Withdrawal Sheet for the uMngeni catchment (2017/18)

CHAPTER 8: UPPER UTHUKELA CATCHMENT CASE STUDY

DJ Clark

The uThukela catchment forms part of the Pongola-Mtamvuna WMA, which is situated in the summer rainfall region of KwaZulu-Natal, South Africa, as shown in Figure 8-1. The catchment has its headwaters in the Drakensberg Mountains and drains eastwards into the Indian Ocean. The uThukela River is the largest river in the Pongola-Mtamvuna WMA and is one of the few major river systems in South Africa that has not been fully developed (DWA, 2013). The river is already a source of water for transfers into the Vaal system and into other catchments in KwaZulu-Natal to support important centres of economic growth (DWA, 2013). DWAF (2004b) describes the uThukela catchment as being predominantly rural. The primary economic activities are forestry, agriculture and ecotourism. Due to the availability of surface water in the catchment, there is only a small portion of water use from groundwater (DWAF, 2004b). The population in the catchment is expected to remain relatively stable as there are no major economic centres in the catchment itself (DWAF, 2004b).

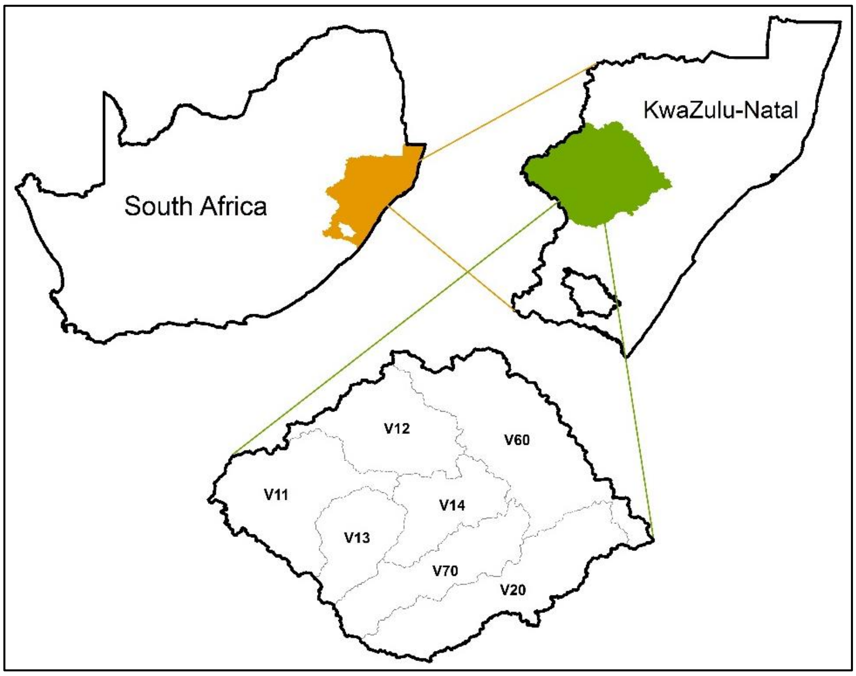

Figure 8-1: Locality map and tertiary catchments for the upper uThukela catchment

For the purpose of this project, the uThukela case study area will comprise the following secondary catchments: upper uThukela (V1), Mooi River (V2), Sundays River (V6) and Boesmans River (V7). Collectively, these catchments will be referred to as the upper uThukela catchment. These catchments were selected as the Mooi River catchment (V2) includes Spring Grove Dam and Mearns Weir, which are the sources of an inter-catchment transfer to the uMngeni catchment. The upper uThukela (V1) and the Mooi River (V2) catchments include significant areas of dryland and irrigated agriculture in addition to protected mountain catchment areas, which will be a useful test for the methodology. The upper uThukela catchment consists of the V1, V2, V6 and V7 secondary catchments. The V1 catchment is further subdivided into four tertiary catchments. The V11, V12, V13, V14, V20, V60 and V70 tertiary catchments are further subdivided into 55 quaternary catchments. The areas of each of the secondary, tertiary and quaternary catchments are shown in Table 8-1.

The quaternary catchment boundaries, rivers, registered dams, water transfers, streamflow gauges, driver rain gauges and driver evaporation stations are shown in Figure 8-2. The DEM altitudes are shown in Figure 8-3. For the purpose of hydrological modelling, the V11D and V11E quaternary catchments were merged as the Woodstock Dam spans the boundary between these two catchments.

Table 8-1: Secondary, tertiary and quaternary catchment areas (km^2) (SLIM, 2014b)

Catchment areas (km^2)													
Secondary	**Tertiary**	**Quaternary**											
V1	V11	V11A	V11B	V11C	V11D	V11E	V11F	V11G	V11H	V11J	V11K	V11L	V11M
	2625	198	259	254	273	178	163	319	131	137	253	311	148
	V12	V12A	V12B	V12C	V12D	V12E	V12F	V12G					
	2156	312	299	171	240	319	241	573					
7621	V13	V13A	V13B	V13C	V13D	V13E							
	1360	234	301	245	291	290							
	V14	V14A	V14B	V14C	V14D	V14E							
	1481	224	172	196	619	270							
V2	V20	V20A	V20B	V20C	V20D	V20E	V20F	V20G	V20H	V20J			
2869	2869	267	190	189	286	609	154	256	610	308			
V6	V60	V60A	V60B	V60C	V60D	V60E	V60F	V60G	V60H	V60J	V60K		
3719	3719	107	532	382	308	761	398	485	340	187	220		
V7	V70	V70A	V70B	V70C	V70D	V70E	V70F	V70G					
1920	1920	281	122	340	196	106	371	504					

The catchment has an area of 16,129 km^2 and the altitude ranges from 3,451 m at Mafadi Peak (the highest peak in South Africa) in the Drakensberg Mountains in the west to 474 m in the east. The MAP varies from approximately 1,900 mm in the west to 500 mm in the drier eastern part of the catchment. The catchment includes part of the Maloti-Drakensberg Park, which is a United Nations Educational, Scientific and Cultural Organisation (UNESCO) world heritage site. Rural areas include subsistence and commercial farming, with extensive irrigated agriculture in the western and southern parts of the catchment. The catchment contains several small towns, including Bergville, Winterton, Ladysmith, Escourt and Mooi River. The catchment contains several large dams, including Woodstock Dam, Driel Barrage, Spioenkop Dam, Braamhoek Dam, Wagendrift Dam, Spring Grove Dam and Cragie Burn Dam. The upper uThukela (V1) catchment includes the lower portion of the Drakensberg Pump Storage Scheme and the lower portion of the new Ingula Pump Storage Scheme. The Drakensberg Pump Storage Scheme is also used to transfer water to the Vaal system via the Drakensberg Pump Storage Scheme. There are additional inter-catchment transfers from the V2 secondary catchment to the upper uMngeni catchment supplied from Spring Grove Dam and Mearns Weir.

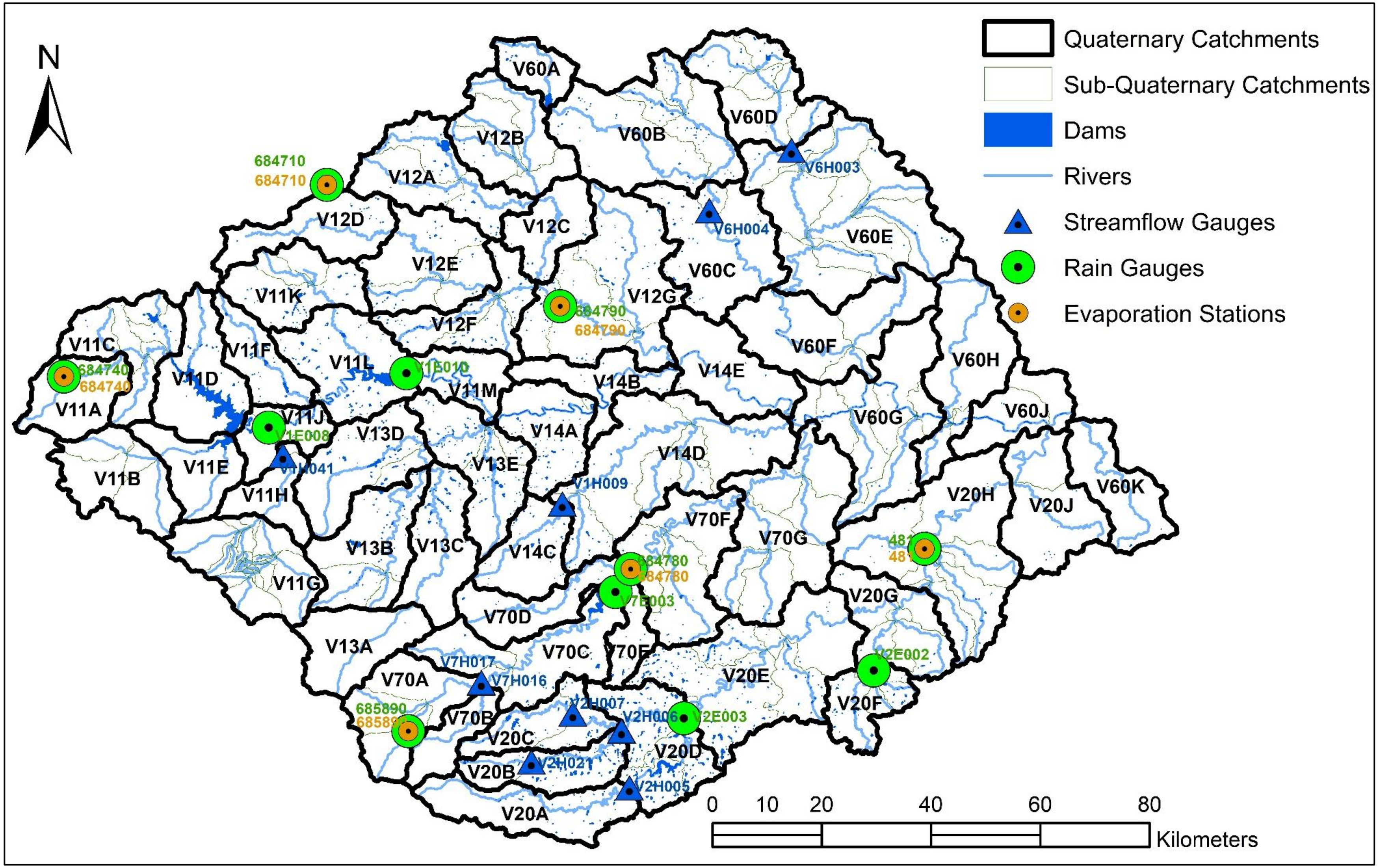

Figure 8-2: **Catchments, rivers, dams, water transfers and measurement stations in the upper uThukela catchment**

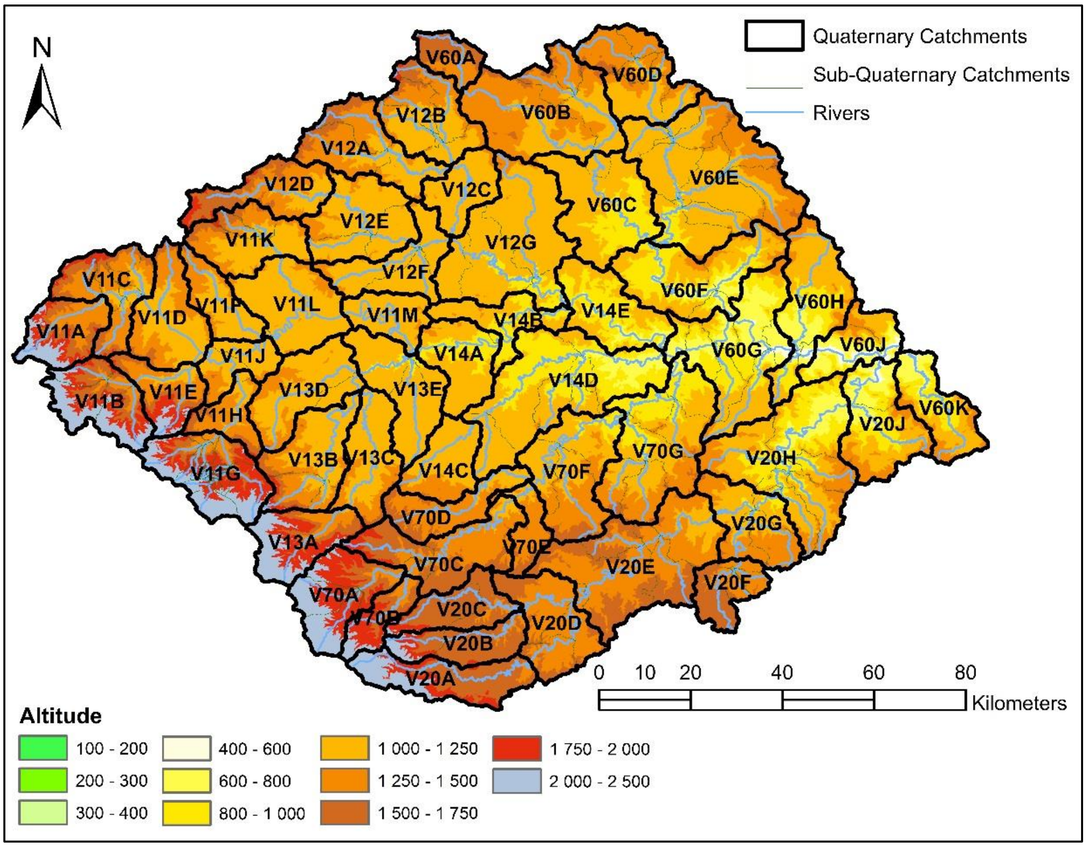

Figure 8-3: DEM altitudes for the upper uThukela catchment (after Weepener et al., 2011e)

8.1 CLIMATE

The uThukela catchment is located in the summer rainfall region of South Africa. Most of the catchment is classified as having mid-summer rainfall, with parts of the eastern side of the catchment classified as having early summer rainfall (Schulze and Maharaj, 2008a). The MAP for the catchment is shown in Figure 7-4. The rainfall is highest along the Drakensberg Escarpment and lower in the central and eastern parts of the catchment. The whole catchment experiences frost in winter (Schulze and Maharaj, 2008d). The rain gauges that were used as driver stations to reduce localised bias in the spatial rainfall estimates are shown in Figure 8-2.

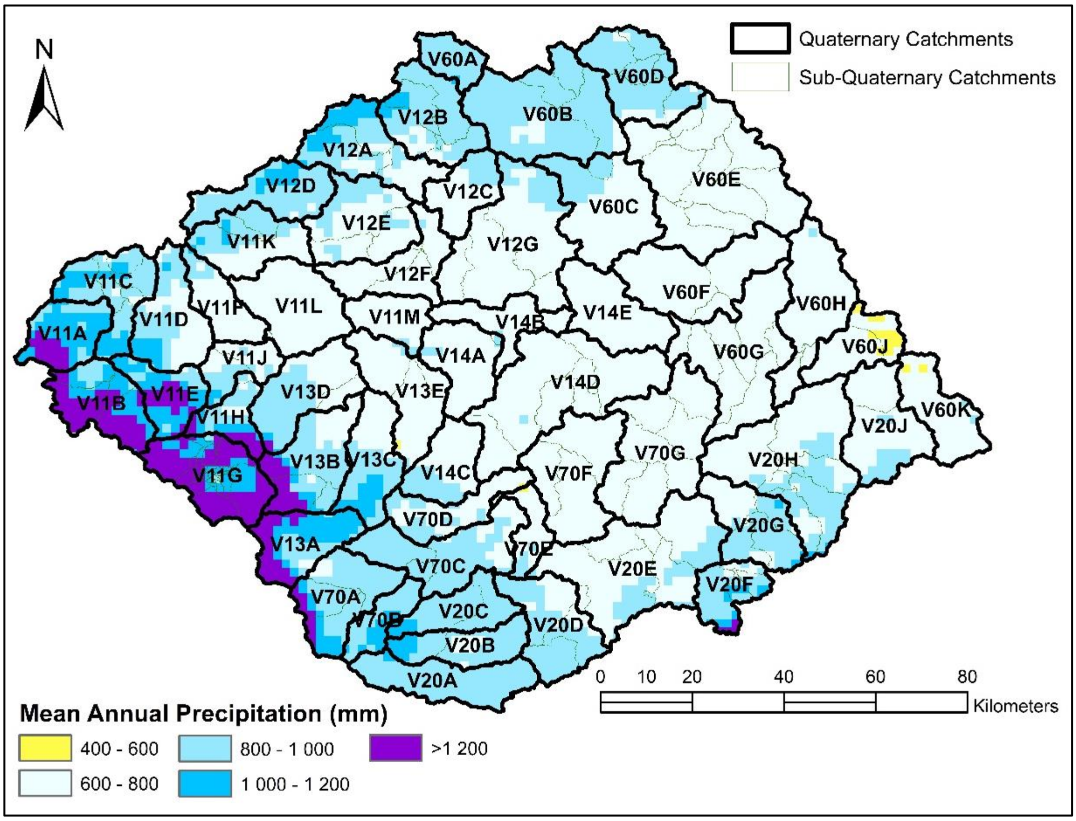

Figure 8-4: Mean snnual precipitation in the upper uThukela catchment (after Lynch, 2004; Schulze and Lynch, 2008a)

8.2 LAND COVER/USE

The spatial distribution of land cover/use for the upper uThukela catchment is shown in Figure 8-5, based on the classification in the 2013/14 national land cover/use raster dataset (NLC 2013-2014) for South Africa (DEA and GTI, 2015). Natural vegetation in the catchment is predominantly grassland, with some thicket/dense bush scattered throughout the catchment, and some patches of indigenous forest in the mountainous areas in the west. There are extensive rural settlements throughout the catchment, as well as several small towns, including Winterton, Bergville, Ladysmith, Weenen, Escourt and Mooi River. There is a substantial area of commercial dryland and irrigated agriculture in the V1 and V2 secondary catchments and also some plantations. In the foothills of the Drakensberg Mountains and in the eastern part of the catchment, there are substantial areas of subsistence agriculture. There are several large dams in the catchment to provide for urban use, irrigation, electrical power generation and inter-catchment transfers, including Woodstock Dam Spioenkop Dam, Wagendrift Dam, Spring Grove Dam and Craigie Burn Dam.

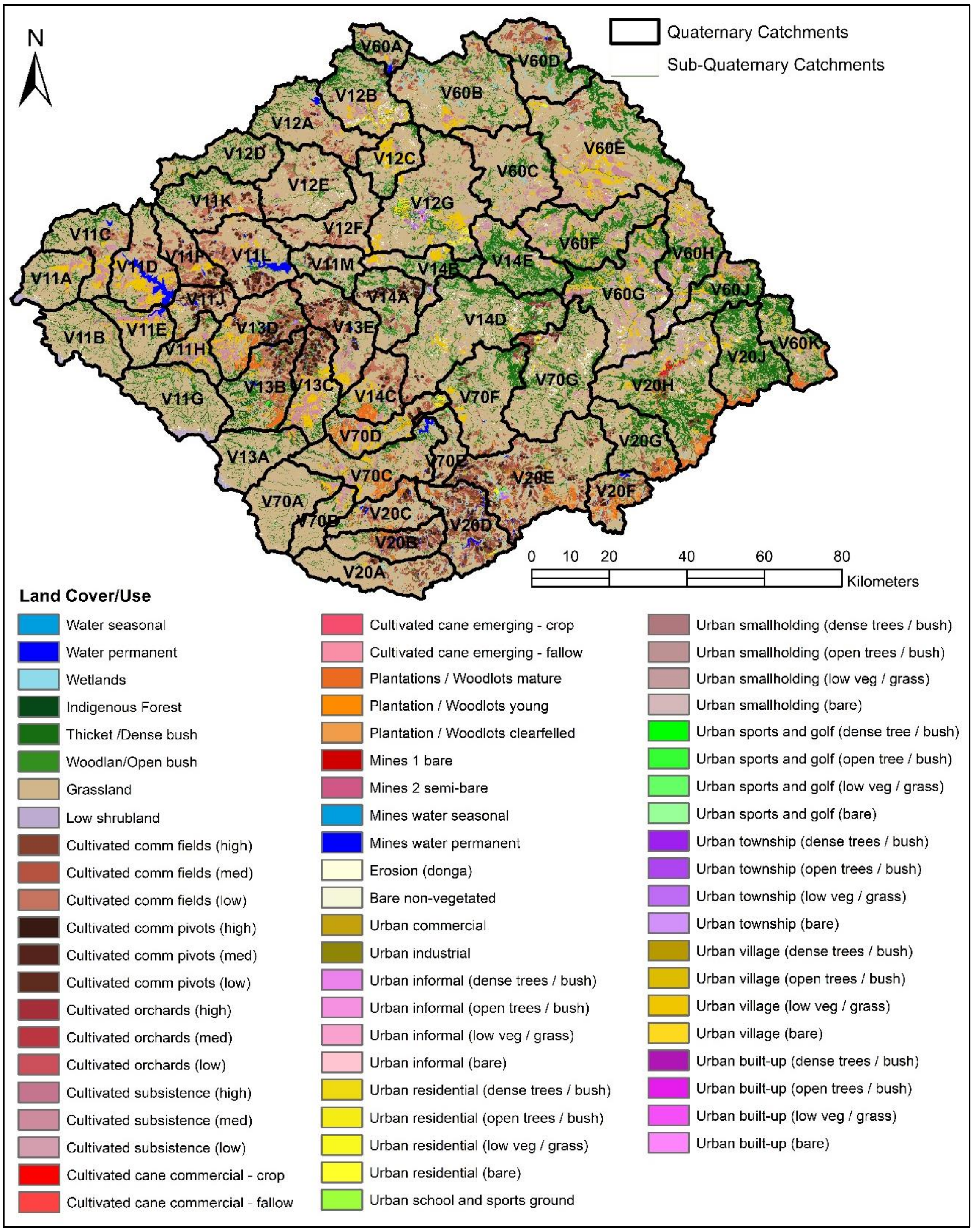

Figure 8-5: Land cover/use classes in the upper uThukela catchment from the NLC 2013-2014 dataset (after DEA and GTI, 2015)

8.3 TRANSFERS, ABSTRACTIONS AND RETURN FLOWS

There are no net inter-catchment transfers into the upper uThukela catchment. However, there are two transfers to neighbouring catchments and two pump storage schemes. These transfers and pump storage schemes are as follows:

- *The Drakensberg Pump Storage Scheme:* In this scheme, water is released from Woodstock Dam to Driel Barrage on the uThukela River from where it is pumped via the TUVA Canal to Jagersrust Dam. From there it is pumped to Kilburn Dam, and then onto the escarpment into the joined Driekloof/Sterkfontein Dam, from where some water is returned to Kilburn Dam to generate electricity, and some water may be transferred from Sterkfontein Dam to the Vaal system to augment the water supply to Gauteng.
- *The new Ingula Pump Storage Scheme:* In this scheme, water is pumped from the Braamhoek Dam up onto the escarpment into the Bedford Dam, from where water is returned to Braamhoek Dam to generate electricity. It is assumed that there is no net transfer of water into or out of the upper uThukela catchment as a result of this scheme.
- *The Mooi-uMngeni Transfer Scheme:* In this scheme, water was initially pumped from Mearns Weir on the Mooi River into the Mpofana River in the uMngeni catchment, which flows into the Lions River and then into the uMngeni River just upstream of Midmar Dam. Spring Grove Dam on the Mooi River upstream of Mearns Weir is used to supply additional water for transfer via the same route into the uMngeni catchment.

Measured transfer flow values from Spring Grove Dam and Mearns Weir and for the TUVA Canal were included in the hydrological modelling to represent these transfers and were thus taken into consideration in the water resource accounts. Water for urban use was assumed to be sourced within the catchments in which it was used. Return flows from urban areas were assumed to occur within the same catchment in which the urban use occurred.

8.4 RESULTS

The ACRU hydrological model was configured for the upper uThukela catchment using the datasets and methodology described in Chapter 0 and in Section 0 to Section 0. The model was run for a five-year period from October 2013 to September 2018. The first hydrological year (2013/14) of the simulated period was regarded as a warm-up year to enable the initialisation of soil water and baseflow stores in the model. Where possible, it is useful to verify modelled water balance variables using measured data. For the purposes of this study, measured streamflow data was used to verify the modelled streamflow at several points in the catchment. The details of this verification exercise are included in Section 0. An acceptable simulation of streamflow was only achieved at one streamflow gauge in the Drakensberg at the top of the catchment. Streamflow was undersimulated at most streamflow gauges. The streamflow volumes were typically better modelled in the less developed catchments, which primarily contain natural land cover. The underestimation of streamflow seems to indicate that only modelling irrigation abstractions for areas with centre pivots was not a big factor in the poor verifications in catchments that contain significant areas of commercial agriculture. Poor rainfall estimates were expected to be the main cause of the poor simulation results, especially as there were large sections of the catchment without a driver rain gauge nearby.

Using simulated catchment water balance variables, water resource accounts were compiled for each sub-quaternary catchment and for each month of the year. These water resource accounts were then spatially and temporally aggregated to compile annual accounts for each quaternary, tertiary and secondary catchment in the upper uThukela catchment. The annual water inflows and outflows for the whole upper uThukela catchment for each hydrological year are shown in Figure 8-6 to provide an overview of flows in the catchment for the four-year period.

The annual Resource Base Sheet accounts for the whole upper uThukela catchment are shown in Figure 8-7 for 2014/15, Figure 8-8 for 2015/16, Figure 8-9 for 2016/17 and Figure 8-10 for 2017/18. An example of the Withdrawal Sheet account for 2017/18 is shown in Figure 8-11. The water volumes shown in the accounts are shown in thousands of cubic metres. The water depths, shown in millimetres, are the water volumes divided by the whole catchment area. Given the poor verification results, the values shown in the accounts should not be quoted as absolute values, but should rather be considered as indicative of the relative significance of the different components of the water balance.

As shown in Figure 8-6, two years with higher rainfall follow two lower rainfall years. In the first year (2014/15), surface water storage decreases, while in the second and fourth years (2015/16 and 2017/18), surface water storage increases. Flow from the catchment is greater in the wetter years, indicating that there may be potential to store and utilise this water.

The only source of water into the catchment is rainfall as there is no flow into the upper uThukela catchment from any upstream catchments. Although the two pump storage schemes result in water being transferred both into and out of the catchment, it was assumed that, in both cases, there would not be a significant net flow of water into the catchment during the course of a year due to these schemes. The Mooi-uMngeni Transfer Scheme results in a flow of water from the catchment, and is included in the *Reserved Outflow* section. No environmental reserve has been included in the accounts.

Looking at the *Landscape ET* section of the accounts, the majority of total evaporation occurs in the natural category, but with a significant portion in the cultivated category, and smaller portions in the urban and waterbodies categories. Irrigated agriculture represents only about 2.7% of the catchment area, and the *Incremental ET* section of the account shows a small portion of total evaporation being contributed by irrigation. Looking at the evaporation processes, the greatest portion of total evaporation is usually through transpiration, followed by soil water evaporation and interception evaporation, with a small amount coming from open water evaporation.

In the Withdrawals Sheet (Figure 8-11), cultivation in the form of irrigated agricultural water is the primary user of water abstracted from dams and rivers in the catchment. However, this irrigation water use may have been underestimated as the NLC 2013-2014 land cover dataset only identifies centre-pivot irrigation.

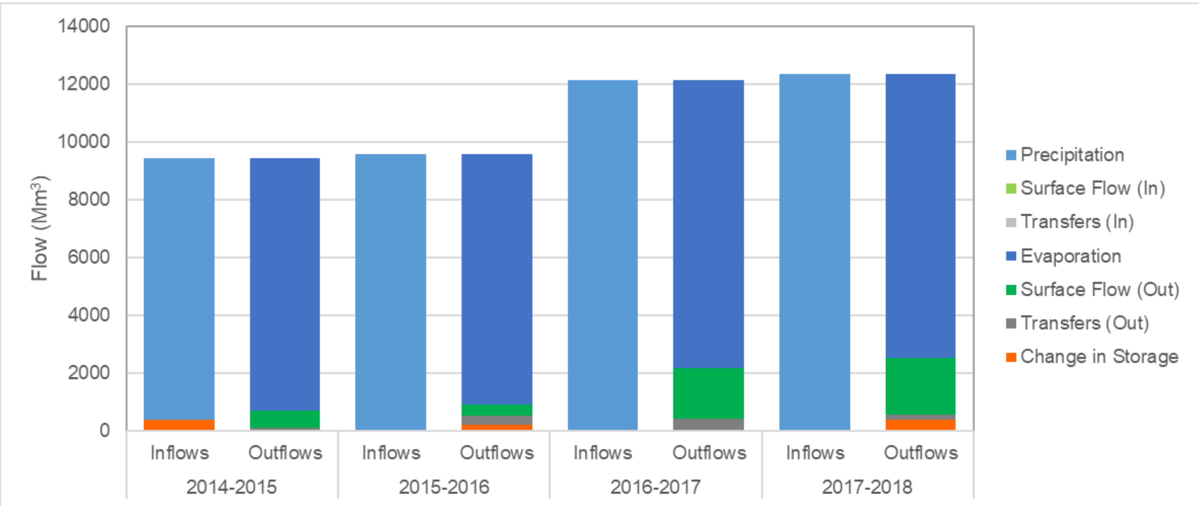

Figure 8-6: Summary of inflows and outflows for the upper uThukela catchment

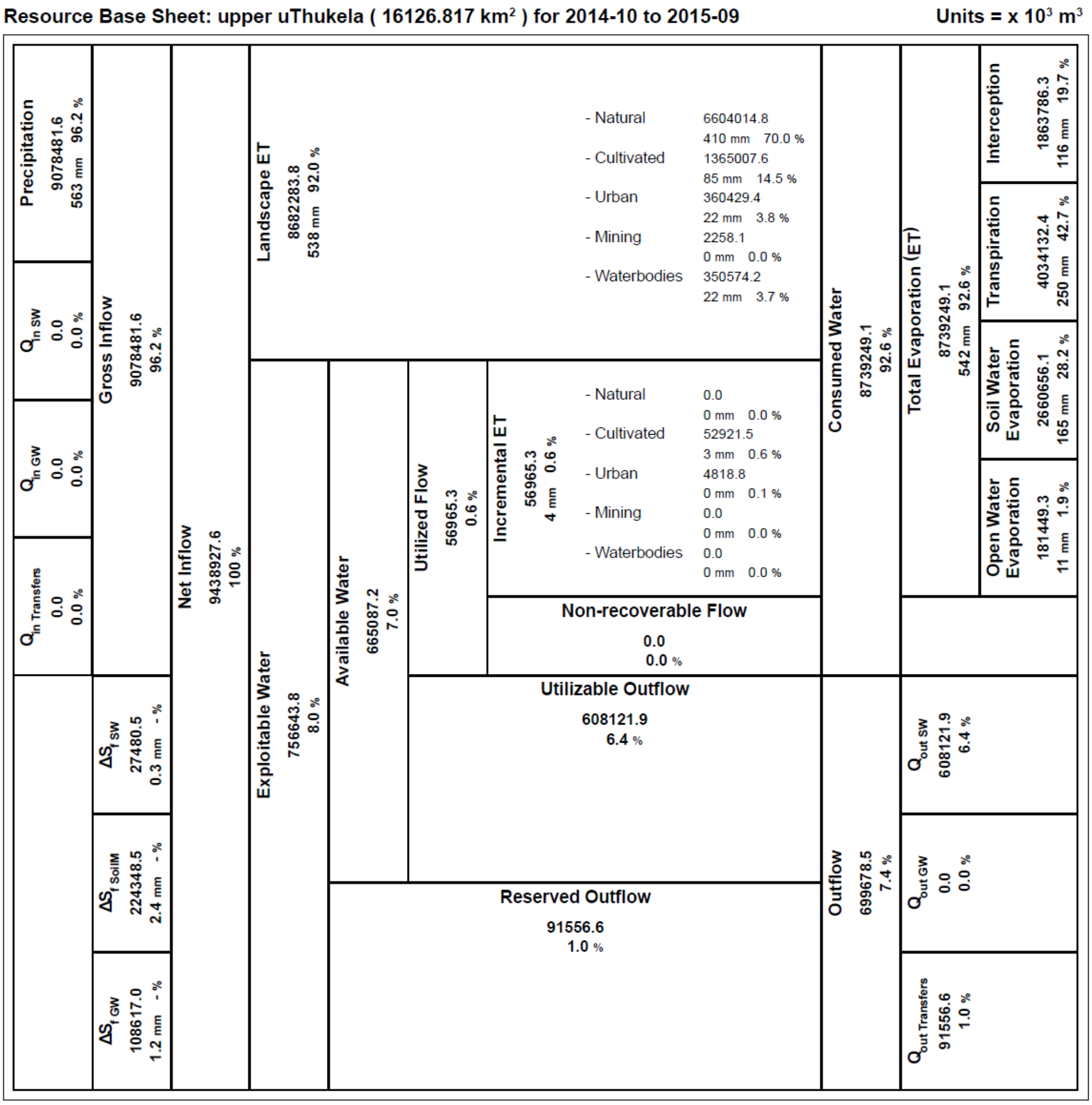

Figure 8-7: Resource Base Sheet for the upper uThukela catchment (2014/15)

Resource Base Sheet: upper uThukela (16126.817 km²) for 2015-10 to 2016-09 Units = x 10³ m³

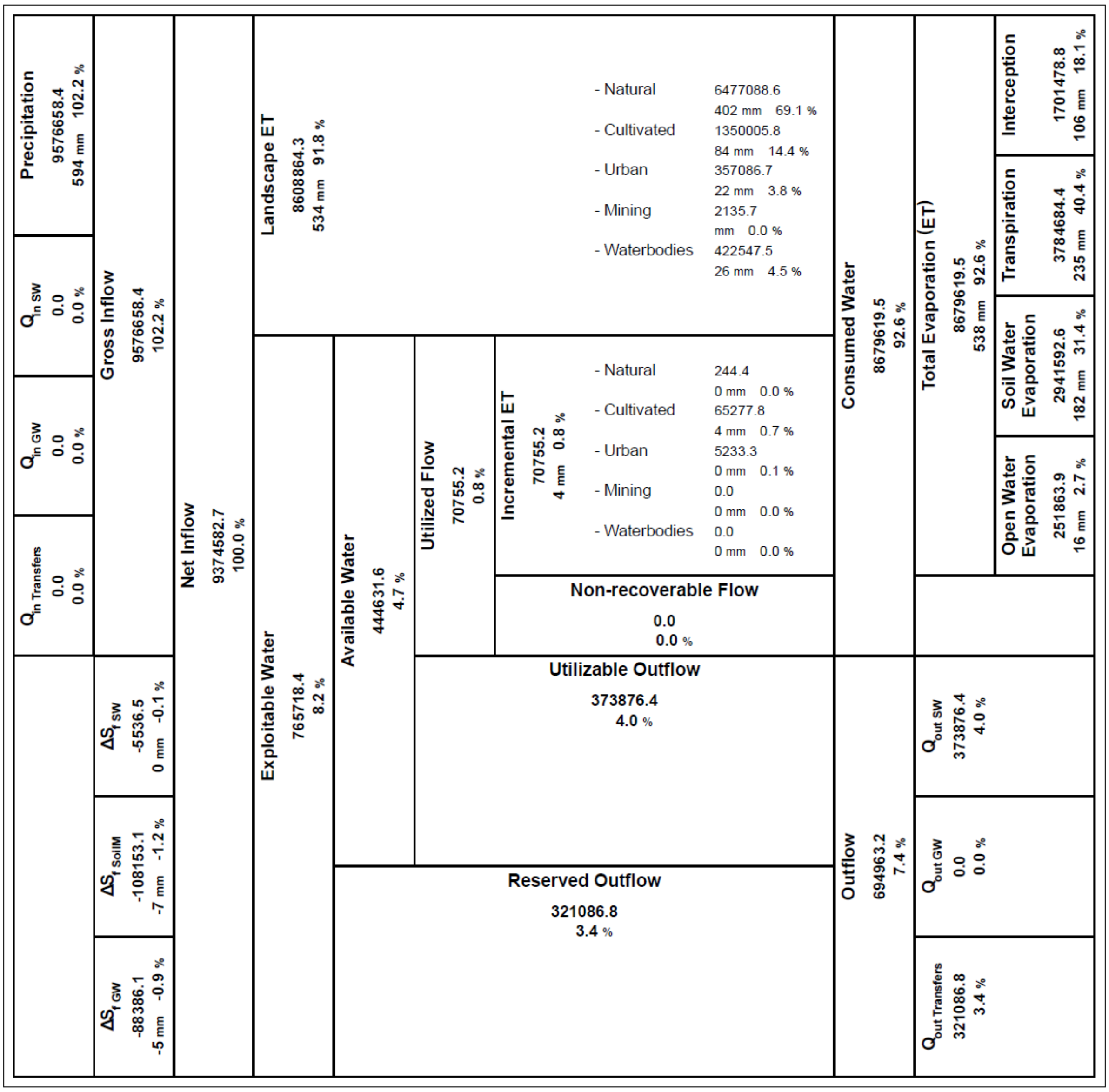

Figure 8-8: Resource Base Sheet for the upper uThukela catchment (2015/16)

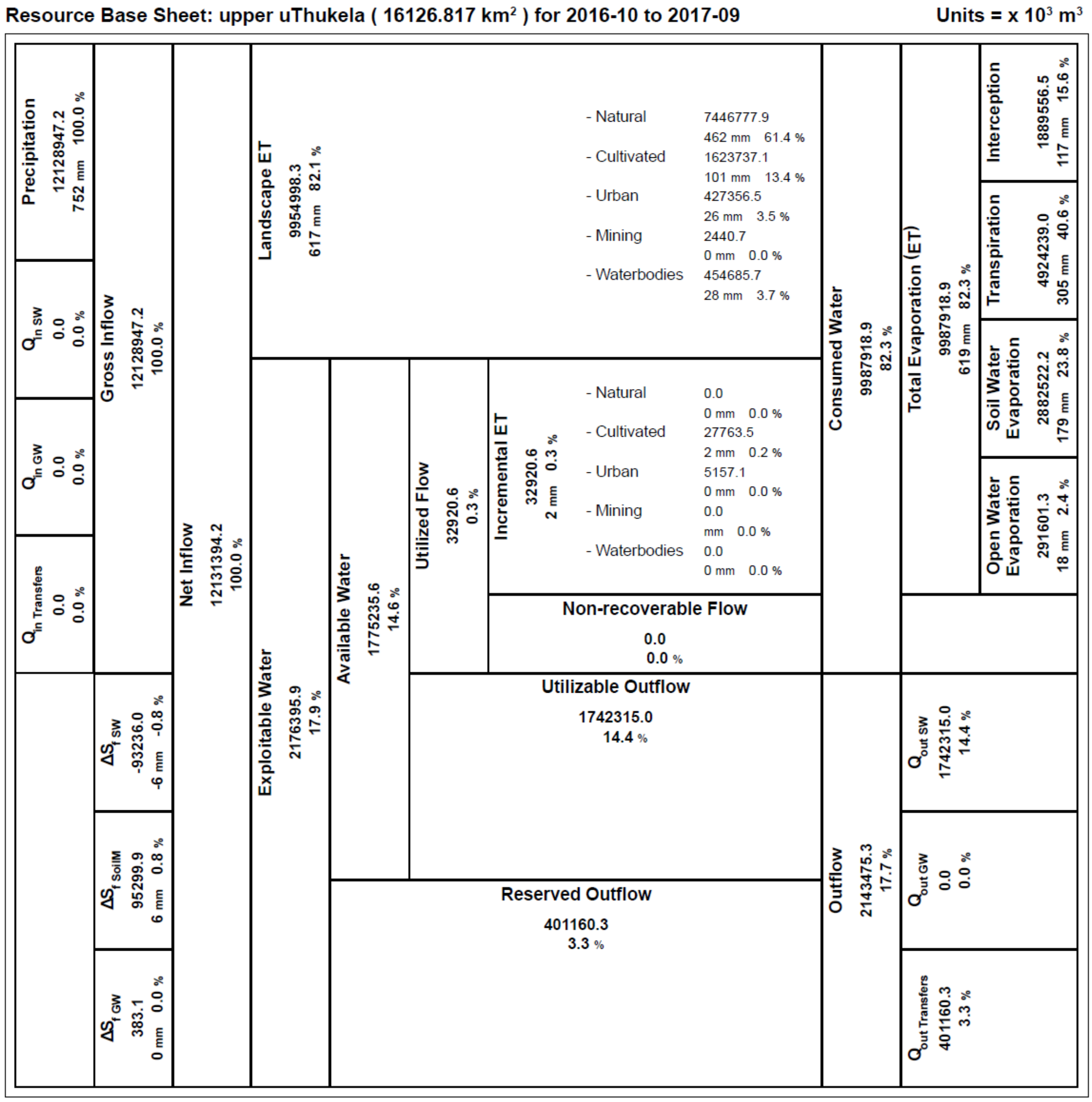

Figure 8-9: Resource Base Sheet for the upper uThukela catchment (2016/17)

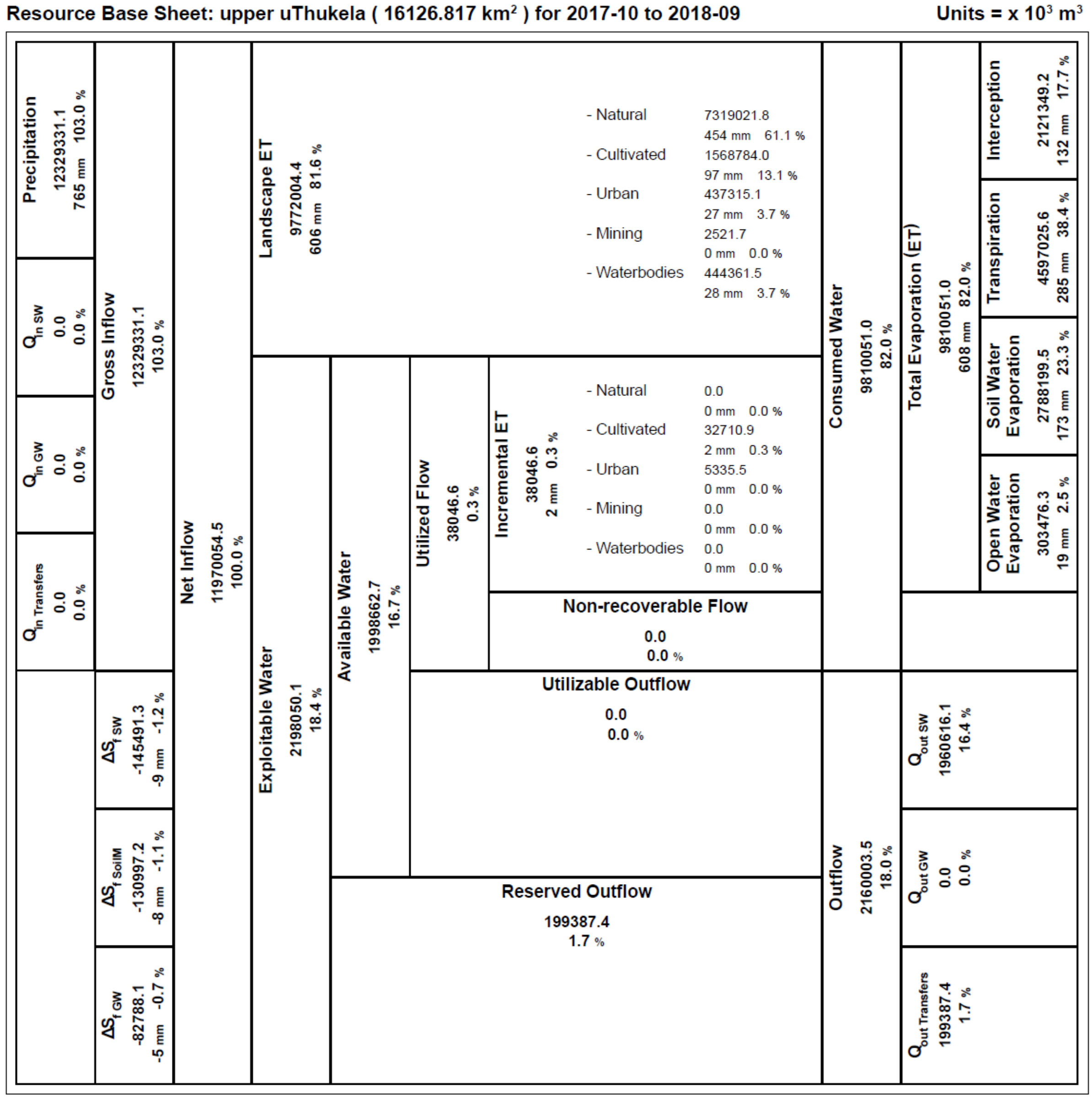

Figure 8-10: Resource Base Sheet for the upper uThukela catchment (2017/18)

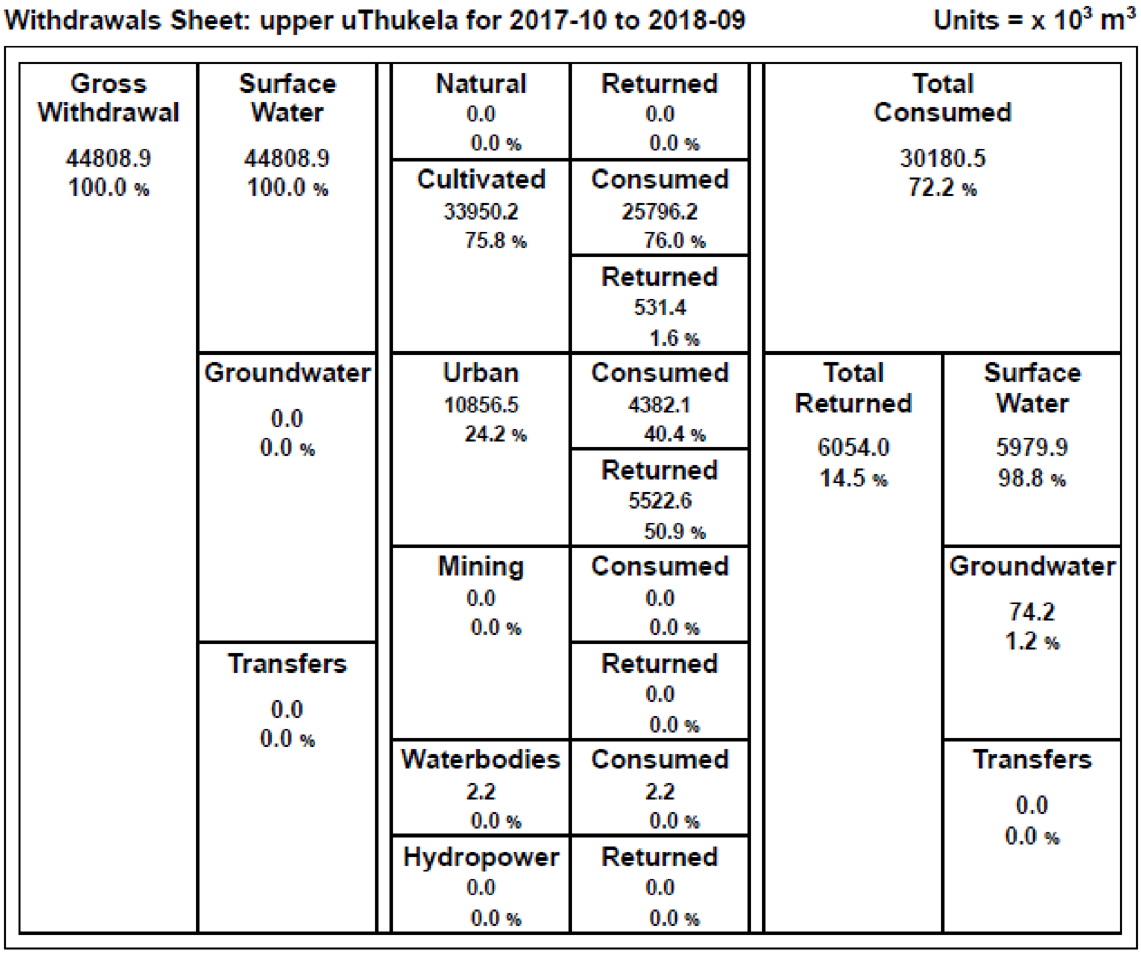

Figure 8-11: Withdrawal Sheet for the upper uThukela catchment (2017/18)

CHAPTER 9: UPPER AND CENTRAL BREEDE CATCHMENT CASE STUDY

DJ Clark

The Breede catchment forms part of the Breede-Gouritz WMA, which is situated in the winter rainfall region of the Western Cape, South Africa. The Breede River has its headwaters in the mountains in the northwestern part of the catchment and drains southeastwards into the Indian Ocean. DWAF (2004b) describes the economy of the Breede catchment as being mainly agriculture-based with some tourism along the coast. Agriculture includes fruit orchards in the northwestern part of the catchment, irrigated vineyards in the western and central part of the catchment, dryland small grain, oil seed and fodder crops in the south and southeastern part of the catchment and livestock. The catchment includes several large dams, and both surface water and groundwater are utilised within the catchment for irrigation and urban use. The catchment is an important source of water transfers to the Berg River system that supplies water to the City of Cape Town. The population in the catchment is expected to remain relatively stable and no significant economic growth is anticipated (DWAF, 2004b). The upper and central Breede catchment, shown in Figure 9-1, comprises the H1, H2, H3, H4 and H5 secondary catchments. It was selected as a case study catchment to test the water accounting methodology in the winter rainfall region. It is expected that the mountainous terrain will also be a good test of the feasibility of the spatial estimation of rainfall using remotely sensed satellite rainfall estimates, especially in this winter rainfall region. Other reasons were that there is extensive irrigated agriculture in the catchment, groundwater is used for irrigation in parts of the Hex River Valley, and the crops grown in the catchment differ from those in the other two case studies.

The catchment has an area of 7,405 km^2. The topography of the catchment is characterised by steep, rocky mountains with flat valleys in between. The altitude ranges from approximately 2,232 m in the north to 79 m in the southeast. The MAP varies from approximately 1,000 mm in the west to 200 mm in the drier central and eastern parts of the catchment. Commercial vineyards, orchards and small grain crops utilise most of the arable land in the catchment. The catchment contains several small towns, including Worcester, Robertson, De Doorns, Montagu, Ceres and Bonnievale. The catchment contains several large dams, used primarily for irrigation, and provides water transfers to the Berg-Olifants WMA. The areas of each of the secondary, tertiary and quaternary catchments are shown in Table 9-1. The quaternary catchment boundaries, rivers, registered dams, water transfers, streamflow gauges, driver rain gauges and driver evaporation stations are shown in Figure 9-2. The DEM altitudes are shown in Figure 9-3. A substantial portion of the catchment in the broad valley along the main Breede River has an altitude of less than 400 m, but there are also steep mountainous areas north and southwest of the valley.

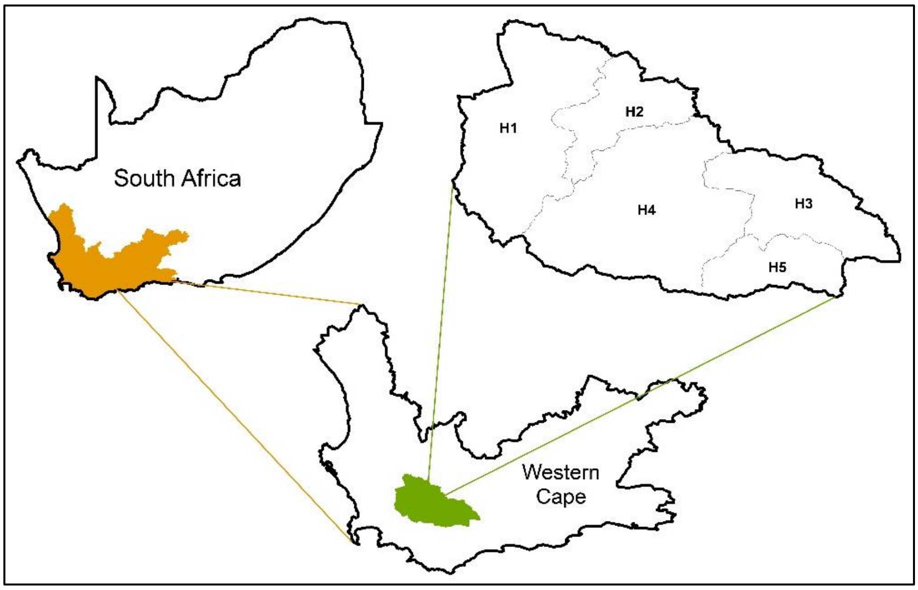

Figure 9-1: Locality map and secondary catchments for the upper and central Breede catchment

Table 9-1: Secondary, tertiary and quaternary catchment areas (km^2) (SLIM, 2014b)

Catchment areas (km²)													
Secondary	**Tertiary**	**Quaternary**											
H1 2062	H10 2062	H10A 240	H10B 164	H10C 257	H10D 96	H10E 84	H10F 250	H10G 271	H10H 236	H10J 215	H10K 196	H10L 51	
H2 843	H20 843	H20A 149	H20B 109	H20C 82	H20D 101	H20E 90	H20F 108	H20G 88	H20H 95				
H3 1208	H30 1208	H30A 283	H30B 316	H30C 318	H30D 135	H30E 156							
H4 2591	H40 2591	H40A 185	H40B 238	H40C 263	H40D 173	H40E 299	H40F 329	H40G 256	H40H 206	H40J 205	H40K 271	H40L 165	
H5 401	H50 401	H50A 266	H50B 435										

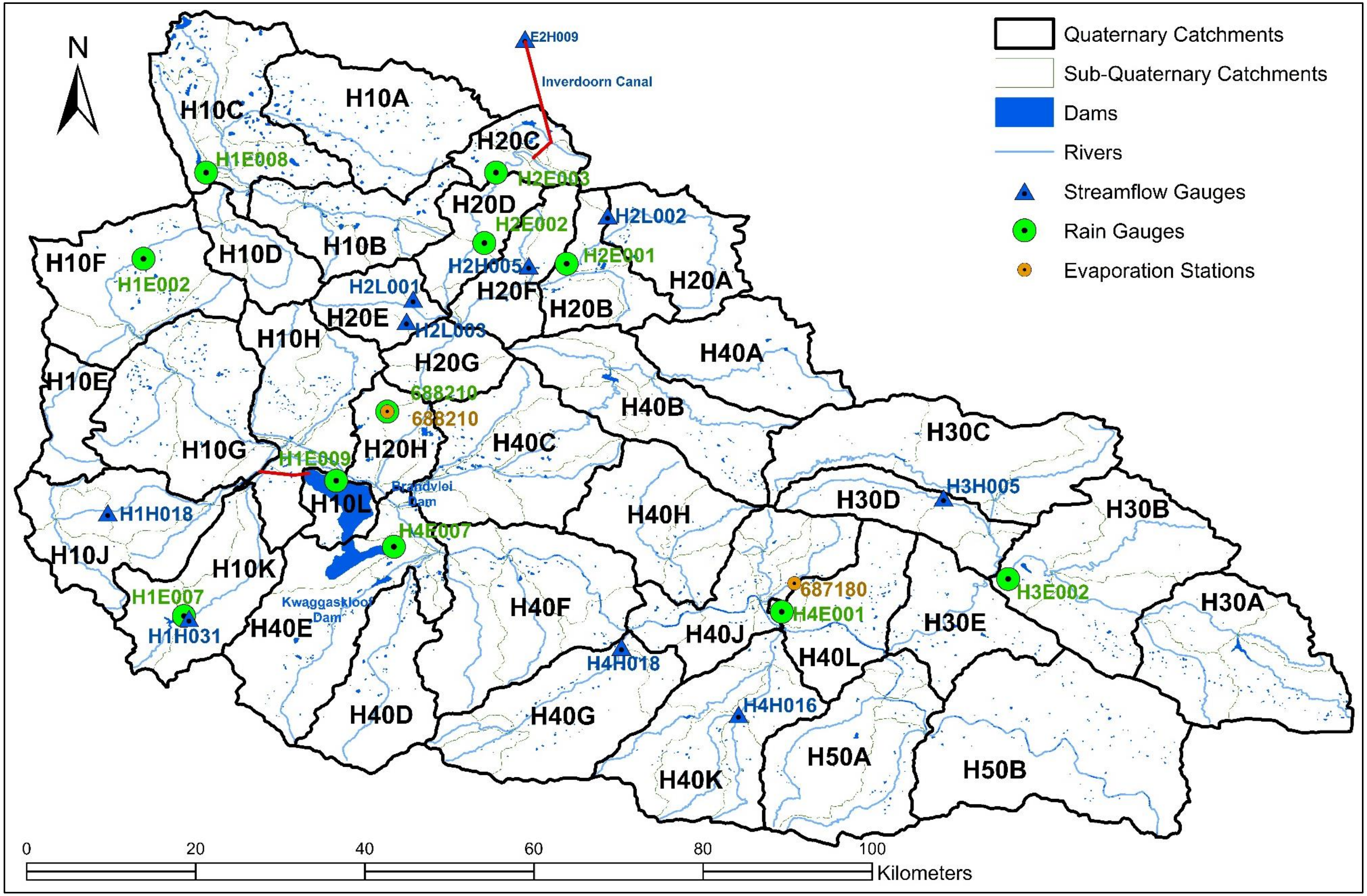

Figure 9-2: **Catchments, rivers, dams, water transfers and measurement stations in the upper and central Breede catchment**

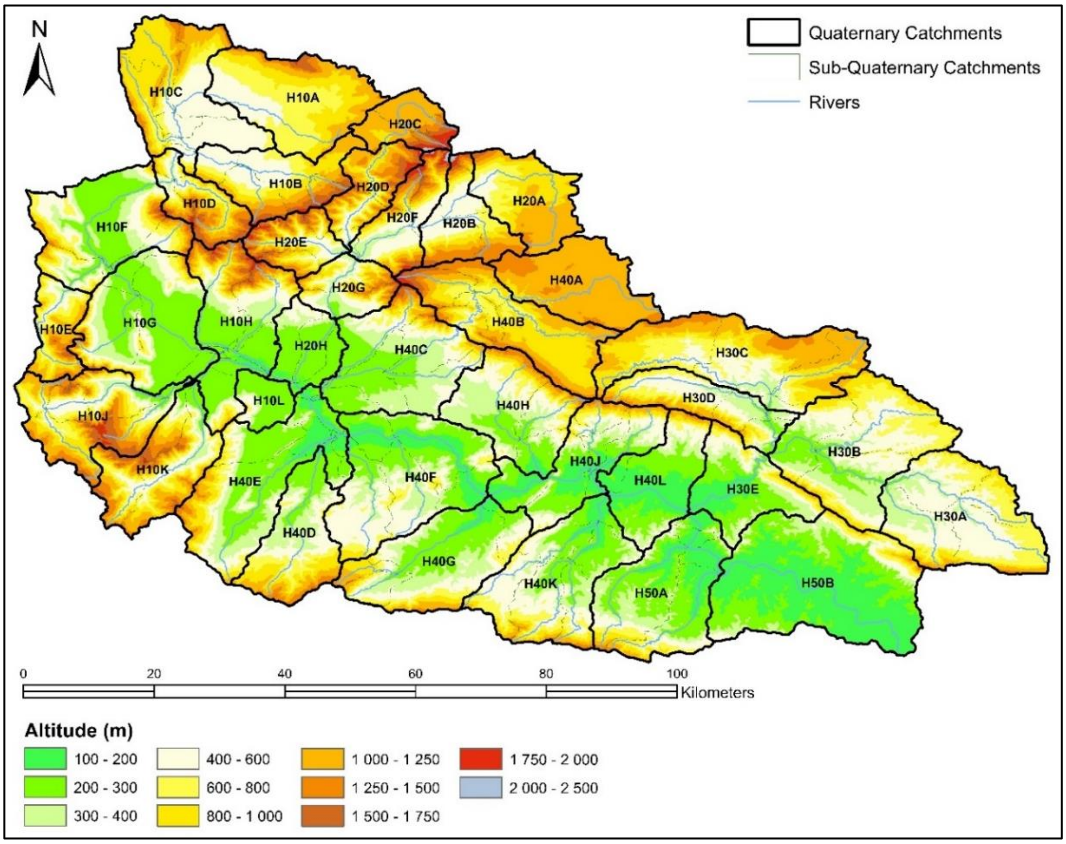

Figure 9-3: DEM altitudes for the upper and central Breede catchment (after Weepener et al., 2011e)

For the purpose of this study, the upper and central Breede catchment case study area comprised the H1, H2, H3, H4 and H5 secondary catchments (shown in Figure 9-1 and Table 9-1):

- The H1 secondary catchment includes the towns of Ceres and Wolseley. There are extensive deciduous fruit and small grain crops in the Ceres Valley and near Wolseley, and vineyards further south.
- The H2 secondary (Hex River) catchment includes the towns of De Doorns and Worcester. Agriculture in the Hex River Valley is predominantly vineyards.
- The H3 secondary catchment includes the towns of Montagu and Ashton. Agriculture in this catchment is constrained by the topography to the narrow valley, bottom-running southeast and northwest, and to the region in the main Breede River Valley where the Kogmanskloof River flows southwest to meet the Breede River. The main crops include vineyards, deciduous fruit, stone fruit and pastures.
- The H4 secondary catchment includes the towns of Robertson and McGregor. Agriculture is predominantly vineyards with some pastures and fruit.
- The H5 secondary catchment includes the town of Bonnievale. Agriculture is predominantly vineyards in the northwest, and predominantly pastures and small grains in the south and east.

9.1 CLIMATE

The upper Breede catchment and the higher altitude parts of the central Breede catchment are classified as having winter rainfall, while the lower altitude parts of the central Breede catchment are classified as having all-year rainfall (Schulze and Maharaj, 2008a). The MAP for the catchment is shown in Figure 9-4. With the exception of the western part, most of the catchment receives low rainfall. Frost can occur throughout the catchment (Schulze and Maharaj, 2008d). The rain gauges that were used as driver stations to reduce the localised biases in the spatial rainfall estimates are shown in Figure 9-2.

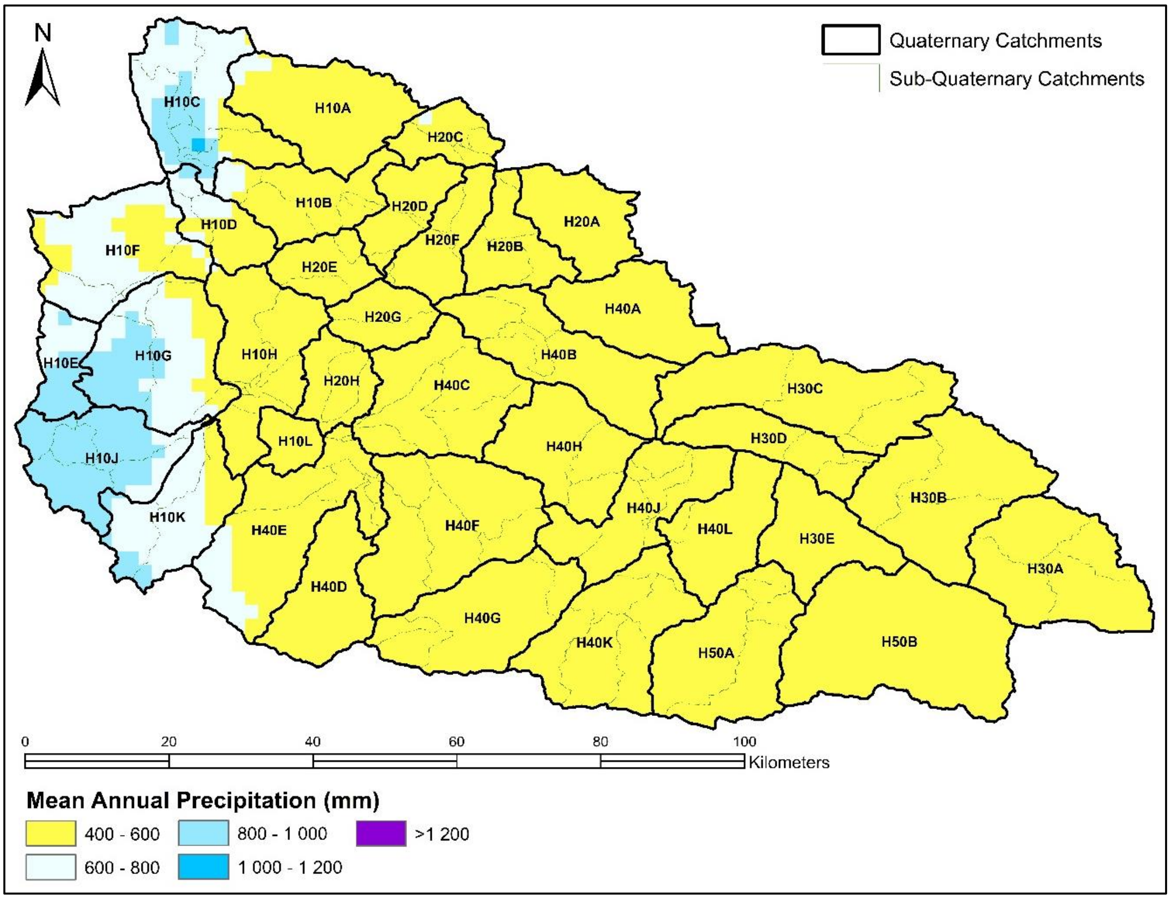

Figure 9-4: Mean annual precipitation in the upper and central Breede catchment (after Lynch, 2004; Schulze and Lynch, 2008a)

9.2 LAND COVER/USE

The spatial distribution of land cover/use for the upper and central Breede catchment is shown in Figure 9-5, based on the classification in the 2013/14 national land cover/use raster dataset (NLC 2013-2014) for South Africa (DEA and GTI, 2015). Natural vegetation in the catchment is predominantly shrubland fynbos, with a smaller amount of thicket/dense bush, especially in the lower altitude parts of the valley, and some low scrubland. In the rocky mountainous areas of the Hex River Valley (the H2 secondary catchment), and extending into the H1 secondary catchment, there is a significant amount of the class bare non-vegetated (white). The extent and location of vineyard, fruit and field crops can also be clearly seen. Some of the bigger towns (yellow) are visible, especially the town of Worcester near the bottom of the H2 secondary catchment. There are several large dams in the catchment to provide for urban use, irrigation and inter-catchment transfers, the largest of these being the Brandvlei and Kwaggaskloof dams just south of Worcester.

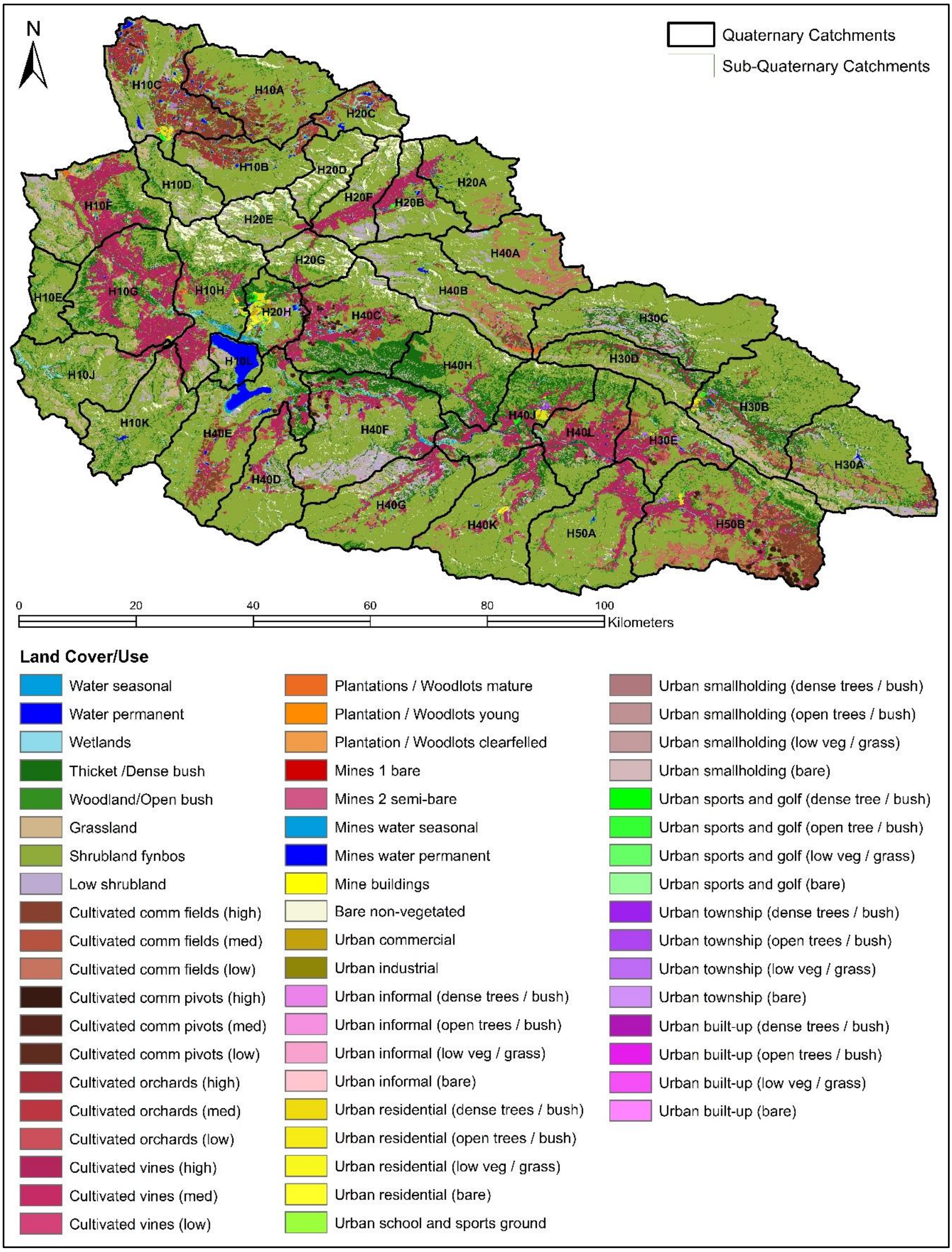

Figure 9-5: Land cover/use classes in the upper and central Breede catchment from the NLC 2013-2014 dataset (after DEA and GTI, 2015)

9.3 TRANSFERS, ABSTRACTIONS AND RETURN FLOWS

There are no inter-catchment transfers into the upper and central Breede catchment. DWAF (2004a) indicates that there are four small inter-catchment transfers from the upper and central Breede catchment: the Inverdoorn Canal (2.5 mm^3/year from quaternary catchment H20C), the Artois Canal (4 mm^3/year from quaternary catchment H10F), the Gawie se Water Scheme (5 mm^3/year from quaternary catchment H10E) and the Du Toits River to Franschhoek transfer (0.6 mm^3/year from quaternary catchment H10J). However, only the Inverdoorn Canal transfer was included in the hydrological modelling and the water resource accounts, as this was the only transfer for which measured flow could be found. It was not clear whether the other transfers were still operational and no flow records could be found.

The upper and central Breede catchment has extensive agriculture, a large proportion of which is high-value irrigated crops such as grapes and fruit. This has led to the extensive development of water infrastructure in the catchment, including dams, river diversions, canals and pipelines, which transfer water between catchments. In addition to water required for irrigation and the processing of agricultural produce, there are also several small towns in the catchment that require water for domestic and commercial use. The Stettynskloof Dam in quaternary catchment H10K provides water for use in the town of Worcester.

The largest dam in the catchment is the Greater Brandvlei Dam, which is used primarily for irrigation. The Greater Brandvlei Dam consists of two linked dams, the original Brandvlei Dam and the Kwaggaskloof Dam in the neighbouring secondary catchment. The Greater Brandvlei Dam has a small natural catchment area, but runoff into the dam is augmented by diversions on two neighbouring rivers. The Smalblaar River (quaternary catchment H10G) is diverted via a canal into the Holsloot River (quaternary catchment H10H), which, in turn, is diverted via a canal into Brandvlei Dam (quaternary catchment H10L). During winter, water can also be pumped into Brandvlei Dam from the adjacent Breede River. However, this was not included in the modelling as no flow data could be found.

The Spek River (quaternary catchment H20C) is diverted via a canal into the Valsgat River (quaternary catchment H20C). The daily time series of flow from DWS gauge H2H009 was used to quantify the diverted flow. The Valsgat River (quaternary catchment H20C) is diverted via a canal into quaternary catchment E22C in the neighbouring Berg-Olifants WMA via the Inverdoorn Canal. The DWS gauge E2H009 was used to quantify the diverted flow.

As far as possible, the main water transfers between catchments in the study were represented in the hydrological modelling and the water resource accounts. However, even when modelling at sub-quaternary scale, it is difficult to represent the entire complexity of the various water schemes in detail.

9.4 RESULTS

The ACRU hydrological model was configured for the upper and central Breede catchment using the datasets and methodology described in Chapter 0 and in Section 0 to Section 9.3. The model was run for a five-year period from October 2013 to September 2018. The first hydrological year (2013/14) of the simulated period was regarded as a warm-up year to enable the initialisation of soil water and baseflow stores in the model. Where possible, it is useful to verify modelled water balance variables using measured data. For the purposes of this study, measured streamflow data was used to verify the modelled streamflow at several points in the catchment. The details of this verification exercise are included in Section 0. An acceptable simulation of streamflow was only achieved at one streamflow gauge in a catchment with natural land cover. However, other similar naturally vegetated catchments were poorly simulated. Streamflow was substantially undersimulated at some streamflow gauges and oversimulated at others.

As with the other case study catchments, poor rainfall estimates were expected to be the main cause of the poor simulation results, especially as there were large sections of the catchment without a driver rain gauge nearby. The water infrastructure, primarily for irrigation in the upper and central Breede catchment, is highly developed and better information is required to describe the sources of surface water for each sub-quaternary catchment and the use of surface water versus groundwater.

Using simulated catchment water balance variables, water resource accounts were compiled for each sub-quaternary catchment and for each month of the year. These water resource accounts were then spatially and temporally aggregated to compile annual accounts for each quaternary, tertiary and secondary catchment in the upper and central Breede catchment. The annual water inflows and outflows for the whole upper and central Breede catchment for each hydrological year are shown in Figure 9-6 to provide an overview of flows in the catchment for the four-year period. The annual Resource Base Sheet accounts for the whole upper and central Breede catchment are shown in Figure 9-7 for 2014/15, Figure 9-8 for 2015/16, Figure 9-9 for 2016/17 and Figure 9-10 for 2017/18. An example of the Withdrawal Sheet account for 2017/18 is shown in Figure 9-11. The water volumes shown in the accounts are shown in thousands of cubic metres. The water depths, shown in millimetres, are the water volumes divided by the whole catchment area. Given the poor verification results, the values shown in the accounts should not be quoted as absolute values, but should rather be considered as indicative of the relative significance of the different components of the water balance.

The low rainfall in 2016/17, compared to the other three years, is shown in Figure 9-6. Surface water storage decreases during this year, but increases in the following wetter year. The surface water outflows at the bottom of the catchment are not representative of the irrigation water use in the upper reaches of the catchment and may include some flow released to reduce salinity in the Breede River.

Looking at the *Landscape ET* section of the accounts, the majority of total evaporation occurs in the natural category, but with a significant portion in the cultivated category, and a smaller portion in the waterbodies category. The small towns that contribute to the urban category do not seem to have much impact on the water resources in the catchment as a whole, but are likely to have a bigger localised impact. Interestingly, compared to the uMngeni and upper uThukela catchment case studies, the ratio of soil water evaporation to transpiration is much higher, most likely due to the differing rainfall and the types of land cover and soil. Looking at the evaporation processes, the greatest portion of total evaporation is usually through soil water evaporation, followed by transpiration and interception evaporation, with a small amount from open water evaporation.

In the Withdrawals Sheet (Figure 9-11), cultivation in the form of irrigated agricultural water is the primary user of water abstracted from dams and rivers in the catchment. There is significant abstraction of water from groundwater for irrigation in the upper and central Breede catchment. The proportion of irrigation water abstracted from surface water and groundwater was estimated based on information in the WARMS database.

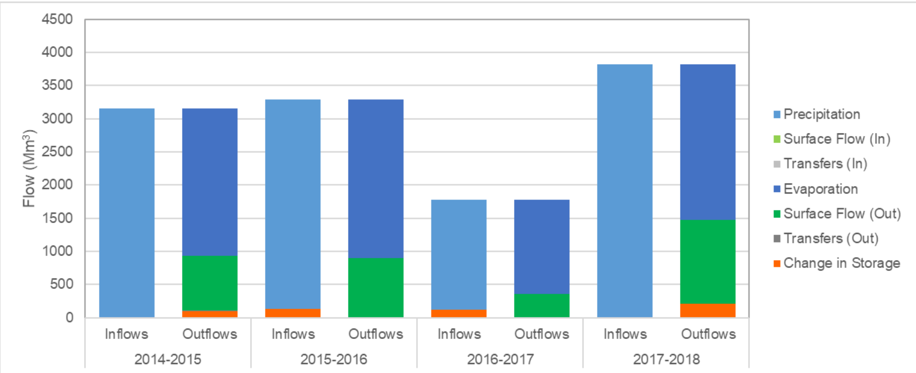

Figure 9-6: Summary of inflows and outflows for the upper and central Breede catchment

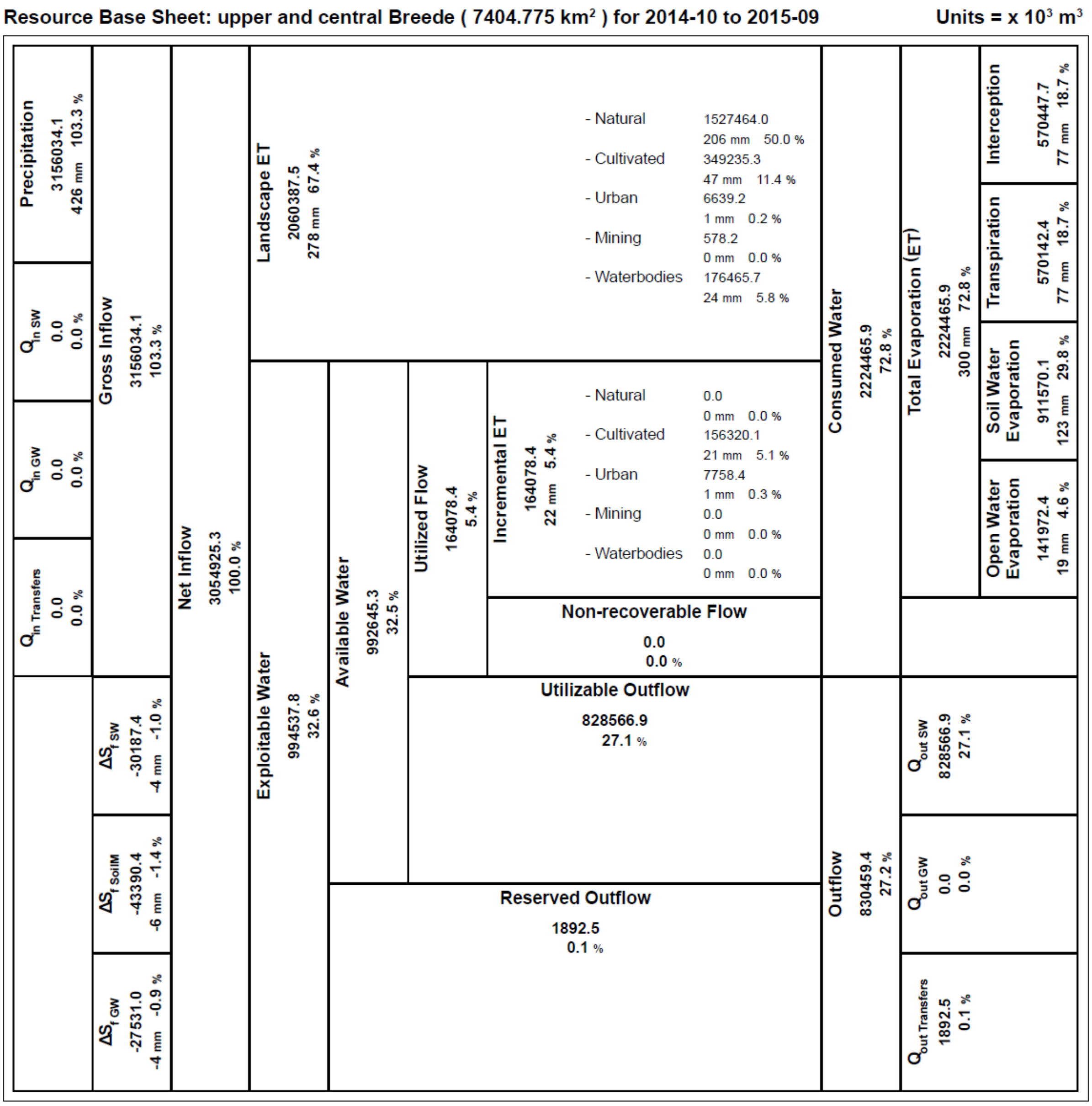

Figure 9-7: Resource Base Sheet for the upper and central Breede catchment (2014/15)

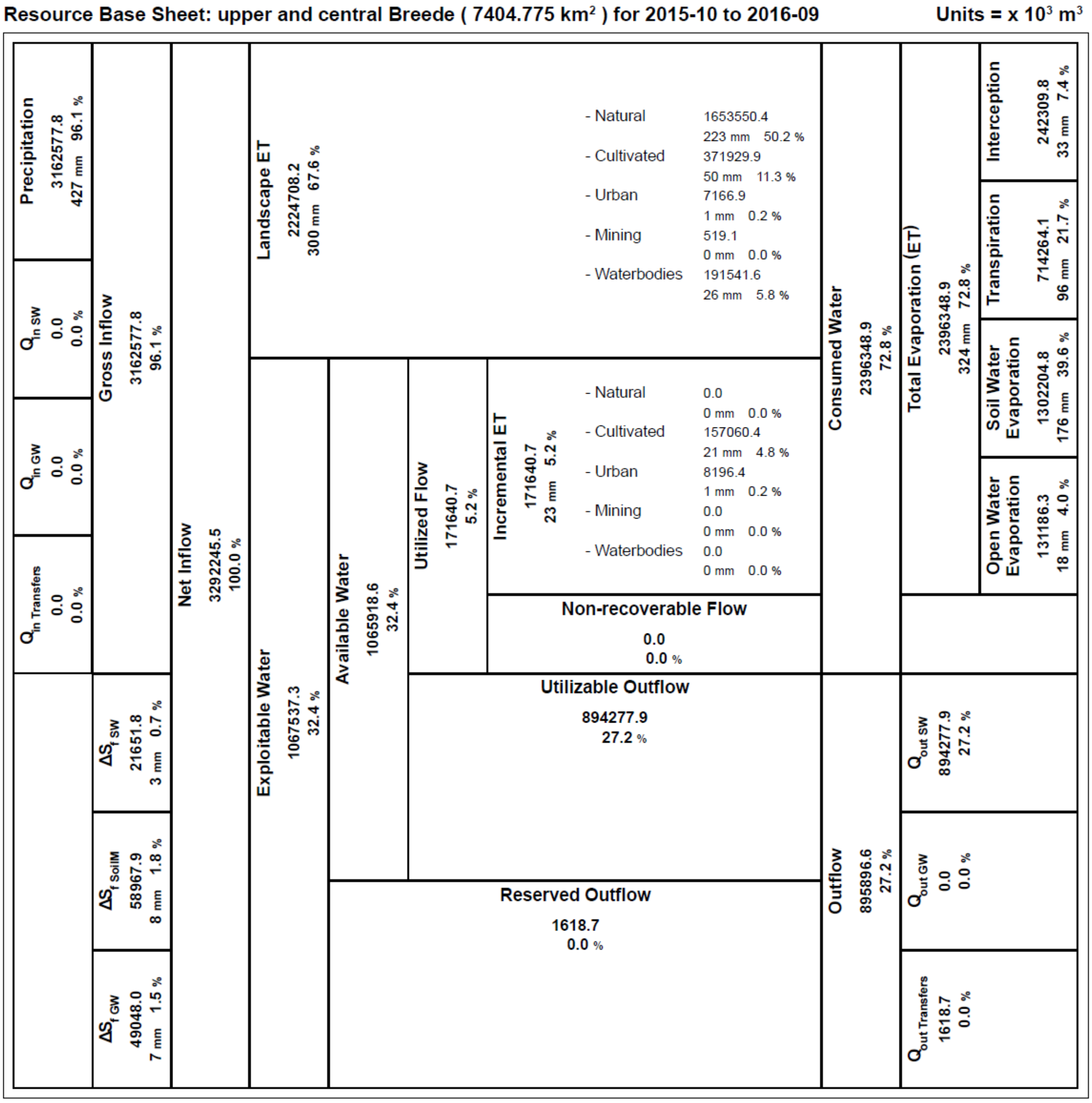

Figure 9-8: Resource Base Sheet for the upper and central Breede catchment (2015/16)

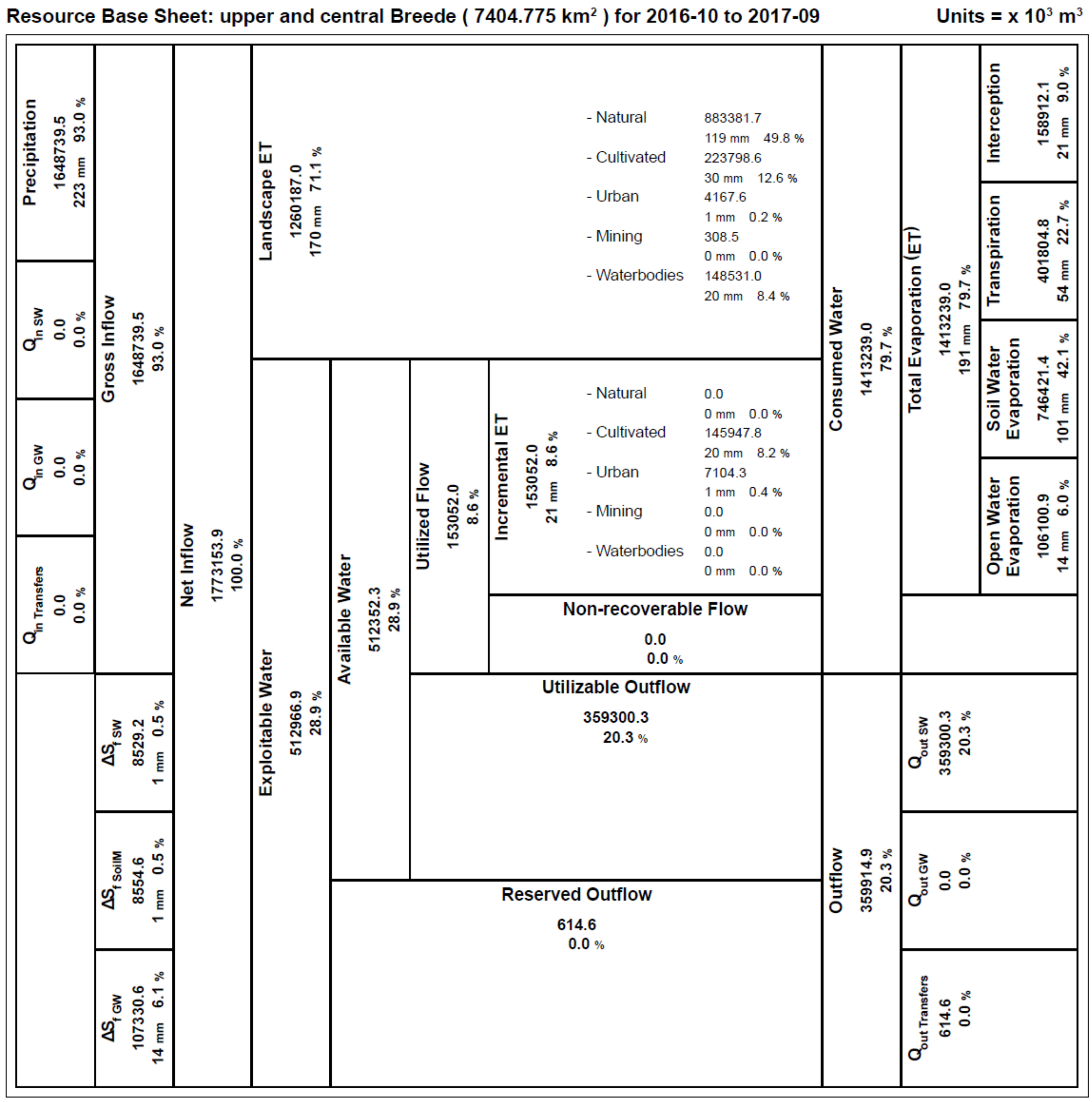

Figure 9-9: Resource Base Sheet for the upper and central Breede catchment (2016/17)

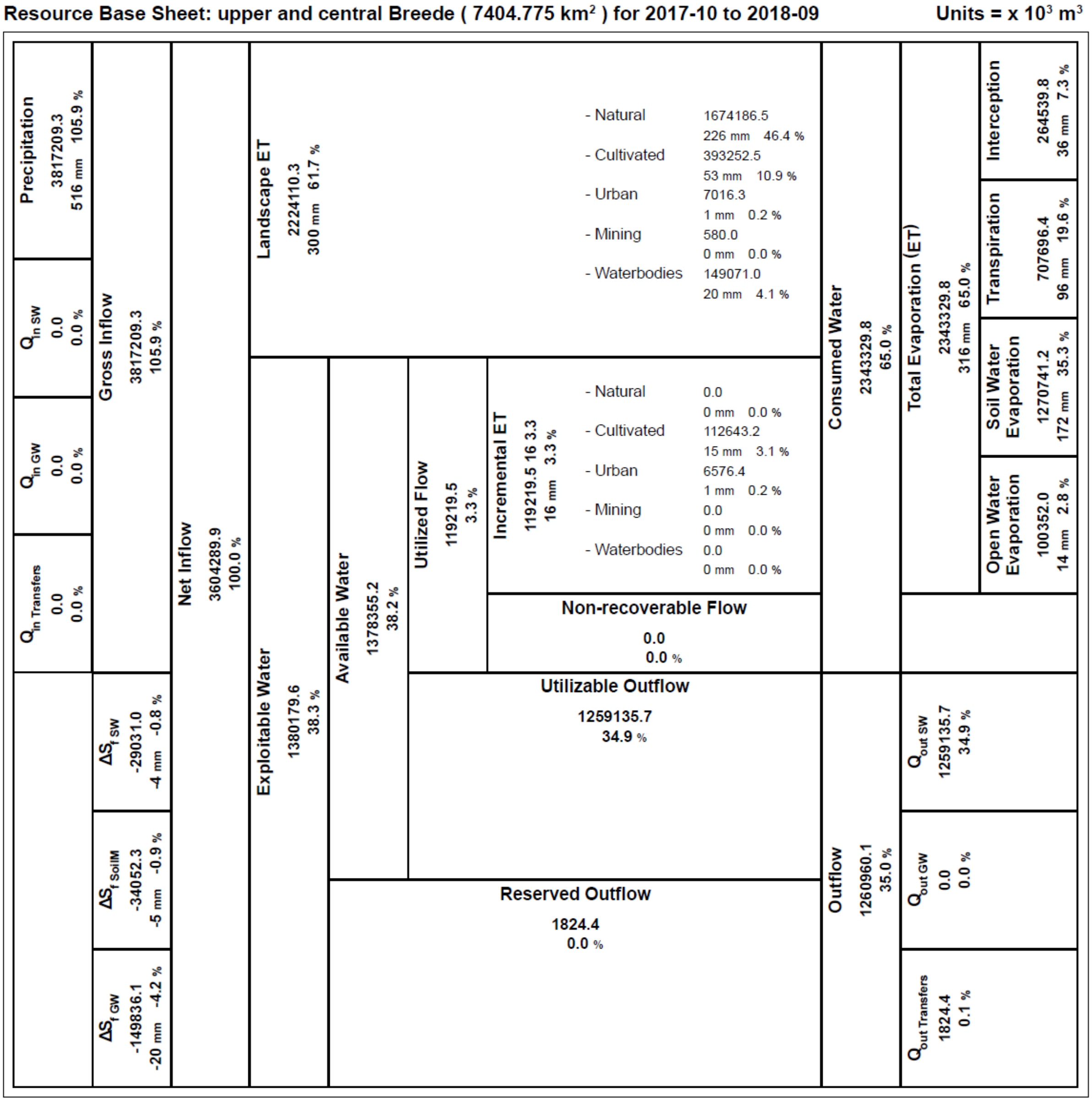

Figure 9-10: Resource Base Sheet for the upper and central Breede catchment (2017/18)

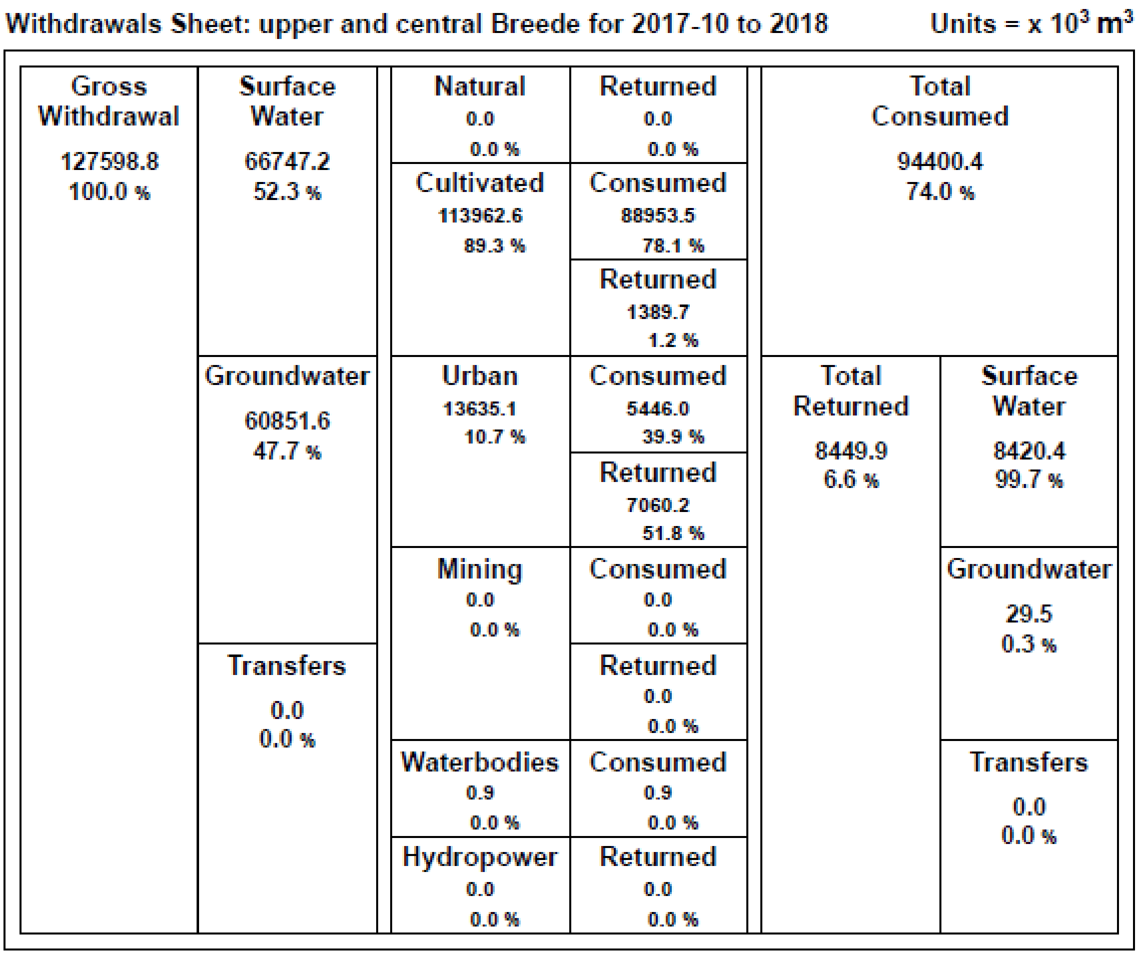

Figure 9-11: **Withdrawal Sheet for the upper and central Breede catchment (2017/18)**

CHAPTER 10: RESULTS AND DISCUSSION

DJ Clark

The purpose of this chapter is to provide a general discussion of the outcome of the further development of the water use quantification and accounting methodology and the results of the case studies.

10.1 FURTHER DEVELOPMENT OF THE METHODOLOGY

It is evident from the water resource accounts that rainfall is the largest source of water entering most catchments, with the exception of small catchments or catchments at the bottom of large river systems. Thus, accurate estimates of catchment-scale rainfall are important to compile accurate water resource accounts. However, rainfall is measured by a spatially sparse network of rain gauges, and rainfall data is not always freely available from the government and the private institutions that measure it. This led to an investigation into the potential application of satellite remotely sensed rainfall datasets in the earlier project. However, it was concluded that it was necessary to use rain gauge data to adjust the remotely sensed rainfall estimates to reduce localised bias in these datasets. The investigation into different remotely sensed rainfall datasets (Section 0) found that the TAMSAT and GPM datasets did not perform any better than the TRMM 3B42, FEWS ARC 2.0 and FEWS RFE 2.0 datasets previously investigated and did not warrant further investigation in this project. The investigation, in Section 0, into several relatively simple methods for adjusting the remotely sensed datasets to reduce localised bias successfully identified a method to use cumulative frequency distributions that seemed to be effective in the upper uMngeni catchment, resulting in acceptably accurate streamflow simulations. However, the poor verification of modelled streamflow against measured streamflow in the three case studies seemed to indicate that inaccurate estimates of catchment-scale rainfall may still be a primary contributing factor to the poor results. The rainfall adjustment methodology is dependent on the availability of suitably representative driver rain gauge data close to the catchment for which localised correction of the remotely sensed data is required.

It is also evident from the water resource accounts that evaporation and transpiration form the largest component of water leaving most catchments, with a large proportion of the rainfall leaving a catchment without becoming available for managed water use. Although remote sensing-based methods for estimating total evaporation using a surface energy balance are well established, a hydrological modelling approach to estimating total evaporation was adopted for the methodology as it provides flexibility for doing “what-if” analyses related to land and water use and – more importantly – enables other components of the catchment water balance, such as runoff and groundwater recharge, to be determined, taking into account the feedbacks and feedforwards between these different hydrological processes. The application of this modelling approach requires catchment-scale estimates of ET_0. The ET_0 dataset originally produced by the SAHG was successfully applied in the earlier project. However, as stated in Section 0, it is disappointing that the production of such useful, locally produced datasets could not be continued. This situation required the investigation of alternative ET_0 datasets in this project for use in the methodology. Several datasets were investigated and compared with ET_0 estimates based on the FAO’s Penman-Monteith approach, together with measured meteorological variables. The LSA-SAF’s ET_0 dataset was identified as a suitable alternative to the SAHG’s ET_0 dataset, although the dataset only includes data from August 2016 onwards. However, as with the rainfall estimates, there is no direct way of checking these catchment-scale ET_0 estimates. Thus, these estimates may also have been a contributing factor in the poor streamflow simulations.

In the earlier project, a decision was made that the accounts should be produced at quaternary catchment level, and that it should be possible for these accounts to be aggregated up to tertiary, secondary and primary catchment levels. However, most quaternary catchments cannot be considered to be homogeneous with respect to climate, land cover/use and soils.

Thus, in this methodology, hydrological modelling is done at sub-quaternary catchment scale, with climate assumed to be homogeneous within the catchment. Different land cover/use classes are modelled as HRUs, each with a single dominant soil type assigned. This approach enables some spatial variability in land cover/use to be accounted for and enables different land cover/use classes, which represent different sectors to be represented separately in the water resource accounts. However, there is no single widely recognised dataset of sub-quaternary catchment boundaries for South Africa. As discussed in Section 0, the NFEPA catchment boundary dataset was selected as a starting point in this project and adapted to fit the newer DWS quaternary catchment boundaries and to take large dams into account. There is a need for a dataset of sub-quaternary catchment boundaries of a good quality for South Africa that is nested within the quaternary catchment boundaries and that takes significant river tributaries, large dams, streamflow gauges, significant inter-catchment transfers and other significant abstraction and return flow nodes into consideration.

Land cover and land use are key characteristics of a catchment with regard to water use, especially evaporation, and other hydrological processes, such as runoff and groundwater recharge. In the earlier project, the most recent and most comprehensive national dataset of actual land cover/use was the NLC 2000 dataset (ARC and CSIR, 2005; Van den Berg et al., 2008) and thus more recent provincial land cover use datasets were used in the case studies. However, this was not ideal for the development of a methodology that can be applied consistently across the whole country. The different datasets have different spatial resolutions and – more importantly – use different classifications of land cover/use. An important component of the earlier project was the development of a dataset of land cover/use classes and their hydrological characteristics, and a hierarchy of these classes to enable the different land cover/use classes to be applied in a consistent manner. In this project, the NLC 2013-2014 land cover/use dataset for South Africa (DEA and GTI, 2015) was applied. The land cover/use hierarchy and class dataset made it easy to apply this dataset as part of the methodology. However, there are a few aspects of the NLC 2013-2014 dataset that result in it not being ideal for water accounting purposes. The two main problems were that the dataset does not have a separate class for dams, meaning that it was not possible to distinguish between dams, river reaches and wetlands with open water surfaces, and only centre-pivot irrigation was identified, meaning that the extent of irrigated agriculture is potentially underestimated in some catchments. The NLC 2013-2014 dataset does also not distinguish between areas with natural vegetation in a good condition and areas with natural vegetation in a degraded state. The NLC 2013-2014 dataset was applied "as is" in this project, but could potentially be enhanced by overlaying other datasets, such as the dataset of irrigated areas developed by Van Niekerk et al*.* (2018).

In some catchments, the presence of a large number of farm dams can have a significant impact on the hydrology of the catchment, especially early in the rainy season when they are only partially full and intercept runoff from upstream. In this project, several improvements were made to the representation of farm dams, including better estimates of the area and storage volume of these dams and a determination of the portion of a catchment that contributes runoff to these dams. These improvements should result in more accurate simulation of streamflow in catchments with several farm dams. The ACRU model was also further developed to enable the modelling of linked dams such as the Brandvlei and Kwaggaskloof dams, which are in separate catchments.

The WARMS database was investigated as a potential source of information for use in configuring the model, including information on specific crop types, irrigation system types, dams sizes and irrigation water source types. In the Breede catchment, a significant portion of the water used for irrigation is from groundwater, and the WARMS database made it possible to estimate the proportion of irrigation in each catchment from surface water and groundwater. This information was used in the configuration of the hydrological model and was thus represented in the water resource accounts. Information on dam sizes in the WARMS database was compared with the DWS database of registered dams, and some potential errors were identified in both datasets.

Most importantly, there does not seem to be a single system for identifying individual dams, making it difficult to compare the datasets. The spatial information associated with each data point on the WARMS database is a latitude and longitude point that is of limited use in applying the WARMS data for hydrological modelling. The Surveyor-General code assigned to some data points needs to be investigated further as a possible means of better representing the WARMS data spatially.

In the earlier project, the WA+ Resource Base Sheet and Evapotranspiration Sheet were combined to form a modified Resource Base Sheet. The modified Resource Base Sheet provides a useful summary of the inflows, outflows and changes of storage within a catchment. However, in this sheet, the managed water use component is almost overshadowed by the much larger volumes associated with catchment-scale rainfall and evaporation. In this project, a modified version of the WA+ Withdrawal Sheet was applied to provide an overview of managed flows in a catchment, including abstractions, consumption and returns. The physical conceptual nature of the ACRU model and the internal structure of the model made it possible to access and output the modelled variables that were necessary to compile the Withdrawal Sheet. However, the detail with which the ACRU model needs to be configured to provide meaningful estimates of the variables required for the Withdrawal Sheet became especially apparent in the Breede case study. The Breede catchment contains extensive irrigation water supply infrastructure and, ideally, each farm would need to be configured individually in the model to correctly represent the water sources. However, this is not practical and the simplifications made in configuring the hydrological model may affect the accuracy of the water resource accounts.

The water resource accounts are intended to provide a summary of water resource information for a catchment for a specific time period, which is one year in the context of this project. This sometimes requires a change in mindset for water professionals who are accustomed to longer-term statistical descriptions of water, which are typical in water resources planning. One of the suggestions made at the workshops was to provide some means of viewing the accounts in the context of a longer time period. For this purpose, the main inflow and outflow volumes for each of the four annual water accounts were plotted on a single graph for each case study, which helps provide some context to the individual water accounts. Related to this requirement for account context is the need to show the extent to which flows have been altered from natural conditions, thus affecting the condition of river ecosystems. To this end, the investigation described in Chapter 0 has provided a useful starting point towards the potential development of a new water resource accounting sheet that shows the extent to which flows have been altered from natural conditions.

10.2 CASE STUDIES

Accurate estimates of rainfall are a key component of water resource accounts, and are also an input to the hydrological model from which estimates of other account components are derived. The detailed case study in the upper uMngeni catchment of Clark (2018), described in Section 0, as part of the investigation into methods to improve the catchment rainfall estimates, demonstrated that it was possible to perform suitably accurate hydrological simulations using the methodology, although the results were better at some streamflow gauges than at others.

Despite the improvements made to the methodology in this project, especially related to the estimation of catchment rainfall, the verifications in all three of the case studies (uMngeni, uThukela and Breede) were poor. This was disappointing, as for the water resource accounts to be useful, the estimated variables used to populate the accounts needed to be suitably accurate, although in the case of many of the variables, they cannot be easily verified, especially at a catchment scale. However, one needs to remember that streamflow measurements are also subject to error. The catchment rainfall estimates are still expected to be the primary cause for the poor verifications against measured streamflow. However, streamflow is an integrator of much spatial and hydrological process complexity, which can make it difficult to identify the reason for the discrepancy between measured and simulated streamflow.

The streamflow verifications tended to be better in catchments that were impacted on less by commercial agriculture and urban areas, indicating that rainfall may not be the only cause of the poor simulation results. The uMngeni catchment case study, in particular, highlighted the requirement for more research to improve the representation of more densely populated urban areas, which have large impervious areas and typically higher per capita water use, potentially sourced from other catchments. The Breede catchment case study highlighted the difficulties associated with correctly modelling the water sources for irrigation water users in each catchment, without modelling each individual water user, which is not practical at the scale of the upper and central Breede catchment, let alone for the whole of South Africa. The uMngeni catchment case study required a water source to be assigned to the urban areas within each catchment, but this was easier to do based on a spatial water supply footprint such as that provided by Umgeni Water.

Despite the generally poor verifications against measured streamflow, the case studies were useful for testing the application of the methodology and identifying areas for further research. The case studies were also useful for demonstrating the different catchment accounts and the information that they can provide. The Breede catchment case study was especially useful for demonstrating the application of the Withdrawals Sheet, showing abstractions of water for irrigation from both surface water and groundwater sources. The Withdrawal Sheet provides insight into the consumption and return flows for irrigation use compared to urban use with regard to the portion of abstracted water potentially being made available for reuse downstream in a different catchment from which the water was sourced.

CHAPTER 11: CONCLUSIONS AND RECOMMENDATIONS

DJ Clark

The objectives of the project were met. The most important refinements to the methodology were the identification of a method to improve catchment rainfall estimates, the identification of a suitable ET_0 dataset to replace SAGH's discontinued ET_0 dataset, the improvements made to the representation of dams, and the use of the WARMS dataset to better represent the sources of water for irrigation. The extension of the methodology through the inclusion of the WA+ Withdrawal Sheet and the investigation of a means to show the impact of dams, water abstractions and return flows on river flows were an important step towards making the methodology and accounts more informative. The case studies, representing both the summer and winter rainfall areas, were useful for demonstrating the application of the methodology and providing examples of the various water resources accounts. The case studies also highlighted areas for further development of the methodology and demonstrated the difficulties associated with modelling complicated operational catchments. The workshops provided an opportunity to inform potential users about water accounting in general and the water resource accounts in particular. The delegates at the workshop provided valuable feedback regarding the accounts. The delegates' interest in having a configured hydrological model for a catchment that could be used in testing scenarios for planning and for operational management decisions was noted. This confirmed that the decision to use a modelling approach to compile water resource accounts was sound and indicated that there is a need for such a tool.

The compilation of water accounts is data intensive, and the non-availability of suitable data is a potential stumbling block to the production of water accounts. Other studies related to water use quantification and water accounting, most recently Maila et al. (2018) and Van Niekerk et al. (2018), have also highlighted the availability of data as a problem. However, the water resource accounts can be useful for highlighting areas where further monitoring is required, where better quality control of data is required and where better data archiving systems are required. Unfortunately, many of the variables required for the accounts are not, or cannot, be easily measured at a catchment scale. Remote sensing is one possible solution to this problem. However, although significant advances are being made in the application of remote sensing, further work is still required to improve the accuracy of remotely sensed estimates of many of the variables required for water accounting. There are also many variables in the accounts that cannot be estimated using remote sensing. Thus, the adoption of a hydrological modelling approach seems to be justified, despite its data-intensive nature. This project, together with the earlier project, has made a valuable contribution in identifying and evaluating a range of different datasets to test their suitability for application in hydrological modelling. South Africa has many useful datasets to inform hydrological modelling and water accounting, including actual land cover/use, soil characteristics, registered dams, the WARMS dataset, rainfall, evaporation, streamflow and dam levels. In addition, many of these datasets are freely accessible for application in the methodology. However, not all of this data is reliable, quality controlled or organised in a manner that makes it easy to apply. Rainfall and evaporation are the two main hydrological drivers, and accurate estimates of both are important in the compilation of accurate water resource accounts. Given the small proportion of rainfall that ends up as streamflow, relatively small errors in rainfall estimates can result in big errors in the estimates of streamflow. However, in addition to the sparse measurement network, ground-based measurements of rainfall and evaporation data are the least freely available. The application of satellite remotely sensed rainfall estimates has been demonstrated to have potential, but still requires rain gauge measurements. The evaluation and assignment of driver rain gauges for each catchment to reduce localised bias also requires some trial and error. With a few assumptions and generalisations, natural land cover, dryland agriculture and dams can be modelled relatively easily for the whole country.

However, estimation of irrigation and urban water use and their representation in the accounts are more complicated as data on actual daily use is not readily available and it cannot be assumed that the source of water and the point at which unconsumed water is returned to the system are in the same catchment as the water user, with the source of water affecting its availability to meet the users' requirements. Local knowledge of the catchment being modelled, especially the water infrastructure and potential sources of data, is invaluable in configuring the model to produce water resource accounts.

A vision that has directed the development of the water use quantification and accounting methodology has been to eventually produce annual water resource accounts at quaternary catchment scale for the whole country every year. These water resource accounts would have significant potential application in catchment-scale water management, as a source of information for use in the SEEA-Water environmental economic accounts, to inform reporting on water-related SDGs, and to inform reconciliation strategies, catchment management strategies and national water resources strategies. Given the effort that is required to obtain and process the data required to configure even the case study catchments at a suitable level of detail, could the methodology be applied operationally for the whole country? Rainfall and evaporation are typically the two dominant flows at a quaternary catchment scale, with the stocks, flows and abstractions of water in dams, rivers and groundwater typically being smaller in magnitude, but socially and economically important. The land cover/use-based methodology is suitable to be applied operationally for the whole country to provide estimates of the dominant rainfall and evaporation flows, while acknowledging that there is scope to improve the accuracy of these estimates. Much of the complication and effort in configuring the hydrological model comes from configuring the irrigation, mining and urban water use aspects required to include detailed and accurate estimates of sectoral water use in the accounts. The estimation of water used for irrigation, in urban areas, for mining and for power generation, and the representation of the related flow networks would require some simplifying assumptions to be made for the methodology to be applied operationally for the whole country, acknowledging that this may reduce the accuracy of the accounts. The operational production of water resource accounts for the whole country would require the implementation of a data workflow, management and archiving system. The Reference Group recommended that it was important, in the short term, to start producing water resource accounts operationally for the whole country, while working on refining the accuracy and detail of the accounts in priority catchments as a longer-term goal. Thus, two sets of recommendations are made for the application and further development of the methodology: recommendations related to applying the methodology to produce water resource accounts operationally for the whole country, and recommendations related to refining and extending the methodology. Producing water resource accounts for the whole country would help to demonstrate their usefulness, and also identify where additional data is required. Refining the methodology in selected key catchments would help to build confidence in the account estimates and hopefully lead to a wider acceptance of the methodology and the accounts.

Recommendations for further research relating to the operational application of the methodology to produce water resource accounts for the whole country include the following:

- The development of a set of simplifying assumptions for the estimation of water quantities used for irrigation, in urban areas, for mining and for power generation, and the representation of the related flow networks.
- The selection of a hierarchical set of sectors and sub-sectors to be used in reporting sectoral water use.
- The development of a dataset of sub-quaternary catchment boundaries for South Africa, taking into consideration significant river tributaries, large dams, streamflow gauges, significant inter-catchment transfers and other significant abstraction and return flow nodes.
- The evaluation and implementation of a data workflow, management and archiving system, such as Delft-FEWS or Kepler.

- The investigation and implementation of a means of spatially displaying annual water resource accounts and their individual components for nested sets of catchments, ranging from quaternary to primary catchments.

Recommendations for further research to improve the accuracy of the accounts and to extend the methodology include the following:

- Bias correction and the downscaling of remotely sensed rainfall data needs to be further investigated to improve the accuracy of catchment rainfall estimates.
- Additional datasets need to be sourced to enable the modelling of more specific agricultural crop types and, if possible, the representation of land management practices. Additional datasets need to be sourced to identify and enable the modelling of different irrigation systems and scheduling methods. Further investigation of the WARMS database is required as one of the potential sources of this information.
- The more recent and more detailed map of Mucina and Rutherford (2006) of natural vegetation types offers better spatial representation and should be investigated further when the current WRC Project K5/2437, “Resetting the baseline land cover against which streamflow reduction activities and the hydrological impacts of land use change are assessed”, has developed a set of hydrological modelling parameters for the natural vegetation types of Mucina and Rutherford (2006).
- Include the modelling of water use by alien vegetation to estimate its impact on the water balance in a catchment.
- The uMngeni catchment case study indicated the need to better represent the runoff from urban areas, possibly through better estimates of the area of impervious surfaces in urban areas.
- Although urban areas may not be high net users of water, they require a large supply of water at a high assurance of supply, and thus often have a significant localised effect on streamflow. Additional datasets on domestic and industrial water use and return flows, or the modelling of water use and return flows, are required to improve estimates of gross and net water use from these sectors.
- A common problem when water resources are modelled over short periods of time is the initialisation of water stores at the start of a simulation. Sources of information to initialise dam storage volumes and soil moisture at the start of a simulation period need to be further investigated.
- Accounts are for a specific temporal domain, but it would be useful to develop accounts that show how components of other accounts, such as streamflow or dam levels, relate to long-term historical values such as on a cumulative frequency distribution.
- Accounts that show the impact of dams, water abstractions and return flows on river flows, which may have an effect on the condition of river ecosystems, need to be further developed.
- Accounts that show the productivity of water in producing crops need to be developed.
- The feasibility of using climate forecasts to produce forecast water resource accounts needs to be investigated.
- Further work needs to be done to engage with water managers, especially at CMA level, to understand how the accounts might be useful to them and how the water accounts might need to be adjusted and further developed to meet their needs.

Water is a scarce and limiting resource in South Africa, and a better understanding of water resource systems and the impact of water on society and the economy is required to manage the country’s water resources efficiently and sustainably. Significant progress has been made in identifying suitable datasets and in developing a methodology for compiling catchment-scale water resource accounts that show sectoral water use with a strong land cover/use focus. In conclusion, despite the challenges associated with producing accurate and detailed water resource accounts at a catchment scale, the objective of being able to produce these accounts annually for the whole country to build an understanding of our country’s water resources is still valid and needs to be urgently pursued.

CHAPTER 12: CAPACITY BUILDING

DJ Clark

Several forms of capacity building took place as a result of the project, including postgraduate students, staff development, institutional development (the Centre for Water Resources Research (CWRR) at the University of KwaZulu-Natal), three workshops organised as part of the project, a conference presentation and a presentation on water accounting to two government delegations from South Sudan.

The postgraduate students that contributed to the project are shown in Table 12-1. Mr Shuaib Suleman's studies were fully funded by the project, while Ms Maqsooda Mahomed's studies were partially funded by the project.

Table 12-1: Postgraduate students likely to contribute to the project

Student	Degree	Contribution
Mr David Clark	PhD	Project leader Hydrological modelling and compiling water accounts (submitted for examination)
Ms Kershani Chetty	PhD	Remotely sensed rainfall estimates and methods for bias correction and downscaling (still in progress)
Mr Shuaib Suleman	MSc	Remotely sensed rainfall estimates and their use in hydrological modelling (degree awarded)
Ms Maqsooda Mahomed	MSc	ET_a and ET_0 estimates (degree awarded *cum laude*)
Mr Maiyuran Vethakuddikurukkal	BSc Hons	Delineation of response regions within quaternary catchments (degree awarded)
Mr Kyle Reddy	BSc Hons	Effect of improved agricultural land use information on modelled hydrological variables (degree awarded)

Most of the members of the CWRR receive funding from the WRC and are involved in the teaching of hydrology courses at both undergraduate and postgraduate levels, as well as the supervision of postgraduate research projects. The CWRR employs undergraduate and postgraduate students in research projects during the long university vacations (July and December) and as interns throughout the year. This practice provides students with additional skills that are useful to them both in seeking employment and in continuing with postgraduate studies in hydrology. This exposure to hydrological research has proven to be successful in attracting students to later postgraduate studies.

Due to the nature of the project, which requires a wide range of expertise in water resources, several staff within the CWRR were involved with the project to some extent and, in the process, gained valuable experience. This project has also built capacity within the University of KwaZulu-Natal, which recognises the need for expertise in water resources in South Africa.

As reported in Chapter 0, three workshops were held as part of the project. Two introductory workshops were held near the beginning of the project: one in the uMngeni and one in the Breede case study catchments. The first workshop was held at the offices of the Breede-Gouritz CMA in Worcester on 1 July 2016. The second workshop was held at the University of KwaZulu-Natal in Pietermaritzburg on 21 July 2016. A feedback workshop was held at the WRC's offices in Pretoria on 30 October 2018.

The project leader, Mr David Clark presented a paper titled "An integrated water resources accounting methodology for South Africa – initial development and application in the upper uMngeni catchment" at the South African National Hydrology Symposium, which was held in Durban in September 2016. The purpose of the paper was to inform delegates of the water accounting work that had been completed in WRC Project K5/2205.

Mr Clark was given the opportunity to attend a three-day Delft-FEWS training course titled "Forecast Early Warning System Master Class". The course, which was held at the Moses Mabhida Stadium in Durban from 1 to 3 August 2017, was organised and facilitated by the Coastal Stormwater and Catchment Management Department at the eThekwini Municipality and the Municipal Institute of Learning. The Delft-FEWS software could potentially be used as a tool for managing the data required for hydrological modelling to produce water resource accounts operationally.

Mr Clark was a member of the Reference Group for WRC Project K5/2419. "Water accounts for South Africa". This enabled Mr Clark to gain a better understanding of the more economics-based water accounting methodology of SEEA-Water and its application at WMA level in South Africa.

Mr Clark is one of the researchers that will be working on the natural capital accounting component of the large Global Environment Facility (GEF)-funded Development Bank of South Africa (DBSA) and SANBI project titled "Unlocking biodiversity benefits through development finance in critical catchments". This project will enable the catchment-scale water resource accounting methodology developed in WRC Project K5/2205 and WRC Project K5/2512 to be applied further in additional catchments. Linkages between water resource accounts, land accounts and ecosystem accounts will also be investigated.

Mr Clark also participated in workshops for a European Union-funded project titled "Natural capital accounting and valuation of ecosystem services", which will run in parallel with the GEF-funded project. Both these projects will promote capacity building through the collaborative sharing of expertise between the various natural capital accounting domains.

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APPENDICES

APPENDIX A: LAND COVER/USE MAPPING FOR THE DEA AND GTI (2015) DATASET

The land cover/use class mapping file to map from the NLC 2013-2014 (DEA and GTI, 2015) classes to the standard land cover/use classes in the *LCU_Classes.xml* file is shown in Table A-1. The land cover/use class mapping file column headings are described as follows:

- *Dataset_ID* = land cover/use dataset class ID
- *Dataset_Desc* = land cover/use dataset class description
- *LCU_Class* = land cover/use class ID in the *LCU_Classes* database

Table A-1: Land cover/use mapping for the DEA and GTI (2015) dataset

Dataset_ID	Dataset_Desc	LCU_Class
0	Missing data	UnknownLCU
1	Water seasonal	Waterbodies_Natural_Rivers
2	Water permanent	Waterbodies_Artificial_Dams
3	Wetlands	Waterbodies_Natural_Wetlands_General
4	Indigenous Forest	Natural_Typical_General
5	Thicket /Dense bush	Natural_Typical_General
6	Woodlan/Open bush	Natural_Typical_General
7	Grassland	Natural_Typical_General
8	Shrubland fynbos	Natural_Typical_General
9	Low shrubland	Natural_Typical_General
10	Cultivated comm fields (high)	Agriculture_Commercial_General_Dryland_Annual_General
11	Cultivated comm fields (med)	Agriculture_Commercial_General_Dryland_Annual_General
12	Cultivated comm fields (low)	Agriculture_Commercial_General_Dryland_Annual_General
13	Cultivated comm pivots (high)	Agriculture_Commercial_General_Irrigated_Annual_General
14	Cultivated comm pivots (med)	Agriculture_Commercial_General_Irrigated_Annual_General
15	Cultivated comm pivots (low)	Agriculture_Commercial_General_Irrigated_Annual_General
16	Cultivated orchards (high)	Agriculture_Commercial_General_Irrigated_Perrenial_General
17	Cultivated orchards (med)	Agriculture_Commercial_General_Irrigated_Perrenial_General
18	Cultivated orchards (low)	Agriculture_Commercial_General_Irrigated_Perrenial_General
19	Cultivated vines (high)	Agriculture_Commercial_GrapesGeneral_Irrigated
20	Cultivated vines (med)	Agriculture_Commercial_GrapesGeneral_Irrigated
21	Cultivated vines (low)	Agriculture_Commercial_GrapesGeneral_Irrigated

Dataset_ID	Dataset_Desc	LCU_Class
22	Cultivated permanent pineapple	Agriculture_Commercial_Pineapples_Dryland
23	Cultivated subsistence (high)	Agriculture_Subsistence_General_Dryland_Annual_General
24	Cultivated subsistence (med)	Agriculture_Subsistence_General_Dryland_Annual_General
25	Cultivated subsistence (low)	Agriculture_Subsistence_General_Dryland_Annual_General
26	Cultivated cane pivot - crop	Agriculture_Commercial_Sugarcane_Irrigated
27	Cultivated cane pivot - fallow	Agriculture_Commercial_Sugarcane_Irrigated
28	Cultivated cane commercial - crop	Agriculture_Commercial_Sugarcane_Dryland
29	Cultivated cane commercial - fallow	Agriculture_Commercial_Sugarcane_Dryland
30	Cultivated cane emerging - crop	Agriculture_Commercial_Sugarcane_Dryland
31	Cultivated cane emerging - fallow	Agriculture_Commercial_Sugarcane_Dryland
32	Plantations / Woodlots mature	Forest Plantations_General
33	Plantation / Woodlots young	Forest Plantations_General
34	Plantation / Woodlots clearfelled	Forest Plantations_General
35	Mines 1 bare	Mines and Quarries_Surface_Tailings/Dumps
36	Mines 2 semi-bare	Mines and Quarries_Surface_Tailings/Dumps
37	Mines water seasonal	Mines and Quarries_Water
38	Mines water permanent	Mines and Quarries_Water
39	Mine buildings	Mines and Quarries_Buildings
40	Erosion (donga)	Natural_Degraded_Bare_ErosionGullies
41	Bare none vegetated	Natural_Typical_Bare
42	Urban commercial	Urban/Built-up_Commercial
43	Urban industrial	Urban/Built-up_Industrial/Transport
44	Urban informal (dense trees / bush)	Urban/Built-up_Residential_Informal - High Density (Informal Townships)
45	Urban informal (open trees / bush)	Urban/Built-up_Residential_Informal - High Density (Informal Townships)
46	Urban informal (low veg / grass)	Urban/Built-up_Residential_Informal - High Density (Informal Townships)
47	Urban informal (bare)	Urban/Built-up_Residential_Informal - High Density (Informal Townships)
48	Urban residential (dense trees / bush)	Urban/Built-up_Residential_Formal - Medium Density (Suburbs)

Dataset_ID	**Dataset_Desc**	**LCU_Class**
49	Urban residential (open trees / bush)	Urban/Built-up_Residential_Formal - Medium Density (Suburbs)
50	Urban residential (low veg / grass)	Urban/Built-up_Residential_Formal - Medium Density (Suburbs)
51	Urban residential (bare)	Urban/Built-up_Residential_Formal - Medium Density (Suburbs)
52	Urban school and sports ground	Urban/Built-up_Commercial_Education Health IT
53	Urban smallholding (dense trees / bush)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
54	Urban smallholding (open trees / bush)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
55	Urban smallholding (low veg / grass)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
56	Urban smallholding (bare)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
57	Urban sports and golf (dense tree / bush)	Urban/Built-up_Open Spaces (Golf Courses and Sports Fields etc)
58	Urban sports and golf (open tree / bush)	Urban/Built-up_Open Spaces (Golf Courses and Sports Fields etc)
59	Urban sports and golf (low veg / grass)	Urban/Built-up_Open Spaces (Golf Courses and Sports Fields etc)
60	Urban sports and golf (bare)	Urban/Built-up_Open Spaces (Golf Courses and Sports Fields etc)
61	Urban township (dense trees / bush)	Urban/Built-up_Residential_Formal - High Density (Formal Townships)
62	Urban township (open trees / bush)	Urban/Built-up_Residential_Formal - High Density (Formal Townships)
63	Urban township (low veg / grass)	Urban/Built-up_Residential_Formal - High Density (Formal Townships)
64	Urban township (bare)	Urban/Built-up_Residential_Formal - High Density (Formal Townships)
65	Urban village (dense trees / bush)	Urban/Built-up_Residential_Informal - Low Density Rural
66	Urban village (open trees / bush)	Urban/Built-up_Residential_Informal - Low Density Rural
67	Urban village (low veg / grass)	Urban/Built-up_Residential_Informal - Low Density Rural
68	Urban village (bare)	Urban/Built-up_Residential_Informal - Low Density Rural
69	Urban built-up (dense trees / bush)	Urban/Built-up
70	Urban built-up (open trees / bush)	Urban/Built-up
71	Urban built-up (low veg / grass)	Urban/Built-up
72	Urban built-up (bare)	Urban/Built-up

APPENDIX B: ISIC CODES ASSIGNED TO LAND COVER/USE CLASSES

The SEEA-Water water accounting framework uses the UN's ISIC system to classify economic activity (UN, 2012). For each of the agricultural, forestry and mining classes in the database of land cover/use classes, an ISIC code has been assigned as shown in Table B-1.

Table B-1: Land cover/use classes and their associated ISIC codes

Class name	ISIC code	Description	Section	Division	Group	Class
Agriculture_Commercial_General_Dryland_Annual_General	011	Growing of non-perennial crops	A	01	011	
Agriculture_Commercial_General_Irrigated_Annual_General	011	Growing of non-perennial crops	A	01	011	
Agriculture_Subsistence_General_Dryland_Annual_General	011	Growing of non-perennial crops	A	01	011	
Agriculture_Commercial_Canola_Dryland_Winter	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Canola_Irrigated_Winter	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_GrainSorghum_Dryland_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_GrainSorghum_Irrigated_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Maize_Dryland_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Maize_Irrigated_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Soyabeans_Dryland_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Sunflower_Dryland_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Sunflower_Irrigated_Summer	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Wheat_Dryland_Winter	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Wheat_Irrigated_Winter	0111	Growing of cereals (except rice), leguminous crops and oil seeds	A	01	011	0111
Agriculture_Commercial_Vegetables_Irrigated	0113	Growing of vegetables and melons, roots and tubers	A	01	011	0113
Agriculture_Commercial_Sugarcane_Dryland_FarNorthCoast	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Commercial_Sugarcane_Dryland_FarNorthCoast	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Commercial_Sugarcane_Dryland_Inland	0114	Growing of sugarcane	A	01	011	0114

Class name	ISIC code	Description	Section	Division	Group	Class
Agriculture_Commercial_Sugarcane_Dryland_NorthCoast	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Commercial_Sugarcane_Dryland_SouthCoast	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Commercial_Sugarcane_Irrigated	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Subsistence_Sugarcane_Dryland	0114	Growing of sugarcane	A	01	011	0114
Agriculture_Commercial_Lucerne_Dryland_Summer	0119	Growing of other non-perennial crops	A	01	011	0119
Agriculture_Commercial_Lucerne_Irrigated_Summer	0119	Growing of other non-perennial crops	A	01	011	0119
Agriculture_Commercial_General_Irrigated_Perrenial_General	012	Growing of perennial crops	A	01	012	
Agriculture_Commercial_GrapesGeneral_Irrigated	0121	Growing of grapes	A	01	012	0121
Agriculture_Commercial_GrapesTable_Irrigated	0121	Growing of grapes	A	01	012	0121
Agriculture_Commercial_GrapesWine_Irrigated	0121	Growing of grapes	A	01	012	0121
Agriculture_Commercial_Avocado_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Bananas_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Granadillas_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Guava_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Litchies_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Mangos_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Pawpaws_Irrigated	0122	Growing of tropical and subtropical fruits	A	01	012	0122
Agriculture_Commercial_Citrus_Irrigated_TransvaalNatal	0123	Growing of citrus fruits	A	01	012	0123
Agriculture_Commercial_Citrus_Irrigated_TransvaalNatal	0123	Growing of citrus fruits	A	01	012	0123
Agriculture_Commercial_DeciduousFruit_Irrigated	0124	Growing of pome fruits and stone fruits	A	01	012	0124
Agriculture_Commercial_StoneFruit_Irrigated	0124	Growing of pome fruits and stone fruits	A	01	012	0124
Agriculture_Commercial_Blueberries_Irrigated	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125
Agriculture_Commercial_CashewNuts_Dryland	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125
Agriculture_Commercial_Kiwifruit_Irrigated	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125
Agriculture_Commercial_Macadamias_Irrigated	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125
Agriculture_Commercial_PecanNuts_Irrigated	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125

Class name	ISIC code	Description	Section	Division	Group	Class
Agriculture_Commercial_Pomegranates_Irrigated	0125	Growing of other tree and bush fruits and nuts	A	01	012	0125
Agriculture_Commercial_Coffee_Irrigated	0127	Growing of beverage crops	A	01	012	0127
Agriculture_Commercial_Ginger_Irrigated	0128	Growing of spices, aromatic, drug and pharmaceutical crops	A	01	012	0128
Forest Plantations_Eucalyptus_General	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Mature_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Mature_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Mature_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Medium_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Medium_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Medium_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Young_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Young_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Eucalyptus_Young_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_General	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_General	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Mature_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Mature_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Mature_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Medium_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Medium_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Medium_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Young_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Young_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Pine_Young_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Poplar_General	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_General	0210	Silviculture and other forestry activities	A	02	021	0210

Class name	ISIC code	Description	Section	Division	Group	Class
Forest Plantations_Wattle_Mature_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Mature_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Mature_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Medium_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Medium_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Medium_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Young_Intensive	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Young_Intermediate	0210	Silviculture and other forestry activities	A	02	021	0210
Forest Plantations_Wattle_Young_Pitting	0210	Silviculture and other forestry activities	A	02	021	0210
Mines and Quarries_Buildings	B	Mining and quarrying	B			
Mines and Quarries_Subsurface_Subsurface Mine	B	Mining and quarrying	B			
Mines and Quarries_Surface_Opencast Mine/Quarry	B	Mining and quarrying	B			
Mines and Quarries_Surface_Tailings/Dumps	B	Mining and quarrying	B			
Mines and Quarries_Water	B	Mining and quarrying	B			

APPENDIX C: STREAMFLOW VERIFICATION IN CASE STUDY CATCHMENTS

A modelling approach was selected for the water use quantification and accounting methodology as many of the components of the water accounts are difficult to measure or are only measured at a sparse network of gauges that are not representative of the spatial variability in climate, land cover/use and soils. It is necessary to verify the modelled results, where possible, using measured data. The focus of the verifications described in this section was primarily to investigate the accurate representation of climate and land cover/use.

The results of the hydrological modelling in each case study catchment were verified by comparing simulated streamflow volumes with measured streamflow data. The measured streamflow data was obtained from the Hydrological Services – Surface Water (Data, Dams, Floods and Flows) page of the DWS's website [http://www.dwa.gov.za/hydrology/]. The streamflow gauges selected for verification were those that did not have too much missing data, that were not immediately downstream of large dams, and that were perceived to be significantly affected by the water infrastructure upstream. The statistics and the graphs that compared the simulated and measured streamflow were based on monthly values aggregated up from daily data values. Monthly values were used due to the phase error between the daily simulated and measured streamflow data, as discussed in Section 0, and also because the water resource accounts are at an annual time step, so verification at a daily time step is not necessary. The hydrological simulations were run for the period 1 October 2013 to 30 September 2018. The first year of the simulated period was regarded as a warm-up year to enable the initialisation of soil water and baseflow stores in the model.

For the purpose of comparing simulated streamflow volumes with measured streamflow data, the following three comparative statistics were selected:

- *Mean percentage difference:* This is the percentage difference between the mean of the simulated daily streamflow and the mean of the measured daily streamflow. This gives an indication of how closely the total simulated streamflow volume matches the total measured streamflow volume over the full comparison period.
- *Coefficient of determination:* This is the R^2 between the simulated daily streamflow and the measured daily streamflow. It is the square of the Pearson's correlation coefficient (r) and is an indicator of the linearity of the relationship between the simulated daily streamflow values relative to the measured daily streamflow values.
- *Nash-Sutcliffe efficiency*: The NSE (Nash and Sutcliffe, 1970) provides a relative index of the degree of association between measured and simulated streamflow values.

UMngeni catchment case study

In the uMngeni catchment, nine streamflow gauges were selected for the verification exercise. The location of the streamflow gauges is shown in Figure 7-2. The statistics comparing modelled with measured streamflow at each streamflow gauge are shown in Table C-, with a brief description of the land cover/use upstream of each gauge to provide context. Graphs that enable a visual comparison of the time series of modelled with measured streamflow are shown for each gauge in Figure C-1 to Figure C-9.

The uMngeni catchment is highly developed with extensive areas of commercial agriculture, including sugarcane, forest plantations and large areas of different types of urban development. It is necessary to import water into the catchment from the neighbouring Mooi River catchment to provide for the growing urban water requirement. The comparative statistics indicate that the flow at most of the gauges was not simulated accurately, with the simulated streamflow volumes over the four-year period being undersimulated by more than 50% in several of the gauged catchments.

The simulation of flow volumes at gauge U2H013 (Figure C-1) on the upper uMngeni River is relatively good, compared to many of the other gauges, but not as good as that reported in Section 0. In part, this may be due to the shorter time period and different years being simulated in the verification study. However, the ARC rain gauge at Ivanhoe Farm in quaternary catchment U20A, which was available to Clark (2018), was not available for use in the verification study and thus rain gauge U2E003 at Midmar Dam had to be used as the driver rain gauge.

A good simulation was achieved at gauge U2H061 (Figure C-2) on the Mpofana River. However, this was to be expected as the catchment is relatively small and the flows at gauge U2H061 consist predominantly of the inter-catchment transfer from the Mooi River catchment, the outfall of which is just upstream of the gauge. The inter-catchment transfer was modelled using measured pumped flow values at the sources of the two components of the transfer. Gauge U2H007 (Figure C-3) is on the Lions River, downstream of gauge U2H061. The flow volumes were not simulated well at gauge U2H007, and it is interesting to note that the measured flows at gauge U2H007 are often substantially less than the inter-catchment transfer flows that should have been received from upstream. Given the close agreement between the measured transfer flows and the flows at U2H061, these transfer flow measurements would appear to be correct, which means that either the flow measurements at gauge U2H007 are inaccurate or a substantial portion of the flow between the two gauge is being lost.

The simulation at gauge U2H006 in quaternary catchment U20D was poor. The catchment is impacted on by forest plantations and commercial agriculture, but better simulations at this gauge were reported in Section 0. As was the case with quaternary catchment U20A, the ARC rain gauge at Everdon Estate in quaternary catchment U20D, which was available to Clark (2018), although no longer operational, was not available for use in the verification study.

Gauge U2H012 is situated on the Mpolweni River in quaternary catchment U20F. Except for the 2014/15 hydrological year, the flows at this gauge are significantly underestimated. This is contrary to what would be expected in a catchment whose land use almost entirely comprises forest plantations and sugarcane. The reason for the poor simulation at this gauge is not clear, and the rainfall data for the driver rain gauge should be further investigated.

The flow volumes at gauge U2H011 on the upper uMsunduzi River in quaternary catchment U20H were not were not particularly well simulated. There is no driver rain gauge in or close to the catchment. The source of water for the rural settlements needs to be further investigated.

The simulations of streamflow volumes at U2H057, U2H058 and U2H041 were all poor with flows being substantially underestimated. These three gauges are all heavily impacted on by the extensive urban areas surrounding them. One potential cause for these underestimations is that the impervious surfaces associated with these urban areas are being underestimated. A better method of estimating the impervious fraction of these catchments needs to be investigated.

Table C-1: Verification statistics for the uMngeni catchment for 2014/15 to 2017/18 using adjusted FEWS RFE 2.0 rainfall

Gauge	Statistic		Description
U2H013 Catchment U20A_01_07	Mean percentage difference	-21.94	Natural vegetation and some forest plantations upstream.
	R^2	0.70	
	NSE	0.68	
U2H061 Catchment U20B_02_01	Mean percentage difference	3.94	Just downstream of the outfall for inter-catchment transfer from the Mooi River catchment. Natural vegetation, commercial agriculture and forest plantations upstream.
	R^2	0.94	
	NSE	0.94	
U2H007 Catchment U20C_01_01	Mean percentage difference	39.33	Downstream of gauge U2H061 and thus impacted on by the inter-catchment transfer. Natural vegetation, commercial agriculture and forest plantations upstream.
	R^2	0.793	
	NSE	0.40	
U2H006 Catchment U20D_05_01	Mean percentage difference	-53.63	Natural vegetation, commercial agriculture and forest plantations upstream.
	R^2	0.57	
	NSE	0.34	
U2H012 Catchment U20F_05_01	Mean percentage difference	-69.90	Land cover/use upstream is almost entirely forest plantations and commercial sugarcane farms, with an area of rural settlements in the vicinity of the weir.
	R^2	0.01	
	NSE	-0.68	
U2H011 Catchment U20H_01_05	Mean percentage difference	-37.17	Land cover/use upstream consists of natural vegetation, rural settlements and some forest plantations.
	R^2	0.56	
	NSE	0.41	
U2H057 Catchment U20J_01_05	Mean percentage difference	-79.38	Henley Dam is upstream. Some natural vegetation, forest plantations and rural settlements, but possibly impacted on by a portion of the Greater Edendale urban township.
	R^2	0.35	
	NSE	-1.55	
U2H058 Catchment U20J_02_03	Mean percentage difference	-75.67	Natural vegetation, forest plantations and rural settlements in the upper part of the catchment, but possibly impacted on by a portion of the Greater Edendale urban township.
	R^2	0.47	
	NSE	-0.08	
U2H041 Catchment U20J_03_12	Mean percentage difference	-76.36	On the Msunduzi River downstream of the city of Pietermaritzburg and the Darville sewerage works.
	R^2	0.12	
	NSE	-0.22	

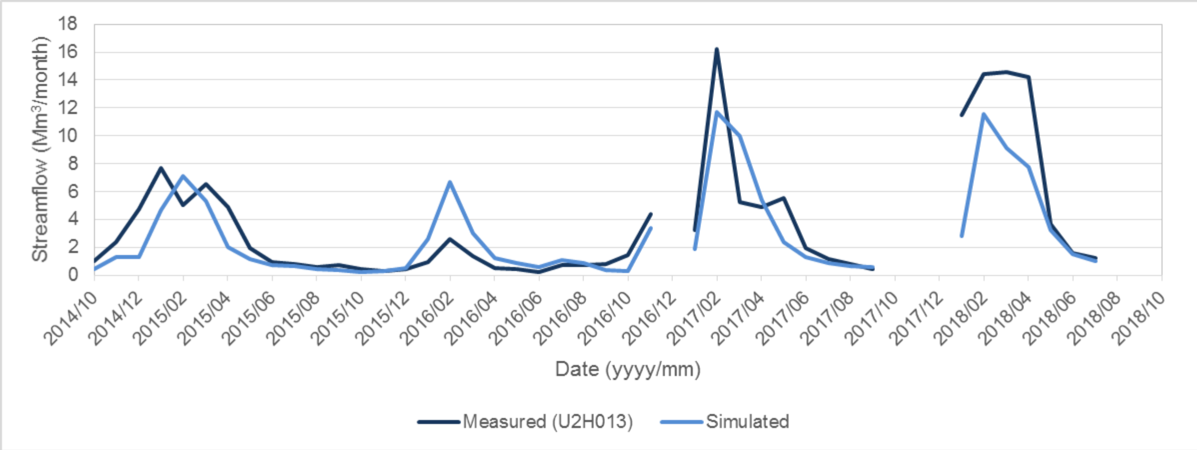

Figure C-1: Gauge U2H013 – comparison of measured and simulated monthly streamflow volumes

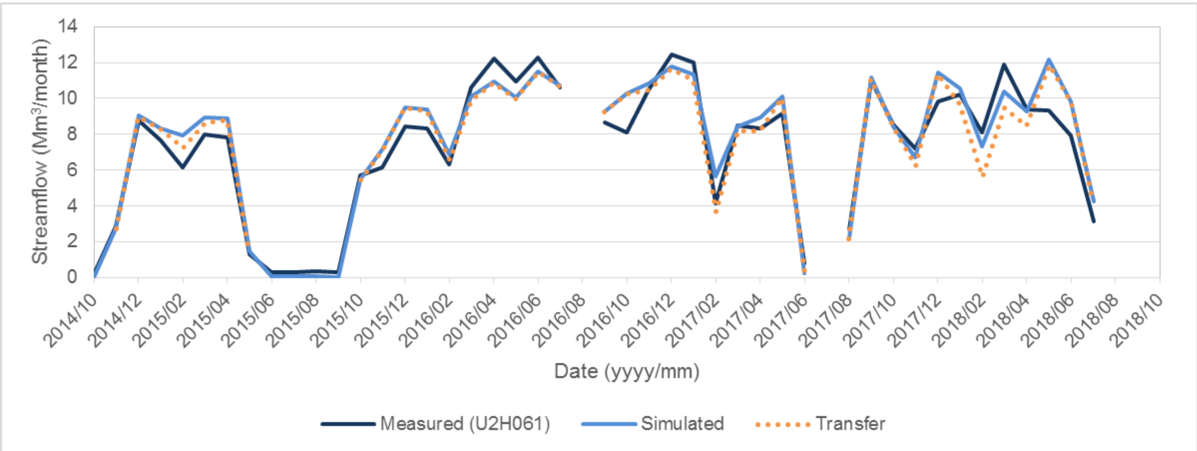

Figure C-2: Gauge U2H061 – comparison of measured and simulated monthly streamflow volumes

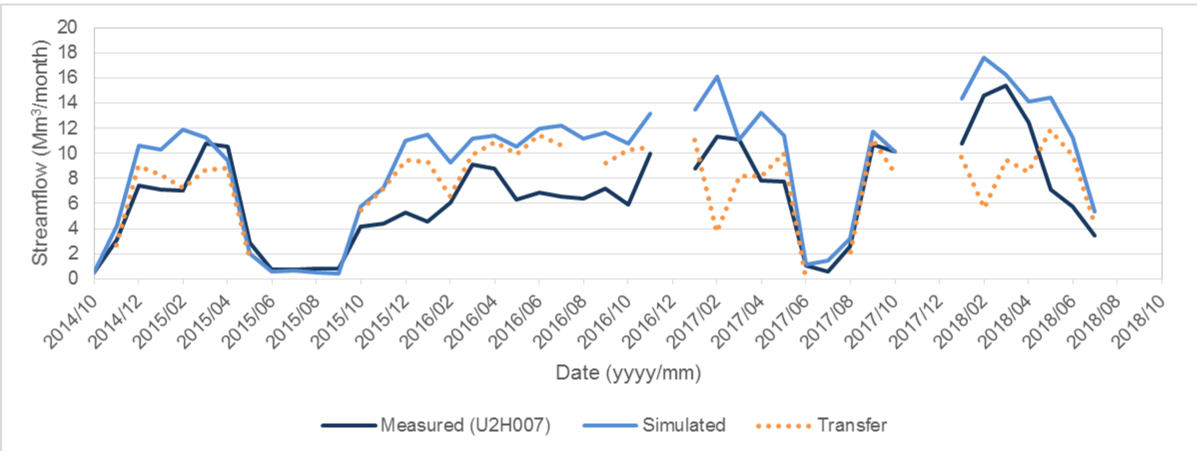

Figure C-3: Gauge U2H007 – comparison of measured and simulated monthly streamflow volumes

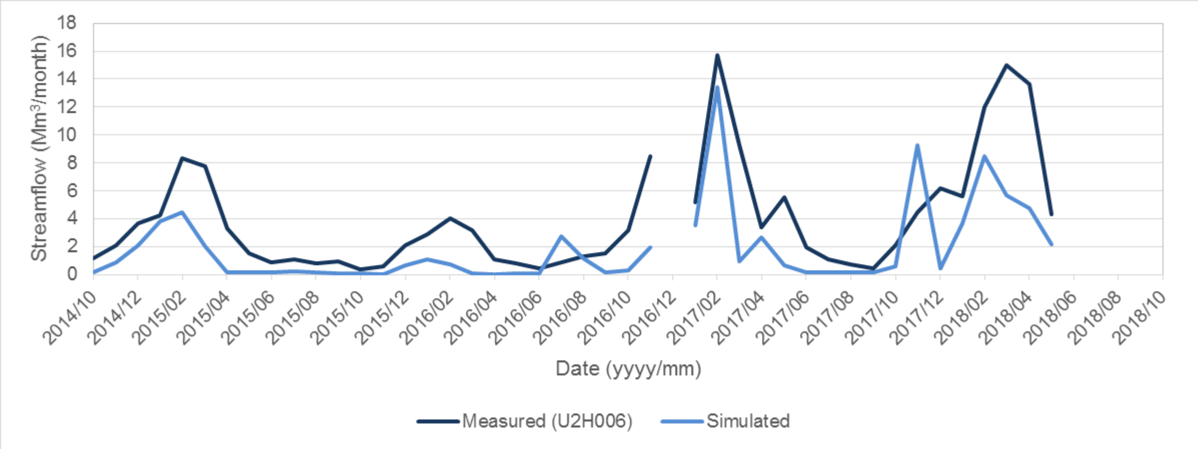

Figure C-4: **Gauge U2H006 – comparison of measured and simulated monthly streamflow volumes**

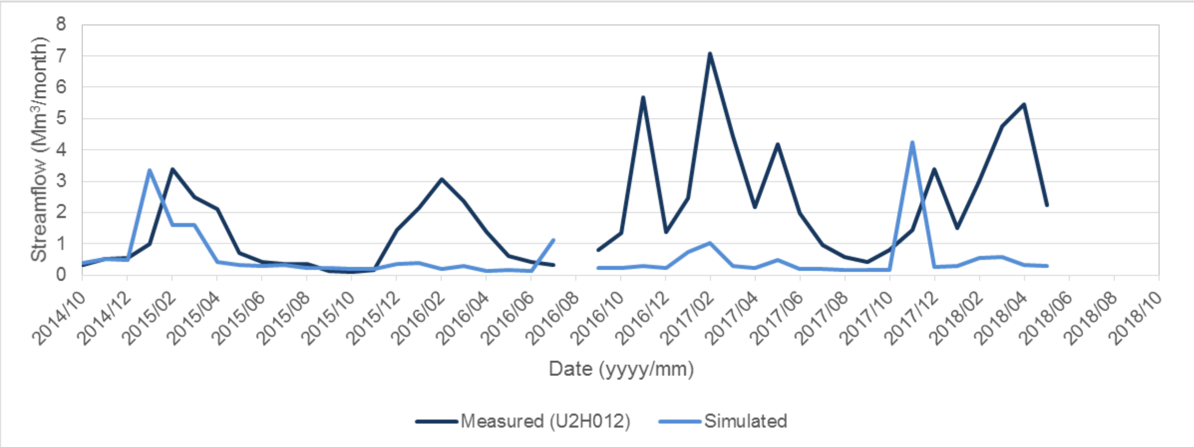

Figure C-5: **Gauge U2H012 – comparison of measured and simulated monthly streamflow volumes**

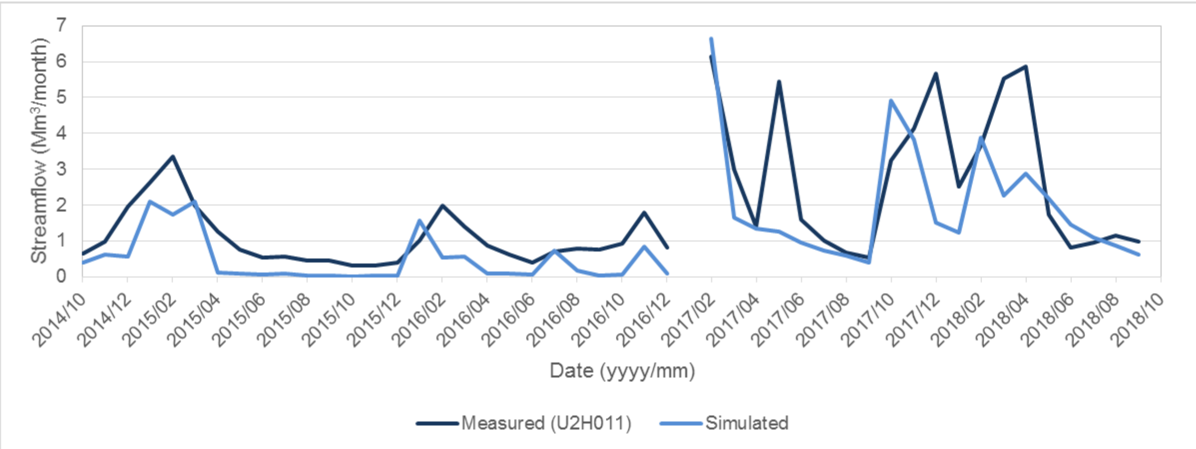

Figure C-6: **Gauge U2H011 – comparison of measured and simulated monthly streamflow volumes**

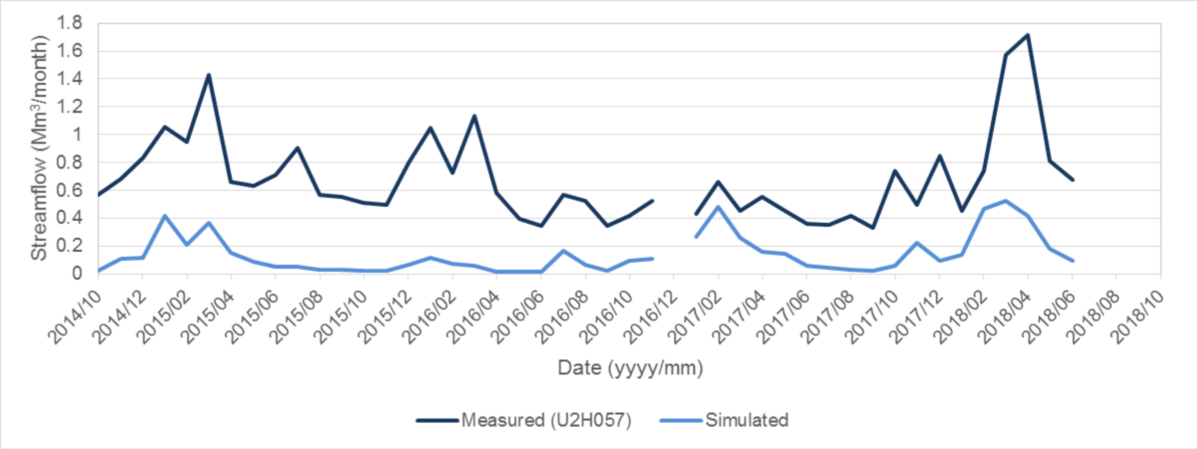

Figure C-7: **Gauge U2H057 – comparison of measured and simulated monthly streamflow volumes**

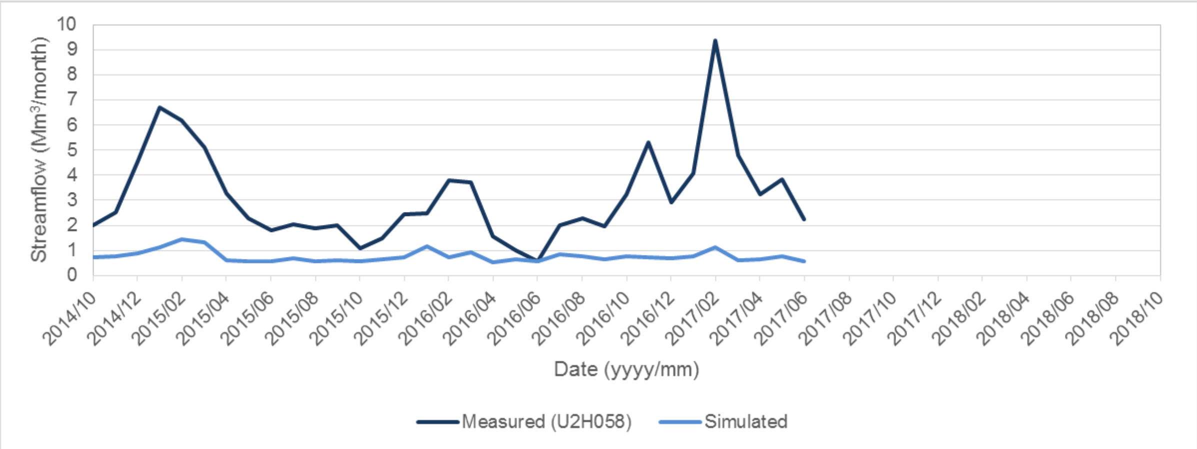

Figure C-8: **Gauge U2H058 – comparison of measured and simulated monthly streamflow volumes**

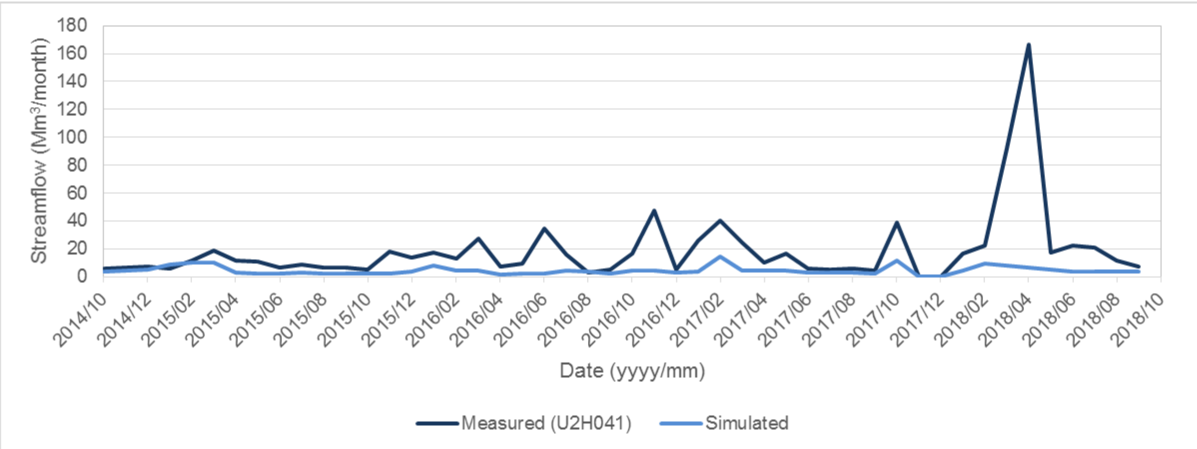

Figure C-9: **Gauge U2H041 – comparison of measured and simulated monthly streamflow volumes**

Upper uThukela catchment case study

In the upper uThukela catchment, ten streamflow gauges were selected for the verification exercise. The location of the streamflow gauges is shown in Figure 8-2. The statistics that compare modelled streamflow with measured streamflow at each streamflow gauge are shown in

Table C-2, with a brief description of the land cover/use upstream of each gauge to provide context. Graphs that enable a visual comparison of the time series of modelled streamflow with measured streamflow are shown for each gauge in Figure C-10 to Figure C-19.

The land cover in the upper uThukela catchment is predominantly natural vegetation with some substantial areas of irrigated commercial agriculture in the centre of the V1 secondary catchment and in the upper V2 secondary catchment. The comparative statistics indicate that the flow at many of the gauges was not simulated accurately, with the simulated streamflow volumes over the four-year period being undersimulated by more than 50% in some of the gauged catchments. At many of the gauges, the flows were poorly estimated in the first year (2014/15), possibly indicating the need for a better initialisation of baseflows in the catchment in this study catchment.

The flows at gauge V1H042 on the Mlambonja River (Figure C-10) were simulated well. The V11G quaternary catchment in the Drakensberg Mountains has a high MAP and the land cover is almost entirely natural vegetation. The downstream H11H quaternary catchment, in addition to natural vegetation, contains rural settlements and subsistence cultivation, with a small area of commercial agriculture just upstream of the weir. Over the four-year period, the total flow volume at gauge V1H009 (Figure C-11) in quaternary catchment V14C appears to be simulated well. However, the flows in individual years are not simulated well. The reason for the poor simulation is not clear. The rainfall estimates and the effect of commercial agriculture could be two possible causes.

Streamflow is not simulated well at any of the four catchments in the upper part of the V2 secondary catchment, gauges V2H005, V2H021, V2H006 and V2H007. All four catchments contain natural land cover and varying areas of commercial agriculture. Subcatchment V20B_02 has extensive areas of commercial irrigated agriculture with several dams. The flow volumes at gauges V2H004 and V2H021 are substantially undersimulated, although the pattern of the flows looks correct, possibly indicating a problem with the magnitude of the rainfall estimates. The magnitudes of the simulated flows are better at gauges V2H006 and V2H007.

The land cover in the upper part of the V6 secondary catchment is predominantly natural vegetation with small areas of commercial agriculture. Over the four-year period, the total flow volume at gauge V6H004 (Figure C-16) downstream of quaternary catchment V60A and V60B appears to be simulated well. However, the undersimulation of flow in some years balances the oversimulation in other years. The monthly flow volumes are mostly oversimulated at gauge V6H003 (Figure C-17). There are no driver rain gauges in or close to these catchments, which may have affected the rainfall estimates.

Gauges V7H017 (Figure C-18) and V7H016 (Figure C-19) are situated at the bottom of neighbouring quaternary catchments V70A and V70B respectively. Both catchments have predominantly natural land cover, with some rural settlements and subsistence agriculture just upstream of the gauges. The flow volumes are underestimated at both gauges, although the pattern of the flows is well represented.

Table C-2: Verification statistics for the upper uThukela catchment for 2014/15 to 2017/18 using adjusted FEWS RFE 2.0 rainfall

Gauge	Statistic		Description
V1H041 Catchment V11H_01	Mean percentage difference	-18.86	Upper mountainous part of the catchment is natural vegetation. The lower part of the catchment also contains rural settlements and subsistence cultivation.
	R^2	0.89	
	NSE	0.86	
V1H009 Catchment V14C_01	Mean percentage difference	15.36	Natural vegetation with some rural settlements, forest plantations and commercial agriculture.
	R^2	0.11	
	NSE	-0.12	
V2H005 Catchment V20A_01	Mean percentage difference	-78.42	Mostly natural vegetation with some commercial agriculture.
	R^2	0.67	
	NSE	-0.18	
V2H021 Catchment V20B_01	Mean percentage difference	-85.63	Mostly natural vegetation with some forest plantations and commercial agriculture.
	R^2	0.46	
	NSE	-0.84	
V2H006 Catchment V20B_02	Mean percentage difference	-41.12	Some natural vegetation with substantial area of commercial agriculture and several farm dams.
	R^2	0.42	
	NSE	0.34	
V2H007 Catchment V20C_01	Mean percentage difference	-53.15	Natural vegetation with a small amount of forest plantations and some commercial agriculture and two big farm dams.
	R^2	0.45	
	NSE	0.31	
V6H004 Catchment V60C_01	Mean percentage difference	0.60	Mostly natural vegetation with small areas of rural settlements, subsistence cultivation and commercial agriculture.
	R^2	0.31	
	NSE	0.12	
V6H003 Catchment V60D_05 V60D_06	Mean percentage difference	65.93	Mostly natural vegetation with some commercial agriculture in the upper part of the catchment.
	R^2	0.49	
	NSE	-0.68	
V7H017 Catchment V70A_03	Mean percentage difference	-44.68	Mostly natural vegetation, with small areas of forest plantations, rural settlements and subsistence cultivation in the lower part of the catchment.
	R^2	0.76	
	NSE	0.56	
V7H016 Catchment V70B_01	Mean percentage difference	-38.77	Mostly natural vegetation, with some rural settlements and subsistence cultivation in the lower part of the catchment.
	R^2	0.75	
	NSE	0.59	

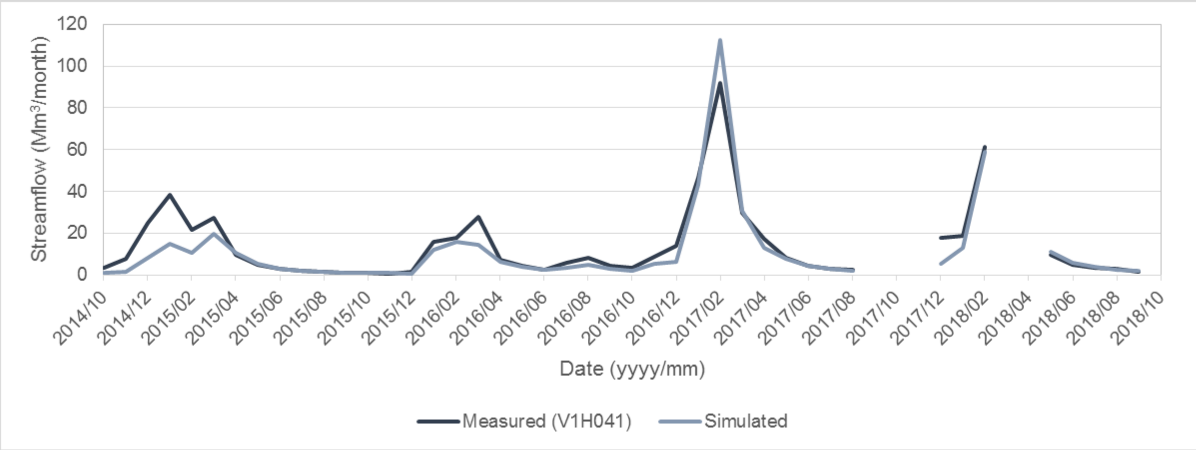

Figure C-10: Gauge V1H041 – comparison of measured and simulated monthly streamflow volumes

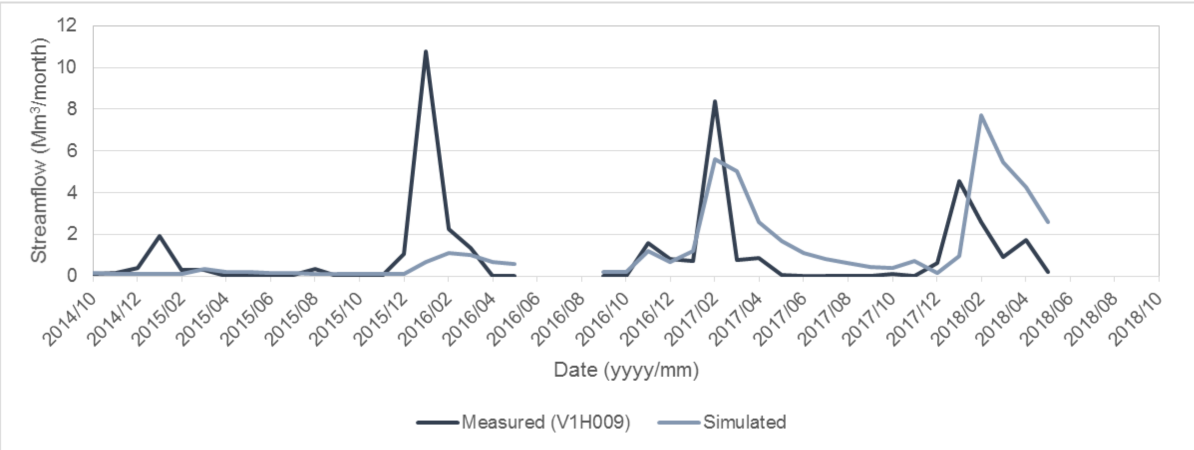

Figure C-11: Gauge V1H009 – comparison of measured and simulated monthly streamflow volumes

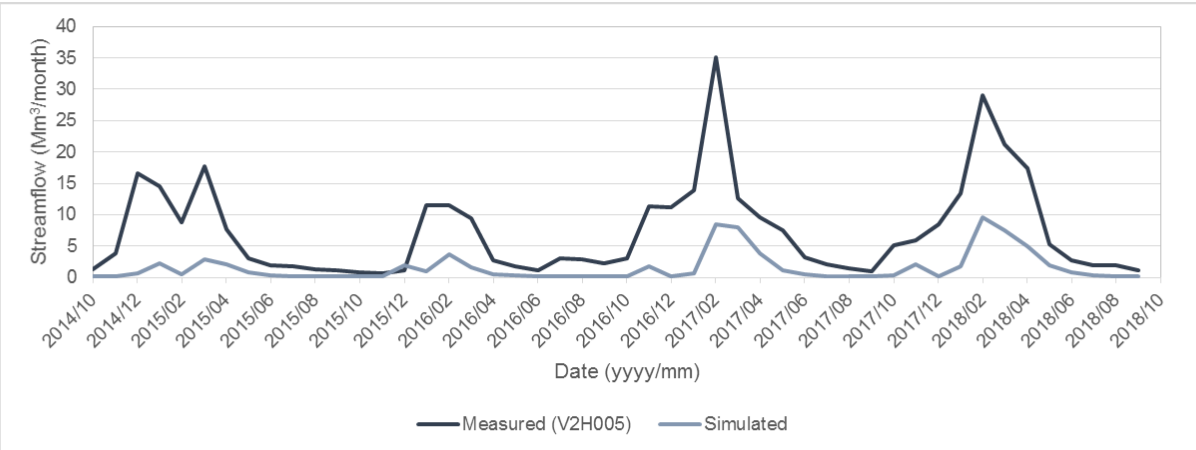

Figure C-12: Gauge V2H005 – comparison of measured and simulated monthly streamflow volumes

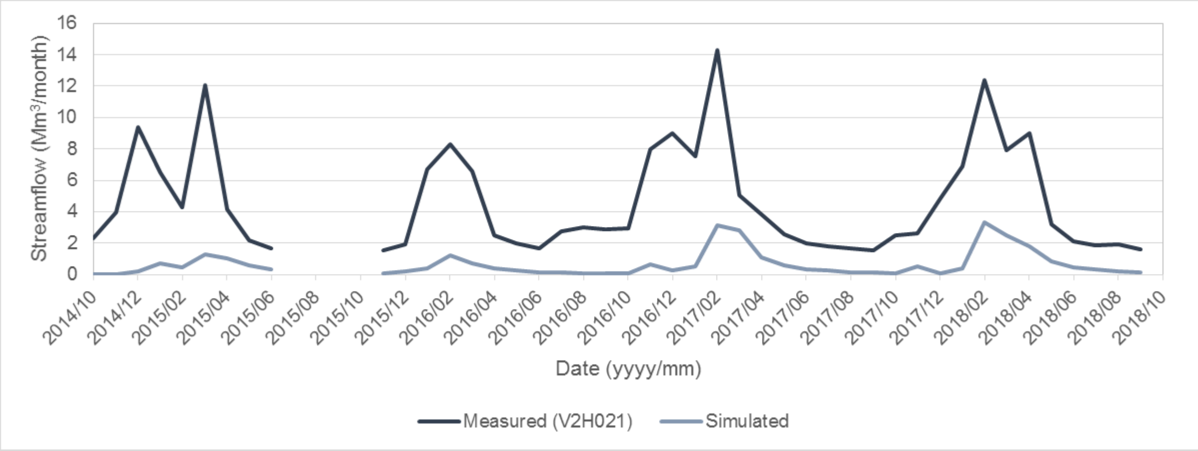

Figure C-13: Gauge V2H021 – comparison of measured and simulated monthly streamflow volumes

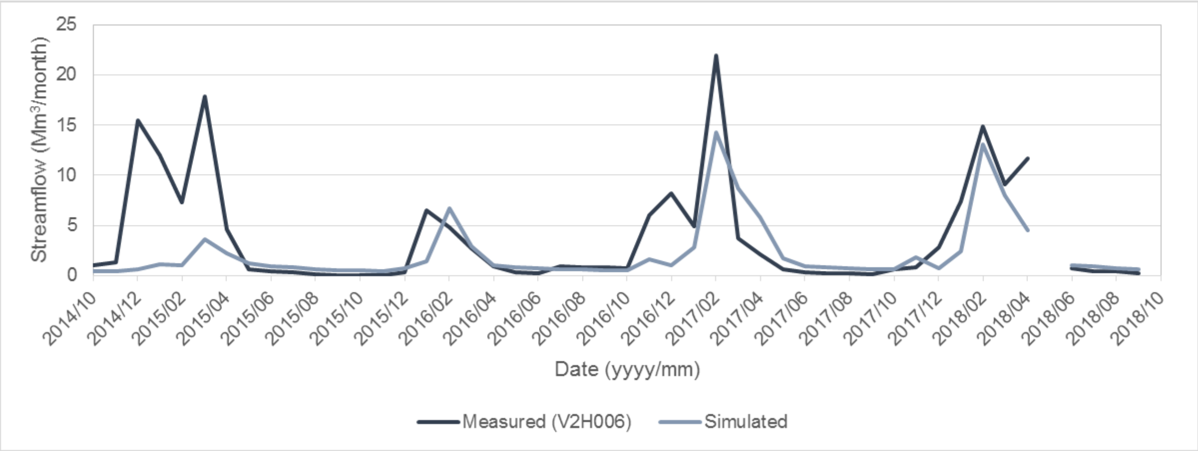

Figure C-14: Gauge V2H006 – comparison of measured and simulated monthly streamflow volumes

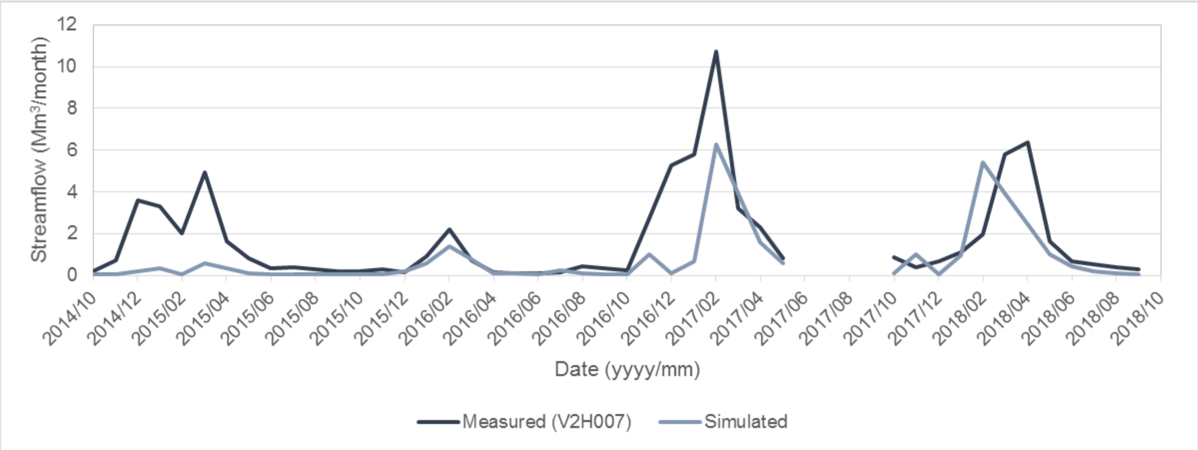

Figure C-15: Gauge V2H007 – comparison of measured and simulated monthly streamflow volumes

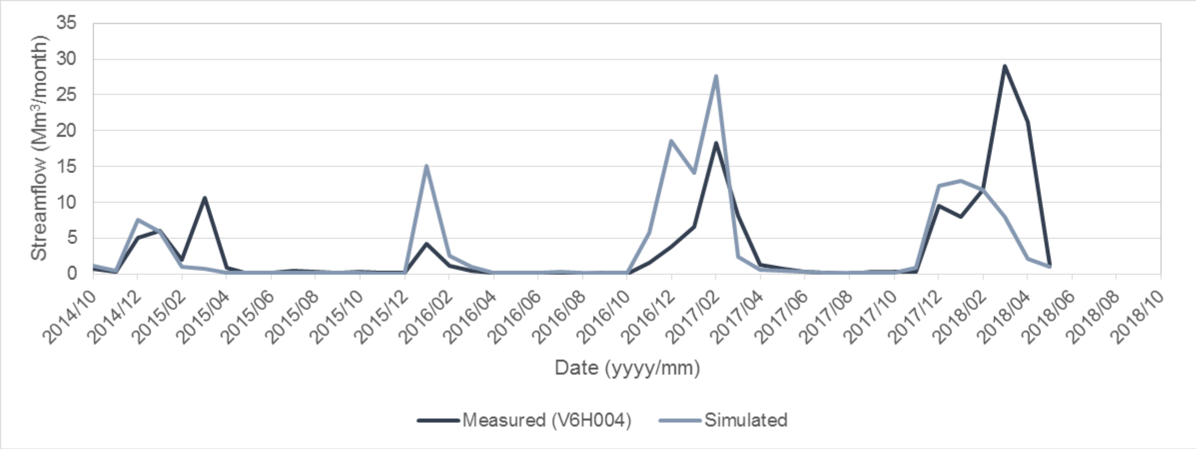

Figure C-16: Gauge V6H004 – comparison of measured and simulated monthly streamflow volumes

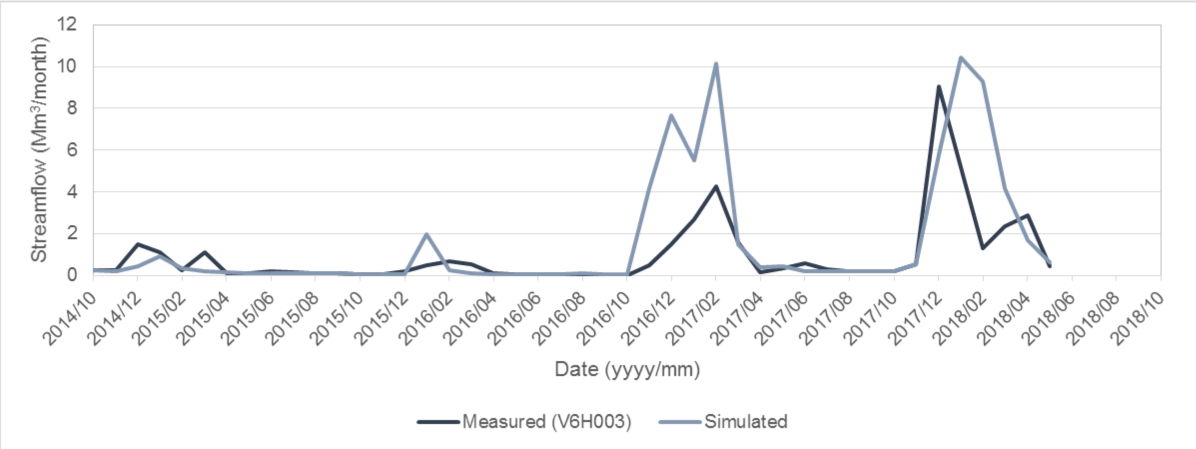

Figure C-17: Gauge V6H003 – comparison of measured and simulated monthly streamflow volumes

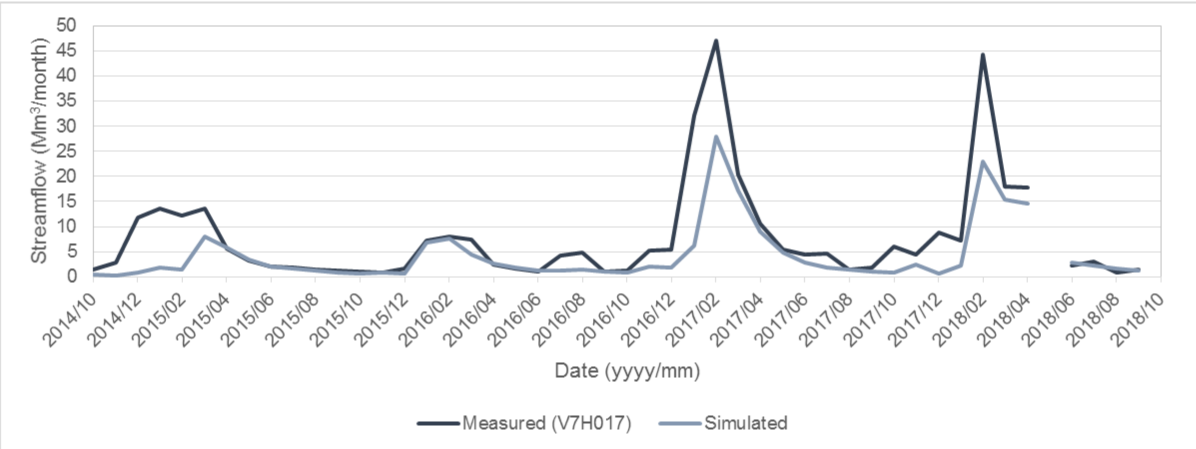

Figure C-18: Gauge V7H017 – comparison of measured and simulated monthly streamflow volumes

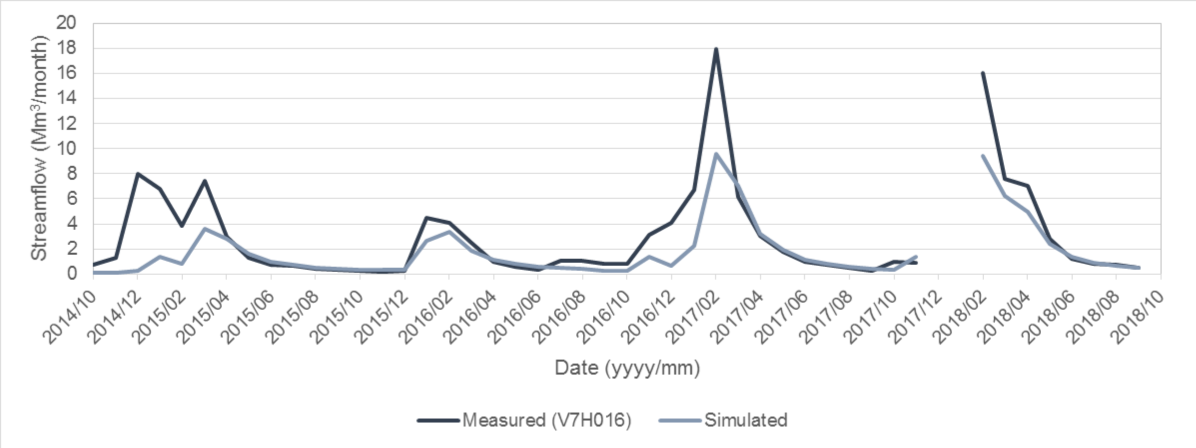

Figure C-19: Gauge V7H016 – comparison of measured and simulated monthly streamflow volumes

Upper and Central Breede catchment case study

In the upper and central Breede catchment, nine streamflow gauges were selected for the verification exercise. The location of the streamflow gauges is shown in Figure 9-2. The statistics that compare modelled streamflow with measured streamflow at each streamflow gauge are shown in Table C-, with a brief description of the land cover/use upstream of each gauge to provide context. Graphs that enable a visual comparison of the time series of modelled streamflow with measured streamflow are shown for each gauge in Figure C-20 to Figure C-28.

The topography of the upper and central Breede catchment is characterised by steep mountain ridges and broad valleys. The land cover is predominantly natural vegetation, with a few small towns and extensive irrigated agriculture in some areas, mostly in the valley bottom. Although some of the higher altitude parts of the catchment have a high MAP, rainfall in the catchment is relatively low, which has resulted in extensive development of infrastructure to store and transport irrigation water. The comparative statistics indicate that the flow was poorly simulated at all except one of the gauges. The investigation into methods to reduce localised bias in remotely sensed datasets, summarised in Section 0, led to a decision to apply the FEWS RFE 2.0 remotely sensed rainfall dataset in the case studies. However, given the poor simulation results in the upper and central Breede catchment, the TRMM 3B42 remotely sensed dataset was also applied in this case study to determine whether it was better at representing the winter rainfall regime in this catchment. At most of the gauges used for verification, as shown by the statistics in Table C-, the TRMM 3B42 dataset resulted in poorer estimates of streamflow volumes, except for the two gauges in the H4 secondary catchment.

The pattern of flows is well represented at gauges H1H033 and H1H018, but the flow volumes are underestimated. These catchments both have predominantly natural land cover and the rainfall estimates are expected to be the main cause for the underestimation of streamflow. Gauge H1H018 is downstream of gauge H1H033 and the poor simulation may be as a result of the poor simulation in the upstream catchment.

The four verification catchments within the H2 secondary catchment were all relatively small catchments, with land cover being mostly natural vegetation with varying proportions of bare rock. With the exception of gauge H2L001 in subcatchment H20E_01, the streamflow simulations in these catchments were poor. The flow volume at gauge H20E_02 was overestimated, while the flow at H20B_01 and H20F_02 were underestimated. It is not clear why one catchment should be well simulated, while the other three similar catchments were not. In addition to the possibility that the rainfall estimates were poor in these high-altitude steep catchments, the underlying rocky geology of the individual catchments may have a significant impact on the hydrological response in these catchments.

The land cover in subcatchment H30D_02, represented by gauge H3H005 (Figure C-26), is predominantly natural vegetation with vineyards in the valley bottom along the river. The flow volumes in this catchment were substantially oversimulated. Again, the rainfall estimates are the most likely cause of the poor simulations.

In secondary catchment H4, the two gauges, H4H018 (Figure C-27) and H4H016 (Figure C-28), both have catchments with predominantly natural land cover, but also significant areas of vineyards in the valley bottom. The town of McGregor is just upstream of gauge H4H016. The simulations at both these gauges were poor.

Table C-3: Verification statistics for the upper and central Breede catchment for 2014/15 to 2017/18 using adjusted FEWS RFE 2.0 rainfall

Gauge	Statistic		Description
H1H033 Catchment H10J_01	Mean percentage difference	-50.87	Natural vegetation.
	R^2	0.77	
	NSE	0.46	
H1H018 Catchment H10J_03	Mean percentage difference	-54.58	Natural vegetation with significant wetland areas upstream.
	R^2	0.78	
	NSE	0.45	
H2L002 Catchment H20B_01	Mean percentage difference	-81.09	Natural vegetation with large bare rocky area.
	R^2	0.45	
	NSE	-0.31	
H2L001 Catchment H20E_01	Mean percentage difference	4.68	Natural vegetation with large bare rocky area and some wetlands.
	R^2	0.65	
	NSE	0.45	
H2L003 Catchment H20E_02	Mean percentage difference	92.37	Natural vegetation with some bare rocky area and some wetlands.
	R^2	0.30	
	NSE	-3.13	
H2H005 Catchment H20F_02	Mean percentage difference	-81.58	Natural vegetation with some bare rocky area.
	R^2	0.60	
	NSE	-0.23	
H3H005 Catchment H30D_02	Mean percentage difference	94.31	Mostly natural vegetation with vineyards in the valley bottom along the river.
	R^2	0.39	
	NSE	-4.48	
H4H018 Catchment H40G_03	Mean percentage difference	-52.58	Mostly natural vegetation with vineyards in the valley bottom along the river.
	R^2	0.02	
	NSE	-0.34	

Gauge	Statistic		Description
H4H016 Catchment H40K_03 H40K_04	Mean percentage difference	-70.27	Mostly natural vegetation with some vineyards and a small area of wetlands. Just downstream of the town of McGregor.
	R^2	0.78	
	NSE	0.49	

Table C-4: Verification statistics for the upper and central Breede catchment for 2014/15 to 2017/18 using adjusted FEWS RFE 2.0 rainfall

Gauge	Statistic		Description
H1H033 Catchment H10J_01	Mean percentage difference	-57.00	Natural vegetation.
	R^2	0.41	
	NSE	0.16	
H1H018 Catchment H10J_03	Mean percentage difference	-63.46	Natural vegetation with significant wetland areas upstream.
	R^2	0.65	
	NSE	0.24	
H2L002 Catchment H20B_01	Mean percentage difference	-72.93	Natural vegetation with large bare rocky areas.
	R^2	0.01	
	NSE	-0.73	
H2L001 Catchment H20E_01	Mean percentage difference	1.58	Natural vegetation with large bare rocky areas and some wetlands.
	R^2	0.53	
	NSE	0.34	
H2L003 Catchment H20E_02	Mean percentage difference	93.67	Natural vegetation with some bare rocky areas and some wetlands.
	R^2	0.26	
	NSE	-3.17	
H2H005 Catchment H20F_02	Mean percentage difference	-83.69	Natural vegetation with some bare rocky areas.
	R^2	0.06	
	NSE	-0.54	
H3H005 Catchment H30D_02	Mean percentage difference	103.88	Mostly natural vegetation with vineyards in the valley bottom along the river.
	R^2	0.04	
	NSE	-8.43	
H4H018 Catchment H40G_03	Mean percentage difference	-21.39	Mostly natural vegetation with vineyards in the valley bottom along the river.
	R^2	0.00	
	NSE	-2.16	
H4H016 Catchment H40K_03 H40K_04	Mean percentage difference	-56.60	Mostly natural vegetation with some vineyards and a small area of wetlands. Just downstream of the town of McGregor.
	R^2	0.27	
	NSE	0.03	

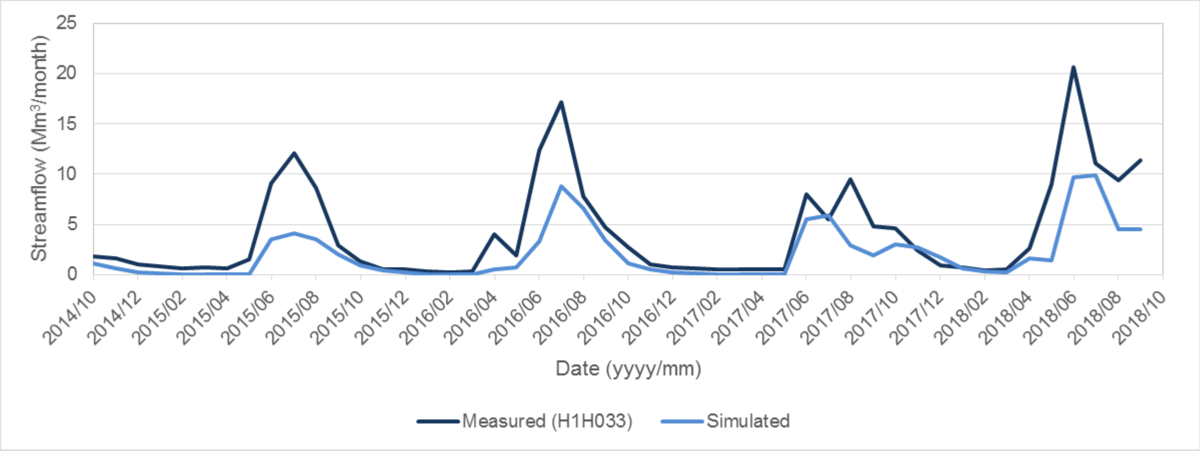

Figure C-20: Gauge H1H033 – comparison of measured and simulated monthly streamflow volumes

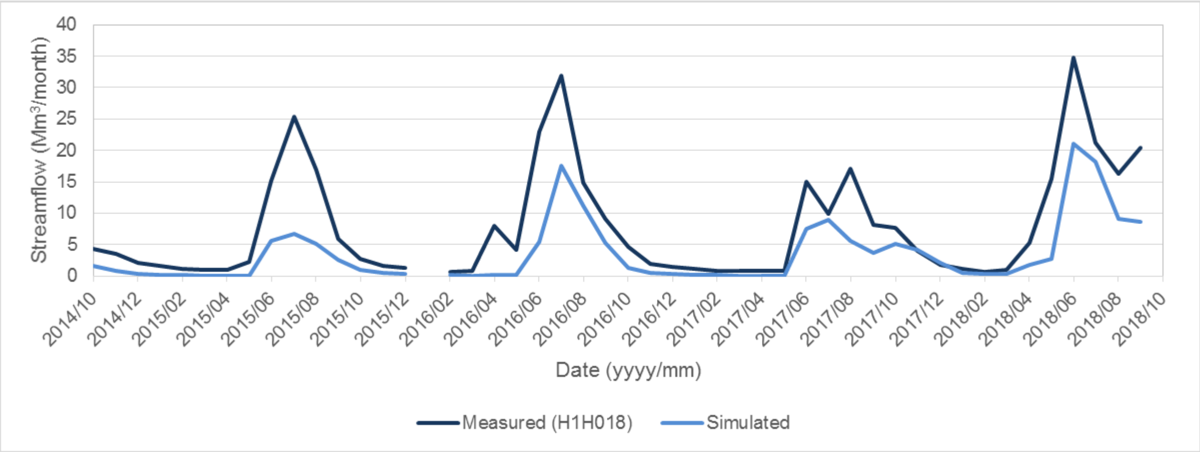

Figure C-21: Gauge H1H018 – comparison of measured and simulated monthly streamflow volumes

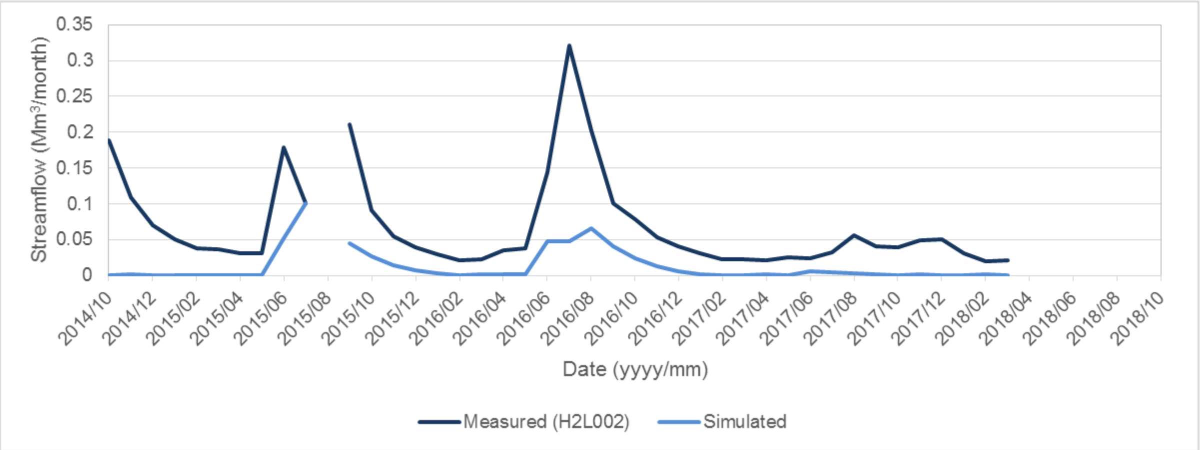

Figure C-22: Gauge H2L002 – comparison of measured and simulated monthly streamflow volumes

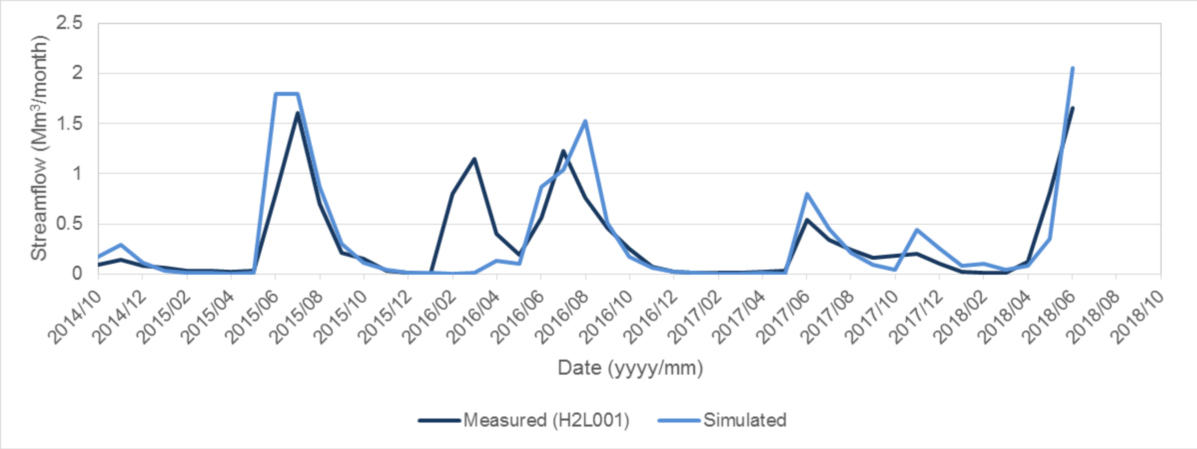

Figure C-23: Gauge H2L001 – comparison of measured and simulated monthly streamflow volumes

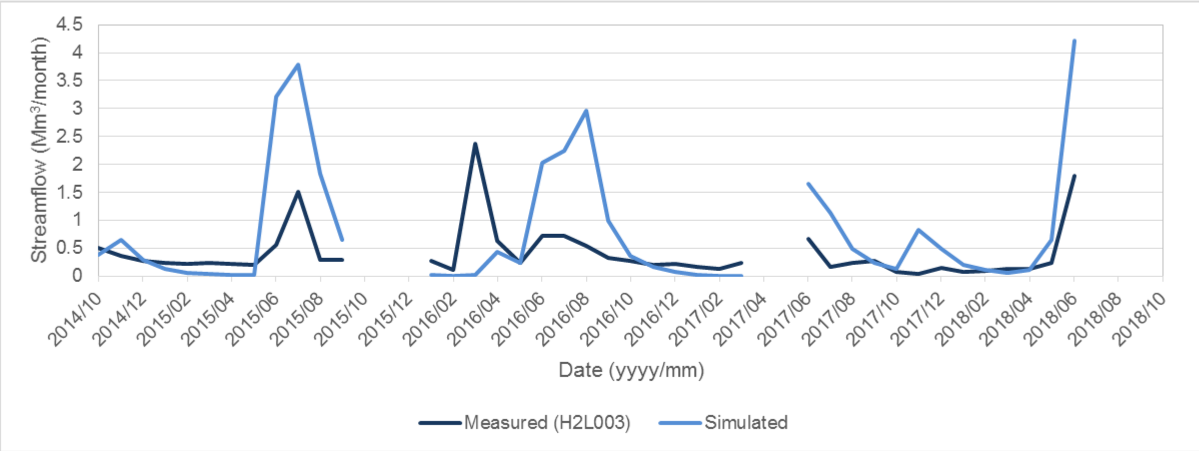

Figure C-24: Gauge H2L003 – comparison of measured and simulated monthly streamflow volumes

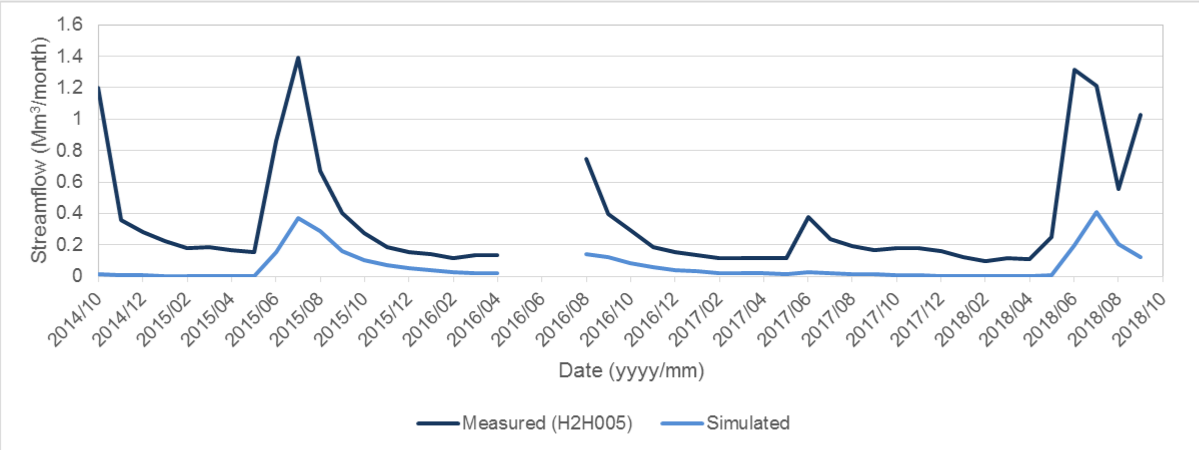

Figure C-25: Gauge H2H005 – comparison of measured and simulated monthly streamflow volumes

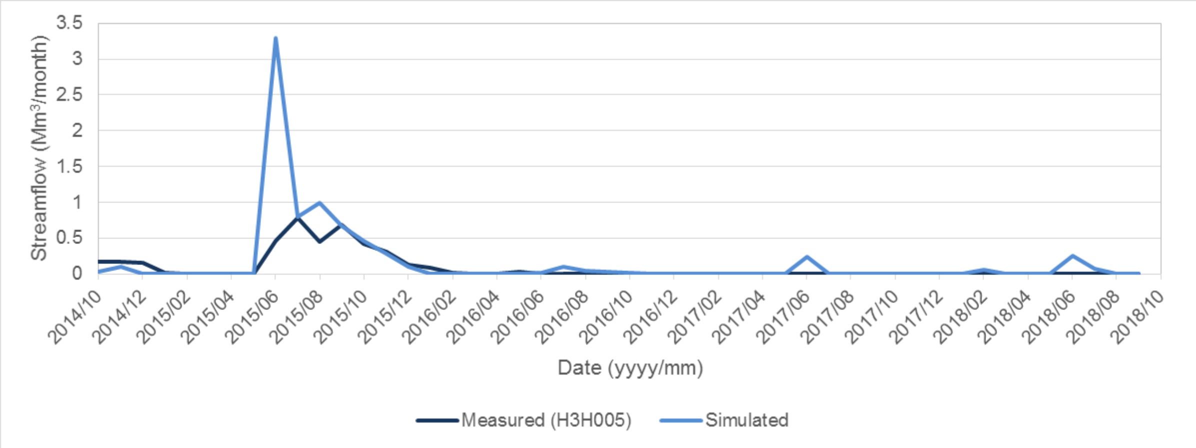

Figure C-26: Gauge H3H005 – comparison of measured and simulated monthly streamflow volumes

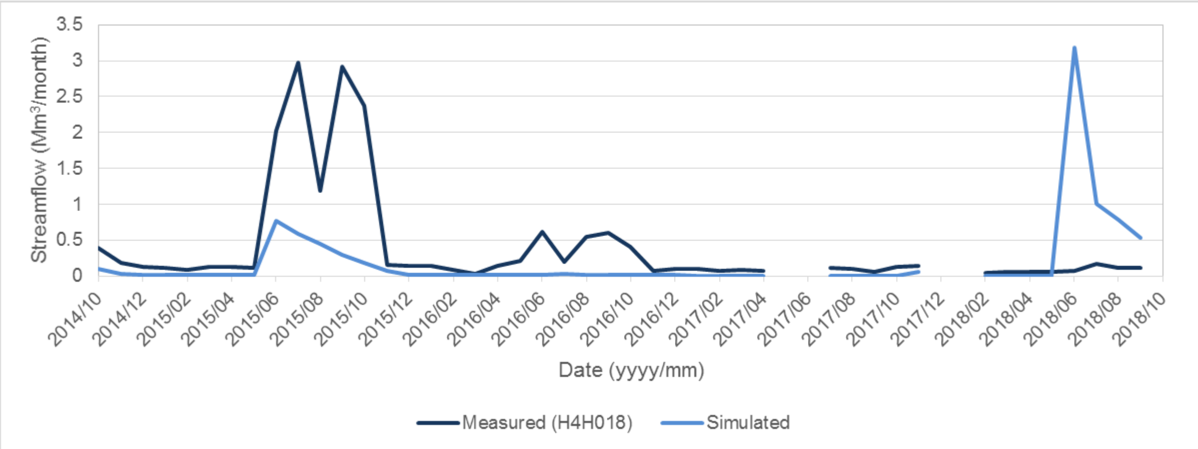

Figure C-27: Gauge H4H018 – comparison of measured and simulated monthly streamflow volumes

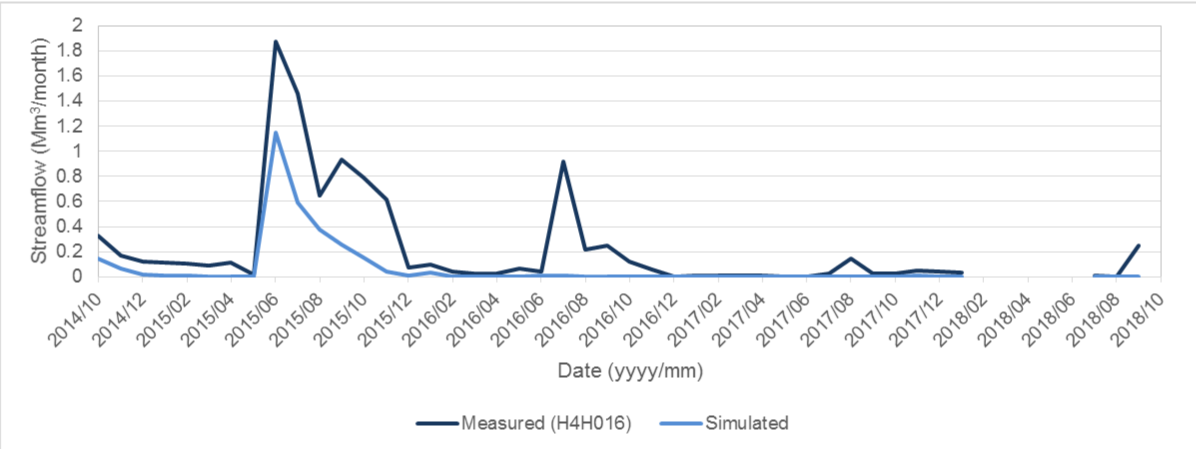

Figure C-28: Gauge H4H016 – comparison of measured and simulated monthly streamflow volumes