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

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by

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EXECUTIVE SUMMARY

RATIONALE

An assessment of water availability versus demand, reported by the Department of Water and Sanitation (DWS) in DWAF (2004) for the year 2000, indicated that though South Africa had a national surplus of water, demand exceeded supply in 10 out of the 19 Water Management Areas (WMAs). All, except one, of the 19 WMAs are linked by inter-catchment transfers that assist in the spatial redistribution of water from areas with adequate supply and low demand, to highly developed areas with high demand (DWAF, 2004). This situation is not unique to South Africa; Molden *et al.* (2007) state that 1.2 billion people live in river basins where utilisation of water resources is not sustainable. Karimi *et al.* (2013a) state that the time has come for water users from different sectors to communicate and cooperate to develop objectives for sustainable water and environmental management. However, it is a challenge to describe integrated water resources management issues in a simple but sufficiently comprehensive manner (Karimi *et al.*, 2013a). Water accounting enables 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 the water resources available in a catchment with an understanding of the potential impacts on all water users (IWMI, 2013).

OBJECTIVES AND AIMS

The objectives of this project were to: (i) review existing water accounting frameworks and their application internationally, (ii) demonstrate the use of a water resource accounting framework to help in understanding water availability and use at a catchment scale, and (iii) 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 and to distinguish between (i) use by different sectors, (ii) different hydrological components (i.e. green and blue water), (iii) beneficial and non-beneficial water use, and (iv) consumptive and non-consumptive use.

REVIEW OF WATER ACCOUNTING FRAMEWORKS

Several water resource accounting frameworks exist, each 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, namely (i) the IWMI Water Accounting (WA) system, (ii) the Water Accounting Plus (WA+) framework, (iii) the United Nations System of Environmental-Economic Accounting for Water (SEEA-Water) and (iv) the Australian Water Accounting Standard (AWAS). The IWMI WA framework and the conceptually similar WA+ framework both have a strong land use focus, 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 to its suitability for catchment scale water accounts, its strong land cover/use focus and that its simple format makes it suitable for use as a communication tool.

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 to guide the development of a methodology for estimating water availability and use at a catchment scale. The data sources and methodologies investigated included:

- 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, and
- reserved flows.

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 Catchment Management Agencies (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 which 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 the most useful for catchment scale water management. The water abstractions and return flows 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 which are likely to be most sensitive, which 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.

DEVELOPMENT OF THE METHODOLOGY

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

The WA+ Resource Base Sheet was modified to suit the purpose of the project by (i) including inter-catchment transfers into and out of the accounting domain, (ii) replacing the four land water management categories with five broad water use sectors, (iii) including the interception, transpiration, soil water evaporation and open water partitions of total evaporation, and (iv) other minor changes. A land and water use summary table was also 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 and 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 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 describing 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 *WaterBody* 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 in the case study catchments.

The project database spreadsheet, in which the spatial configuration of catchments, subcatchments, HRUs, river flow network, 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, though implementation by individual models will require different model specific assumptions. A library of Python scripts was developed to process datasets and to populate the project database spreadsheet. 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 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.

APPLICATION OF THE METHODOLOGY

The methodology was applied in two case study catchments (i) the uMngeni Catchment in KwaZulu-Natal and (ii) the Sabie-Sand Catchment in Mpumalanga. These case studies demonstrated the use of available datasets, data processing tools, hydrological model configuration and compilation of water accounts. These case studies also served to highlight many areas where the methodology requires further development.

DISCUSSION AND CONCLUSIONS

In conclusion, this project has successful in that it (i) reviewed existing water accounting frameworks, (ii) demonstrated the application of a water resource accounting framework to help in understanding water availability and use at a catchment scale, and (iii) 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 aggregation of results from finer to coarser spatial and temporal scales, and also at different levels of land cover/use detail. Although there is still much work to be done to refine the methodology, a good foundation has been set for the development of a system that in future will enable annual Quaternary Catchment scale water resource accounts to be compiled for the whole country.

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 at sub-Quaternary catchment scale due to variations in climate, soils, 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 from 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 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 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 titled "*Resetting the baseline land cover against which stream flow 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. Further sheets showing 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 reference potential evaporation 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.

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LIST OF ABBREVIATIONS

AADD	Annual Average Daily Demand
ALOS	Advanced Land Observing Satellite
ACCESS	Applied Centre for Climate and Earth Systems Science
AMSR-E	Advanced Microwave Sounding Radiometer-Earth
AMSU	Advanced Microwave Sounding Unit
APAR	Absorbed Photosynthetic Active Radiation
ARC	Agricultural Research Council
ARC 2.0	African Rainfall Climatology – Version 2.0
ARS	Automatic Rainfall System
ASAR	Advanced Synthetic Aperture Radar
ASCAT	Advanced Scatterometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AWAS	Australian Water Accounting Standard
AWS	Automatic Weather Station
BOCMA	Breede-Overberg Catchment Management Agency
BOM	Australian Bureau of Meteorology
CGIAR	Consultative Group on International Agricultural Research
CMA	Catchment Management Agency
CMAP	CPC Merged Analysis of Precipitation
CMB	Chloride Mass Balance
CMORPH	CPC Morphing Technique
CPC	Climate Prediction Center
CPCAPC	Climate Prediction Center African Daily Precipitation Climatology
CSIR	Council for Scientific and Industrial Research
CSV	Comma Separated Value
CWRR	Centre for Water Resources Research
DEM	Digital Elevation Model
DEA	Department of Environmental Affairs
DSO	Dam Safety Office
DWA	Department of Water Affairs, formerly
DWAF	Department of Water Affairs and Forestry, formerly
DWS	Department of Water and Sanitation
ECMWF	European Centre for Medium-Range Weather Forecasts
EF	Evaporative Fraction

ERWR	External Renewable Water Resources
ET_0	Reference potential evaporation
ET	Total evaporation
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAO	Food and Agriculture Organisation
FDF	Frequency Distribution Functions
FEWS	Famine Early Warning Systems
FEWS-NET	Famine Early Warning Systems Network
FFG	Flash Flood Guidance
GDA	Geographical Differential Analysis
GDAL	Geospatial Data Abstraction Library
GDP	Gross Domestic Product
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
GPCC	Global Precipitation Climatology Center
GPCP	Global Precipitation Climatology Project
GPI	GOES Precipitation Index
GPWA	General Purpose Water Accounting
GRACE	Gravity Recovery and Climate Experiment
GTI	GeoTerraImage (Pty) Ltd
GTS	Global Telecommunications System
HRU	Hydrological Response Unit
IAP	Invasive Alien Plant
ICFR	Institute for Commercial Forestry Research
ICMA	Inkomati Catchment Management Agency
IDW	Inverse Distance Weighting
IMF	International Monetary Fund
IPWG	International Precipitation Working Group
IR	Infrared
IRWR	Internal Renewable Water Resources
IRWS	International Recommendations for Water Statistics
ISCW	Institute for Soil, Climate and Water
ISIC	International Standard Industrial Classification
IUCMA	Inkomati-Usuthu Catchment Management Agency
IWMI	International Water Management Institute
KZN	KwaZulu-Natal

LAI	Leaf Area Index
LAS	Large Aperture Scintillometer
LCA	Life Cycle Assessment
LCU	Land Cover/Use
LSA-SAF	Land Surface Analysis Satellite Application Facility
LST	Land Surface Temperature
LUE	Light Use Efficiency
LUE	Light Use Efficiency
MAP	Mean Annual Precipitation
METRIC	Mapping EvapoTranspiration with high Resolution and Internalised Calibration
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NESDIS	National Environmental Satellite, Data and Information Service
NFEPA	National Freshwater Ecosystem Priority Areas
NLC	National Land Cover
NOAA	National Oceanic and Atmospheric Administration
NSE	Nash-Sutcliffe Efficiency
NWA	National Water Act of South Africa, Act 36 of 1998
NWCA	National Water Consumption Archive
NWRS	National Water Resources Strategy
NWRS	National Water Resources Strategy
OECD	Organisation for Economic Co-operation and Development
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PR	Precipitation Radar
PyTOPKAPI	Python TOPographic Kinematic APproximation and Integration
RFE 2.0	Rainfall Estimator – Version 2
RQIS	River Quality Information Service
SAEON	South African Environmental Observation Network
SAHG	Satellite Applications Hydrology Group
SANBI	South African National Biodiversity Institute
SANBI	South African National Biodiversity Institute
SAR	Synthetic Aperture Radar

SASA	South African Sugar Association
SAWS	South African Weather Service
SCWAWL	Statement of Changes in Water Assets and Water Liabilities
SEBAL	Surface Energy Balance Algorithm for Land
SEBS	Surface Energy Balance System
SEBS	Surface Energy Balance System
SEE	Standard Error of Estimates
SEEA	System of Environmental-Economic Accounting
SLIM	Spatial and Land Information Management
SNA	System of National Accounts
SRTM	Shuttle Radar Topography Mission
SSI	Soil Saturation Index
SSM	Surface Soil Moisture
SSM/I	Special Sensor Microwave Imager
StatsSA	Statistics South Africa
SVG	Scalable Vector Graphics
SWAT	Soil and Water Assessment Tool
SWAWL	Statement of Water Assets and Water Liabilities
SWIM	System-Wide Initiative on Water Management
SWF	Statement of Water Flows
TIR	Thermal Infra-Red
TMI	TRMM microwave imager
TMPI	Threshold-Matched Precipitation Index (TMPI)
TOPKAPI	TOPographic Kinematic APproximation and Integration
TRMM	Tropical Rainfall Measurement Mission
TRWR	Total Renewable Water Resources
TSEB	Two-Source Energy Balance
UKZN	University of KwaZulu-Natal
UMARF	Unified Meteorological Archive and Retrieval Facility
UN	United Nations
UNSC	United Nations Statistical Commission
UNSD	United Nations Statistics Division
USAID	US Agency for International Development
VITT	Vegetation Index / Temperature Trapezoid
WA+	Water Accounting Plus
WASB	Water Accounting Standards Board

WFN	Water Footprinting Network
WMA	Water Management Area
WRC	Water Research Commission
WRPM	Water Resources Planning Model
WRYM	Water Resources Yield Model
WUA	Water User Association
WUE	Water Use Efficiency
XML	Extensible Markup Language

1 INTRODUCTION AND OBJECTIVES

DJ Clark

Globally there is increasing pressure on water resources as a result of increases in population and industrialisation, and Molden *et al.* (2007) state that globally 1.2 billion people live in catchments where utilization of water resources is not sustainable. Assessments of water availability versus demand, reported by the Department of Water and Sanitation (DWS) in the National Water Resources Strategy (DWAF, 2004; DWA, 2013) indicate that there are many key catchments in South Africa where already demand equals or exceeds supply. (DWAF, 2004) estimates that for the year 2000, although South Africa had a national surplus of water, demand exceeded supply in 10 out of the former 19 Water Management Areas (WMAs). All, except one, of the former 19 WMAs are linked by inter-catchment transfers that assist in the spatial redistribution of water from areas with adequate supply and low demand, to highly developed areas with high demand (DWAF, 2004). Water resources development has high economic, social and ecological costs, and there needs to be a change in emphasis from development to better water management practices that result in more efficient use and allocation of water resources (IWMI, 2013; Karimi *et al.*, 2013a). 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 resources monitoring networks are crucial, yet expensive to establish and maintain, but technological innovations such as remote sensing are starting to fill data gaps. Water resource systems, consisting of both natural and engineered components, are inherently complex, making them difficult to measure, understand and describe. A multidisciplinary approach is required so as to provide a systems perspective for the development of integrated water resource management solutions. This is especially true when projecting future development and negotiating trade-offs between users and uses for water resources planning. It will also be important for water managers and users from different sectors to communicate and cooperate to develop objectives for sustainable water management, but difficulties in describing complex water resource systems in a simple yet sufficiently comprehensive manner are a constraint (Karimi *et al.*, 2013a).

1.1 What is Water Accounting?

A simple global water balance, or water account, is shown in Figure 1.1. Water enters the terrestrial water system as rainfall, some of this rainfall infiltrates into the soil profile, which may be referred to as "green water", and some of this rainfall runs off into river flow networks, which may be referred to as "blue water". Some of the rainfall entering the soil profile may result in recharge of groundwater stores, which contribute baseflow to river flow networks. Evaporation and transpiration from natural vegetation, forest plantations and dryland (rainfed) agricultural crops result in green water being lost from the terrestrial water system. In some regions blue water may be used for irrigation of agricultural crops to supplement green water, and further water is lost due to evaporation and transpiration. Due to seasonal and annual variability in rainfall, water is stored in dams (reservoirs). Further water is lost from the terrestrial water system due to evaporation from open water surfaces, such as rivers, lakes and dams. Blue water is also abstracted from rivers, lakes and dams for domestic and industrial use, some of which is lost to evaporation and some returns as blue water. Some blue water flows downstream and is lost to seas and oceans from which evaporation occurs to complete the water cycle.

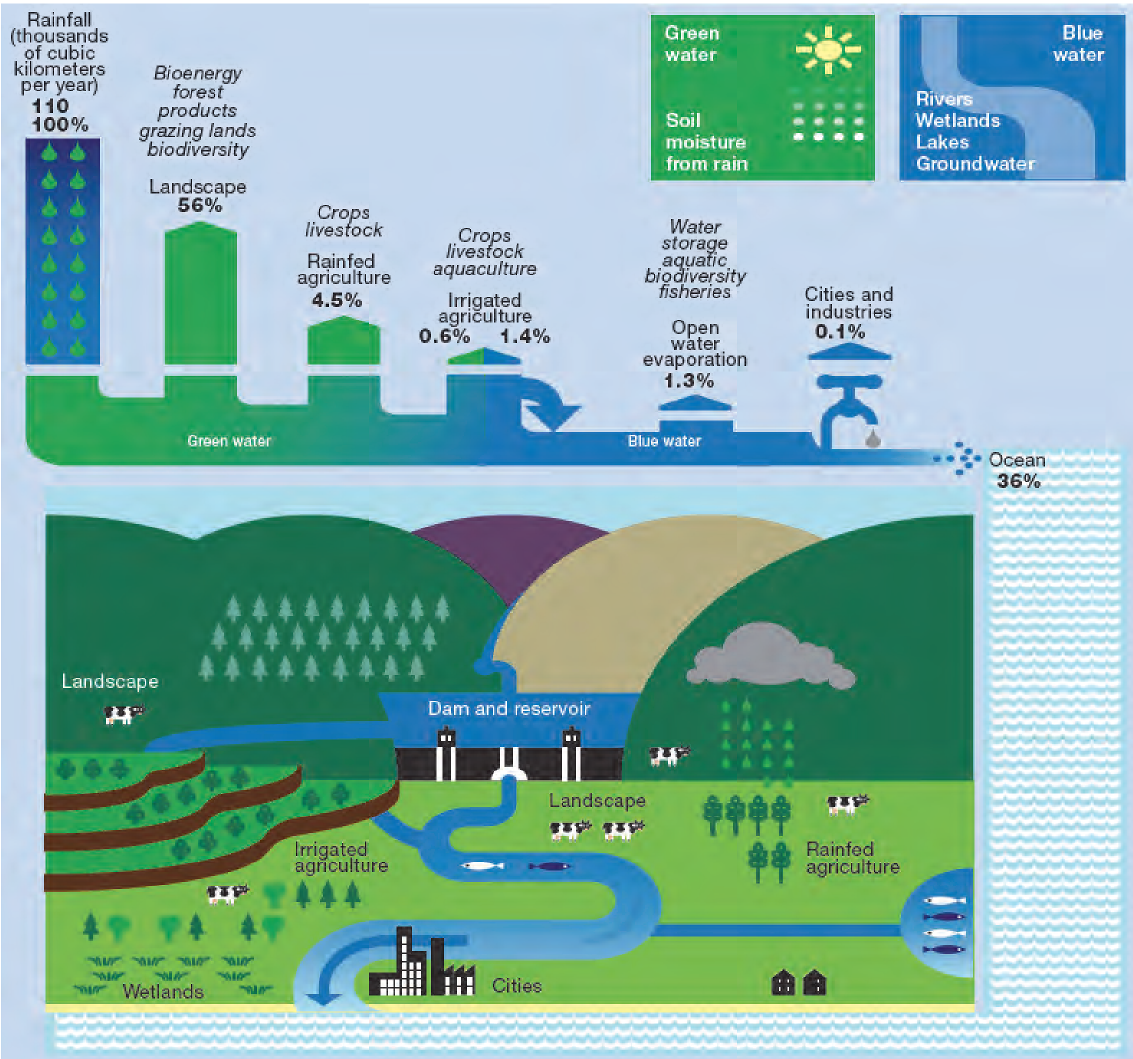


Figure 1.1 Global water use (Molden, 2007)

In its simplest form water resource accounting is the quantification and communication of these water inflows, depletions and outflows, as shown in Figure 1.1. A more formal definition of water accounting used in this project is as follows:

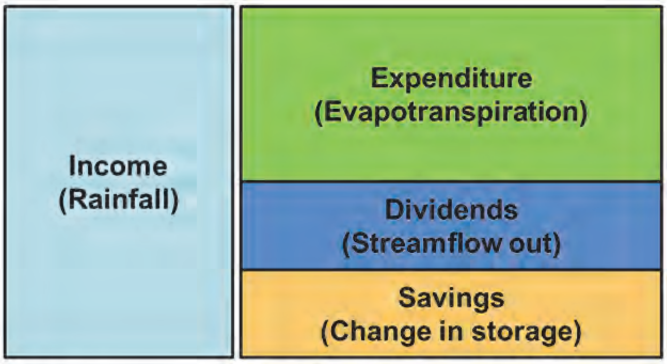
> "*Water resource accounts describe the water resources within a specified spatial and temporal water accounting domain, including the source and quantity of water inflows, water use by different sectors within the domain, and the destination and quantity of water outflows.*"

The concept of accounting and standard accounting practices is well established in the financial field. The concept of accounting is not new to the water field either. The science of hydrology revolves around attempts to quantify and understand, by measurements and modelling, the different components of the hydrological cycle. Water accounts have many similarities to financial accounts and several water accounting approaches (or frameworks) exist that specify the structure of the accounts and the prescribed or recommended procedures for compiling the accounts.

1.2 Why is Water Accounting Needed?

Water, especially freshwater, is a finite resource. In South Africa and also globally, there are regions where unsustainable levels of water use have been reached with demand for water exceeding natural supply. This situation requires water policy makers, water managers and water users to have a better knowledge and understanding of water supply and use, and a means to be able to communicate with each other.

The analogy of a monthly cash flow statement of a business is sometimes useful, and a simple example is shown in Figure 1.2. From measurements of rainfall, typically point measurements from rain gauges, one can make an estimate of what the "income" was for the month. Measurements of total evaporation (ET), are much more difficult, but are important as ET is likely to contribute to a large portion of the water losses or "expenditure" for the month. Estimates of ET are typically based on land use information and point measurements of reference evaporation from an A-pan or S-tank, or estimates of reference evaporation from measurements of meteorological variables, such as temperature, relative humidity, wind speed and net solar radiation used in equations such as Penman-Monteith. Remote sensing has enabled spatial estimates of rainfall and ET to be made with varying degrees of accuracy. Between the start and end of an accounting period there may be changes in surface water, soil water and groundwater storage within a catchment, which represent the expenditure or accumulation of “savings”. Measurements of streamflow are also useful in helping us to understand the hydrology of a catchment and, in the cash flow analogy, is the portion of income that was not depleted as expenditure or reserved as savings. In a sense, streamflow is “profit”, except that it is lost to the catchment and so, for the purpose of the analogy, could be considered as “payment of dividends”. Though streamflow is in some regards a point measurement at the exit of a catchment, it represents the net result of all the hydrological processes that have taken place within a catchment. Streamflow may consist of flows required for downstream use as well as excess flow that could potentially have been used within the catchment. Streamflow that leaves a catchment, in excess of downstream requirements, represents an opportunity cost. In a simple catchment scenario a mass balance can be used to estimate the change in water storage in the catchment by subtracting total evaporation and streamflow out of the catchment from rainfall.



Opening Balance	**R300.00**	Catchment storage at t_0
Income	R1000.00	Rainfall and inflows
Expenditure	R500.00	Evapotranspiration (ET_a)
Tax / Dividends	R300.00	Streamflow out
Closing Balance	**R500.00**	Catchment storage at t_1
Savings	R200.00	Change in catchment storage

Figure 1.2 Simple cash flow statement / water resource account analogy

A simple cash flow statement or water account such as that shown in shown in Figure 1.2, is useful, but only really tells us whether we are making a profit and whether we are saving anything. It does not tell us where the income came from or where the expenses were incurred, whether the expenses were fixed or variable, or whether the expenses were beneficial or not. Similarly, to understand and manage the water resources in a catchment we need more detailed information. There are really two main solutions to this problem: (i) to directly or indirectly measure everything everywhere, which may be expensive and impractical, and (ii) to run hydrological simulation models that use some measured inputs together with physical and empirical relationships and mass balances to estimate more detailed water account components. Modelling also enables sensitivity analyses or land use scenarios to be performed to determine their impact on the water balance in a catchment. Hydrological models do more than just produce estimates of streamflow, which are an accumulation of hydrological processes within a catchment, they can generate large quantities of information about the various components of the water balance within a catchment. However, some means is required to summarise and communicate this information. Karimi *et al.* (2013a) explain that a water accounting framework can be considered as a means of displaying hydrological modelling results in a standardised manner.

Karimi *et al.* (2013a) propose that water professionals, will require a common water accounting framework that enables hydrological flows to be associated with water use sectors and the benefits that can be derived from these flows. 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). Thus, there is a need for a standard hydrological and water management summary to enable interpretation and communication of water resources data by interdisciplinary groups of water professionals involved in making water management decisions (Karimi *et al.*, 2013a). Water accounting can also help to indicate where more comprehensive studies or monitoring are required (Molden and Sakthivadivel, 1999). 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 (FAO), the International Water Management Institute (IWMI) and the United Nations (UN) Bureau of Statistics.

The South African National Water Act (Act 36 of 1998) (NWA, 1998) is based on the principles of equality, sustainability and efficiency in the management and use of the nation's water resources. The purpose of the National Water Resources Strategy (NWRS) (DWAF, 2004; DWA, 2013) is to: (i) provide information about water resource management and the institutions to be established to do this, (ii) quantify current and estimated future availability and demands for water in each WMA, and (iii) propose interventions to reconcile demand and availability (DWAF, 2004). A standard water accounting framework is required for South Africa to provide water resource managers and policy makers with a standard means of interpreting and communicating the integrated use of water by different water use sectors and whether this water use is beneficial or not. This water accounting framework should ideally be suitable for application at a range of spatial and temporal scales and enable accumulation of results from finer to coarser spatial and temporal scales. In addition, a methodology to quantify the use of water by the different water use sectors is required to enable the water accounting framework to be populated. Water accounts are not the end product; they are an aid to assist water policy makers, water managers and water users in visualising water states and flows for various scenarios, and in communicating with each other. This study will focus on water quantity, as although water quality and economics are an important part of water management decisions, it is necessary to start with water quantity as the foundation.

1.3 Existing Water Accounting Systems

A number of water accounting systems have been developed by different institutions for different purposes and the following list provides a brief overview of some of these systems and their specific purpose.

- The System of Environmental-Economic Accounting for Water (SEEA-Water) framework is a comprehensive United Nations Bureau of Statistics standard for compiling national water accounts and has a strong economics emphasis (UN, 2012b). In simple terms 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 containing country and regional level water and agriculture statistics (Eliasson *et al.*, 2003; FAO, 2003a)
- The IWMI Water Accounting (WA) system is a methodology to account for the use and productivity of water resources in a river basin (Molden and Sakthivadivel, 1999).
- The Water Accounting Plus (WA+) framework based on the IWMI Water Accounting (WA) 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).
- The Australian Water Accounting Standard (AWAS) was developed by the Water Accounting Standards Board (WASB) of the Australian Bureau of Meteorology (BOM) to provide 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 to 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. LCA is part of the ISO 14000 environmental management standards [http://www.iso.org/iso/iso14000].

Both the SEEA-Water and the AWAS have previously been applied in South Africa. The FAO's Aquastat global information system on water and agriculture is more of a global database of country and regional level water statistics than an accounting standard, and thus will not be discussed further in this report. The Water Footprinting and Life Cycle Assessment systems were included in this list for completeness as they are a form of water accounting. However, they are not the type of catchment water resource accounting frameworks defined in Section 1.1 and will not be discussed further in this report. Water auditing investigates and reports the institutional aspects related to compliance between water allocations and water consumption. Although there is potential to use water resource accounts for water auditing the concept of water auditing was outside the scope of this project and will also not be discussed further in this report.

1.4 National Water Resource Assessments In South Africa

Several national water resources assessments have been completed for South Africa in the last 63 years. Initial studies include Midgley (1952), Midgley and Pitman (1969) and Midgley *et al.* (1981). More recently the Water Research Commission (WRC) has funded a series of water resource assessment studies, the WR90 study (Midgley *et al.*, 1994), the WR2005 study (Middleton and Bailey, 2008) and the Water Resources 2012 study [http://www.waterresourceswr2012.co.za] which is still in progress. These studies, referred to here as the Water Resources 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 from 1920 onwards. The WRSM2000 model, which is a combination of the Pitman rainfall-runoff model and other models, was used for the assessments. These estimates are used by the DWS in their Water Resources Yield Model (WRYM) and Water Resources Planning Model (WRPM) for long term planning of water resources in South Africa. In the process of producing these assessments other useful datasets such as rainfall, observed streamflow, land use, water use, afforestation and irrigation are also produced.

The Environmental Economic Accounts section at Statistics South Africa (StatsSA) compiled a National Water Account for the year 2000 (StatsSA, 2009). This water account was compiled using the SEEA-Water framework at Water Management Area (WMA) scale for the 19 WMAs in use at that time. These accounts included estimates of water use and production by different economic sectors, including agriculture, mining, electricity, commercial and industrial and domestic. The WRC is currently managing and funding a research project (WRC Project K5/2419) on behalf of StatsSA titled "Water Accounts for South Africa". This project will use the SEEA-Water framework to compile updated water accounts for South Africa. It is anticipated that these accounts will be at national and WMA scale for the recently consolidated 9 WMAs.

1.5 Who Will Benefit From Water Accounting?

Just as a cash flow statement is a useful tool to an individual bank account holder, or a small business or a large multinational company, water accounts can be compiled for different scales of water resource systems, from individual fields to whole countries. For national policy makers and large scale planning, water accounts at national, provincial or large basin scale may be useful in deciding where development potential exists and where policy needs to be developed to ensure sustainable and equitable use of water resources. Examples of such accounts are those produced by the Food and Agriculture Organisation (FAO) in the Aquastat global information system on water and agriculture (Eliasson *et al.*, 2003; FAO, 2003a; FAO, 2003b). In South Africa the Department of Water and Sanitation (DWS) has the responsibility for broad-scale long-term national scale planning of water resources in South Africa, and has investigated heavily in the tools, such as the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM) required for this. The South African National Water Act (Act 36 of 1998) (NWA, 1998) makes provision for the establishment of a Catchment Management Agency (CMA) in each of the nine Water Management Areas (WMAs). The purpose of these CMAs is to delegate regional and catchment level water resource management and to involve local communities in catchment management (NWA, 1998). The National Water Act also makes provision for Water User Associations (WUAs) which are defined as "*co-operative associations of individual water users*" who participate in mutually beneficial water-related activities, such a group of farmers sharing a privately funded dam built to store water for irrigation. Catchment scale modelling and water resource accounts would be useful to CMAs in assessing and managing the water resources under their control and in communicating with WUAs and other individual water users. It is expected that catchment scale water resource accounts could assist both in long-term planning and in making short term (monthly) and medium term (seasonal, annual) operational decisions. At a field scale, water resource accounts may help farmers and researchers to optimise water use and crop yield.

1.6 At What Spatial Scale Should Accounts Be Compiled?

This project focused on developing a methodology for compiling catchment scale water accounts, as this was where there was perceived to be the greatest need. But for what size of catchment should the accounts be generated? The Quaternary Catchment scale is widely recognised and used in South Africa for water resource assessments and planning. However, soils, land cover, land use and climate can vary significantly within a Quaternary Catchment and thus it will probably be necessary for the hydrological modelling to be carried out at a finer spatial scale that takes into account climatic variability and enables different land uses to be represented in the accounts. Thus the modelling spatial scale may be different to the accounting spatial scale. The accounting framework should make it possible to aggregate the Quaternary Catchment scale accounts up to Tertiary, Secondary and Primary Catchment scales.

1.7 At What Temporal Scale Should Accounts Be Compiled?

Climate is not only highly variable in time and space, but is also dynamic in the sense of long term climate change. Hydrological systems are also dynamic as land use, management practices, economic drivers and water policy change with time. Water accounts are not intended to provide long term means or frequency distributions of water availability and use. Their purpose is to provide a statement of estimated actual water use and availability for a specified spatial and temporal domain. Thus water accounts would typically be compiled for the recent past. In addition to accounts of estimated actual water use, accounts could be generated for a variety of modelled scenarios to enable these scenarios to be evaluated relative to each other. This project focussed on compiling annual accounts, but accounts compiled for seasonal and possibly even monthly time domains could also be useful for catchment management. Annual, seasonal and daily cycles occur within water resource systems and it is proposed that the hydrological modelling should take place at a daily time step to adequately represent the dominant hydrological processes. Thus the temporal scale used for modelling may be different to the accounting temporal scale. The accounting framework should make it possible to aggregate up from finer to coarser temporal scales.

1.8 Factors To Be Considered In Developing The Methodology and Water Accounts

Availability of data on water storage, use and flows is a major constraint for compiling reliable water accounts worldwide (Karimi *et al.*, 2013b). Karimi *et al.* (2013a) make the point that large components of water storage, use and flows in catchments are not measured, are often difficult or expensive to measure *in situ*, and even in catchments where measurements are made, these are at selected points and may not be representative of the catchment as a whole. Remotely sensed spatial datasets are becoming more widely available, can have a relatively low cost, are immediately available, and make it possible compile water accounts in ungauged or poorly gauged catchments (Karimi *et al.*, 2013a). This means that the input data required to compile water accounts will need to be derived from multiple sources, possibly including a combination of *in situ* measurements, remote sensing and hydrological modelling. Methods to estimate the use of water by the different water use sectors will be required.

The dependence on some degree of hydrological modelling to compile water accounts is borne out in the literature. Eliasson *et al.* (2003) mention the use of remote sensing and hydrological models to estimate data inputs for compiling Aquastat accounts in instances where limited information is available. Molden and Sakthivadivel (1999) mention the use of modelling in their application of the IWMI Water Accounting System in Sri Lanka. BOM (2012) mention the possible use of modelling to determine inputs such as evaporation for use in the Australian Water Accounting Standard. Trewin (2006) mentions the use of modelling to estimate runoff, total evaporation and deep drainage for use in the Australian National Water Accounts. UN (2007) and UN (2012b) mention the use of modelling to estimate total evaporation for use in the SEEA-Water accounting framework. UN (2012b) state that the use of models to generate hydrological and meteorological data inputs for accounts can improve overall data quality, accuracy and coverage, especially when models use two or more sets of measurements, such as field and remotely sensed measurements. UN (2012b) also make the point that models can be used to extrapolate available data and generate data outputs at larger catchment or even national scales. In their case study in the Indus Basin, Karimi *et al.* (2013b) used various sources of data to determine the data inputs for the WA+ accounting framework including the Soil and Water Assessment Tool (SWAT) model. Gibson *et al.* (2009) mention using the GIS-based WetSpass model to estimate runoff, total evaporation and groundwater recharge to help in generating a water account for their study in the Piketberg. A hydrological model that is sensitive to land cover and land use, and capable of running at a daily time step in order to represent natural daily fluctuations in the water balance of the climate/plant/soil continuum is required. Hydrological modelling will also enable what-if type scenarios, such as changes in land use to be evaluated.

An integrated methodology that enables data from various sources to be combined without double accounting will be required. As part of developing the methodology, the accuracy of the various potential data sources will need to be evaluated. However, detailed validation of remotely sensed data is not an objective of this project. The methodology should focus on quantifying actual water use rather than gross withdrawals, especially from blue water sources, as data on withdrawal and return flow quantities are often difficult to obtain (Karimi *et al.*, 2013a), and to minimise the risk of double accounting of water that is recycled within the accounting domain.

As far as possible the methodology should be developed such that it can be easily and consistently applied to other catchments outside the case study catchments used for the project. With regard to remotely sensed data, the methodology should aim to use available remote sensing data products, rather than requiring processing of raw remotely sensed datasets due to the skill and resources required to do this. Another argument in favour of using available remote sensing data products is that they are usually available within a few days of the images being captured, which makes it possible to compile accounts for use in making short-term operation decisions. The cost and accessibility of data will be key criteria in the selection of data sources, to facilitate application of the methodology after the project has been completed.

The integrated methodology should be suitable for use at a variety of catchment scales and temporal domains and the accounting framework should enable aggregation of results from finer to coarser spatial and temporal scales. The spatial and temporal resolution of the remote sensing data products and the hydrological model selected should be suitable for the spatial and temporal domain for which the accounts are to be compiled. The sensitivity of the water accounts to the resolution and accuracy of the data inputs should be investigated. A mass balance approach enables the estimation of unknown components of the accounts based on the quantity of water required to balance the account. However, it should be recognised that hydrological systems are complex and such deductions require some degree of certainty in the quantification of the “known” components of the account. Where available, streamflow records could either be used to help verify the accuracy of the water accounts or could be used in accounts to estimate the quantity of water that was used or the quantity of water that was stored.

The integrated methodology will need to include the identification, and if necessary development, of suitable software tools to process the data and information required to compile the accounts.

1.9 Project Objectives

In simple terms the purpose of this project was to: (i) review existing water accounting frameworks and their application internationally, (ii) demonstrate the use of a water resource accounting framework to help in understanding water availability and use at a catchment scale, and (iii) 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 and to distinguish between (i) use by different sectors, (ii) different hydrological components (i.e. green and blue water), (iii) beneficial and non-beneficial water use, and (iv) consumptive and non-consumptive use.

The specific objectives of the project were to:

- Review existing water accounting frameworks for the purpose of informing the selection of a suitable framework for catchment level water accounts.
- Review and assess data sources and methodologies for quantifying water use, directly and indirectly.
- Integrate appropriate sources of data, information and methodologies into a single, internally-consistent water use quantification and accounting system.
- Apply the system to assess sectoral water use and all components of the hydrological cycle in selected study areas in South Africa.
- Use available observed/measured and simulated fluxes of the components of the hydrological cycle to assess the impact of errors on the water balance and quantify the uncertainties associated with poor and/or unavailable data.

1.10 Project Outline

Several water resource accounting frameworks exist, each developed by different organisations for a different purpose. The project started with a review of these existing water resource accounting frameworks to gain an understanding of each framework to inform the decision regarding which framework would be most suitable for application for the purposes of the project but also for water resources planning and management in South

Africa. The original review report was subsequently condensed as a review paper and was submitted to WaterSA for publication on 14 July 2015. Based on this review the WA+ framework was recommended for use in the project.

An initial investigation was conducted into the data requirements to compile the WA+ accounts. Potential sources of water resources data and information in South Africa were also investigated, including: ground-based measurements, remote sensing and modelling. Based on these investigations a methodology was proposed. These initial investigations and the proposed methodology were summarised in an Inception Report and then presented at an Inception Workshop held on 28 August 2013 at the University of KwaZulu-Natal in Pietermaritzburg. The objectives of the workshop were to inform workshop delegates of the objectives and proposed methodology for the project, and to seek their input regarding the methodology.

Based on the review of water resource accounting frameworks, recommendations in the Inception Report and discussion at the Inception Workshop the following key decisions were made:

- The water resource accounts should be based on the Water Accounting Plus (WA+) water resource accounting 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 project should aim to produce annual accounts at a Quaternary Catchment scale.
- The project should focus on the Resource Base Sheet component of the WA+ framework, dealing with water availability and depletions.
- The most effort should be concentrated on the components of the accounts which are likely to be most sensitive, which are expected to be rainfall and total evaporation estimates at a catchment scale.
- Although the focus of the project is on water use quantification, the project team need to consider that water quality and economics would be important additional components of the accounts in the future.

The compilation of water resource accounts is data intensive and many of the data parameters are highly variable in both space and time. Some of the data parameters are available from ground-based measurements such as rainfall, reference potential evaporation and streamflow. By nature ground-based measurements are made at discrete points and the relatively sparse water resources monitoring networks means that it is difficult to achieve good spatial representation. Water resources monitoring networks are crucial, yet expensive to establish and maintain, but technological innovations such as remote sensing are starting to fill data gaps. Water resources modelling is also data intensive, but can also be an invaluable tool for estimating water resources in ungauged catchments and for estimating water resources parameters that cannot be easily measured. Potential datasets that could be used for compiling water resource accounts in South Africa are described and evaluated in Chapter 3. Chapter 3 is a literature review of water quantification methodologies and datasets, which is focussed on those applied or available in South Africa or southern Africa.

The primary aim of the project was to develop a methodology to integrate appropriate sources of data and information, and methods of estimating water availability and use into a single, internally-consistent water use quantification and accounting system. The methodology developed in this project is described in Chapter 4. The methodology has a strong land cover/use focus. The development of the methodology was to some extent an iterative process, with the Reference Group providing valuable feedback during the development process.

The water use quantification and accounting methodology was applied and evaluated in two case study catchments. The first case study catchment was the uMngeni Catchment in the Pongola-Umzimkulu WMA, which is described in Chapter 5. This catchment was familiar to the project team, is a highly developed catchment and is an important catchment for the economic development of the KwaZulu-Natal province. The second case study catchment was the Sabie-Sand Catchment in the Inkomati-Usuthu WMA, which is described in Chapter 6. This catchment was selected to demonstrate the use of the land cover/use class hierarchy developed as part of the methodology, as is it includes a variety of horticultural crops grown near Sabie, large areas of rural undeveloped land and the lower part of the catchment is in the Kruger National Park.

The outcomes of the project are discussed in Chapter 7, including an appraisal of the water use quantification and accounting methodology and availability of water resources data. Recommendations for future research to refine the methodology are listed in Chapter 8.

2 A REVIEW OF WATER ACCOUNTING FRAMEWORKS FOR POTENTIAL APPLICATION IN SOUTH AFRICA

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This chapter consists of a review paper that was submitted on 14 July 2015 for publication in WaterSA and is currently under review by that journal.

2.1 Abstract

Globally and in South Africa there are many catchments that have reached a stage of development where demand exceeds supply. Management of these catchments requires a clear understanding of water availability and use within them and a clear means for water managers and water users to communicate. Water accounting frameworks are one tool that can be used to aid both understanding and communication by providing a standardised summary of water stocks, flows, fluxes and consumption for a specified spatial and temporal domain. The objective of this review is to describe the concept of water accounting and to review four existing water accounting frameworks that could be applied in South Africa, namely (i) the IWMI Water Accounting (WA) system, (ii) the Water Accounting Plus (WA+) framework, (iii) the United Nations System of Environmental-Economic Accounting for Water (SEEA-Water) and (iv) the Australian Water Accounting Standard (AWAS). The IWMI WA framework and the conceptually similar WA+ framework both have a strong land use focus, SEEA-Water has a strong economic focus and the AWAS is closely related to financial accounting. The review focuses on accounting for water quantities, although it is recognised that water quality and the economic value of water are also important for water management. A key constraint to the application of these water accounting frameworks will be the availability of data and information to populate them, and the uncertainty associated with the accuracy of the data and information. The selection of a water accounting framework will ultimately depend on the intended purpose.

Keywords: *water, accounting, framework, management*

2.2 Introduction

An assessment of water availability versus demand, reported by the Department of Water and Sanitation (DWS) in DWAF (2004) for the year 2000, indicated that although South Africa had a national surplus of water, demand exceeded supply in 10 out of the 19 Water Management Areas (WMAs). All, except one, of the 19 WMAs are linked by inter-catchment transfers that assist in the spatial redistribution of water from areas with adequate supply and low demand, to highly developed areas with high demand (DWAF, 2004). This situation is not unique to South Africa. Molden *et al.* (2007) state that globally 1.2 billion people live in catchments where use of water resources is not sustainable. This requires a change in emphasis from water resources development, which also has high economic, social and ecological costs, to better water management practices (IWMI, 2013; Karimi *et al.*, 2013a). Karimi *et al.* (2013a) believe that the time has come for water users from different sectors to communicate and cooperate in order to develop objectives for sustainable water management. However, difficulties in describing complex water resource systems in a simple but sufficiently comprehensive manner are a constraint. Karimi *et al.* (2013a) postulate that water professionals will require a common water accounting framework that enables hydrological flows to be associated with water use sectors and the benefits that can be derived from these flows. 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). Thus, there is a need for a standard hydrological and water management summary to enable interpretation and communication of water resources data by interdisciplinary groups of water professionals involved in making water management decisions (Karimi *et al.*, 2013a). In addition water accounting can help to indicate where more comprehensive studies or monitoring are required (Molden and Sakthivadivel, 1999). 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 (FAO), the International Water Management Institute (IWMI) and the United Nations (UN) Bureau of Statistics.

The South African National Water Act (Act 36 of 1998) (NWA, 1998) is based on the principles of equality, sustainability and efficiency in the management and use of the nation's water resources. The purpose of the National Water Resource Strategy (NWRS) (DWAF, 2004) is to provide information and propose interventions to reconcile demand and availability. The application of a standard water accounting framework in South Africa would provide policy makers, water managers and water users with a consistent means of interpreting and communicating the abstraction and consumption of water by different water use sectors and whether this water use is beneficial or not. This water accounting framework should ideally be suitable for application at a range of spatial and temporal scales and enable accumulation of results from finer to coarser spatial and temporal scales.

The objective of this review paper is to describe the concept of water accounting and to review four existing water accounting frameworks that could potentially be applied in South Africa, namely (i) the IWMI Water Accounting (WA) system, (ii) the Water Accounting Plus (WA+) framework, (iii) the United Nations System of Environmental-Economic Accounting for Water (SEEA-Water) and (iv) the Australian Water Accounting Standard (AWAS). Both the SEEA-Water and the AWAS have previously been applied in South Africa. The FAO's Aquastat global information system on water and agriculture (Eliasson *et al.*, 2003; FAO, 2003a) was not reviewed as it is more of a global database of country and regional level water statistics than an accounting standard. The Water Footprint of Modern Consumer Society (Hoekstra, 2013) and Aqueduct Water Risk Framework (Reig *et al.*, 2013) are examples of other databases and are also not reviewed. For the purpose of this review, water accounting is defined as an analytical framework within which stocks, flows, fluxes and consumption of water are quantified within a defined spatial and temporal domain, as opposed to the related concepts of water auditing and water footprinting. Water auditing investigates and reports the institutional aspects related to compliance between water allocations and water consumption. Typically, water footprinting refers to the process of quantifying the sum of the direct and indirect water use by a product, process, producer or consumer. In this paper, the term "water use" is used in the general sense, which includes both consumptive and non-consumptive utilisation of water.

2.3 IWMI Water Accounting (WA)

2.3.1 Overview

The IWMI WA framework is described as a standardised water accounting procedure and was developed as one of the activities of the System-Wide Initiative on Water Management (SWIM) of the Consultative Group on International Agricultural Research (CGIAR) (Molden, 1997). It is described by Molden and Sakthivadivel (1999) as a methodology to account for water resource use and productivity. IWMI (2013) explain that it "*provides a clear view of water resources in a river basin*", showing the quantity of water flowing into a system, where it is going, how it is used, and how much is available for further use. According to Molden (1997) and Molden and Sakthivadivel (1999), the WA framework was developed from an irrigation perspective to help improve understanding of the impacts of irrigation, but that it is general enough to be applied to any water resource use, making it suitable for the evaluation of water management scenarios that include users from several water use sectors.

2.3.2 Details

Molden (1997) states that the WA framework uses a water balance approach, and integrates water balance information with uses of water to indicate the influence of human interventions on the hydrologic cycle. A water account is developed for a specific domain defined by spatial and temporal boundaries and, for this domain, conservation of mass requires that inflows are equal to outflows plus any change in storage. Molden (1997) cautions that, although the water balance approach is conceptually simple, many components of the water balance are often unknown or are difficult to estimate.

A schematic representation of the WA framework described by Molden (1997), Molden and Sakthivadivel (1999) and IWMI (2013), with definitions of the key components, is shown in Figure 2.1. Starting from the left, *Gross Inflow* to the catchment is shown; which includes precipitation, surface and subsurface inflows. Changes in surface and subsurface storage are then added to, or subtracted from, *Gross Inflow* to calculate *Net Inflow*. Moving towards the right, *Net Inflow* is divided into water available for use in the catchment, and water that is committed to downstream users and environmental requirements. Part or all of the *Available* water is depleted, and is therefore unavailable for further use. Note that the WA framework uses the term “depletion”, however, the term “consumptive use” is becoming more commonly used (Perry, 2007; FAO, 2012; Hoekstra, 2013). The WA framework includes four generic types of depletion: (i) evaporation of water from surfaces or by transpiration, (ii) flows to sinks from which it cannot be recovered, such as outflows to sea or to saline groundwater, (iii) pollution such that the water is unsuitable for further use, and (iv) incorporation into a product, such as during manufacturing, bottling water or storage in plant tissues. Depletions are categorized as *Beneficial*, such as transpiration by crops, or *Non-Beneficial*, such as evaporation from fallow lands. *Beneficial* depletions are further categorized as *Process* or *Non-Process* depletions. Molden (1997) explains that *Process* depletions are those that produce an intended good, and *Non-Process* depletions are depletions that are beneficial, but are not depleted by the processes that result in the intended good. *Committed* water is the portion of outflow that may not be used in the catchment as it is committed to downstream users or environmental flows. The portion of net inflow that remains after depletions and committed flows have been subtracted, is termed *Uncommitted Outflow*. *Uncommitted Outflow* is water that is potentially available for use for further development within a catchment, or to be exported to another catchment, but is lost due to a lack of storage or poor management. *Uncommitted Outflow* is *Utilizable* if better management of existing infrastructure would enable the flow to be used beneficially in the catchment, and *Non-Utilizable* if there is insufficient storage infrastructure to capture the outflow. Molden (1997), Molden and Sakthivadivel (1999) and IWMI (2013) discuss several indicators that can be used to characterize a system.

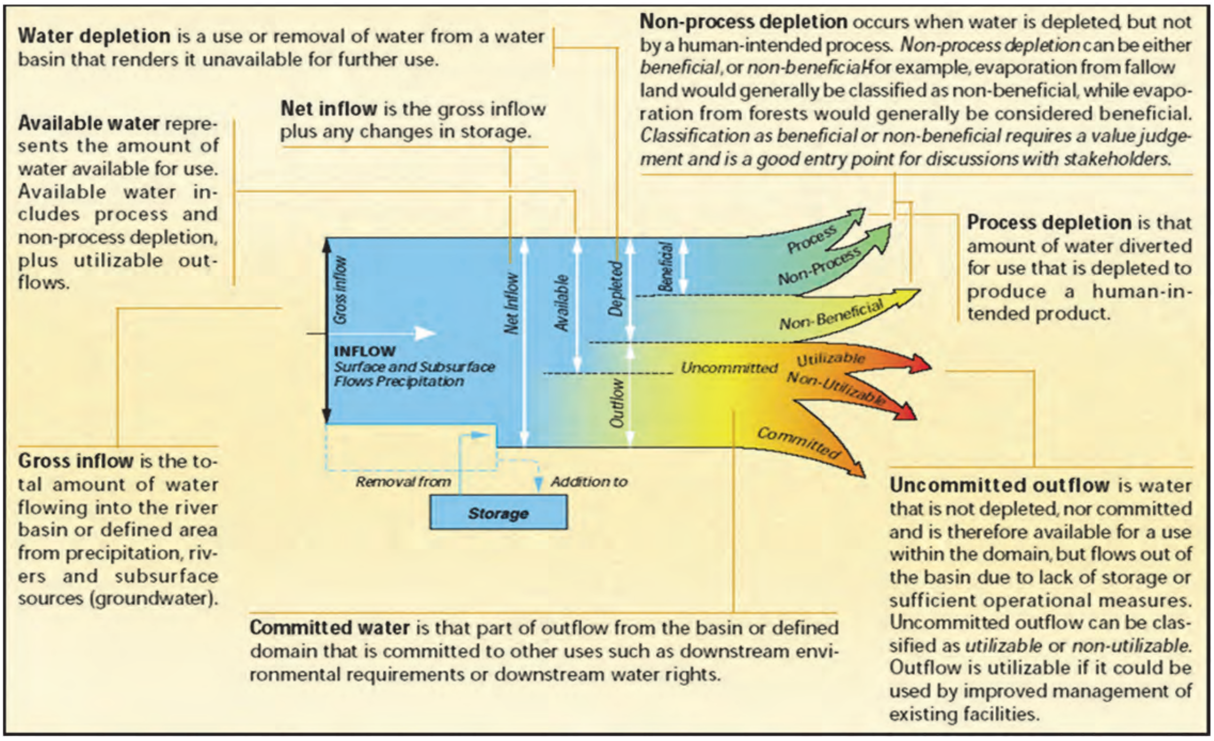

Figure 2.1 Schematic representation of the WA framework (IWMI, 2013)

2.3.3 Application

The WA framework has been applied at many locations, at different scales and for a variety of purposes. Some reported applications of the WA framework are summarised in Table 2.1.

Table 2.1 Applications of the WA framework

Description	Scale	Reference
Irrigation in the Hisar and Sirsa Circles of the Bhakra area in India	Field System	Molden (1997)
Irrigation practices for rice in the Zhanghe Irrigation System in China	Field System Catchment	Dong *et al.* (2004) Loeve *et al.* (2004)
The Makichchawa system of cascading irrigation reservoirs in the Malwatu Oya River catchment in Sri Lanka	System	Molden and Sakthivadivel (1999)
Irrigation system water productivity in the Yellow River catchment in China	System	Khan *et al.* (2008)
Nile River downstream of the High Aswan Dam in Egypt, including non-irrigation uses of water	Catchment	Molden (1997) Molden and Sakthivadivel (1999)
Impact of inter-catchment water transfers from the Indrawati River catchment in Nepal	Catchment	Bhattarai *et al.* (2002)
Water accounting in the Yellow River catchment in China	Catchment	Zhu *et al.* (2004)
Surface water and groundwater availability in the Singkarak-Ombilin River catchment, Indonesia	Catchment	Peranginangin *et al.* (2004)
Impact of irrigation on water resources in the Krishna River catchment in southern India	Catchment	Biggs *et al.* (2007)
East Rapti catchment of Nepal including the Chitwan National Park	Catchment	Shilpakar *et al.* (2011)
Karkheh River catchment in upstream of the Hoor-al-Azim swamp Ramsar site in Iran	Catchment	Karimi *et al.* (2012)
Variability in the annual water balance for Sri Lanka	Country	Bastiaanssen and Chandrapala (2003)
Assessment of current and projected future water use in India	Country	Amarasinghe *et al.* (2007)

2.4 Water Accounting Plus (WA+)

2.4.1 Overview

The Water Accounting Plus (WA+) framework was initiated by Bastiaanssen (2009) and is described by Karimi *et al.* (2013a) as "*a new framework designed to provide explicit spatial information on water depletion and net withdrawal processes in complex river basins*" and as a "*simple, understandable, and standardized way of describing the overall land and water management situation in complex river basins*". More recent work of WA+ uses the term "consumption" in place of "depletion" to be more consistent with international standard terminology, though the term "depletion" is still used to describe atmospheric water that flows out of a given spatial domain. Karimi *et al.* (2013a) state that WA+ is based on the WA framework (Molden, 1997) developed by IWMI, but has been updated to make it easier to use with regard to availability of input data, especially through the use of remotely sensed data, and improved information to facilitate better decision making. The WA+ framework is being continuously developed as a multi-institutional effort by IWMI, UNESCO-IHE and FAO (Water Accounting+, 2014). Similar to the WA framework, WA+ uses a mass water balance approach and accounts for water consumption rather than abstractions, as data on abstractions is often not available from water users, but recognises that advances in remote sensing technology are making it easier to measure certain types of consumptive use independently (Karimi *et al.*, 2013a). Most of the data inputs for WA+ can be derived from satellite measurements, but other data measurements and simulated output from hydrological models can also be used (Karimi *et al.*, 2013a). Hydrological models are useful to provide information on abstractions and return flows, for both surface water and groundwater.

2.4.2 Details

Karimi *et al.* (2013a) explain that WA+ consists of four sheets and each sheet includes a set of performance indicators that jointly provide a summary of the water resources for the spatial region and time span represented by the water account. A time series of these indicators will enable the effect of water management interventions, or lack thereof, to be monitored (Karimi *et al.*, 2013a). As a result of new development the WA+ framework now consists of 10 sheets which are summarized in Table 2.2. More detailed descriptions of the key sheets are provided below.

Table 2.2 Summary of the sheets in the updated WA+ framework (Water Accounting+, 2014)

Sheet Name	Main Purpose
Resource Base Sheet	General overview of water balance at catchment scale including unmanageable, manageable, exploitable, reserved, utilized and utilizable flows. This sheet is largely based on the WA framework described by (Molden, 1997)
Utilized Flow Sheet	Tracks water abstractions from surface water and groundwater and consumed, non-consumed, recoverable and non-recoverable portions of these flows.
Evapotranspiration Sheet	Describes consumptive use due to evapotranspiration in more detail.
Water Source	Describes the sources of consumed water, such as precipitation, soil moisture, surface water, groundwater and desalinisation.
Surface Water Sheet	Expresses land drainage, flows, abstractions, return flows and utilizable flows that occur at points in a catchment moving from upstream to downstream.
Groundwater Sheet	Quantifies groundwater recharge and abstractions that occur naturally and by anthropogenic water management.
Supply and Demand	Tracks water supply and demand at points in a catchment moving from upstream to downstream.
Agricultural Services Sheet	Describes agricultural water consumption by rainfed and irrigated crops – as well as non-crops (fish, timber) and the related production per unit of land (kg/ha) and per unit of water (kg/m^3).
Environmental Services Sheet	Summarizes the water related services in terms of water yield, greenhouse gas emissions, atmospheric carbon sinks, vector-borne diseases, erosion, etc.
Sustainability Sheet	Shows water induced changes in the landscape such as desertification, salinization, waterlogging, reduced biomass production, loss of biodiversity.

Resource Base Sheet

The Resource Base Sheet, shown schematically in Figure 2.2, contains information about water volumes, including inflows, outflows and consumptive use (Karimi *et al.*, 2013a). Similar to the WA framework, starting from the left, inflows to the catchment are shown; including precipitation, surface and groundwater inflows, which are termed *Gross Inflow*. Changes in surface water, soil moisture and groundwater storage are then added to, or subtracted from, *Gross Inflow* to calculate *Net Inflow*. *Net Inflow* is partitioned into: (i) evapotranspiration of water (provided through precipitation) from the landscape (*Landscape ET*) and (ii) total runoff (i.e. surface runoff, interflow and baseflow) referred to as *Exploitable water*, which is the component of net inflow that is not evaporated and thus physically present in the surface water network and aquifers for potential abstraction and consumption. *Landscape ET* is divided based on four land use categories which indicate the extent to which land use and water use in these categories can potentially be managed, and thus indicates the potential to reduce consumptive use through managing evapotranspiration, as discussed in Wu *et al.* (2014). The four land use categories are (Karimi *et al.*, 2013a):

- Managed water use – includes land use classes where the natural water cycle is influenced by infrastructure that supplies, removes or controls water, such as in irrigated agriculture and urban areas.
- Modified land use – includes land use classes where land use is significantly modified by human activity, with corresponding changes in hydrological processes, such as in dryland agriculture and plantations.
- Utilized land use – includes land use classes that provide ecosystem services without being significantly altered, such as grazing on grassland and collection of firewood.
- Protected land use – includes national parks and other protected areas where human changes are kept to a minimum.

The *Exploitable water* is further divided into water available for use within the catchment, flows reserved for outflow to downstream catchments and non-utilizable flows such as flood water. Available water is further divided into flow that is utilized in the catchment, such as evapotranspiration of irrigated water (termed *Incremental ET*), water that is too hot or polluted for reuse, and unused flows that could be used for further development in the catchment. Total outflows from the catchment are summarised on the right, which includes surface water outflow, groundwater outflow and atmospheric circulation processes. Note that part of the consumed water will return back inside the physical boundaries of the catchment through atmospheric moisture recycling (van der Ent and Savenije, 2011).

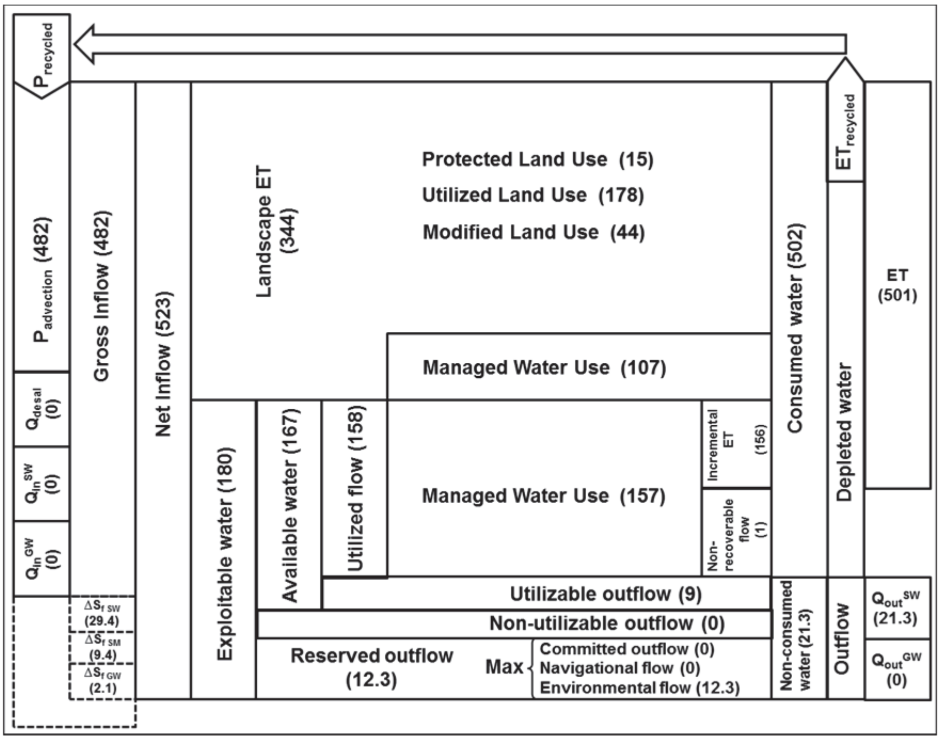

Figure 2.2 Schematic representation of the WA+ Resource Base Sheet (after Karimi *et al.*, 2013b; Water Accounting+, 2014)

Differences between the WA+ Resource Base Sheet and the WA framework include: removal of the concept of process and non-process depletion which was too generic at a catchment scale, the separation of evapotranspiration of water from precipitation and irrigation sources, and linking water use to land use.

Evapotranspiration Sheet

The Evapotranspiration Sheet shown schematically in Figure 2.3 contains information on consumptive use due to evapotranspiration in terms of the extent to which they are managed or are potentially manageable, partitions evapotranspiration into interception, transpiration and evaporation components, and indicates whether the depletions are beneficial or not (Karimi *et al.*, 2013a). The depletion amounts for the four main land use categories are shown on the left. On the right hand side, the partitioned transpiration, soil water evaporation and interception evaporation components of evapotranspiration are shown, together with an indication of whether these are beneficial or not. The classification of whether a water use is beneficial or not is, to some extent, subjective, and may differ depending on the purpose for which the water account is being generated. Karimi *et al.* (2013a) explain that beneficial use generally refers to water use that generates some form of economic, social or environmental benefit, such as agriculture, industry, domestic use, hydropower or recreation. Some examples of non-beneficial use would be, evaporation of intercepted water, transpiration by weeds and excessive evaporation from the soil surface, such as in fallow lands.

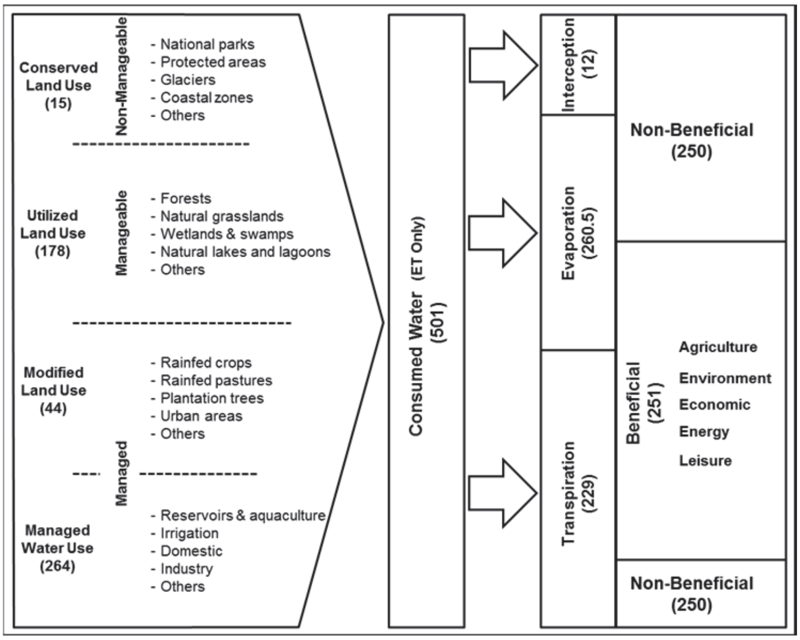

Figure 2.3 Schematic representation of the WA+ Evapotranspiration Sheet (after Karimi *et al.*, 2013b; Water Accounting+, 2014)

Utilized Flow Sheet

The purpose of the Utilized Flow Sheet, shown schematically in Figure 2.4, is to provide a clear overview of managed flows in a catchment, including abstractions, consumption and returns, for managed water. Abstractions from surface water and groundwater sources are summed to give a *Gross Withdrawals* quantity, shown on the left. Moving to the right, the portions of the *Gross Withdrawal* used by each of seven water user categories are shown, followed by the *Incremental ET* and *Return flow* quantities for each water user category. On the right-hand side the sum of the *Incremental ET* quantities (in effect, net abstraction), the sum of the return flows, and the portions of the return flows contributing to surface water and groundwater are shown. Interaction between surface water and groundwater sources can also be shown in the Withdrawals Sheet.

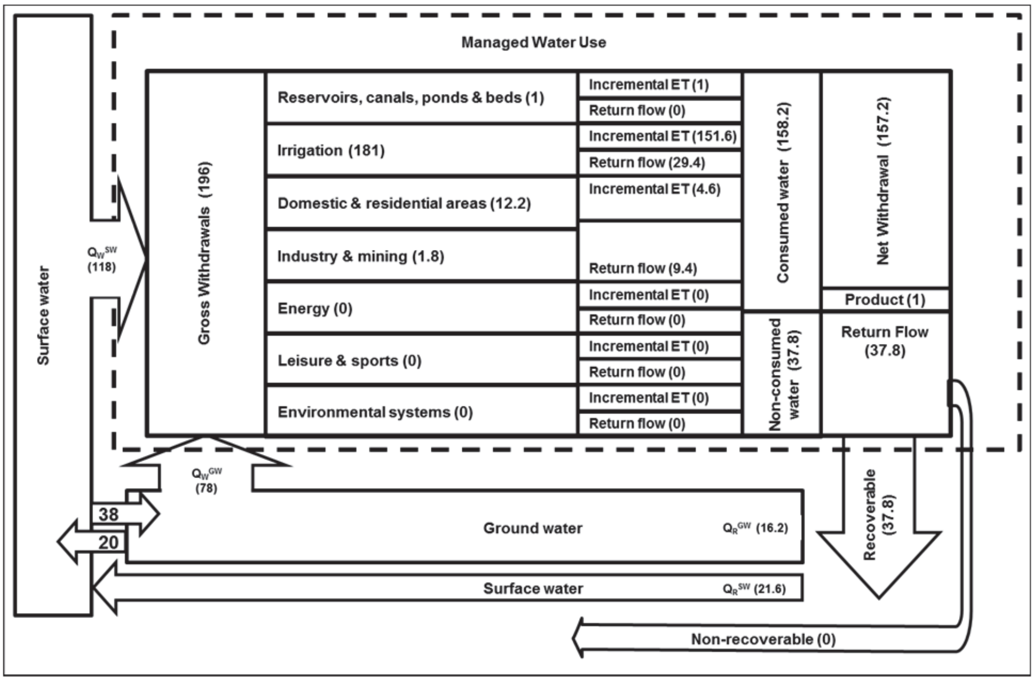

Figure 2.4 Schematic representation of the WA+ Withdrawal Sheet (after Karimi *et al.*, 2013b; Water Accounting+, 2014)

2.4.3 Application

As WA+ is a relatively new framework it has not yet been widely applied. Droogers *et al.* (2010) applied WA+ in a water accounting study for the Okavango River Basin. Karimi *et al.* (2012) provide a simple example of the WA+ Resource Base Sheet in the Nile River Catchment. Dost *et al.* (2013) undertook a similar study for the Awash River Basin, as summarized by Karimi *et al.* (2014), and extended with an uncertainty analysis. Karimi *et al.* (2013b) describe a more comprehensive application of WA+ in the 1160 000 km^2 Indus

River catchment in South Asia. Their purpose was to demonstrate how remotely sensed estimates of inputs such as land use, land cover, precipitation, the components of total evaporation and biomass production can be used to produce a water account using the WA+ framework. The completed water account showed that in the Indus River catchment more than 95% of available water is used and that agriculture, mostly irrigated agriculture, was the biggest water consumer, responsible for 59% of the total depletion. Karimi *et al.* (2013b) conclude that water productivity was low due to poor agronomical practices and water management, and that reducing soil evaporation is the key to sustainable water use in the catchment. The progress of other WA+ application studies can be monitored on the open-access platform website [www.wateraccounting.org].

2.5 System Of Environmental-Economic Accounting For Water (SEEA-WATER)

2.5.1 Overview

The System of Environmental-Economic Accounting for Water (SEEA-Water) is described as a conceptual framework for organizing and integrating hydrological and economic information clearly and consistently (UN, 2011; UN, 2012b). The objective in developing SEEA-Water was to standardize concepts and methods in water accounting to facilitate the compilation of water accounts, thus enabling comparison between countries and between different time periods (UN, 2012b). UN (2012b) recognises that water accounting is multidisciplinary and that a common language and terminology is required to enable hydrologists, environmentalists and economists to communicate. SEEA-Water is based on a systems approach which includes all the stocks and flows relevant to developing water policies, and enables sets of clearly defined, consistent indicators to be calculated (UN, 2011). UN (2012b) explains that SEEA-Water consists of a conceptual framework complemented by a set of standard tables and a set of supplementary tables that enable the connections and interactions between water resources and the economy to be analysed. There is a set of standard tables containing hydrological and economic information and a set of supplementary tables containing information on social aspects of water. SEEA-Water also includes quality accounts to describe the quality of water resources, though these are not yet fully developed (UN, 2012b). SEEA-Water includes the following standard information (UN, 2012b):

- Stocks and flows of water within the environment.
- Pressures imposed on the environment by the economy in the form of water abstraction and emissions.
- The supply of water for domestic use and production.

- The reuse of water within the economy.
- The costs of collection, purification, distribution and treatment of water, including service charges paid by water users and how these costs are financed.
- The payment for permits to abstract water or to discharge wastewater.
- The current hydraulic stock and investments in hydraulic infrastructure.
- The quality of water resources.

The System of National Accounts (SNA) is a standard system, adopted internationally through the UN, for the purpose of compiling economic statistics and calculating internationally comparable economic indicators, such as gross domestic product (GDP), for use in economic analysis and modelling, consistently (UN, 2011; UN, 2012b). The System of Environmental-Economic Accounts (SEEA) (SEEA, 2012), based on the SNA, was developed by the United Nations Statistics Division (UNSD) in collaboration with Eurostat, the International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), the World Bank and experts from various countries, to provide an internationally agreed standard system of statistics describing the interactions between the environment and the economy (UN, 2011). In the SEEA-Water the term "environment" refers to rivers and aquifers which act as water sources to the economy and water sinks for return flows from the economy (Perry, 2012). SEEA-Water is a subsystem of SEEA and builds upon the existing SNA and SEEA frameworks to ensure that water, environmental and economic statistics are consistent, and to facilitate the evaluation of how water resources interact with other natural resources, ecosystem services and the economy (UN, 2011). The International Recommendations for Water Statistics (IRWS), documented in UN (2012a) were developed as part of the implementation of the SEEA-Water framework (UN, 2011). The IRWS include recommendations for compiling internationally comparable water statistics and their integration into water accounts (UN, 2011).

UN (2012b) states that SEEA-Water has an advantage over other water information systems due to the direct link between water, environment and economic accounts which enables an integrated cross-sectoral perspective on water issues. Karimi *et al.* (2013a) note that SEEA-Water accounts treat abstractions and consumption separately, making it suitable for accounting for a range of water uses and resources, but that the emphasis is on domestic and industrial water use. UN (2012b) states that SEEA-Water generally views water as: (i) a material input for production and consumption, and (ii) a sink for the disposal of waste materials, and that the role of water in providing ecosystem habitat is only considered in terms of water quality and in identifying users of water. Perry (2012) states that SEEA-

Water does not include the water use and economic value of the natural environment, such as areas with natural land cover which are largely unmanaged. Perry (2012) also suggest that the accounts should differentiate between natural land cover, dryland agriculture and irrigated agriculture, all of which are significant users of water and also potentially economically important, especially in the perspective of payment for ecosystem services.

2.5.2 Details

The SEEA-Water framework is applied to a "territory of reference", or spatial domain, which may be a country, administrative region or a catchment, for a specified accounting period consistently (UN, 2011; UN, 2012b). A territory consists of an inland water resource system (IWRS) and an economy. The IWRS is composed of (i) surface water, which includes rivers, lakes, reservoirs, snow and ice; (ii) groundwater (aquifers) and (iii) soil water, and the natural flows between these components (UN, 2011; UN, 2012b). Water in the atmosphere and the sea are considered to be separate from the IWRS, but flows to and from these resources are represented in the framework (UN, 2012b). The economy is composed of water users that require water for production and consumption and develop water storage, treatment and distribution infrastructure for this purpose (UN, 2012b). There are flows within the IWRS and the economy, and interactions between these two systems. Water can be transferred between separate IWRSs, in the form of flows from upstream territories or to downstream territories, or exchanged between economies as imports or exports of water between territories (UN, 2012b). UN (2012b) explains that water users in the economy use water in different ways. In some cases the economy physically removes and uses water from the environment, which includes water from the inland water system, the sea and precipitation. Some of these water uses may result in part or all of the water being returned to the environment where the water becomes available for other uses, though often at a reduced quality. These uses may consume water or result in a change in quality, and are thus included in both quantity and quality accounts. In some cases water in the IWRS is used *in situ* for recreation, navigation and fishing, without being depleted or displaced. These uses are not included in the quantity accounts, but may be included in the quality accounts if they result in a change in quality.

UN (2012b) explains that SEEA-Water consists of five categories of accounts:

- Category 1 – Physical supply and use tables and emission accounts. The physical supply and use tables contain information about water volumes abstracted and returned between the environment and the economy and volumes of water supplied and used within the economy. These accounts distinguish between water abstracted from surface water groundwater and soil water. The emission accounts contain information about the quantity of pollutants added to or removed from the water resulting from use by households or economic activity.

- Category 2 – Hybrid and economic accounts. These accounts combine physical information contained in the physical supply and use tables with economic information contained in the SNA monetary supply and use tables. These accounts enable physical quantities to be evaluated against economic flows, for example, the volume of water used relative to the value added by a production process. These accounts also contain information about the cost of water abstraction, purification, distribution and treatment associated with water use and supply, and how these costs are financed.
- Category 3 – Asset accounts. These are accounts of water resource assets, they state the stocks available at the start and end of an accounting period, and the changes that occur during the accounting period. Changes in stocks due to precipitation, ET, inflows, outflows, abstractions and return flows are recorded. These accounts associate water abstractions and return flows to the availability of water in the environment indicating the effect of the economy on water availability.
- Category 4 – Quality accounts describing the quality of water stocks at the start and end of an accounting period. These accounts have not been fully developed, partly due to challenges in linking water quality with economic measures.
- Category 5 – Valuation of water resources. These accounts associate a value with water and water resources. Water is gradually becoming recognised as an economic good, in the sense that it is rented for use in production, its inclusion in goods and as a service. These accounts have not been fully developed, but their importance in policy development and the value of water stocks to a country are recognised.

Data sources and methods to populate these accounts are discussed in UN (2012a). Hydrological and meteorological data are typically based on field measurements by government agencies and remote sensing. Data for the domestic, industrial and agricultural sectors are based on surveys and administrative records. Research data can also be used where this is available. The data shown in the examples of accounts in this review comes from the fictitious “SEEA-Water-land” database used by UN (2012b).

This review will only consider the Category 1 and Category 3 accounts which deal with water quantities; whereas the other categories deal with the quality and economics of water. The SEEA-Water emission accounts that deal with water quality have also not been included in this review.

Standard physical supply and use tables for water

The standard physical use and supply tables for water, shown in Figure 2.5 with example data from UN (2012b), quantify flows of water including abstractions from the environment, supply and use within the economy, and discharges back to the environment. SEEA-Water and the SNA use the United Nations system International Standard Industrial Classification of All Economic Activities (ISIC) to classify economic activity (UN, 2012b). ISIC is not a classification of industries, goods and services, but represents the type of production in which an industry engages (UN, 2012b). A summary of ISIC codes and economic activities that are relevant for water management are shown in Table 2.3.

A. Physical use table (millions of cubic metres)		**Industries (by ISIC category)**							**Households**	**Rest of the world**	**Total**
		1-3	**5-33, 41-43**	**35**	**36**	**37**	**38, 39, 45-99**	**Total**			
From the environment	**1. Total abstraction (= 1.a + 1.b = 1.i + 1.ii)**	108.4	14.5	404.2	428.7	100.1	2.3	**1158.2**	10.8		**1169.0**
	1.a. Abstraction for own use	108.4	114.6	404.2	23.0	100.1	2.3	**752.6**	10.8		**763.4**
	1.b. Abstraction for distribution				405.7			**405.7**			**405.7**
	1.i. From inland water resources:	108.4	114.5	304.2	427.6	0.1	2.3	**957.1**	9.8		**966.9**
	1.i.1. Surface water	55.3	79.7	301.0	4.5	0.1	0.0	**440.6**	0.0		**440.6**
	1.i.2. Groundwater	3.1	34.8	3.2	423.1	0.0	2.3	**466.5**	9.8		**476.3**
	1.i.3. Soil water	50.0						**50.0**			**50.0**
	1.ii. Collection of precipitation							**100.0**	1.0		**101.0**
	1.iii. Abstraction from the sea			100.0	1.1	100.0	0.0	**101.1**			**101.1**
Within the economy	**2. Use of water received from other economic units**	50.7	85.7	3.9	0.0	427.1	51.1	**618.5**	239.5		**858.0**
	2.a. Reused water	12.0	40.7					**52.7**			**52.7**
	2.b. Wastewater to sewerage										
	2.c. Desalinated water										
	3. Total use of water (= 1 + 2)	**159.1**	**200.2**	**408.1**	**428.7**	**527.2**	**53.4**	**1776.7**	**250.3**		**2027.0**

B. Physical supply table (millions of cubic metres)		**Industries (by ISIC category)**							**Households**	**Rest of the world**	**Total**
		1-3	**5-33, 41-43**	**35**	**36**	**37**	**38, 39, 45-99**	**Total**			
Within the economy	**4. Supply of water to other economic units**	17.9	127.6	5.6	379.6	42.7	49.1	622.5	235.5		858.0
	4.a. Reused water		10.0			42.7		52.7			52.7
	4.b. Wastewater to sewerage	17.9	117.6	5.6	1.4		49.1	191.6	235.5		427.1
	4.c. Desalinated water				*1.0*			*1.0*			*1.0*
Into the environment	**5. Total returns (= 5.a + 5.b)**	65.0	29.4	400.0	47.3	483.8	0.7	1026.2	4.8		1031.0
	5.a. To inland water resources (= 5.a.1 + 5.a.2 + 5.a.3)	65.0	23.5	300.0	47.3	227.5	0.7	664.0	4.6		668.6
	5.a.1. Surface water			300.0		52.5	0.2	352.7	0.5		353.2
	5.a.2. Groundwater	65.0	23.5		47.3	175.0	0.5	311.3	4.1		315.4
	5.a.3. Soil water							0.0			0.0
	5.b. To other sources (e.g., sea water)		5.9	100.0		256.3		362.2	0.2		362.4
	6. Total supply of water (= 4 + 5)	**82.9**	**157.0**	**405.6**	**426.9**	**526.5**	**49.8**	**1648.7**	**240.3**		**1889.0**
	7. Consumption (= 3 - 6)	**76.2**	**43.2**	**2.5**	**1.8**	**0.7**	**3.6**	**128.0**	**10.0**		**138.0**
	7.a. Losses in distribution not because of leakages				0.5			0.5			0.5

Figure 2.5 SEEA-Water standard physical use and supply tables (after UN, 2012b)

Table 2.3 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 the water abstracted by public or private entities, possibly treated and supplied through mains to industries and households.
37	Sewerage, including 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.
No code	Households as consumers.	Households usually receive water from water utilities (ISIC-36) and return wastewater through sewerage utilities (ISIC 37).

An abstraction is a quantity of water removed from a source in the environment, either permanently or temporarily, for consumption and production activities (UN, 2012b). In the physical use table, a differentiation is made between water abstracted for own use, or for distribution to other economic units, possibly after being treated. Abstractions are also classified according to the water source, including inland water resources, precipitation and the sea. Use of water received from other economic units is also represented, and occurs when one economic unit receives water from another economic unit, either within the same economy, or as an import from another economy. The total water use of an industry is the sum of the quantities of water abstracted directly from the environment and those received from other economic units (UN, 2012b). The physical supply table includes water supplied to other economic units and water returned to the environment during the accounting period. Water supply to other economic units occurs when one economic unit provides water to another economic unit, either within the same economy, or as an export to another economy. Total returns of water from the economy to the environment are classified according to whether the destination of the return flow is inland water resources or the sea; there is no classification in this table of the quality of the water returned. The total water supply includes the quantities of water supplied to other economic units and those returned to the environment (UN, 2012b). Water consumption is the quantity of water depleted or lost by the economy during use, due to incorporation into products, evaporation, transpiration or simple consumption by households and livestock (UN, 2012b). Water consumption can also be computed for each economic unit (UN, 2012b). Some water might be stored temporarily in the economy but changes in the stored inventory between the start and end of an accounting period are generally small and are thus not included in the physical use and supply tables (UN, 2012b). In the physical use and supply tables, it is possible to include a more detailed breakdown of some sections, for example, abstractions for own use or total returns to the environment. A matrix of water transfers within the economy can be used to provide a view of water flows within the economy by showing detailed information about the source and destination of water flows (UN, 2012b).

Distribution losses are the difference between the quantities of water supplied and received, and include losses due to evaporation, leakage, illegal use and inaccuracies in metering water use (UN, 2012b). The physical use and physical supply tables do not explicitly show distribution losses as these are included in water use or return flows, however, a supplementary table can be used to show distribution losses. In this supplementary table both gross and net supplies of water within the economy are shown, in addition to the distribution losses.

Asset Accounts

Asset accounts state the stocks available at the start and end of an accounting period, and also the changes in stocks that occur within the accounting period (UN, 2012b). UN (2012b) explains that asset accounts link natural flows and water use by the economy, in the form of abstractions and return flows, to stocks of water in a territory. Stocks increase as a result of returns flows from the economy, precipitation and inflows from neighbouring environments. Stocks decrease as a result of abstractions, ET and outflows. UN (2012b) defines water resource assets as water in freshwater, brackish surface water and groundwater bodies existing within a territory, which may provide direct current or future benefits through use as a raw material which may result in quantitative depletion of the water asset.

An example of the standard asset account table for water resources is shown in Figure 2.6. SEEA-Water specifies several classes of water asset, which are shown as columns in the asset account table. The rows of the asset account table show the details of the opening stocks, increases and decreases in stocks, and closing stocks for each asset class.

The asset accounts are linked to the physical supply and use tables through corresponding abstractions and return flows. Andreu *et al.* (2012) states that this link is important to provide information about sources of water for the economy and destinations of water discharges from the economy. It also enables the impact of the economy on the environment, in terms of abstractions and return flows, to be evaluated (UN, 2012b).

	EA.131. Surface water				EA.132 Groundwater	EA.133 Soil water	Total
	EA.1311 Artificial reservoirs	EA.1312 Lakes	EA.1313 Rivers	EA.1314 Snow, ice and glaciers			
1. Opening stocks	**1500**	**2700**	**5000**	**0**	**100000**	**500**	**109700**
Increases in stocks							
2. Returns	300	0	53		315	0	**669**
3. Precipitation	124	246	50			23015	**23435**
4. Inflows	1 054	339	20137		437	0	**21967**
4.a. From upstream territories			17650				**17650**
4.b. From other resources in the territory	1 054	339	2 487	0	437	0	**4317**
Decreases in stocks							
5. Abstraction	280	20	141		476	50	**967**
6. Evaporation/actual evapotranspiration	80	215	54			21125	**21474**
7. Outflows	1000	100	20773	0	87	1787	**23747**
7.a. To downstream territories			9430				**9430**
7.b. To the sea			10000				**10000**
7.b. To other resources in the territory	1000	100	1343	0	87	1787	**4317**
8. Other changes in volume							**0**
9. Closing stocks	**1618**	**2950**	**4272**		**100189**	**553**	**109583**

Figure 2.6 Example of SEEA-Water standard asset account table (after UN, 2012b)

The details of flows of water between water resource assets are described in a table containing a matrix of flows, as shown in Figure 2.7. This table provides information about the source and destination of water flows between water resources assets within a territory (UN, 2012b). The information in this table also enables calculation of internally renewable water resources and reduces the possibility of double accounting as a result of flows between surface and groundwater water resource assets.

	EA.131. Surface water				EA.132 Groundwater	EA.133 Soil water	Outflows to other resources in the territory
	EA.1311 Artificial reservoirs	EA.1312 Lakes	EA.1313 Rivers	EA.1314 Snow, ice and glaciers			
EA.1311. Artificial reservoirs			1000				**1 000**
EA.1312. Lakes			100				**100**
EA.1313. Rivers	1000	293			50		**1 343**
EA.1314. Snow, ice and glaciers							**0**
EA.132. Groundwater			87				**87**
EA.133. Soil water	54	46	1300		387		**1 787**
Inflows from other resources in the territory	**1054**	**339**	**2487**	**0**	**437**	**0**	**4317**

Figure 2.7 Example of SEEA-Water matrix of flows between water resource assets (after UN, 2012b)

2.5.3 Application

SEEA-Water was submitted to the United Nations Statistical Commission (UNSC) and was adopted at the 38th session of the UNSC in 2007 as an interim international statistical standard, and the UNSC also encouraged implementation of SEEA-Water in national statistical systems (UN, 2012b). UN (2012b) includes examples of how SEEA-Water can be applied and where it has been applied, which include Australia, Botswana, China, Denmark, Namibia, Netherlands, South Africa and Sweden. UN (2012b) indicates that countries would not typically apply the whole SEEA-Water at one time, but would typically initially apply the physical use and supply, asset and emission accounts according to their individual requirements, and only implement the economic accounts later. UN (2012b) uses a standard example dataset to demonstrate the application of SEEA-Water. A review of water accounting practices by the Australian Government Bureau of Meteorology's Water Accounting Standards Board (BOM, 2011) indicates that the following organisations and countries have used the SEEA-Water accounting framework: European Environment Agency, Eurostat, Peru, Jordan, Israel, Botswana, Namibia and South Africa. UN (2011) provides simple examples of the application of SEEA-Water in Mauritius and Mexico. UN (2011) states that experience has shown that country water accounts compiled according to SEEA-Water and IRWS can be integrated with existing data sources and that they help to integrate data from different sources to improve understanding of water resources.

The Australia Bureau of Statistics have based their *Water Account, Australia* reports on the SEEA starting with the 2000-2001 report (Trewin, 2004) and on the SEEA-Water framework starting with the 2005-2004 report (Trewin, 2006). These water accounts describe the flow of water between the environment and the economy, and provide information on the supply and use of water within the economy (Trewin, 2004). Trewin (2006) states that Australia was a leading contributor to the development of SEEA-Water and that SEEA-Water has strengthened the conceptual basis of the Australian Water Accounts and acted as a guide to the practical compilation of accounts. Perry (2012) states that Australia appears to be the only country for which detailed information regarding the implementation of SEEA-Water is available.

SEEA-Water has been applied in South Africa, in the Orange River catchment (Lange *et al.*, 2007), the Upper Vaal Water Management Area (WMA) (StatsSA, Unknown) and nationally for the year 2000 for the 19 WMAs (StatsSA, 2004; StatsSA, 2006; StatsSA, 2009). Lange *et al.* (2007) conclude that the accounts for the Orange River catchment include information on water supply, use and productivity, which are important for water resource management, whereas the NWRS for South Africa (DWAF, 2004) contains detailed information on water supply only.

2.6 Australian Water Accounting Standard (AWAS)

2.6.1 Overview

The Australian Water Accounting Standard (AWAS) was developed by the Water Accounting Standards Board (WASB) of the Australian Bureau of Meteorology (BOM) as part of the National Water Initiative (NWI) to provide a guideline for compiling General Purpose Water Accounting (GPWA) reports, as described by BOM (2012). BOM (2013a) defines water accounting as the "*systematic process of identifying, recognising, quantifying, reporting, assuring and publishing information about water, the rights or other claims to that water, and the obligations against that water*". The AWAS refers to a *water report entity*, which is defined by BOM (2012) as an entity that holds or transfers water; holds or transfers rights or claims to water, or has inflows or outflows of water. BOM (2012) states that the purpose of the Standard is to ensure that GPWA reports are consistent so that the GPWA reports can be compared, either for a particular entity for different reporting periods, or for two different entities for the same reporting period. The AWAS refers only to water that is in the terrestrial phase of the water cycle and does not include water in the marine or atmospheric phases (BOM, 2012). The AWAS is based strongly on financial accounting practices, but quantifies water by volume and not by monetary value (BOM, 2012). The AWAS is intended to be used at range of scales from a single dam or business up to the Australian National Water Account.

2.6.2 Details

A GPWA report contains the following components (BOM, 2012):

- a Contextual Statement,
- an Accountability Statement,
- a Statement of Water Assets and Water Liabilities (SWAWL),
- a Statement of Changes in Water Assets and Water Liabilities (SCWAWL) (where relevant),
- a Statement of Water Flows (SWF) (where relevant), and
- note disclosures, containing additional information.

The Contextual Statement contains contextual information, such as geographical location and storage capacity, about the water assets, liabilities and flows of a water report entity to assist users in understanding the GPWA report (BOM, 2012). The Accountability Statement indicates whether the GPWA account has been prepared according to Australian Water Accounting Standards, with reasons for any deviations from the standard (BOM, 2012). The note disclosures are cross referenced notes providing additional information that is not a part of the standard account statements, in order to assist readers in understanding the accounts (BOM, 2012). The SWAWL and the SCWAWL are prepared on an accrual basis which means that transactions, transformations and events affecting assets and liabilities are accounted for at the time that the decisions or commitments that initiate them occur and which might not coincide with the time at which the physical water transaction, transformation or event occurs (BOM, 2012). The method of quantification to be used to determine water assets, liabilities and flows is not prescribed, though information about the method used and the accuracy should be stated in the account notes.

Statement of Water Assets and Water Liabilities (SWAWL)

The AWAS states that the SWAWL provides information about the nature and volumes of the water assets and liabilities for a water report entity on a specified reporting date (BOM, 2012). The AWAS specifies and gives examples of what can be considered to be assets and liabilities for different types of water report entity in different situations. The AWAS does not prescribe a particular format for the SWAWL, though it must specify all water assets, water liabilities and the net water assets for the report entity. An example of a SWAWL from the 2013 accounts for the Murray-Darling Basin in Australia is shown in Figure 2.8.

Statement of Water Assets and Water Liabilities for Murray – Darling Basin as at 30 June 2013		
	2013 Mℓ	**2012 Mℓ**
WATER ASSETS		
Surface water assets		
1.1 Storages	**16 011 790**	21 187 196
1.2 Unregulated river	**-**	-
1.3 Regulated river	**1 019 262**	1 326 012
1.4 Lakes and wetlands	**1 799 526**	1 811 372
1.5 Inter-region claim on water	**306 397**	913 776
1.10 Other surface water assets	**20 592**	19 952
Total surface water assets	**19 157 567**	25 258 308
Groundwater assets		
2.1 Water table aquifer	**-**	-
2.2 Underlying aquifers	**-**	-
2.5 Other groundwater assets	**4 193 166**	4 013 615
Total groundwater assets	**4 193 166**	4 013 615
TOTAL WATER ASSETS	**23 350 733**	29 271 923
WATER LIABILITIES		
Surface water liabilities		
5.1 Surface water allocation remaining	**4 204 314**	7 297 452
5.2 Surface water allocation remaining – urban water system	**0**	0
Total surface water liabilities	**4 204 314**	7 297 452
Groundwater liabilities		
6.1 Groundwater allocation remaining	**1 907**	2 498
6.2 Groundwater allocation remaining – urban water system	**0**	0
Total groundwater liabilities	**1 907**	2 498
TOTAL WATER LIABILITIES	**4 206 221**	7 297 452
OPENING NET WATER ASSETS	**21 971 973**	17 422 866
ADD/(LESS): CHANGE IN NET WATER ASSETS	**(2 827 461)**	4 549 107
CLOSING NET WATER ASSETS	**19 144 512**	21 971 973

Figure 2.8 Example of a simple SWAWL (after BOM, 2014)

Statement of Changes in Water Assets and Water Liabilities (SCWAWL)

The AWAS states that the SCWAWL provides information about changes in the nature or volume of a water report entity's net water assets during a specified reporting period (BOM, 2012). As shown in Figure 2.9, it includes information about transactions, transformations and events that result in changes to water assets or liabilities (BOM, 2012). The AWAS does not prescribe a particular format for the SCWAWL, but it must specify all water asset increases and decreases, water liability increases and decreases, and changes in net water assets.

Statement of Changes in Water Assets and Water Liabilities for Murray – Darling Basin for the year ended 30 June 2013		2013	2012
		Mℓ	**Mℓ**
WATER ASSET INCREASES			
Surface water increases			
9.1	Precipitation on surface water	**1 160 129**	1 648 950
9.2	River inflow to region	**451 000**	0
9.4	Runoff to surface water	**25 143 874**	57 597 996
9.5	Point return from irrigation scheme	**212 773**	198 314
9.6	Overbank flood return to river channel	**-**	-
9.9	Discharge from urban water system	**31 636**	34 325
9.10	Direct discharge by user	**-**	-
9.15	Increase of inter-region surface water claim on water	**1 748 700**	2 560 022
Total Surface water increases		**28 748 112**	62 039 607
Groundwater increases			
10.1	Groundwater inflow from outside region	**2 646**	2 797
10.2	Groundwater inflow from outside region at coast	**50**	53
10.3	Recharge from landscape	**1 539 098**	3 125 927
10.5	Leakage from off-channel water storage	**-**	-
10.6	Leakage from urban water system	**-**	-
10.7	Leakage from irrigation scheme	**-**	-
10.8	Managed aquifer recharge – other schemes	**631**	2 340
10.13	Other groundwater increases	**270 109**	2 683 660
Total Groundwater increases		**1 812 534**	5 814 777
Total water asset increases		**30 560 646**	67 854 384
WATER LIABILITY DECREASES			
Surface water liability decreases			
13.1	Adjustment and forfeiture of surface water allocation	**2 007 538**	2 215 350
13.2	Adjustment and forfeiture of surface water allocation – urban water system	**173 439**	286 743
Total Surface water liability decreases		**2 180 977**	2 502 093
Groundwater liability decreases			
14.1	Adjustment and forfeiture of groundwater allocation	**1 205 242**	1 078 199
14.2	Adjustment and forfeiture of groundwater allocation – urban water system	**31 792**	17 079
Total Groundwater liability decreases		**1 237 034**	1 095 278
Total water liability decreases		**3 418 011**	3 597 371
WATER ASSET DECREASES			
Surface water decreases			
17.1	Evaporation from surface water	**3 036 866**	2 986 402
17.2	River outflow from the region	**5 179 600**	9 565 600
17.4	Surface water leakage to landscape	**-**	-
17.5	Overbank flood spilling	**437 901**	299 151
17.6	Surface water diversions – other statutory rights	**68 210**	68 209
17.7	Entitled diversion of non-allocated surface water to users	**2 066 946**	1 614 049
17.8	Entitled diversion of non-allocated surface water to urban water system	**13 073**	9 861
17.10	River and floodplain leakage, evaporation and errors	**14 499 374**	37 581 242
17.17	Decrease of inter-region surface water claim on water	**215 000**	625 000
Total Surface water decreases		**25 516 970**	52 749 514
Groundwater decreases			
18.1	Groundwater outflow to outside region	**21**	19
18.2	Groundwater outflow to outside region at coast	**1 446**	1 551
18.3	Discharge to landscape	**2 733 597**	2 518 361
18.7	Groundwater extractions – other statutory rights	**230 416**	194 176
18.18	Other groundwater decreases	**90 558**	24 271
Total Groundwater decreases		**3 056 038**	2 738 378
Total water asset decreases		**28 573 008**	55 487 892
WATER LIABILITY INCREASES			
Surface water liability increases			
21.1	Surface water allocation announcements	**7 758 577**	9 011 661
21.2	Surface water allocation announcements – urban water system	**539 037**	583 020
Total Surface water liability increases		**8 297 614**	9 594 681
Groundwater liability increases			
22.1	Groundwater allocation announcements	**2 146 993**	1 685 528
22.2	Groundwater allocation announcements – urban water system	**68 816**	25 993
Total Groundwater liability increases		**2 215 809**	1 711 521
Total water liability increases		**10 513 423**	11 306 202
UNACCOUNTED-FOR DIFFERENCE			

Figure 2.9 Example of a simple SCWAWL (after BOM, 2014)

Statement of Water Flows (SWF)

The AWAS states that the SWF provides information about the nature and volume of water inflows and outflows for a water report entity during a specified reporting period, there is no accrual (BOM, 2012). The AWAS does not prescribe a particular format for the SWF, but it must specify all water inflows, outflows, changes in storage, opening storage and closing storage. An example of a SWF is shown in Figure 2.10.

Statement of Water Flows for Murray – Darling Basin
for the year ended 30 June 2013

		2013 Mℓ	2012 Mℓ
WATER INFLOWS			
Surface water inflows			
9.1	Precipitation on surface water	1 160 129	1 648 950
9.2	River inflow to region	451 000	0
9.4	Runoff to surface water	25 143 874	57 597 996
9.5	Point return from irrigation scheme	212 773	198 314
9.6	Overbank flood return to river channel	-	-
9.9	Discharge from urban water system	31 636	34 325
9.10	Direct discharge by user	-	-
9.11	Delivery of water under inter-region agreement to surface water	2 141 079	1 491 312
Total Surface water inflows		29 140 491	60 970 897
Groundwater inflows			
10.1	Groundwater inflow from outside region	2 646	2 797
10.2	Groundwater inflow from outside region at coast	50	53
10.3	Recharge from landscape	1 539 098	3 125 927
10.5	Leakage from off-channel water storage	-	-
10.6	Leakage from urban water system	-	-
10.7	Leakage from irrigation scheme	-	-
10.8	Managed aquifer recharge – other schemes	631	2 340
10.13	Other groundwater inflows	270 109	2 683 660
Total Groundwater inflows		1 812 534	5 814 777
Total water inflows		30 953 025	66 785 674
WATER OUTFLOWS			
Surface water outflows			
17.1	Evaporation from surface water	3 036 866	2 986 402
17.2	River outflow from the region	5 179 600	9 565 600
17.4	Surface water leakage to landscape	-	-
17.5	Overbank flood spilling	437 901	299 151
17.6	Surface water diversions – other statutory rights	68 210	68 209
17.7	Entitled diversion of non-allocated surface water to users	2 066 946	1 614 049
17.8	Entitled diversion of non-allocated surface water to urban water system	13 073	9 861
17.10	River and floodplain leakage, evaporation and errors	14 499 374	37 581 242
17.11	Entitled diversion of allocated surface water to users	8 844 177	6 279 196
17.12	Entitled diversion of allocated surface water to urban water system	365 598	296 302
Total Surface water outflows		34 511 745	58 700 012
Groundwater outflows			
18.1	Groundwater outflow to outside region	21	19
18.2	Groundwater outflow to outside region at coast	1 446	1 551
18.3	Discharge to landscape	2 733 597	2 518 361
18.7	Groundwater extractions – other statutory rights	230 416	194 176
18.11	Entitled extraction of allocated groundwater to users	942 342	606 970
18.12	Entitled extraction of allocated groundwater to urban water system	37 024	8 914
18.18	Other groundwater outflows	90 558	24 271
Total Groundwater outflows		4 035 404	3 354 262
Total water outflows		38 547 149	62 054 274
UNACCOUNTED-FOR DIFFERENCE			
Unaccounted-for difference			
25.1	Unaccounted-for difference	(2 280 313)	108 554
Total Unaccounted-for difference		(2 280 313)	108 554
Opening water storage		28 358 147	23 735 301
Add/(Less): Change in water storage		(5 313 811)	4 622 846
Closing water storage		23 044 336	28 358 147

Figure 2.10 Example of a simple SWF (after BOM, 2014)

2.6.3 Application

The AWAS was used as a guideline in the compilation of the National Water Account for Australia for 2010, 2011, and 2012 (BOM, 2013b). The Australian Bureau of Meteorology is responsible for compiling the National Water Account for Australia under the Commonwealth Water Act of 2007 (BOM, 2013b). The purpose of the National Water Accounts is to provide an overview of water resources management for a year-long period at a national and regional scale, including: the total water resource, water available for abstraction, rights to abstract water and the actual abstraction quantities (BOM, 2013b). BOM (2013b) explains that the National Water Account complements *Water Account, Australia* compiled by the Australian Bureau of Statistics, which is based on the SEEA-Water framework and provides information about the supply and use of water within the Australian economy.

The AWAS was applied by Hughes *et al.* (2012) to compile a GPWA report for the Amatole region in the Eastern Cape province of South Africa to investigate potential constraints for the implementation of GPWA in water management institutions in South Africa. Hughes *et al.* (2012) concluded that GPWA reports are a sound approach for South Africa for the reasons that they are standardised, transparent and makes provision for specifying uncertainties related to the quantification of water resources. However, Hughes *et al.* (2012) identified the availability of, and access to, suitable data, and lack of human resource capacity, as the main problems that could prevent implementation of GPWA in South Africa. Hughes *et al.* (2012) indicated the need to be able to compile water quality accounts, and also some means of evaluating the economic and social benefits of water supplies.

Andreu *et al.* (2012) applied the AWAS to the Jucar Water Resources System (JWRS) in eastern Spain. Andreu *et al.* (2012) concluded that the GPWA reports are a powerful tool that can be used to improve transparency in water management. However, they state that in trying to be representative at a wide range of scales, some of the components are difficult to estimate at some scales, which affect the accuracy of the accounts and increases uncertainty. Andreu *et al.* (2012) also make the point that for some types of entities and scales of application the data required may be easy to obtain, but at large scales and when trying to represent details of the whole hydrological cycle, the availability of data will need to be addressed first before accounts can be compiled.

2.7 Discussion And Conclusions

From the four water accounting frameworks reviewed there appear to be three quite different types of frameworks. The WA and extended WA+ frameworks are typically applied at a catchment scale and provide a detailed mass balance of the components of the hydrological cycle by land use class and water sector. Both WA and WA+ have a strong land use and evapotranspiration focus. The SEEA-Water framework has an economics focus, considering flows of water into and out of the economy and the economic value of water, and it does not consider water consumption by natural vegetation or agriculture in any detail. The SEEA-Water framework is typically applied at a country or administrative area scale. The AWAS has a strong financial accounting background and represents water in terms of assets and liabilities with accrual, and facilitates the representation of water allocations and water trading (related to water auditing). The AWAS with its very generic financial accounting structure could really be applied at any scale. These three types of water accounting frameworks should not be seen as competing methodologies as they have different purposes and could each play a different role in describing the water situation within a country. For example, in Australia, both SEEA-Water and AWAS are applied, and in Vietnam both SEEA-Water and WA+ are being applied. The WA framework and WA+ are intended to provide an understanding of the hydrological components of the water balance in a domain to facilitate understanding and communication. The SEEA-Water framework with its strong economic focus is a useful tool for policy makers and economists. The AWAS would be more appropriate in a water auditing role. A comparison of the four water accounting frameworks reviewed, based on the literature reviewed, is shown in Table 2.4.

Table 2.4 Comparison of the four water accounting frameworks reviewed

Criteria	WA	WA+	SEEA-Water	AWAS
Easy to understand	Easy	Easy	Moderate	Moderate
Easy to apply	Easy	Moderate	Complex	Moderate
Degree of detail	Low	Moderate	Moderate-High	Moderate
Communication tool	Yes	Yes	Possibly	No
Represents hydrological cycle	Partial	Yes	Partial	No
Represents all water use sectors	Yes	Yes	Yes, but mainly domestic and industrial	Yes
Represents all land use classes	Yes	Yes	No, only economy related	Only report entity
Spatial scale	Any	Any, but primarily catchment	Catchment, region, country	Any
Temporal scale (typical)	Monthly, Annual	Monthly, Annual	Annual	Annual
Reports stocks (assets)	No	Partially	Yes	Yes
Reports abstractions	No	Yes	Yes	Yes
Reports consumption	Yes	Yes	Yes	Yes
Reports return flows	No	Yes	Yes	Yes
Reports internal reuse	No	No	Yes	No
Includes water quality	No	No	Partial	No
Includes water productivity	No	Yes, crop yield, timber, livestock, fish	Yes, economic	No
Includes economics	No	No	Yes	No
Useful for auditing	No	No	No	Possibly
Data requirements	Moderate	Moderate	Detailed	Detailed
Detailed application guidelines	No	No	Yes	Yes
Application	Internationally	New	Internationally	Primarily Australia

Although this review focussed on accounting for quantities of water, there are two other characteristics of water, (i) quality and (ii) economic value, which need to be considered in managing a country's water resources. However, water quality and economic value are potentially even more difficult to quantify than water quantity, especially at large spatial scales. The WA framework, WA+ and AWAS frameworks do not make specific provision for accounting for water quality, although if data are available there is no reason why water quality could not be accounted for in a similar manner to water volumes. The SEEA-Water framework makes specific provision for accounting for water quality through emission accounts that specify emission of pollutants into water used for production and consumption, and also through a set of water quality accounts which are still under development (UN, 2012b). The SEEA-Water framework has a strong economic component, which is its main purpose. The WA framework, WA+ and AWAS frameworks do not make specific provision for accounting for the economic value of water, though BOM (2012) indicates that the AWAS permits accounts to be compiled based on monetary value instead of water volumes. The Agricultural Services Sheet in WA+ indicates the productivity of land and water resources.

The frameworks also differ in the way in which they represent water use, and terms such as ‘abstraction’, ‘withdrawal’, ‘use’, ‘consumption’ and ‘depletion’ need to be understood in the context of each individual framework. WA framework and WA+ focus on accounting for changes in surface water, groundwater and soil water storage (changes in stocks) and quantities of water that are removed from further use (consumption) within the accounting domain. Accounting for water consumption can help in avoiding errors where water is reused within the accounting domain and also enables representation of evapotranspiration from areas with natural vegetation or by dryland agriculture, which is often significant, though no abstractions from rivers or dams occur. In a field, catchment or country scale spatial domain, especially in arid and semi-arid regions, evapotranspiration is likely to be the main form of water consumption, but it may not necessarily result in a significant direct economic contribution, whereas industry may require large quantities of water though not deplete it significantly, but may result in deterioration in quality. However, quantification of abstractions for domestic use, industry and irrigated agriculture is important for the planning and management of water storage and distribution infrastructure. The WA+ Utilized Flow Sheet accounts for water abstractions and return flows within the accounting domain in a relatively simple manner, while SEEA-Water provides a framework for detailed information about flows between various components of the economy. The AWAS accounts for changes in assets and liabilities, and inflows and outflows, it does not represent any flows within the accounting domain, and is therefore less suitable for groundwater monitoring, reporting and verification. When accounting for abstractions and return flows, care needs to be taken regarding the source of water abstractions and the destination of water return flows relative to the boundary of the spatial domain of the account. The selection of a water accounting framework will ultimately depend on the intended purpose.

Although the SEEA-Water and the AWAS frameworks have already been applied in South Africa (StatsSA, 2004; StatsSA, 2006; StatsSA, 2009; StatsSA, 2010; Hughes *et al.*, 2012), the WA+ accounts would be a good starting point as a common water accounting framework to facilitate better understanding of the water balance at a catchment level and as a common, relatively simple, format for water managers and users to communicate about water availability and use. The WA framework is almost too simplified, including only water availability and depletions; it does not include information on abstractions and return flows which are necessary for assessing licences and allocations and for operations planning. Before the important, but more complicated, aspects of water quality and the economic value of water can be addressed, it is important to be able to accurately quantify water availability and use. Compilation of WA+ accounts is feasible using direct data measurements together with remote sensing and modelling, though availability of data on blue water abstractions and return flows may be a constraint. Implementation of the WA+ accounts at a catchment level would highlight areas where better data and information are required, for example, monitoring of actual abstractions of blue water, which are also required for auditing water allocations. Catchment level WA+ accounts would provide the water quantity information required to populate SEEA-Water accounts at larger catchment, regional or national scales, from which the economic components of the accounts could be compiled. The economic focus of SEEA-Water makes it more suitable for broad scale water resources management and informing water policy decisions in South Africa. Monitoring of water quality and compiling some form of water quality accounts associated with the WA+ and SEEA-Water accounts would be the next step. The economic value of water should be associated with water quality as water use is often accompanied by a change in water quality, even if the water is not depleted. An advantage of the AWAS is that it is based on well-established financial accounting practices, but requires detailed flow and allocation data and is better suited to a water auditing role than a general water management role to which WA+ and SEEA-Water are better suited.

A key constraint to the application of these water accounting frameworks will be the availability of data and information to populate them, and the uncertainty associated with the accuracy of the data and information. Hughes *et al.* (2012) and StatsSA (2010) both indicate that availability and access to suitable data and information from the public sector is a constraint to compiling water accounts in South Africa. Hughes *et al.* (2012) noted problems with monitoring and access to data, and that even with modelling and other estimation methods there would still be data gaps. StatsSA (2010) noted problems with statistical quality of data, lack of data on water in economic units, and that data available from the public sector is not always classified according to the International Standard Industrial Classification of all Economic Activities. Some data on physical stocks and flows of water related to major dams, streamflow and major abstractions is available from the Department of Water and Sanitation. It is expected that availability of data on water abstractions, consumption and return flows by different water use sectors will be the main constraint to compiling water accounts in South Africa. Hughes *et al.* (2012) stress the importance of implementing water accounting in South Africa in order to achieve more effective and efficient water resources management, and implementation would help to highlight where data gaps need to be addressed. Better water resources data will result in more accurate and comprehensive water accounts to guide water managers and policy makers in their decisions.

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3 DATASETS AND METHODOLOGIES FOR WATER USE QUANTIFICATION AND ACCOUNTING

DJ Clark

The purpose of water accounts is to provide a clear view of the water resource states and flows in a domain for a specified time period, but these accounts are data intensive and the more accurate the data and information the more useful the accounts are. However, many of the data parameters are highly variable in both space and time. Karimi *et al.* (2013b) point out that 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, (i) direct measurement, (ii) remote sensing, and (iii) 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 use and streamflows within a catchment. 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. Remote sensing may provide a better spatial representation if imagery at a suitable resolution is available, but measurements are at a point in time which depends on the scan interval or when the satellite passes over the study site and the temporal resolution may not be suitable. Another advantage of remote sensing is that the temporally dynamic nature of land use, such as land use change and the harvesting of agricultural crops, is easily taken into account. However, direct measurements are often required to calibrate remotely sensed measurements and to infill data sets, especially data from orbiting satellites, which is not temporally continuous due to cloud cover and intervals between satellite passes. Generally some form of modelling is required to produce data products, such as precipitation or ET, from remote sensing measurements. Remote sensing estimates are generally less accurate than direct measurements, and the models used to produce these estimates are based on numerous assumptions. This project focussed on the use of pre-processed remote sensing data products for ease of application in the methodology and because the detailed studies that are required to develop models to estimate data parameters based on remote sensing estimates was beyond the scope of this project. 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 use, precipitation and reference or total evaporation (or meteorological data such as air temperature, relative humidity and windspeed to estimate it). 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. It is anticipated that a combination of direct measurement, remote sensing and modelling will be required to provide the data that is necessary compile water accounts. The accuracy of the various data sources used to compile an account, and the associated uncertainties need to be considered.

The studies by Gibson *et al.* (2009) and Karimi *et al.* (2013b) were especially useful as they tried to quantify all components of the water balance to produce a water account. Gibson *et al.* (2009) conducted a study investigating the use of remote sensing technologies to quantify the water balance components for quaternary catchment G10K in the Piketberg region of the Western Cape in South Africa. Karimi *et al.* (2013b) describe the application of the WA+ accounting framework in the large Indus Basin in Asia, mostly using remotely sensed data.

One useful source of data that needs particular mention is the South African Atlas of Climatology and Agrohydrology (Schulze, 2008b) which was compiled in WRC Project 1489, and in particular the DVD-ROM (Schulze *et al.*, 2008b) accompanying the report, which contains several useful datasets in ESRI shapefile vector format and ESRI GRID raster format.

The objective of this chapter is to investigate and identify suitable datasets and water quantification methodologies that could be used to compile water resource accounts in South Africa, and to identify where potential information gaps exist. This investigation of datasets and methodologies was not exhaustive and was to a large extent limited by the requirements of the project and focussed on methodologies already applied in South Africa. This investigation was not intended to be an in-depth review of the science behind these methodologies, which especially in the case of remote sensing data is beyond the scope of this study. There was also a focus on the use of freely available datasets so that the methodology can be easily applied outside of the case study catchments by anyone. The methodology for water use quantification and accounting that was developed in this project was to a large extent influenced by the availability and suitability of the datasets identified in this chapter.

3.1 Altitude and Catchment Boundaries

To compile catchment scale water accounts a dataset of catchment boundaries at an appropriate scale is required. 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.

3.1.1 Altitude

Good altitude data is important for determining catchment boundaries and altitude is also a key factor in describing the spatial variability of climate. In a recent WRC funded project (K5/1908), a gap-filled Digital Elevation Model (DEM) (Weepener *et al.*, 2011d) was developed by Weepener *et al.* (2011a) for South Africa from the 90m resolution Shuttle Radar Topography Mission (SRTM) (Farr *et al.*, 2007) DEM. A hydrologically improved DEM (Weepener *et al.*, 2011b) was also developed by Weepener *et al.* (2011a) to ensure correct delineation of flow paths. Other related products developed by (Weepener *et al.*, 2011a) include:

- polygon shapefiles of Primary, Secondary, Tertiary and Quaternary catchment boundaries,
- a line vector shapefile dataset of flow paths,
- a raster dataset of flow accumulations,
- a raster dataset of flows directions,
- a raster dataset of slope,
- a raster dataset of aspect, and
- a hill shape raster.

A coarser resolution (1.7 km) raster dataset of altitude that could be used to determine mean catchment altitude is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\altitude]. The derivation of this dataset is described by Schulze and Horan (2008a).

3.1.2 Primary, Secondary, Tertiary and Quaternary catchments

The geographical region of South Africa, Lesotho and Swaziland has been divided up by the Department of Water and Sanitation (DWS) into a hierarchical system of catchments, composed of 22 Primary Catchments containing, Secondary, Tertiary and Quaternary

Catchments. The Quaternary Catchments are widely used in South Africa for water resources assessments.

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 pour points were defined for each of the Quaternary Catchments by hydrologists at the DWS, 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 such 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 Directorate of Spatial and Land Information Management at the DWS.

3.1.3 Sub-Quaternary catchments

There is no official DWS national dataset of sub-Quaternary (i.e. Quinary) level catchment boundaries. The sub-Quaternary catchment boundary datasets produced in two previous WRC projects were investigated. The National Freshwater Ecosystem Priority Areas (NFEPA) (Nel *et al.*, 2011) catchment boundaries were investigated as these would help this project to tie in with the Experimental Ecosystem Accounts research work being done by South African National Biodiversity Institute (SANBI) and Statistics South Africa (StatsSA). Although the NFEPA catchment boundaries match the new Quaternary Catchment (SLIM, 2014b) boundaries fairly well, they do not match exactly and would need to be adjusted. Unfortunately the NFEPA catchment boundaries do not take into account large dams resulting in some dams being intersected by several sub-Quaternary catchments, and also some Quaternary Catchments are not sub-divided while others have very small subdivisions. The River Network Quinary Catchments boundaries developed by Maherry *et al.* (2013) in WRC project K5/2020 was also investigated. As the River Network Quinary Catchments were developed using the SRTM 90m DEM the boundaries match the new Quaternary Catchment (SLIM, 2014b) boundaries fairly well, but they do not match exactly and would need to be adjusted. Unfortunately the River Network Quinary Catchments also do not take into account large dams and a superficial investigation of this dataset for the uMngeni Catchment revealed numerous errors which would have to be repaired. An example of these sub_Quaternary catchments for Quaternary Catchments U20A, U20B and U20C in the uMngeni Catchment is shown in Figure 3.1. A set of sub-Quaternary catchment boundaries adapted from a dataset used by Umgeni Water and by Warburton (2011) is shown in Figure

3.1a, the NFEPA catchment boundaries in Figure 3.1b and the River Network Quinary Catchments boundaries in Figure 3.1c.

a) Umgeni Water catchment boundaries	b) NFEPA catchment boundaries	c) River Network Quinary catchments boundaries

Figure 3.1 Comparison of different sub-Quaternary catchment boundary datasets

Geographic Information System (GIS) tools do exist to delineate catchments using a DEM and user defined pour points, however, these are difficult to automate over large areas as evidenced by the River Network Quinary Catchments.

An alternative to dividing Quaternary Catchments into true topological subcatchments based on watersheds, is to subdivide a Quaternary Catchment into sub-units each containing relatively homogeneous climate, soils and land cover, however this can result in a large number of sub-units. As a pragmatic alternative to this, in another WRC funded study, Schulze and Horan (2010) describe the division of each Quaternary Catchment in South Africa into three regions based on natural breaks in altitude. These are termed “Quinary Catchments” by Schulze and Horan (2010), though they are not strictly catchments. The primary justification for using altitudinal subdivisions is that spatial variations in two of the main hydrological drivers, rainfall and reference potential evaporation, are strongly related to altitude (Schulze and Horan, 2010). The outcome of the study by Schulze and Horan (2010) was the subdivision of the Quaternary Catchments in South Africa, Lesotho and Swaziland into 5838 “Quinary Catchment” regions with more homogeneous altitude, soils characteristics and land use. For modelling purposes the surface water outflow from the highest altitude region within a Quaternary Catchment flows into the mid-altitude region which in turn flows into the lowest altitude region. The lowest altitude region of a Quaternary Catchment is assumed to flow into the lowest altitude region of the downstream Quaternary Catchment. One important point to note with regard to the altitudinal Quinary Catchments is that some Quinary Catchments may consist of more than one discrete spatial unit (i.e. polygon) (Schulze and Horan, 2010), which needs to be considered when extracting data from spatial datasets. One potential disadvantage of these altitudinal subdivisions for use in water resource accounting is that it is difficult to represent the actual river flow network and include abstractions, return flows and inter-catchment transfers within a Quaternary catchment.

3.2 Climate

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 in understanding and managing this variability. The accuracy of water resource accounts is highly dependent on good climate data.

3.2.1 Rainfall

Rainfall is a critical variable for catchment scale water accounts as it is often a primary source of water to a catchment. Rain gauge measurements, or radar or satellite estimates, are required as an 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 also subject to errors, generally have a sparse spatial distribution, and as they are point measurements they 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 project as these are not available for the whole of South Africa. The accuracy of rainfall measurements or estimates will have a significant effect on the accuracy of water resource accounts.

3.2.1.1 Mean annual and monthly rainfall

Mean annual precipitation (MAP) represents the long term average total annual rainfall at a particular location and is a widely used variable in water resources planning and hydrological design. Although MAP would not be used directly in an annual water resource account it can serve as a useful check of the accumulated daily rainfall for the catchment for the rainfall dataset being used for the account. The MAP dataset derived by Lynch (2004), and available as a raster on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\gmap], is shown in Figure 3.2. The Lynch (2004) rainfall database is currently being updated in a WRC project (K5/2241) titled

"*Revision of the Mean Annual Precipitation (MAP) estimates over Southern Africa*" from which one of the products will be a revised MAP dataset (Pegram and Sinclair, 2013).

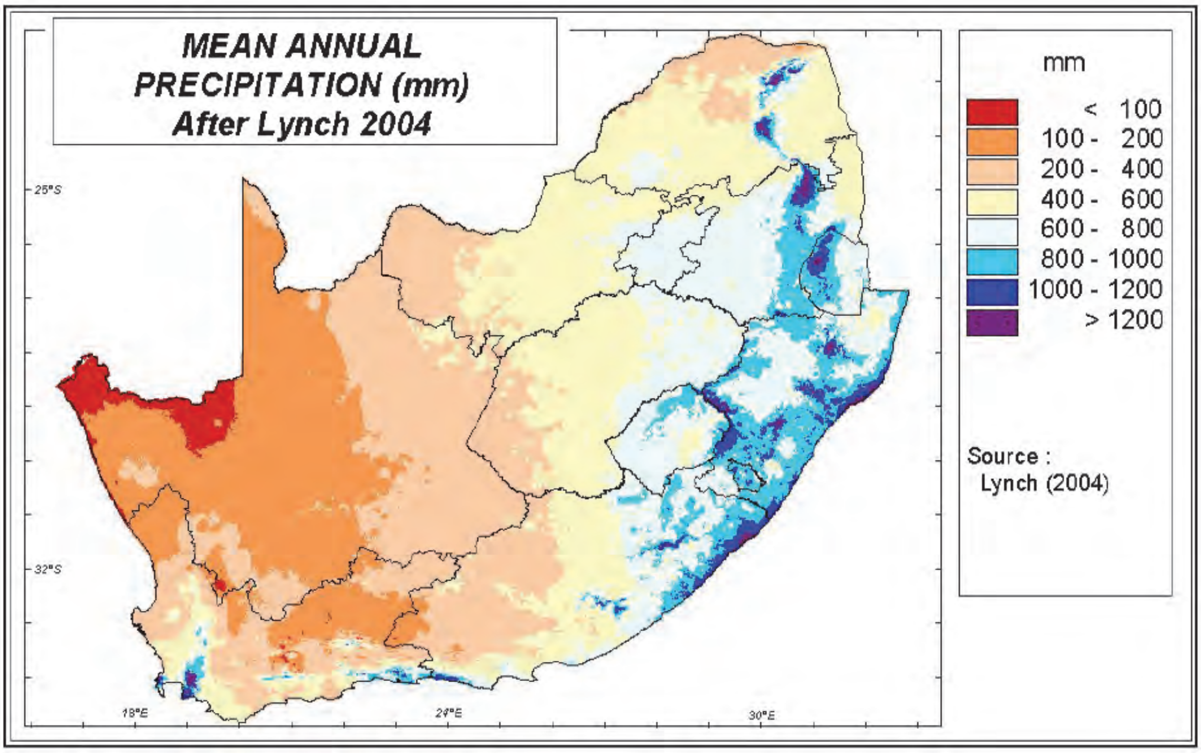


Figure 3.2 Map of mean annual precipitation (Schulze and Lynch, 2008a)

Similar to MAP a mean of the monthly rainfall totals can be calculated for each calendar month. These long-term mean monthly rainfall values give an indication of the temporal distribution of rainfall within a year. The mean monthly rainfall datasets derived by Lynch (2004) are available from the Centre for Water Resources Research (CWRR).

3.2.1.2 Median monthly rainfall

Median values are sometimes more useful than mean values as they are not influenced by a few outlier events that can distort mean values. Long-term median monthly rainfall datasets were also derived by Lynch (2004) and are available as raster datasets on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\gmednrfl1 .. D:\GISData\grids\gmednrfl12]. These long-term median monthly rainfall datasets have been used by Schulze *et al.* (2010) to calculate 12 month-of-year multiplicative rainfall adjustment factors to estimate daily rainfall for a catchment from the daily rainfall values at a nearby driver rain gauge. For each calendar month: (i) a spatial average of the median monthly rainfall is calculated for the catchment, then (ii) the median monthly rainfall is calculated for the timeseries of driver rain gauge data, and (iii) the correction factor is calculated as the ratio of the catchment median to the driver rain gauge median.

3.2.1.3 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 regions of South Africa. For example, wheat is a major crop typically grown in the winter and all-year rainfall regions, and maize is a major crop typically grown in the summer rainfall regions. A map of rainfall seasonality, shown in Figure 3.3, in ESRI shapefile format is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\shape_files\rfl_seasconc.shp]. The derivation of this dataset is described by Schulze and Maharaj (2008a).

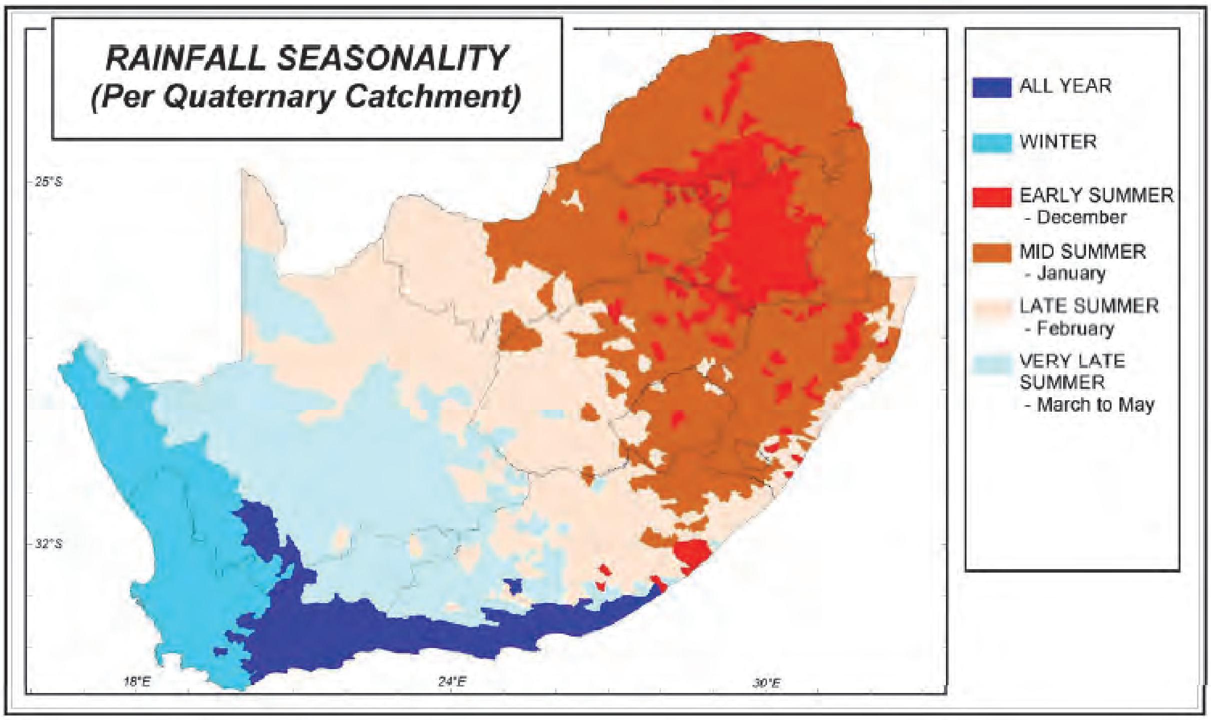


Figure 3.3 Map of rainfall seasonality (Schulze and Maharaj, 2008a)

3.2.1.4 Rain gauge rainfall data

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. Lynch (2004) reported that for daily rainfall data that there were approximately 3800 active daily rain gauges in the mid-1980s which had reduced to less than 2800 by 2000. de Coning (2013b) states that the rain gauge network in South Africa consists of a total of 1748 stations, including 166 Automatic Weather Stations, 169 Automatic Rainfall Stations, 1,214 manual rainfall stations, and 199 synoptic stations. It is not clear whether the rain gauges referred to by de Coning (2013b) are just South African Weather Service gauges.

Rain gauge and other meteorological data are collected by several organisations including: the South African Weather Service (SAWS), the Department of Water and Sanitation (DWS), the Agricultural Research Council (ARC), the South African Sugar Association (SASA), the Institute for Commercial Forestry Research (ICFR), the Applied Centre for Climate and Earth Systems Science (ACCESS) and South African Environmental Observation Network (SAEON). Some details of where this data can be obtained are listed in Table 3.1.

Table 3.1 Sources of measured rainfall and other meteorological data

Organisation	**Access to Rainfall Data**
SAWS	Rainfall and other meteorological data can be requested from SAWS (http://www.weathersa.co.za/climate). Historical time series of hourly and daily data is available. There is a charge for data.
DWS	Rainfall, reference evaporation, streamflow, pipeline and dam level data can be requested from the "Hydrological Services – Surface Water (Data, Dams, Floods and Flows)" page of the DWS website (http://www.dwa.gov.za/hydrology/) which provides access to near real-time data and historical time series of primary, daily and monthly data stored by DWS in their HYDSTRA database. Users can search the website using DWS station IDs and download data in a simple text format. There is no charge for data.
ARC	Rainfall and other meteorological data can be requested from the Climate Network Manager at the Institute for Soil Climate and Water (http://www.arc.agric.za/arc-iscw/). Historical time series of hourly, daily, monthly and annual data is available for approximately 500 weather stations. There is a charge for data.
SASA	Rainfall and other meteorological data can be requested from the "SASRI WeatherWeb" page of the SASRI website (http://portal.sasa.org.za/weatherweb/) which provides access to near real-time data and historical time series of daily, weekly, monthly and annual data stored in their database. Users can search the website using station names or IDs and download data in a simple text format. There is no charge for data.
ICFR	-
ACCESS	-
SAEON	-

In a report to the WRC titled "*Development of a raster database of annual, monthly and daily rainfall for southern Africa*" Lynch (2004) describes the development of a database of spatial rainfall measured daily or monthly using rain gauges. The rainfall database includes data for South Africa and neighbouring countries Lesotho, Swaziland, Namibia, Botswana, Zimbabwe and Mozambique (Lynch, 2004). The rainfall database consists of data from a wide variety of organisations and individuals including: SAWS, ARC, SASA, ICFR, municipalities, private companies and individuals (Lynch, 2004). The measured dataset was infilled to provide a dataset starting in the 1899/1900 hydrological year and ending in the 1999/2000 hydrological year (Lynch, 2004). In addition surfaces of MAP and median/mean monthly data were generated, and surfaces of daily data were generated for just one year (1980) (Lynch, 2004). In addition to updating the database of daily rain gauge data for South Africa, other products expected from WRC Project K5/2241 include sets of annual and monthly bias corrected rainfall grids for South Africa.

Some of the potential difficulties associated with using rain gauge data for water resource accounts are:

- Although the rain gauge network in South Africa is relatively dense compared to other African countries the number and distribution of rain gauges is still too sparse to give a good spatial representation.
- Rainfall measurements need to be quality controlled and missing data infilled, this is labour intensive, expensive and time consuming.
- There can be a lag in data availability, due to collection and entry for manual rainfall stations, and the time required to quality control and infill missing data.

3.2.1.5 Remotely sensed rainfall data

Remotely sensed rainfall datasets offer some potential advantages over using rain gauge data for water resource accounts. Although remotely sensed rainfall datasets have a fairly coarse resolution, in the order of 0.1° to 0.5°, they can give better spatial representation of rainfall, especially in areas with a sparse rain gauge network. The production of remotely sensed rainfall datasets is an automated process and some datasets are available in near-real time. Also, many remotely sensed rainfall datasets are freely available and can be downloaded over the internet. A potential disadvantage of remotely sensed rainfall datasets is that, although they may give a reasonable indication of when and where rainfall occurs, the estimated rainfall amount may not be accurate enough for use in water accounts and this needs to be investigated further. There are many different remotely sensed rainfall datasets available developed based on measurements from different instruments on different satellites and with rainfall modelled using different algorithms. The International Precipitation Working Group (IPWG) began a project in 2003 to validate and compare remotely sensed daily rainfall estimates with each other and with rain gauge measurements. These comparisons can be found on the IPWG validation project's website [http://cawcr.gov.au/projects/SatRainVal/validation-intercomparison.html]. South Africa is one of the countries that contribute to these validations and the validations for South Africa can be found on the SAWS website [http://rsmc.weathersa.co.za/IPWG/ipwgsa_qlooks.html]. These comparisons show the correlation and bias for each remotely sensed dataset against rain gauge data for each day giving a very useful comparison of the datasets, but unfortunately these is no comparison of the datasets at monthly, seasonal or annual time scales. The following literature references were found that discussed the use of remotely sensed datasets in or near South Africa or for use in WA+.

<u>Adeyewa and Nakamura (2003)</u>

Adeyewa and Nakamura (2003) conducted a validation study of three monthly rainfall products from the Tropical Rainfall Measurement Mission (TRMM) satellite against rain gauge data for five climatic regions in Africa at a 1° grid spacing for 36 months. Rain gauge data was obtained from the Global Precipitation Climatology Center (GPCC) which compiles regular global estimates of monthly precipitation for a 1° grid using rain gauge measurements from several sources. The three rainfall products investigated were the TRMM precipitation radar (PR), the threshold-matched precipitation index (TMPI) and the TRMM and other satellites/sources (3B43) precipitation estimate. The five climatic regions studied were: semi-arid, savanna, tropical wet, and the South Atlantic Ocean. The semi-arid region that was evaluated in southern Africa included the region from 17°-22°S and 17°-30°E. Each year was divided into four seasons of 3 months each. Adeyewa and Nakamura (2003) found that TRMM PR significantly overestimated rainfall in the tropical-rain-forest region for the two seasons December to May and that the bias is generally high in the dry seasons for all the products evaluated but that this was less pronounced in the dry seasons of southern African climatic regions. Adeyewa and Nakamura (2003) found that the 3B43 product generally closely matches rain gauge data. Adeyewa and Nakamura (2003) found that for all three products, the random and systematic errors were sensitive to seasonal and regional differences. In the southern African semi-arid zone there was a better agreement with rain gauge data than in the northern African semi-arid zone. Adeyewa and Nakamura (2003) conclude that TRMM PR precipitation data at 1° (or lower) resolution are only reliable in the wettest seasons of the northern savanna and southern African semi-arid regions, and that the TRMM PR data do not appear to be suitable as stand-alone product, but need to be combined with other satellite and rain gauge data, as was done to compile the 3B43 product. The 3B43 product was found to be more reliable than the TMPI.

Hughes (2006)

A study by Hughes (2006) investigated the potential for using rainfall data from satellites for hydrological modelling through a comparison with rain gauge data for the Okavango River basin, the Kafue Basin, Thukela River basin and the Kat River basin. Hughes (2006) states the need in developing countries for data that is accessible and simple to use, and thus the study focuses on the use of available derived satellite rainfall products rather than data calibration. Hughes (2006) selected two satellite rainfall datasets, the Global Precipitation Climatology Project (GPCP) 1DD dataset (Huffman *et al.*, 2001) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) dataset (Sorooshian *et al.*, 2000), due to the ease which they could be accessed and processed. Hughes (2006) explains that the GPCP dataset is a combined product produced by the GPCP Merge Development Centre at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Centre from estimates compiled by various groups from individual data sources. The GPCP datasets had a temporal resolution of 1 day and a spatial resolution of 1°. Hughes (2006) explains that the PERSIANN datasets are based on infrared images from geosynchronous satellites (GOES-8, GOES-9/10, GMS-5, Metosat-6 and Metosat-7) and TRMM microwave imager (TMI) instantaneous rainfall estimate from NASA. The PERSIANN datasets had a temporal resolution of 6 hours and a spatial resolution of 0.25°. Hughes (2006) found that for the PERSIANN dataset there were missing data in most months, but that less than 5% of accumulated days were missing. Hughes (2006) commented that for both datasets used it was not possible to download data for a specific region making it expensive to download the large data sets. Hughes (2006) postulated that as the spatial resolution of the satellite rainfall datasets is relatively coarse, they are best suited for assessment of water resources in large basins. Hughes (2006) compared historical rain gauge data with satellite derived rainfall data based on time series of monthly rainfall totals using visual interpretation of the time series and simple statistics (R^2 and slope) of the best fit linear regression line between the time series pairs. Hughes (2006) cautions, that in some cases the overlap between the time series was not sufficient to allow meaningful comparison of the data.

The study in the Kafue Basin (156,995 km^2) in Zambia compared point rain gauge and satellite data for three 1° grid squares. The MAP for the rain gauge data varied from over 1300 mm in the north to less than 900 mm in the south, with the GPCP data varying from 900 to 800 mm and the PERSIANN data varying from 1300 to 1050 mm. Hughes (2006) commented that there was less spatial variation in the satellite rainfall data than the gauge data and that this was probably related to the resolution of the satellite data calibration process indicating a need for regional correction factors to be applied.

For the study in the Okavango River basin (530,000 km^2 in Angola, Botswana and Namibia) there was no recent rain gauge data, but for two 1° grid squares GPCP and PERSIANN rainfall data were compared against satellite data that had been calibrated against rain gauge data in the WERRD project by Wilk *et al.* (2006). Hughes (2006) commented that there was not a good relationship between the WERRD satellite data and the GPCP. A better relationship was found between the WERRD satellite data and the PERSIANN data, with the PERSIANN data appearing to over-estimate the rainfall as occurred in the southern parts of the Kafue basin.

The study in the Thukela River basin (29,046 km^2) in South Africa compared point rainfall from 4 rain gauges and satellite data for one 1° grid square. Hughes (2006) commented that the GPCP data appeared to be a reasonable estimate of the basin average rainfall, with a tendency to overestimate rainfall, and the PERSIANN data showed an even greater overestimation. Hughes (2006) noted that the PERSIANN data contained substantial variations in monthly rainfall totals between the four grid points, though the variations were lower than those between the four rain gauges data as the PERSIANN data already includes some spatial averaging. Though it was not clear whether these spatial variations were realistic, Hughes (2006) felt that it was an indication that it would be possible to simulate spatial variations in runoff response. However, Hughes (2006) also found that both GPCP and PERSIANN underestimated the rainfall in the high rainfall area in the Drakensberg mountains indicating that the topographic influences would need to be accounted for in calibration of the satellite data.

The Kat River basin (1715 km^2) in South Africa is small in relation to the resolution of the GPCP data and includes significant topographic influences on rainfall. Rain gauge data was available for five gauges, two gauges in the southern part of the basin which has lower rainfall, and three gauges in the higher altitude higher rainfall northern part of the basin. Despite a relatively low correlation between GPCP and rain gauge data, Hughes (2006) felt that the GPCP data represent the variations in rainfall within the basin reasonably well. In the Kat River basin the PERSIANN data were not found to be generally higher than the GPCP data, as was found in the other basins. Again Hughes (2006) found that in this basin the satellite data was not able to represent topographical influences on the spatial variation in rainfall, indicating that some form of local calibration would be required.

Hughes (2006) concludes that the analysis in these four basins suggests that the GPCP and PERSIANN datasets cannot be used without modifications and require some form of local calibration to represent topographical influences and make them compatible with available rain gauge data. However, Hughes (2006) points out that one problem when attempting to calibrate satellite data is that the datasets are currently too short to represent the variability of rainfall-runoff responses that typically occur within southern Africa.

Sawunyama and Hughes (2008)

Sawunyama and Hughes (2008) describe and evaluate the use of a frequency of exceedance curve algorithm that has been used to merge rain gauge and high resolution (0.1°) satellite rainfall estimates, such that the merged rainfall datasets are statistically compatible with the rain gauge datasets. The study by Sawunyama and Hughes (2008) used the Climate Prediction Center African Daily Precipitation Climatology (CPCAPC) gridded daily rainfall totals at 0.1° spatial resolution for Africa developed by NOAA's Climate Prediction Center and described by Love *et al.* (2004). Sawunyama and Hughes (2008) first used the gridded rainfall totals to calculate a simple average daily rainfall total for each sub-basin. Sawunyama and Hughes (2008) then transformed the daily rainfall dataset for each sub-basin to be statistically consistent with the corresponding rain gauge based spatially averaged WR90 dataset by relating the frequency of exceedance curves for the two datasets. Sawunyama and Hughes (2008) evaluated this transformation technique in 20 catchments across South Africa by using WR90, original CPCAPC and transformed monthly rainfall total as an input to the revised groundwater version of the Pitman model and compared simulated streamflow time series. Sawunyama and Hughes (2008) report that the transformation technique resulted in improved simulation results in most of the study catchments. The technique did not result in improvements in coastal areas affected by frontal rainfall systems, and spatial rainfall was still significantly underestimated in orographic rainfall regions due to the satellite estimates ignoring rainfall variations due to altitude. However, Sawunyama and Hughes (2008) conclude that the results of the study demonstrate the potential to generate or extend rainfall records and to establish continuous datasets using satellite rainfall estimates.

Gibson *et al.* (2009)

In the study by Gibson *et al.* (2009), the study catchment contained three weather stations and an additional 16 weather stations were identified within a 20 km buffer around the catchment. These weather stations belong to Agricultural Research Council's Institute for

Soil, Climate and Water (ARC-ISCW), Hortec, SAWS and private farms or individuals. Based on the finding by Műnch (2004), Gibson *et al.* (2009) explored the possibility of using kriging to interpolate rainfall measured at these weather stations for the 2007/2008 hydrological year. A semivariogram showed no trends and it was concluded that kriging could not be used in their study catchment due to the large variations in the data and the distance between weather stations for which these variations occurred. Gibson *et al.* (2009) also tested the Inverse Distance Weighting (IDW) method to interpolate both monthly and annual rainfall in the same study catchment and found that though the influence of topography on rainfall distribution could be seen it did not realistically follow the topography. The methodology selected by Gibson *et al.* (2009) for their study was rainfall grids created by the ARC-ISCW by interpolation using rainfall data from about 550 automatic stations and satellite rainfall estimates downloaded from African Data Dissemination Service, using the five closest rainfall stations to each point at which rainfall is estimated. Gibson *et al.* (2009) validated the rainfall grids for their study area using weather station data which was not included in the ARC-ISCW interpolation. Gibson *et al.* (2009) concluded that the spatial rainfall pattern provided by the ARC-ISCW interpolated rainfall grids was sound, but that there was a significant underestimation of rainfall in the G10K study catchment. They attributed this underestimation to: underestimation of rainfall in the ARC-ISCW interpolated rainfall grid, errors in the direct rainfall measurements, and the possible unquantified contribution of condensation to total precipitation. They report that one limitation of this method is that the resolution of the ARC-ISCW rainfall grids is 1 km and the resolution of the satellite rainfall estimates is 8 km. Gibson *et al.* (2009) also noted that although advances have been made in estimating precipitation using remote sensing, these estimates are instantaneous and thus do not necessarily provide reliable estimates of accumulated daily, monthly or annual precipitation. They conclude that directly measured weather station data may still be the most accurate even though it does not provide the spatial distribution of remote sensing data.

<u>De Coning and Poolman (2011)</u>

De Coning and Poolman (2011) report that the SAWS rain gauge network consists of approximately 1500 rain gauges measuring 24-hour rainfall and that in 2009 80 Automatic Rainfall Systems (ARSs) were installed to provide real-time rainfall information. Sinclair and Pegram (2010) indicate that the SAWS Automatic Weather Station (AWS) network consists of 164 stations.

De Coning and Poolman (2011) report that in 2009 South Africa had a radar network of ten C-band and two S-band radars covering approximately two-thirds of the country, and that SAWS were in the process of migrating to S-band (2.8 GHz) radars which were expected to improve radar based precipitation estimates. De Coning and Poolman (2011) state that the radars are not ideally spaced for the observation of relatively shallow stratiform rain systems, but are better for the observation of relatively deep convective storms. De Coning and Poolman (2011) explain that though radars can be used to provide an indirect measurement of rainfall, coverage of the whole area of interest is required and they are expensive to purchase and maintain.

De Coning and Poolman (2011) explain that South Africa and Africa has access to the European Geostationary Meteosat Second Generation (MSG) satellite image data and products, where Meteosat-9 includes 12 channels with 11 of these sampling every 15 minutes at 3 km intervals. De Coning and Poolman (2011) state that although estimates of rainfall from satellite are not as accurate as those from rain gauges or radar, they provide extensive spatial coverage and are available at the high temporal resolutions. De Coning and Poolman (2011) explain that the Unified Model is a suite of atmospheric and oceanic numerical modelling software, developed by the UK Met Office, and that SAWS run their own version of the Unified Model to provide hourly forecasts of atmospheric conditions at a 12 km spatial resolution for the region. De Coning and Poolman (2011) explain that Autoestimator (AE) is an algorithm developed by the NOAA's National Environmental Satellite, Data and Information Service (NESDIS) to estimate high intensity rainfall using brightness temperatures measured by satellites together with a curve derived using 6000 collocated radar and satellite pixels. They explain further that Hydroestimator (HE) is a version of the AE algorithm developed for use in regions without radar coverage, and that SAWS run a local version of HE using brightness temperatures from the MSG satellite and output from the Unified Model, including temperature, humidity, surface pressure and the 700 hPa wind field. De Coning and Poolman (2011) note that although the HE algorithm is simple, it is still widely used, as more accurate but more complex algorithms have input data requirements that are not feasible in many countries, including South Africa. In their study De Coning and Poolman (2011) found that 24 hour rainfall intensity estimated by HE is substantially different to rain gauge measurements by the rain gauges, but that the spatial extent of occurrence is reasonable. They noted that HE performs well for convective events, though it overestimates the convection intensity, and as expected underestimates stratiform rainfall along the coast. They explain that the Unified Model performs well for synoptic scale weather features such as frontal systems which are accompanied by stratiform rainfall which occurs on the coast of South Africa, but is less accurate for convective precipitation associated with thunderstorms. A study by De Coning and Poolman (2011) proposed to improve precipitation estimates by: determining the bias of the HE, bias correcting the stratiform precipitation estimates from the Unified Model though comparison with rain gauge measurements, and then combining the bias corrected HE and Unified Model rainfall estimates. The combined bias corrected rainfall estimates were found to be closer to rain gauge measurements for the 2-year (2008 and 2009) study period. (De Coning, 2013a) reports that recently five years of data (2008 to 2012) have been used to calculate combined bias corrected rainfall estimates, but that the biases only differ slightly from those calculated using two years of data. De Coning (2013a) states that the combined bias corrected rainfall estimate product is available on the SAWS archive server in gridded binary format from 2010 to 2012 on an hourly basis, though there may be a charge for the use of this data. De Coning (2013a) also states that Hydroestimator rainfall estimates are available on the SAWS archive server in gridded binary format from 2008 onwards as daily totals.

Sinclair and Pegram (2010) and Sinclair and Pegram (2013)

Sinclair and Pegram (2010) and Sinclair and Pegram (2013) describe the use of the TOPographic Kinematic APproximation and Integration (TOPKAPI) model to estimate soil moisture estimates of soil moisture state at a 3 hour timestep for a 0.125° spatial grid over South Africa. The TRMM 3B42RT real-time rainfall product was used as the source of rainfall data for the TOPKAPI model. Sinclair and Pegram (2013) investigated the effect of rainfall bias on soil moisture estimates by comparing the Frequency Distribution Functions (FDFs) calculated from daily rain gauge data with those calculated from corresponding accumulated daily TRMM 3B42RT rainfall estimates. Sinclair and Pegram (2013) then adjusted the TRMM rainfall estimates using quantile-matching to create bias adjusted rainfall datasets. They found that the TRMM FDFs were clearly biased relative to the rain gauges, and concluded that careful bias adjustment of TRMM rainfall datasets was necessary, especially in some coastal areas.

Novella and Thiaw (2012)

Novella and Thiaw (2012) describe a new daily remotely sensed precipitation product for Africa called the African Rainfall Climatology, version 2 (ARC2). The dataset contains 29 years of daily rainfall data, from 1983 to present, at a 0.1° spatial resolution.

The Climate Prediction Center developed the Rainfall Estimator (RFE) algorithm in 1998, and subsequently a more advanced algorithm RFE2 in 2001, to provide higher resolution operational daily rainfall estimates to support the humanitarian aid programs of the US Agency for International Development's (USAID) Famine Early Warning Systems Network (FEWS-NET) (Novella and Thiaw, 2012). RFE2 uses inputs from four sources (i) 24 hour rainfall totals from Global Telecommunications System (GTS) rain gauges, (ii) the Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI) calculated from 3-hourly geostationary EUMETSAT cloud-top infrared (IR) temperatures, (iii) Special Sensor Microwave Imager (SSM/I)-based estimates, and (iv) Advanced Microwave Sounding Unit (AMSU) rainfall estimates (Novella and Thiaw, 2012). 1988). Put simply, the bias-corrected satellite measurements are used to define the spatial distribution and extent of rainfall, and the rain gauge measurements are used to determine the magnitude of the rainfall (Novella and Thiaw, 2012). Novella and Thiaw (2012) state that RFE is unique compared to other satellite rainfall products because of its high, 0.1° spatial resolution, and the near real-time blending of rain gauge and satellite measurements to provide daily rainfall estimates for the African continent. However, as the RFE2 only has a relatively short dataset (2001 onwards). The original Africa Rainfall Climatology (ARC1) algorithm was developed based on the RFE2 algorithm, but only used the GTS rain gauge and geostationary IR cloud temperature data due to their availability and consistency over time, and their better spatial coverage and reliability compared to passive microwave data from 1983 onwards (Novella and Thiaw, 2012). Novella and Thiaw (2012) state that the main objective of ARC1 was to construct a stable and consistent rainfall dataset, though excluding the microwave inputs may potentially result in lower estimation accuracy, especially for localised heavy rainfall events. The ARC2 algorithm described in Novella and Thiaw (2012) was developed using longer historical rain gauge and IR data to produce a longer and more climatologically stable dataset, and also to remove a processing bias present in ARC1.

Novella and Thiaw (2012) report that ARC2 rainfall estimates are an improvement over ARC1 estimates and are consistent with with other long-term datasets, such as GPCP and Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP). The ARC2 estimates compared favourably in validations against rain gauge measurements relative to TRMM 3B42 and CMORPH products (Novella and Thiaw, 2012). Novella and Thiaw (2012) investigated a marginal summer dry bias that occurs over West and East Africa, and concluded that both daily and monthly validations indicated that underestimation of rainfall by ARC2 may be due to the unavailability of some daily GTS data in real time, and to possible deficiencies in the satellite estimates associated with rainfall processes over coastal and orographic areas. Novella and Thiaw (2012) state that the long ARC2 daily rainfall dataset will help in understanding climate variability and change, as it is produced using consistent and reliable data inputs, which is important for continuity and homogeneity, and minimises error and biases.

Bangira (2013) used ARC2 daily rainfall estimates in a study that mapped areas of high flash flood potential in the Western Cape province in South Africa. Bangira (2013) used ARC2 as although TRMM 3B42 was found to have better accuracy, it was not available in near real time.

Karimi *et al.* (2013b)

Karimi *et al.* (2013b) suggest using freely available precipitation data products such as Tropical Rainfall Measurement Mission (TRMM), the Climate Prediction Center Morphing Technique (CMORPH), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN). Karimi *et al.* (2013b) chose to use calibrated TRMM rainfall data from a study by Cheema and Bastiaanssen (2012) in which TRMM data was calibrated for the Indus Basin using two methods (i) regression analysis against rain gauges and (ii) Geographical Differential Analysis (GDA). For the regression analysis, Cheema and Bastiaanssen (2012) state the assumption that TRMM data correctly describes spatial variations, including those due to topographical variation, but measures the quantity of rain with random deviation around an average. For GDA, Cheema and Bastiaanssen (2012) state the assumption that TRMM data requires a location-specific correction of deviations that are non-random and have a geo-spatial relationship. Cheema and Bastiaanssen (2012) found that both provided improved estimates of the spatial rainfall distribution and showed a reasonable accuracy, but that based on Nash-Sutcliffe efficiency (NSE) and Standard Error of Estimates (SEE) the GDA method resulted in a better correlation against rain gauge data. Cheema and Bastiaanssen (2012) state that the GDA technique can be used to calibrate TRMM rainfall data in basins that have limited rain gauge data to provide estimates suitable for use in water management applications. They mention that the GDA method is highly dependent on the distribution of rain gauges in the study area, and that due to the poor distribution of rain gauges in the Indus Basin underestimation of rainfall in the mountainous regions was likely. Karimi *et al.* (2013b) found that the calculated annual rainfall was in the range of values of long term average rainfall for the Indus Basin reported in literature.

3.2.2 Reference potential and total evaporation

Total Evaporation (ET) refers to the actual combined loss of water from a land surface due to evaporation of intercepted water, evaporation from the soil surface, transpiration by plants and evaporation from open water surfaces. Soil water evaporation depends on solar radiation reaching the soil surface and availability of water. Transpiration depends on the type and growth stage of plants, several meteorological factors and availability of water. ET is another critical variable for catchment scale water resource accounts as it is often the primary form of water depletion from a catchment. The accurate estimation of ET for the different land uses within a catchment will be important for understanding sectoral water use. The partitioning of ET into its components will be useful for differentiating between beneficial and non-beneficial water use.

Direct measurements of A-pan or S-tank reference potential evaporation may be available but generally have a sparse spatial distribution and are point measurements. Penman-Monteith grass-based reference potential evaporation can be estimated from measurements or estimates of solar radiation and meteorological variables such as air temperature, relative humidity and windspeed. Empirical relationships are usually used to estimate potential evaporation from reference potential evaporation for different land cover types, and some form of modelling is usually required to estimate total evaporation based on soil water availability. The estimation of ET using remotely sensed measurements of variables such as solar radiation and albedo, together with estimates of meteorological variables such as air temperature, relative humidity and windspeed, is well advanced and, if estimates at a suitable spatial resolution are available, these can be used in compiling water resource accounts.

3.2.2.1 Mean annual and monthly reference potential evaporation

Mean annual A-pan reference potential evaporation represents the long term average total annual A-pan reference potential evaporation at a particular location. Although these mean annual values would not be used directly in an annual water resource account they can serve as a useful check of the accumulated daily A-pan reference potential evaporation for the catchment being used for the account. A raster dataset of mean annual A-pan equivalent reference potential evaporation is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\apan_mean_an], and is shown in Figure 3.4. The derivation of this dataset using temperature, solar radiation and rainfall data is described by Schulze and Maharaj (2008e).

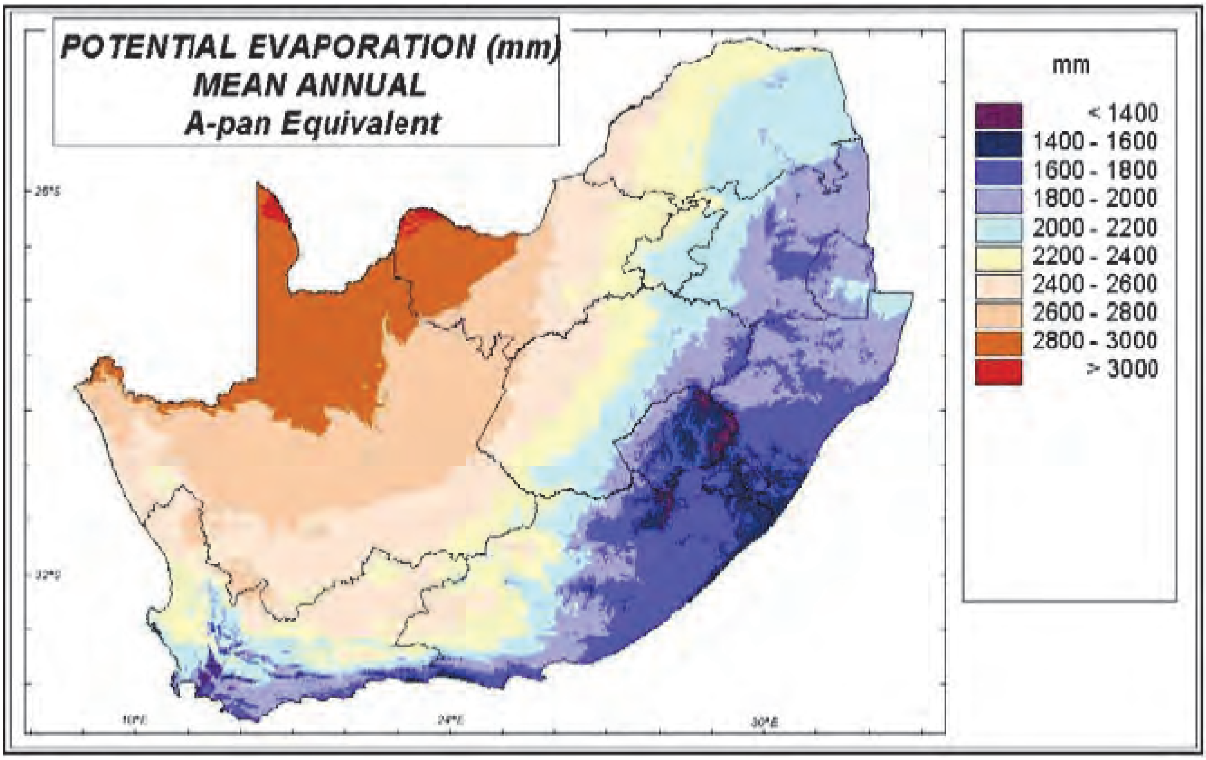


Figure 3.4 Map of mean annual A-pan reference potential evaporation (Schulze and Maharaj, 2008e)

Schulze and Maharaj (2008e) also describe the derivation of a dataset of mean monthly A-pan equivalent reference potential evaporation. This dataset is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\apan_evap_01 .. apan_evap_12]. These long-term mean monthly values give an indication of the temporal distribution of A-pan reference potential evaporation within a year.

Schulze *et al.* (2008a) describe the derivation of a dataset of mean monthly Penman-Monteith reference potential evaporation. This dataset is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\penman01 .. penman12]. These long-term mean monthly values give an indication of the temporal distribution of Penman-Monteith reference potential evaporation within a year.

3.2.2.2 Daily reference potential evaporation

A-pan and S-tank reference evaporation data is collected by several organisations in South Africa, as discussed in Section 3.2.1.4. As with rain gauge data, many of the same potential difficulties exist with the use of this data for water resource accounts. There are also a number of empirically-based methods of estimating A-pan or S-tank equivalent reference evaporation using other meteorological data such as air temperature for which measurements may be readily available. These methods include Blaney and Criddle (1950), Hargreaves and Samani (1982), Hargreaves and Samani (1985), Linacre (1977) and Thornthwaite (1948). An alternative approach is to use readily available remotely sensed land surface temperature (LST) and solar radiation datasets together with empirical equations such as Blaney and Criddle (1950), Hargreaves and Samani (1985) and Thornthwaite (1948) for estimating ET_0 (Gavilán *et al.*, 2006; Aguilar and Polo, 2011; Maeda *et al.*, 2011; Cammalleri and Ciraolo, 2013)

The FAO 56 Penman-Monteith method (Allen *et al.*, 1998) of estimating reference crop potential evaporation is widely used and accepted as a standard and requires measurements of solar radiation, air temperature, air humidity and wind speed. Sinclair and Pegram (2010) and Sinclair and Pegram (2013) describe the use of the TOPKAPI model to estimate soil moisture at a 3 hour timestep for a 0.125° spatial grid over South Africa. ET_0, for use in the TOPKAPI model, was estimated using a modification of the FAO56 reference crop evaporation method using forecasts of meteorological variables from the Unified Model (UM) run by SAWS (Sinclair and Pegram, 2010). Estimates of solar radiation were based on Meteosat data products obtained from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Land Surface Analysis Satellite Application Facility (LSA-SAF) under a research agreement. Sinclair and Pegram (2010) validated the ET_0 estimates by comparing them with ET_0 estimates calculated using observed meteorological data (temperature, relative humidity and wind speed) from a network of weather stations, and found that the FAO56 based estimates were unbiased and relatively highly correlated. Sinclair and Pegram (2013) chose to estimate ET indirectly, rather than by the more complex and data intensive method of using surface atmospheric observations and solving the surface energy balance. Sinclair and Pegram (2013) estimate ET dynamically from ET_0 using a crop factor and water availability. The three-hourly soil moisture and ET_0 estimates described in Sinclair and Pegram (2013) are available on the Satellite Applications Hydrology Group (SAHG) website [http://sahg.ukzn.ac.za/soil_moisture]. The datasets start in August 2008 and estimates are updated periodically.

3.2.2.3 Daily total evaporation

Ground-based measurements of total evaporation (ET) can be made using several techniques such as 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.

Techniques for the estimation of ET at fine spatial scales (30 m) using a surface energy balance approach and remotely sensed data inputs appear to be well advanced. However, there are not many ET products available and those that are available are at a relatively coarse resolution. The Moderate Resolution Imaging Spectroradiometer (MODIS) derived MOD16 ET product from NASA (http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=16) has a spatial resolution of 1 km and is produced at 8 day intervals. The Meteosat Second Generation (MSG) derived ET product (https://landsaf.meteo.pt/) from Land Surface Analysis Satellite Application Facility (LSA-SAF) is daily but has a spatial resolution of 3 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 publically available. These models rely on suitable cloud-free images being available and infilling techniques are used to produce daily time series. The application of remotely sensed measurements together with surface energy balance algorithms to estimate total evaporation for specific catchments has been used by Karimi *et al.* (2013b) for compiling water accounts. The following literature references were found that discussed the use of remotely sensed datasets for estimating total evaporation in or near South Africa or for use in WA+.

<u>Jarmain *et al.* (2007)</u>

A study was conducted by Jarmain *et al.* (2007) to spatially estimate the ET, crop yield and water use efficiency (WUE) of table and wine grapes in the Hexriver valley, Paarl, Worcester and Franschhoek grape producing areas in the Western Cape in South Africa, for two growing seasons (September 2004 to April 2005; September 2005 to April 2006). Jarmain *et al.* (2007) used the Surface Energy Balance Algorithm for Land (SEBAL) model to estimate ET and yield from twelve 30 m resolution Landsat images. The SEBAL ET estimates were compared with estimates based on a field water balance, though it is not clear from Jarmain *et al.* (2007) how this field water balance was calculated. Jarmain *et al.* (2007) found that the SEBAL ET estimates were within 18 % of water balance estimates.

Jarmain *et al.* (2009)

In a study titled "*A Methodology for Near-Real Time Spatial Estimation of Evaporation*" Jarmain *et al.* (2009) selected and applied four models used internationally for the spatial estimation of evaporation, and evaluated these models for different land covers at four study sites in South Africa. The four models evaluated in the study were: (i) the SEBAL model, (ii) the Surface Energy Balance System (SEBS) model, (iii) the Mapping EvapoTranspiration with high Resolution and Internalised Calibration (METRIC) model, and (iv) the Vegetation Index / Temperature Trapezoid (VITT) model. The four study sites were: (i) *Acacia mearnsii* trees at Seven Oaks in KwaZulu-Natal, (ii) an open water body, Midmar Dam in KwaZulu-Natal, (iii) swamp forest, grassland and a sedges wetland in iSimangaliso Wetland Park near St Lucia in KwaZulu-Natal, and (iv) Spekboom thicket and degraded veld in the Kirkwood area in the Eastern Cape. For the Sevenoaks site all four models were evaluated against a field measured evaporation and energy balance dataset, but for differing timesteps and periods using Landsat 5 data. For the Midmar Dam site only SEBAL was evaluated, for one Landsat 5 image, against field measurements of evaporation. For the St Lucia site, using a single Landsat 7 image, instantaneous estimates of the energy balance components from the SEBAL and SEBS models, and daily average estimates of evaporation from the SEBAL, SEBS and VITT models were evaluated against field measurements of energy balance data. At the Kirkwood site, using a single Landsat 7 image, instantaneous estimates of the energy balance components from the SEBAL and SEBS models, and daily average estimates of evaporation from the SEBAL, SEBS and VITT models were evaluated against field measurements of energy balance data.

Jarmain *et al.* (2009) conclude that accurate simulations of net radiation using SEBAL, METRIC, and SEBS were quite simple, but that estimating soil heat flux and heat storage of a water body was more complex and accuracy was more variable. The estimation of sensible heat flux density (*H*) for different land uses was also a complex process. Jarmain *et al.* (2009) found that estimates of evaporative fraction (*EF*) were accurate in many cases, and the corresponding evaporation estimates compared favourably with field measurements of daily evaporation rates. Jarmain *et al.* (2009) found that the evaporation estimates from the VITT were generally the least accurate. In some cases longer simulation periods resulted in improved estimates of evaporation by the models, but extension of the simulation period may have been influenced by the assumption that evaporative fraction was constant. Jarmain *et al.* (2009) state that estimation of evaporation using remote sensing techniques has great potential, though there were still some shortcomings, such as: limited availability of high resolution thermal infra-red (TIR) images, the need for more research into the use of microwave measurements to improve estimates under cloudy conditions, the ability to represent complex evaporation processes in mountainous areas, and difficulties in estimating evaporation from water bodies.

Jarmain and Meijninger (2010)

Jarmain and Meijninger (2010) conducted a study to quantify the impact of clearing Invasive Alien Plants (IAPs) by the Working for Water programme on water availability in the Western Cape and KwaZulu-Natal provinces of South Africa. The ET from areas with IAPs, areas from which IAPs had been cleared and natural vegetation was estimated using the SEBAL model and 250 m resolution MODIS satellite images (70 in each province). ET was estimated for three climatically different years (1 July to 30 June) in each province, 2000-2001 (dry), 2002-2003 (average) and 2006-2007 (wet) in the Western Cape and 2000-2001 (average), 2003-2004 (dry) and 2006-2007 (wet) in KwaZulu-Natal. The study demonstrated that remote sensing could be used to assess the impact of IAPs on water resources through the estimation of ET, and that Jarmain and Meijninger (2010) found that clearing IAPs has a positive effect on water availability.

Gibson *et al.* (2009)

Gibson *et al.* (2009) used the SEBS model developed by Su (2002) to estimate ET using remotely sensed reflectance and radiance data together with meteorological information. Gibson *et al.* (2009) did not use Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) or Landsat data due mostly to poor availability of images and unavailability of shortwave infrared data from ASTER during the study period. Gibson *et al.* (2009) chose to use Moderate Resolution Imaging Spectroradiometer (MODIS) data in their study as images are captured daily for South Africa and therefore good coverage is possible with useable data being obtained every 10-20 days. Gibson *et al.* (2009) reported that the 1000 m resolution of MODIS data made it unsuitable for small study areas such as quaternary catchments, but used it in their study as no other suitable sources of remotely sensed data could be found and it is possible for the image resolution to be downscaled to 250 m if MODIS data products are used. Meteorological data from four weather stations was used, one for each of four climate zones identified for the study area. Gibson *et al.* (2009) compared ET results with land use types and observed that there was a significant variation of ET values within land use classes. Gibson *et al.* (2009) compared estimated ET values from their study with field measurements conducted by Jarmain and Mengistu (2011) using a single sensor eddy covariance system in November 2008 for an apple orchard and concluded that SEBS estimation of ET appeared to be sound for an irrigated apple orchard. However, comparing the total estimated ET (1.397 km^3) from the study catchment with the estimated total rainfall (0.771 km^3), Gibson *et al.* (2009) concluded that the methodology used resulted in an overestimation of ET for the study period, and that the source of the error was not clear without further validation. Gibson *et al.* (2009) noted the issue of image resolution relative to heterogeneity in landscape and land use being important in such studies.

Kongo *et al.* (2011)

Kongo *et al.* (2011) investigated the estimation of ET for different land use classes in 13 Quaternary Catchments in the upper-Thukela basin in South Africa. They estimated ET using the public domain version of the SEBAL and low resolution (1 km) public domain MODIS Level 1B satellite images. The national land use map for South Africa, developed in 2000 by the South African Council for Scientific and Industrial Research (CSIR) was used and the main land use (71%) in the 3028 km^2 study area is unimproved grassland. Estimates of ET were calculated for 28 MODIS images captured between June 2006 and September 2006. Ground measurements using a Large Aperture Scintillometer (LAS) were performed in one Quaternary Catchment (V13D, Potshini) over a 1 km transect and compared with the SEBAL ET estimates. Kongo *et al.* (2011) found that there was a good correlation between the SEBAL estimates and the LAS measurements. Forestry, open water surfaces and wetlands were observed to have high evaporation rates. However, relatively low evaporation rates were observed for open water surfaces during the dry winter season, which was attributed to changes in the areal extent of the open water surfaces which resulted in mixed wet and dry pixels in the low resolution imagery. Kongo *et al.* (2011) noted that this uncertainty associated with the use of low resolution satellite images was a challenge in estimating evaporation for land uses with a relatively small spatial extent, and recommended the use of high resolution images though the inherent poor temporal resolution of these may also affect estimates.

Karimi *et al.* (2013b) and Bastiaanssen *et al.* (2012)

Karimi *et al.* (2013b) list several models including SEBAL, SEBS, Two-Source Energy Balance (TSEB), METRIC, Alexi and ETWatch that have been used to estimate ET from remote sensing data and the freely available 1 km resolution MOD16 ET product. Karimi *et al.* (2013b) used the ETLook algorithm developed by Bastiaanssen *et al.* (2012) for their study in the Indus Basin. ETLook is described by Karimi *et al.* (2013b) as "*a two layer* *surface energy balance model that adopts microwave-based soil moisture data to solve the partitioning of net radiation into latent heat flux, sensible heat flux and soil heat flux*". Karimi *et al.* (2013b) explain that ETLook calculates soil water evaporation and transpiration separately using Leaf Area Index (LAI) to partition total net radiation into canopy and soil components. They also mention that ETLook calculates evaporation of interception water and has a separate subroutine to calculate evaporation from open water surfaces. The ET values calculated by ETLook were compared against field measurements using lysimeters, Bowen ratio flux towers and water balance data in Pakistan and were found to agree well (Bastiaanssen *et al.*, 2012).

Shoko (2014), Shoko *et al.* (2015a) and Shoko *et al.* (2015b)

A study by Shoko (2014), published in Shoko *et al.* (2015a) and Shoko *et al.* (2015b), investigated the effect of spatial resolution on remote sensing estimates of total evaporation in the uMngeni catchment, South Africa and also the spatial variation of total evaporation within the catchment. The study compared the use of multispectral Landsat 8 (30 m resolution, every 16 days) and MODIS (1 km resolution, daily) remote sensing data to estimate total evaporation using SEBS (Su, 2002). The results indicated that Landsat 8 data resulted in better spatial representation of total evaporation compared to the MODIS data, as the mean seasonal and annual total evaporation estimates for all land cover types within the catchment were significantly different while for MODIS there was no significant difference between land cover types. The study also showed that the total evaporation estimates from the different sensors with different spatial resolution were not only sensitive to the total area of each land cover type within the catchment, but were also sensitive to the spatial characteristics, such as patch size and number, of each individual land cover type.

3.2.3 Air temperature

Although air temperature is not directly required for water resource accounts it could potentially be used to estimate reference potential evaporation as mentioned in Section 3.2.2.2 and might also be required for crop yield modelling if water productivity were to be taken into account. Air temperature data is collected by several organisations in South Africa, as discussed in Section 3.2.1.4. As with rain gauge data, many of the same potential difficulties exist with the use of this data for water resource accounts.

In a report to the WRC titled "*Development of a database of gridded daily temperatures for southern Africa*" Schulze and Maharaj (2004) describe the development of a database of spatial daily maximum and minimum air temperature for South Africa and neighbouring countries Lesotho and Swaziland. The temperature database consists of data obtained from SAWS, ARC, SASA (Schulze and Maharaj, 2004). The measured station time series datasets were infilled using derived regional temperature lapse rates to provide complete datasets for the years 1950 to 1999. These infilled station time series were then used to generate daily time series of temperature at each of the 429 700 grid points resulting in a spatial dataset with a resolution of one arc minute. Unfortunately this database has not been updated to include values for years from 2000 onwards.

The derivation of a dataset of mean monthly maximum air temperature is described in Schulze and Maharaj (2008b) and derivation of a dataset of mean monthly minimum air temperature is described in Schulze and Maharaj (2008c). These datasets are available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\tmaxave01c .. tmaxave12c] and the files [D:\GISData\grids\tminave01c .. tminave12c]. These long-term mean monthly values give an indication of the temporal distribution of maximum and minimum air temperatures within a year.

Remotely sensed datasets of land surface temperature (LST) and modelled air temperature datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF) model or one of the National Oceanic and Atmospheric Administration (NOAA) models are other potential sources of data. These datasets and the relationship between LST and air temperature will need to be investigated further for use in South Africa.

The occurrence of frost is related to air temperature and can have an effect on water resources in the sense that certain land cover types such as grasslands may have different interception and transpiration characteristics during different seasons of the year and for different regions of South Africa depending on the occurrence and severity of frost. The derivation of a dataset of the mean number of occurrences of heavy frost is described in Schulze and Maharaj (2008d). This dataset is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\frostnoccc].

3.3 Land Cover/Use

The land cover within catchment is 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 needs to be determined. Land cover and land use within a catchment are dynamic with natural seasonal variations and seasonal changes in agricultural crops, but also from year-to-year due to urban development, agricultural expansion, invasion of alien plants, clear felling of plantations, burning and possibly even climate change. Land cover/use datasets derived by the classification of signatures from remotely sensed multispectral images are invaluable for estimating sectoral water use. However, due to the dynamic nature of land cover/use these datasets are effectively obsolete as soon as they have been created. But for water accounts which are at a catchment scale and for relatively short time periods it can be assumed that land cover/use stays relatively constant and seasonal variations can be taken into account. It is important that as far as possible the land cover\use maps used should represent the land use for the specific time domain of a water account.

3.3.1 Natural vegetation

In instances where detailed information regarding the specific types and condition of natural vegetation in a catchment is not available it is useful to be able to make some assumptions based on maps of baseline natural land cover types. Natural land cover maps for the whole of South Africa have been compiled by Acocks (1988) and Mucina and Rutherford (2006). These maps are useful for characterising land cover in naturally vegetated areas, though the effect of land use, such as grazing for livestock, in these areas must also be considered. These natural land cover maps are also useful in studies in which water use based on actual land cover in a catchment needs to be compared to some sort of baseline. The 70 Veld Types identified by (Acocks, 1988) are a generally accepted scientific accepted mapping of natural vegetation (Schulze, 2008a), and have been widely used in South Africa. In addition (Schulze, 2004) proposes a set of hydrological modelling variable values for each Acocks Veld Type, including crop coefficients, interception capacity, rooting fractions and coefficients of initial abstraction. A map of Acocks Veld Types, shown in Figure 3.5, in ESRI shapefile format is available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\shape_files\acocks.shp]. A discussion on baseline land cover and Acocks Veld Types can be found in (Schulze, 2008a).

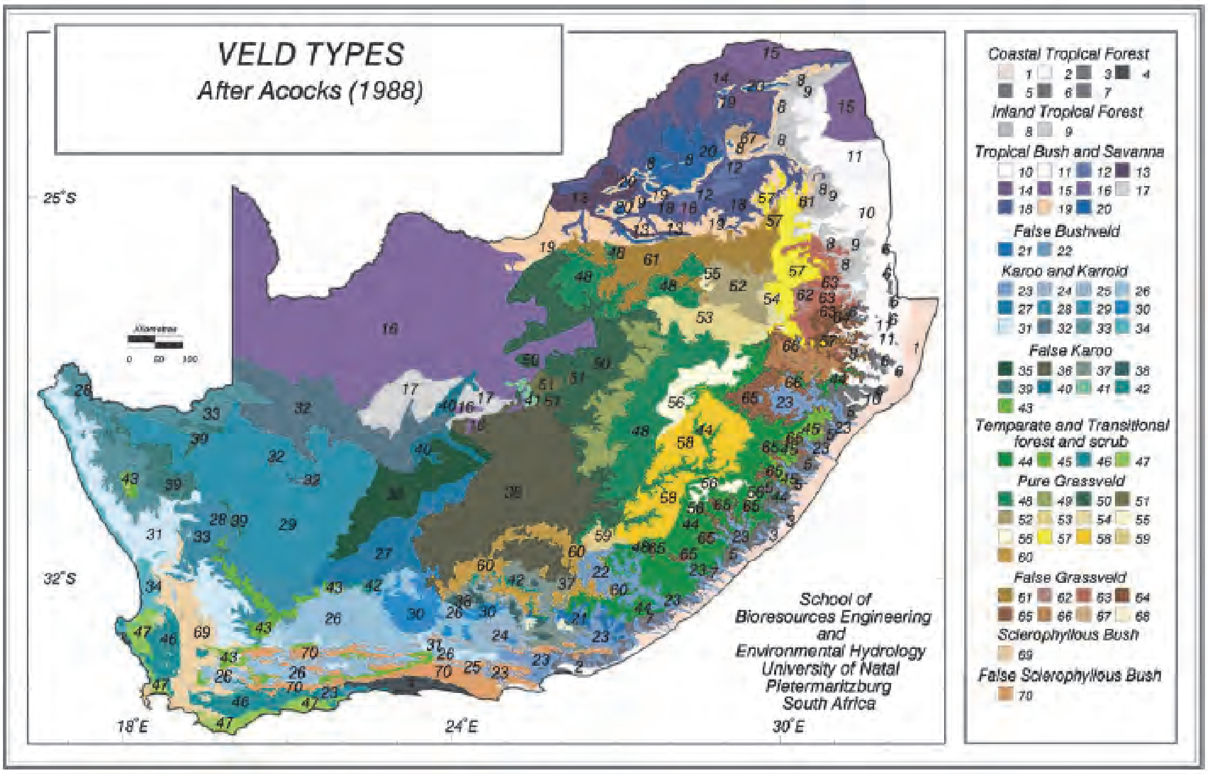


Figure 3.5 Map of Acocks Veld Types (Schulze, 2008a)

The newer and more spatially detailed Mucina and Rutherford (2006) dataset, shown in Figure 3.6, includes 438 natural vegetation types. This dataset in ESRI shapefile format and supporting documentation is freely available from the SANBI Biodiversity GIS website [http://bgis.sanbi.org/BGISDownloads/vegmap2006.zip]. There is currently no similar set of hydrological variable values describing the hydrological characteristics of these vegetation types but this will done as part of the WRC Project K5/2437 titled "*Resetting the baseline land cover against which stream flow reduction activities and the hydrological impacts of land use change are assessed*".

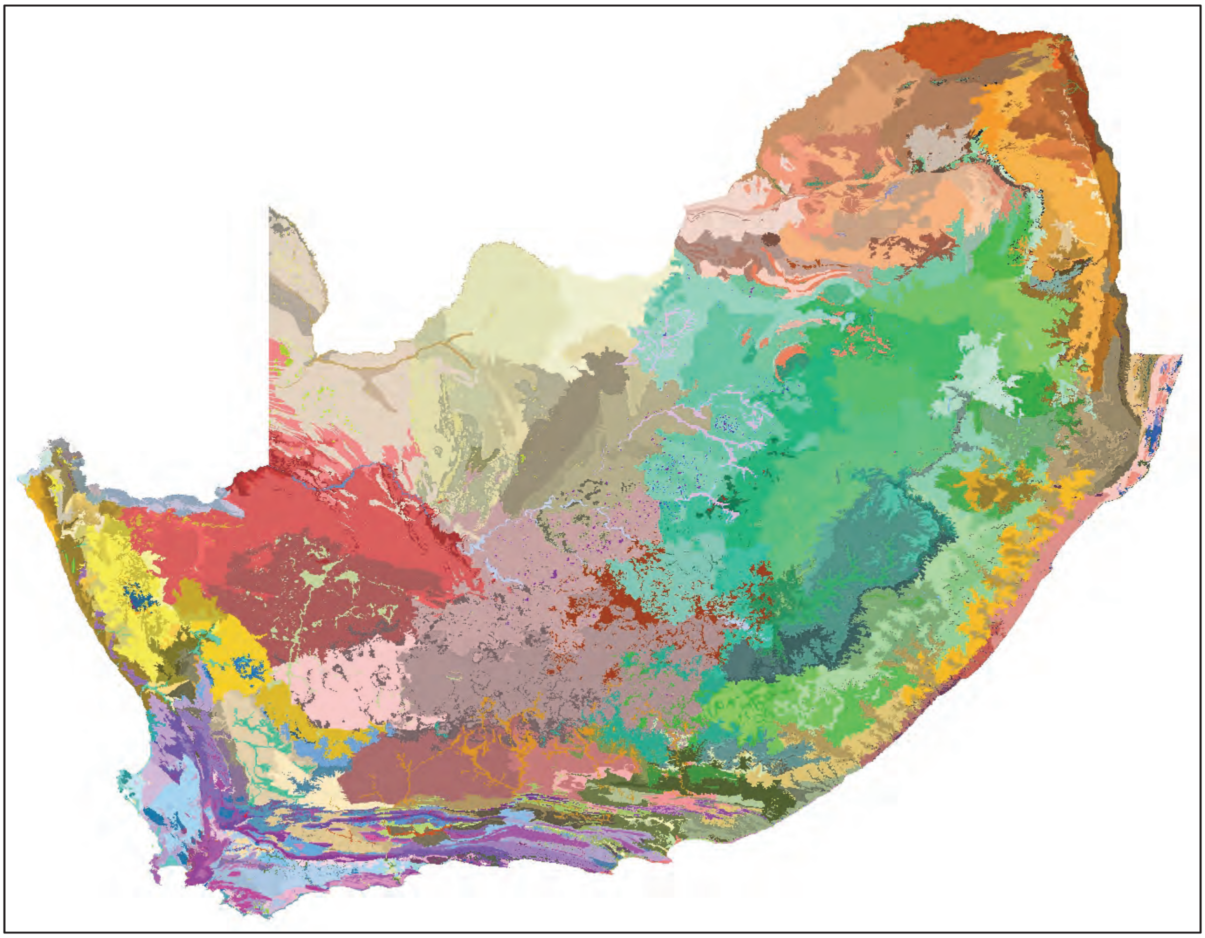


Figure 3.6 Map of Mucina and Rutherford (2006) vegetation types (after Mucina and Rutherford, 2006)

3.3.2 Actual land cover/use

The first National Land Cover (NLC) dataset of actual land cover for South Africa was produced by the CSIR together with the ARC for the year 1994 (NLC 1994) as a vector dataset with a minimum mapping scale of 25 ha and includes 31 land cover/use classes (ARC and CSIR, 1996; Thompson, 1996; Fairbanks *et al.*, 2000). The CSIR and ARC subsequently developed an updated dataset of actual land cover for the year 2000 (NLC 2000) as a vector dataset with a minimum mapping scale of 2 ha which includes 49 land cover/use classes (ARC and CSIR, 2005; Van den Berg *et al.*, 2008). In 2009 SANBI produced an updated land cover raster dataset with a 30 m resolution for South Africa (SANBI, 2009b; SANBI, 2009a). This updated dataset was based on the NLC 2000 map, but in areas where more recent land cover data was available this was used to replace the 2000 data. The 49 land cover/use classes used in NLC 2000 was reduced to just 7 classes: *Natural*, *Cultivation*, *Degraded*, *Urban Built-Up*, *Waterbodies*, *Plantations* and *Mines* (SANBI, 2009b). The SANBI (2009a) raster dataset is freely available from the SANBI Biodiversity

GIS website [http://bgis.sanbi.org/BGISdownloads/landcover_2009.zip]. Unfortunately the small set of very general land cover classes means that this land cover map is of little use for representing the finer hydrological variability of land cover/use within these classes in a catchment. Recently, an updated dataset of actual land cover for the year 2013/2014 (NLC 2013-2014) as a raster dataset with a 30 m resolution which includes 72 land cover/use classes was developed by GeoTerraImage (Pty) Ltd (GTI) for the Department of Environmental Affairs (DEA) (DEA and GTI, 2015; GTI, 2015). The NLC 2013-2014 dataset is freely available from the DEA.

Other datasets of actual land cover/use for specific provinces or catchments in South Africa may be available from various government and conservation institutions, such as DWS, provincial Departments of Agriculture, catchment management agencies, the ARC, ESKOM and Ezemvelo KZN Wildlife. GeoTerraImage (Pty) Ltd (http://www.geoterraimage.com) in Pretoria have extensive experience in remote sensing of land cover and may be able to assist in providing information regarding areas of South Africa where updated land cover maps have been created and who to contact regarding obtaining these maps. Ezemvelo KZN Wildlife has a particularly useful series of datasets of actual land cover/use for the province of KwaZulu-Natal for the years 2005, 2008 and 2011. These Ezemvelo KZN Wildlife datasets are useful as they are updated at regular intervals, providing access to recent land cover/use information and enabling the effect of changes in land cover/use to be evaluated. The 2011 dataset (Ezemvelo KZN Wildlife and GeoTerraImage, 2013) has a resolution of 20 m and includes 47 land cover/use classes. The FAO GeoNetwork website (http://www.fao.org/geonetwork/srv/en/main.home) includes a land cover map of South Africa for 2005 at 300m resolution for 46 land cover/use classes. Other datasets such as the DWS WARMS database and Agricultural census data are other potential sources of information on land cover/use that could be used to supplement the information contained in the remotely sensed spatial datasets.

3.4 Soil Moisture Storage and Soil Characteristics

The water stored in the soil profile of a catchment is one of the water stocks that need 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 need to be known. It is possible that direct point measurements of soil moisture could be available for irrigated fields or in small research catchments, but this is not a feasible option when compiling water accounts for catchments, so remotely sensed or modelled estimates are required.

Gibson *et al.* (2009) state that images of radar backscatter from orbiting satellites have been used extensively to estimate surface soil moisture, and report on testing two soil moisture quantification algorithms with data from two different sources of synthetic aperture radar (SAR) data, Envisat Advanced Synthetic Aperture Radar (ASAR) and Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR). Gibson *et al.* (2009) explain that the dielectric properties of soils are directly related to their moisture content, and that there is a relationship between the backscattering coefficient (σ^0) and the dielectric properties of soils. Gibson *et al.* (2009) applied a linear regression model and a multiple polarization model to estimate soil moisture content. They reported that results were encouraging and correlated well with rainfall patterns, but that they could not verify the results as distributed soil moisture measurements were unavailable for the study period. Gibson *et al.* (2009) point out that one problem with using radar remote sensing data for estimating soil moisture was due to the side-looking geometry, which results in image distortions especially in mountainous regions. Gibson *et al.* (2009) also comment that a problem in the use of linear regression models, is the assumed linear relationship between soil moisture and radar backscatter, though radar backscatter is also influenced by surface roughness and vegetation cover, and that this problem was overcome with the multiple polarization model.

Sinclair and Pegram (2010) compared two methods of estimating soil moisture over South Africa: (i) using the TOPKAPI hydrological model, and (ii) using the remotely sensed Advanced Scatterometer (ASCAT) Surface Soil Moisture product. The purpose of their study was to provide an automated modelling system to estimate soil moisture at a 3 hour timestep for a 0.125° spatial grid over South Africa, for use by SAWS in their national Flash Flood Guidance (FFG) system. Rainfall and ET were the two main forcing variables required to run the TOPKAPI model, and the estimates of these are described in Section 3.2.1.5 and Section 3.2.2.2 respectively. Other model parameters including soil properties, slopes and land use characteristics were determined for each cell. Sinclair and Pegram (2010) explain that the TOPKAPI model was run as a collection of 6984 independent 1×1 km cells, where the cell centres are located on a regular latitude and longitude 0.125° grid. The TOPKAPI simulations were run at 3 hour timestep to estimate the Soil Saturation Index (SSI) which is defined as the percentage of soil void space taken up by water.

Sinclair and Pegram (2010) also obtained ASCAT surface soil moisture (SSM) estimates, where ASCAT is an active microwave instrument on the METOP satellite. ASCAT measures backscatter from terrestrial surfaces, where the backscatter is strongly influenced by the water content of soil. Sinclair and Pegram (2010) obtained 5 months of the 25 km ASCAT soil moisture product for South Africa from the EUMETSAT Unified Meteorological Archive and Retrieval Facility (UMARF) archive. This product is in the form of a relative surface soil moisture (SSM) based on the saturated and residual moisture contents at a particular location. To compare the TOPKAPI SSI and the ASCAT SSM estimates it was necessary for Sinclair and Pegram (2010) to resample both datasets to common 0.25° and 0.50° grid blocks and to apply a weighted temporal filter to the ASCAT SSM data to be more representative of the average soil moisture state below the soil surface, in the whole soil horizon, similar to the SSI modeled by TOPKAPI. Sinclair and Pegram (2010) found that there was good correspondence between the estimated values for several climatic regions, except in the drier Western Cape and Northern Cape areas.

Continuing the work reported by Sinclair and Pegram (2010), Sinclair and Pegram (2013) report that the TOPKAPI hydrological model was extended through the inclusion of a Green-Ampt infiltration module to produce the PyTOPKAPI version of the model, which has been made freely available on the internet. Sinclair and Pegram (2013) then investigated the sensitivity of PyTOPKAPI to systematic bias in the rainfall and ET_0 input variables and to the soil properties used. They explain that the model sensitivity was calculated for 7200 cells across South Africa, for a 2.5 year simulation period at a three hour timestep. Sinclair and Pegram (2013) found that improving rainfall estimates and the parameters used to describe soil moisture storage would result in the best estimates of soil moisture. The three-hourly soil moisture and ET_0 estimates described in Sinclair and Pegram (2013) are available on the SAHG website [http://sahg.ukzn.ac.za/soil_moisture]. The datasets start in August 2008 and estimates are updated periodically.

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 represent the moisture near the surface of the soil only and not the whole soil profile. Apart from the study area used by Gibson *et al.* (2009) no other reference was found that indicated the availability of processed datasets for elsewhere in South Africa.

It is possible to use hydrological modelling to estimate the change in soil moisture storage for a catchment, as done by Sinclair and Pegram (2010) and Sinclair and Pegram (2013), though it should be remembered that a good spatial estimate of soil moisture in a catchment will be dependent on model inputs such as soil characteristics, land use, rainfall and evaporation. One advantage of the modelling approach is that sensitivity analyses or land use scenarios could easily be performed to determine their effect on the water balance in a catchment. The hydrological properties of soils are an important input to any hydrological model, and a useful source of soil hydrological properties for use in the *ACRU* model is an ESRI shapefile available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\shape_files\soils.shp]. The derivation of these soil hydrological properties is described by Schulze and Horan (2008b). The soil hydrological properties included in the dataset are the depth, porosity, drained upper limit and wilting point for each of the A and B horizons, and also the saturated drainage rate from the A to the B horizon. Though these soils properties were principally derived for use in the *ACRU* model they could be used in other hydrological models with similar requirements.

3.5 Surface Water Storage

Surface water storage is understood to be water stored in lakes and dams and in snow and ice, though snow and ice can safely be ignored in South Africa as when snowfalls do occur these generally melt within a few days. The surface water storage of a catchment is another of the water stocks that need 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. To determine the change in surface water stored during the accounting period, only the surface storage at the start and end of the accounting period need to be known. Measured dam levels and remote sensing and modelling estimates are all potential sources of surface storage information.

Measured dam level data can be requested from the "*Hydrological Services – Surface Water (Data, Dams, Floods and Flows)*" page of the DWS website (http://www.dwa.gov.za/hydrology/) which provides access to near real-time data and historical time series of primary, daily and monthly data stored by DWS in their HYDSTRA database. Users can search the website using DWS station IDs and download data in a simple text format. The dam level data is only available for large dams but could be used to estimate changes in surface storage in these dams.

The storage of water in smaller farm dams is unlikely to be available, but as described in Gibson *et al.* (2009), could be estimated using information on dam physical characteristics or generic area:volume relationships (for example, Maaren and Moolman (1985)), together with estimates of surface area using high resolution satellite images at the start and end of an accounting period. These estimates for farm dams may not be accurate, but any estimate is likely to be better than ignoring this potentially significant part of the water balance.

Information on the physical characteristics large dams is readily available but good quality information about small dams is more difficult to find. The 1:50000 topological maps available from the Surveyor General are useful for determining the location and surface area of dams and other large waterbodies within a subcatchment, but there is no information regarding storage capacity or purpose. The DWS WARMS database of dams has some potential as it has information on all dams reported by water users as part of the licencing process, including surface area, storage capacity, purpose, latitude and longitude. However, much of the data in the WARMS database is unverified and should be used with caution. Another source of information is the DWS Dam Safety Office (DSO) database of registered dams (DSO, 2014). This is a database of dams with a storage capacity of more than 50000 m^3 and a wall height of more than 5 m, which by law have to be registered with the DWS. This database is similar to the WARMS database, though smaller, and includes information on the location, surface area and storage capacity of individual registered dams. The DWS database of registered dams appears to have had more data checking done than the WARMS database, but some errors in the location of dams exit. It is unfortunate that there does not appear to be a common system of dam IDs in use in South Africa so it is difficult to compare datasets and do error checking.

Gibson *et al.* (2009) used high resolution (2.5 m) SPOT data together with the Definiens™ software and a relatively simple classification process to identify farm dams in their study catchment and to estimate the surface area of these dams. Gibson *et al.* (2009) then used two different area:volume relationships to estimate the volumes of the dams. Gibson *et al.* (2009) selected three farm dams for which they obtained bathymetric measurements, and used GIS tools to calculate dam volumes from these measurements. Gibson *et al.* (2009) then compared the estimated volumes for these three dams with the registered volumes of these dams in the WARMS database. They found that unexpectedly the volumes from the remote sensing method and the registered WARMS values were most similar, with measured volumes being significantly higher. They concluded that there was either an error in the way in which the field measurement was conducted, or that the WARMS volumes were calculated using an area:volume relationship, or that the remote sensing volumes were coincidentally closest to the WARMS volumes. Gibson *et al.* (2009) warned about inconsistencies encountered when trying to link WARMS data to cadastral farm data or coordinates in the WARMS records.

In their study in the Indus Basin, Karimi *et al.* (2013b) estimated surface storage changes for the main reservoirs using water level fluctuation data obtained from dam operation agencies in Pakistan. But Karimi *et al.* (2013b) note that increasingly remote sensing techniques are being used to estimate water level fluctuations from radar and laser altimetry, where changes in reservoir storage are estimated using these level measurements together with estimates of reservoir surface area.

3.6 Groundwater Storage

The groundwater storage of a catchment is another of the water stocks that need 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 catchment (Karimi *et al.*, 2013b), except possibly for some groundwater research catchments.

Karimi *et al.* (2013b) state that changes in storage can be obtained from gravitational satellites such as the Gravity Recovery and Climate Experiment (GRACE). No literature could be found regarding the application of GRACE in South Africa. From other literature, some drawbacks of this approach seem to be poor accuracy, that it is only suitable for use in large basins (> 10^5 km^2), and that it combines surface water storage, soil moisture storage and groundwater storage.

It would be possible to simulate groundwater recharge, storage and outflows using a groundwater model, though the input data required to do this is unlikely to be available for many catchments. Simpler groundwater modelling in a general purpose hydrological model would be possible. Gibson *et al.* (2009) used a combination of remote sensing, isotope tracing and modelling to understand groundwater recharge and storage in their relatively small study area, however, this type of study may not be feasible when compiling accounts for other catchments. In the study by Karimi *et al.* (2013b) measured basin outflow was available and the total change in groundwater storage was back calculated by closing the water balance.

3.7 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 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.

There are several datasets of rivers available for South Africa, some of which include:

- The flow paths dataset (Weepener *et al.*, 2011c) developed in WRC project K5/1908 using the SRTM 90m DEM as described by (Weepener *et al.*, 2011a). This dataset of rivers was should match the new Quaternary Catchment boundaries dataset developed in the same project. One disadvantage of using the (Weepener *et al.*, 2011c) rivers dataset is that it does not include any river names or other data.
- The DWS River Quality Information Service (RQIS) 1:500000 rivers dataset available from the RQIS website [https://www.dwa.gov.za/iwqs/gis_data/river/rivs500k.aspx].
- The NFEPA rivers dataset available from the SANBI Biodiversity GIS website [http://bgis.sanbi.org.za/BGISdownloads/NFEPA_rivers.zip].
- The rivers dataset that is packaged as part of the WR2005 study by (Middleton and Bailey, 2008) and available from the Water Resources 2012 website [http://www.waterresourceswr2012.co.za].
- Surveyor general.

3.8 Abstractions, Return Flows and Transfers

Water is abstracted from rivers, dams and groundwater for a range of different uses including domestic use, for use in industrial processes, hydropower generation and for 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 to a different portion of the river flow network and possibly with a poorer quality. As development in certain catchments reaches the point where demand exceeds the local supply, one solution is to transfer water in from neighbouring catchments. Information on abstraction, return flows and transfers is an important part of water resource accounts as it quantifies 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 the water supplied to each user is measured. However, there is no single repository for this data, the amount of data is large and it is difficult to get access to this data.

Information contained in the network diagrams for the WRSM2000 model, available from the Water Resources 2012 study website (http://waterresourceswr2012.co.za/), are a useful guide to identifying where inter-catchment transfers, abstractions and return flows occur. The WRSM2000 model input data files prepared for each catchment also contain monthly time series information of abstraction, return flow and transfer quantities. However, there is no detail regarding how much water was supplied to each water use sector and how much return flow was contributed by each sector as this is difficult to determine and beyond the scope of the Water Resources 2012 study.

3.8.1 Urban use and return flows

Depending on the degree of urbanisation present in the accounting domain this could be a significant water use for inclusion in the account. In the general sense urban water use is understood to include residential, commercial and industrial water use. This information will need to come from flow records or some sort of model, though remote sensing can be used to determine depletion due to ET. Water for urban use may come from within the catchment within which it is situated or from a different catchment as is often the case with cities supplied by large dams. Often a large portion of water extracted for urban water use is returned for further use within or downstream of the catchment where it is used, except when used for irrigating gardens, evaporative cooling, and incorporation into food and beverage products. The following literature references were found that discussed the urban water use in South Africa.

Van Zyl and Geustyn (2007)

Van Zyl and Geustyn (2007) explain that residential water consumption depends on several factors, such as stand size, income, household size, climate, water pressure and price. Van Zyl and Geustyn (2007) state that residential water demand and consumption is still not well understood and that various national and municipal guidelines exist. Van Zyl and Geustyn (2007) state that although municipal water meter readings are a good source of information, they are often difficult to access and records are generally only kept for a short time before being discarded. Van Zyl and Geustyn (2007) explain that monthly municipal water meter readings are stored in municipal treasury databases which include land use and stand information, however, this data is not spatially referenced and these treasury systems are not designed to enable statistical analyses and general infrastructure assessments. To overcome some of these shortcomings GLS Consulting Civil Engineers developed software called Swift, which enables them to access demographic and water consumption information contained in municipal treasury databases, and Swift has been implemented by many municipalities in South Africa (Van Zyl and Geustyn, 2007). Swift includes functionality to identify and correct irregularities in the water meter readings and water consumption records due faulty water meters and data capturing errors, and to check the latest readings against the historical meter records (Van Zyl and Geustyn, 2007). The purpose of the study by Van Zyl and Geustyn (2007) was to develop a data format and software to archive data accessed by Swift in a generic and easily accessible form, and then collect, verify, clean and archive data in existing Swift databases. Van Zyl and Geustyn (2007) report that 48 municipal treasury databases were archived to produce the National Water Consumption Archive (NWCA), including four metros (Johannesburg, Tshwane, Ekurhuleni and Cape Town) and 151 cities or towns, mostly in the Gauteng and Western Cape provinces. The archives contain data on metered consumption for different types of users including domestic, commercial, industrial and educational users. As the archives contain sensitive data and data that could be commercially exploited, these archives may be made available solely for research purposes at the discretion of the WRC, subject to a written motivation and acceptance of an indemnity declaration (Van Zyl and Geustyn, 2007).

<u>Van Zyl *et al.* (2007)</u>

In a literature review by Van Zyl *et al.* (2007) it was found that the main factors that affect domestic water demand are stand area, household income, water price, water pressure, type of development and climate. Van Zyl *et al.* (2007) analysed water consumption levels in selected South African cities using data from the NWCA described in Van Zyl and Geustyn (2007). Van Zyl *et al.* (2007) found that comparing average water consumption for 1188 suburbs with the South African design guidelines, that 39% of the data points were below the lower design limit and 8% above the upper design limit. Van Zyl *et al.* (2007) performed step-wise multiple variable regressions on the data to determine which variables showed the strongest correlations and then single variable regressions for the most significant variable for different categories of stand size. The results showed that water demand was greater for inland domestic stands compared to coastal domestic stands, and that there is a positive correlation for stand value, income and stand size. Van Zyl *et al.* (2007) concluded that the South African design guidelines tended to underestimate demand on small stands and overestimate demand on large stands. Van Zyl *et al.* (2007) also used a model developed by (Jacobs, 2004) to estimate demand and return flow for domestic users in four income categories. The results showed that higher income users have a higher demand with a larger variation between summer and winter, due mainly to irrigation in gardens, while for lower income users there was little seasonal variation. Sewer return flows were only linked to indoor demand, with little seasonal variation. Due to irrigation, higher income users have lower return flow percentages than lower income users, but a greater variation in return percentage.

Van Zyl *et al.* (2007) performed step-wise multiple variable regressions for seven categories of non-domestic user (business, education, farming, government and institutional, industrial, parks and sports). The results showed that for non-domestic users stand size and stand value were the most significant variables and that for all the non-domestic categories demand could be described using log-normal probability distributions.

<u>Van Zyl *et al.* (2008)</u>

The purpose of the study by Van Zyl *et al.* (2008) was to revise the 1983 guideline for estimating municipal water demand. Van Zyl *et al.* (2008) use single variable and step-wise multiple variable regression analysis to determine the influence of selected socio-economic and climatic variables on municipal water consumption. The study used the NWCA to provide a study dataset of over one million water meter records from 48 municipal treasury databases, mostly in the Western Cape and Gauteng provinces, with data records for at least 12 months. Van Zyl *et al.* (2008) found that stand area, stand value and geographical location were the dominant variables influencing water demand. Water demand on coastal stands was found to be consistently less than inland stands with the same stand area and value. Van Zyl *et al.* (2008) concluded by proposing a single guideline curve based on stand area alone, together with confidence limits, for estimating water demand in South Africa.

<u>Kriegler and Jacobs (2008)</u>

A study was conducted by Kriegler and Jacobs (2008) to produce guidelines for estimating non-domestic water demand based on stand area using data from the NWCA. In their study Kriegler and Jacobs (2008) used a dataset containing 2189 large users in 15 Western Cape municipalities including the City of Cape Town. The NWCA includes several land use and zoning categories (Commercial, Education, Government/Institutional, Industrial, Recreational, Agricultural and Unknown), but only the Commercial, Education, Government/Institutional and Industrial categories were included in the study by Kriegler and Jacobs (2008). Each of these land use categories was broken down into homogenous land use sub-categories using information about the owner or consumer on each stand, to better represent different water demands within a category. These sub-categories were Commercial (Businesses, Hotels), Education (Schools), Government/Institutional (Churches, Hospitals) and Industrial (Abattoirs, Manufacturing, Wine Cellars). The data was analysed to produce a set of guidelines for annual average daily demand (AADD) in l/day/100m^2 of stand size with 50, 75 and 95-percentile values.

Cloete *et al.* (2010)

The objective of the study by Cloete *et al.* (2010) was to compile a first order inventory of the amount of water used and effluent produced by the industrial, mining and power generation sectors in South Africa and to assess the impact on water quality. As existing datasets were outdated or inadequate, Cloete *et al.* (2010) identified the major water users in the country, as well as metropolitan councils and DWS regional offices, and requested information on water use, production processes, production figures and effluent production. Cloete *et al.* (2010) received mixed responses to the request for data due to limited monitoring and reluctance by both public and private organisations to make sensitive information available. Especially, data regarding effluent production, was often unavailable or incomplete. Using this information Cloete *et al.* (2010) grouped the data by sector and calculated relative percentages per sector. Breweries were found to be major users of water relative to other metropolitan users, and also major contributors to effluent. Also, where they exist in metropolitan areas, pulp, paper and textile industries were major contributors to effluent. The food and beverage industry was the most common industry in metropolitan areas and contributed significantly to the production of effluent. The analysis showed that industry accounted for 55% of water use, followed by mining (23%), power generation (20%) and the food and beverage industry (2%) Cloete *et al.* (2010). Industry produced 74% of effluent, followed by mining (10%), food and beverage (9%) and power generation (7%) Cloete *et al.* (2010). The major water using industries were found to be petroleum (42%), ferrous metals, i.e. metal plating (41%) and pulp and paper (14%) Cloete *et al.* (2010). The major effluent producing industries were found to be pulp and paper (57%) and petroleum (34%) Cloete *et al.* (2010). In the food and beverage industry the main water users were sugar (27%), poultry (24%), cold drink (17%), breweries (15%) and dairies (10%), and the main effluent producers were poultry (31%) followed by cold drinks (20%), breweries (18%) and sugar (16%). Cloete *et al.* (2010) comment that though the electricity generation sector accounts for 2% of water demand in South Africa, most of this water is lost as evaporation and little effluent is produced. Cloete *et al.* (2010) warn about the difficulties in obtaining water demand and effluent production information, as users have concerns regarding confidentiality, fear of prosecution and the costs of treating effluent.

3.8.2 Irrigation water use

Water use for irrigation is strongly linked to climate, soil types and the type of crop grown and if measurements of water abstracted for irrigation are not available then water use can be estimated using a hydrological model or a crop yield model. One potential problem with modelling water use for irrigation is that the land cover/use datasets discussed in Section 3.3.2 have classes that distinguish between dryland and irrigated agriculture, but do not differentiate between the types of irrigated crops, the type of irrigation system or management practices. The DWS WARMS database 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 types of irrigated crops and the type of irrigation system used. A potential problem with using the WARMS data for irrigation is that as the spatial reference is only a latitude and longitude, it may difficult to reconcile this information with the land cover/use datasets.

3.8.3 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 network diagrams for the WRSM2000 model, available from the Water Resources 2012 study website (http://waterresourceswr2012.co.za/), are a useful guide to identifying where the larger scale inter-catchment transfers occur and the monthly flows. Monthly and daily flows for the larger scale inter-catchment transfers are also available from the "*Hydrological Services – Surface Water (Data, Dams, Floods and Flows)*" page of the DWS website (http://www.dwa.gov.za/hydrology/).

3.9 Flows to Sinks

Karimi *et al.* (2013a) explain that in addition to depletion of water resources in a catchment due to evaporative processes or transfers out of the catchment, there may be a quantity of water that even though it physically remains within the catchment it is considered depleted. This includes flows to sinks where it is no longer available for use (e.g. saline groundwater aquifers), or where the quality of the water makes it unfit for further use. In situations where these types of flows are relevant, they would need to be measured directly or modelled.

3.10 Reserved flows

Karimi *et al.* (2013a) explain 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 *Reserved flow* is usually the maximum of these individual downstream requirements as flows reserved for the environment and navigation are not depleted (Karimi *et al.*, 2013a). There is an additional outflow quantity called *Non-utilizable flow*, which Karimi *et al.* (2013a) explain as being flows during flood events that need to be released from a catchment to prevents inundation by flood waters. The *Reserved flow* would need to be determined based on the environmental flow requirements at the exit of a catchment, where these are specified. Flows committed to downstream users would need to be determined in consultation with the water managers responsible for the catchments.

3.11 Measured Streamflow

The flow of surface water and groundwater out of 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 out of a catchment form the balance the account after all inflows outflows and changes in storage have been accounted for. If measured streamflow data is available, then this can be used to verify the accuracy of the estimated surface water outflows. If there are parts of the account that cannot be estimated, such as changes in storage, then the use of measured streamflow in the account would enable these missing parts of the account to be estimated, assuming all the other parts of the account are correct. Measured streamflow data is available from the "*Hydrological Services – Surface Water (Data, Dams, Floods and Flows)*" page of the DWS website (http://www.dwa.gov.za/hydrology/).

4 DEVELOPMENT OF A METHODOLOGY FOR WATER USE QUANTIFICATION AND ACCOUNTING

DJ Clark

The primary aim of the project was to develop a methodology to integrate appropriate sources of data and information, and methods of estimating water availability and use into a single, internally-consistent water use quantification and accounting system. The purpose of this chapter is to describe the methodology developed in this project for this purpose. Although the *ACRU* model was used in the development of the methodology there is no reason why another hydrological model with suitable capabilities should not be used in its place.

Based on the requirements for water use quantification and accounting system discussed in Chapter 1, the review of water resource accounting frameworks in Chapter 2 and the review of available datasets in Chapter 3, 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 Catchment Management Agencies (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 which 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 the most useful for catchment scale water management. The water abstractions and return flows 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 which are likely to be most sensitive, which 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.

4.1 Modified Resource Base Sheet

The Resource Base Sheet provides information on water volumes, including inflows, outflows and depletions (Karimi *et al.*, 2013a). The version of the WA+ Resource Base Sheet that was described in Karimi *et al.* (2013a), shown in Figure 4.1, was subsequently revised to the version that was reviewed in Chapter 2 of this report and shown in Figure 4.2. The main difference between these two versions was the inclusion of the concept that all or part of the total evaporation that leaves the accounting domain is recycled as precipitation and re-enters the accounting domain. Thus the revised version differentiates between precipitation due to recycled total evaporation within the accounting domain and precipitation due to advection into the accounting domain. An additional inflow was also added to account for the inflow of desalinated water. There were also a few changes to the some of the terms used, where (i) *Conserved Land Use* was changed to *Protected Land Use*, (ii) *Depleted* was changed to *Consumed*, and (iii) *Flow to sinks* was changed to *Non-recoverable flow*.

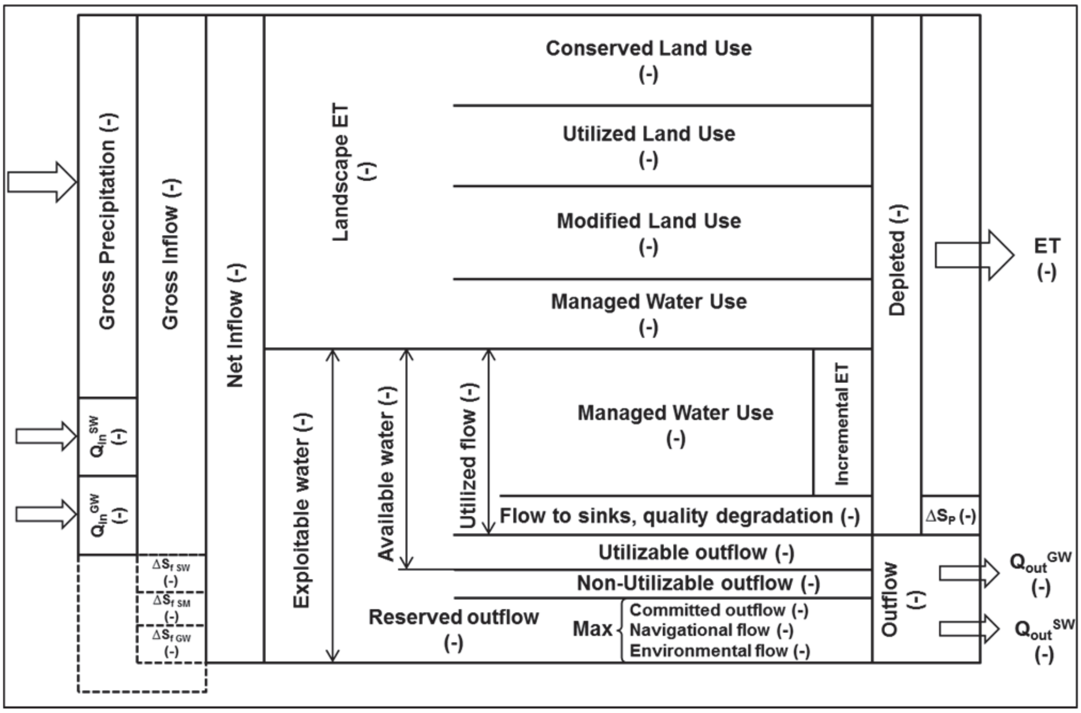


Figure 4.1 Schematic representation of the WA+ Resource Base Sheet (after Karimi *et al.*, 2013a)

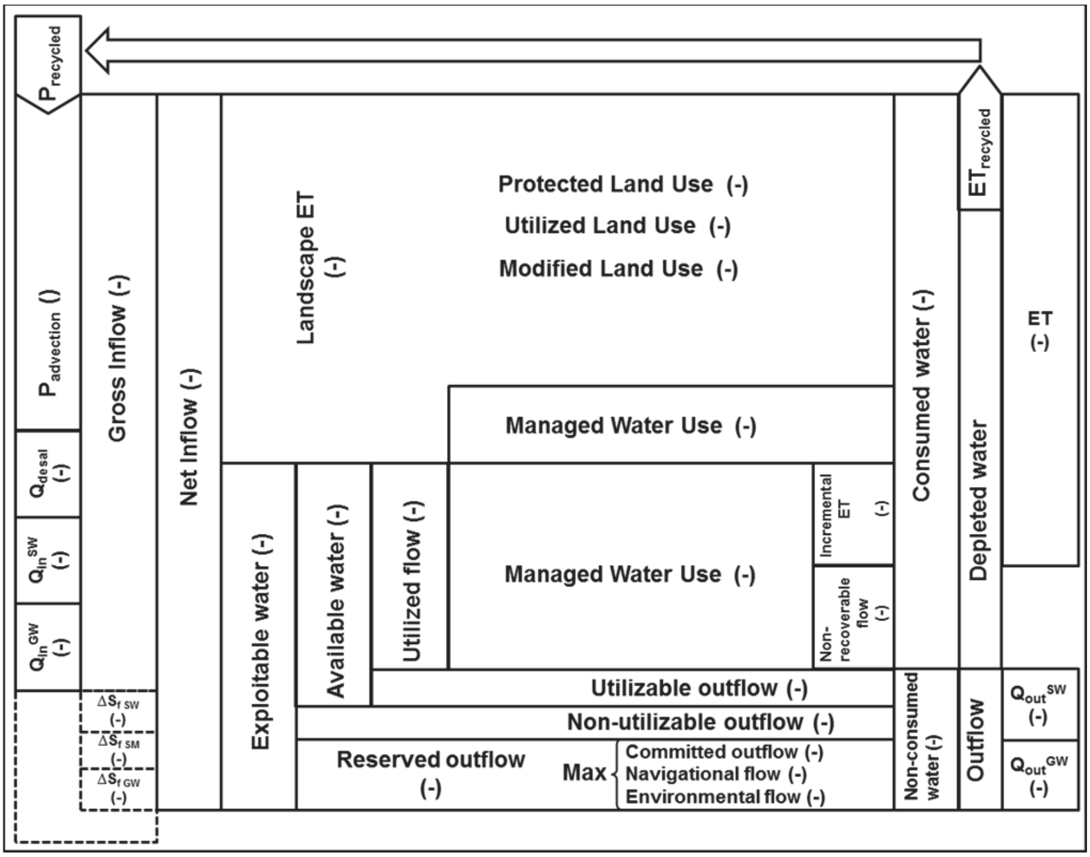


Figure 4.2 Schematic representation of the revised WA+ Resource Base Sheet (after Water Accounting+, 2014)

Based on experience gained during the course of the project the WA+ Resource Base Sheet was modified to suit the requirements of the water use quantification and accounting system developed in this project for use in South Africa. The modified Resource Base Sheet is shown in Figure 4.3. The main differences to the WA+ Resource Base Sheet are as follows:

- Precipitation is represented in the account as a single *Precipitation* component and has not been partitioned into recycled and advective components. Good estimates of catchment scale rainfall are likely to be a constraint to application of the accounts, let alone this type of partitioning at a catchment scale.
- An inflow component $Q_{In\ Transfers}$ representing inflowing inter-catchment transfers and an outflow component $Q_{Out\ Transfers}$ representing outflowing inter-catchment transfers have been included as in South Africa these water transfers are common and need to be represented separately from surface water inflows and outflows.
- The inflow component Q_{desal} representing the inflow of desalinated water has been omitted as desalination is not yet a significant source of water to catchments. Inflows of desalinated water could be represented by the $Q_{In\ Transfers}$ component if necessary.
- The ΔS_{SM} component representing snow and glacier melt has been replaced by ΔS_{SoilM} representing the change in soil moisture storage. Although South Africa does receive some snow this is not extensive and generally melts within a few days and so is not important for water resource accounts. The change in soil moisture is likely to be more important in arid and semi-arid regions.
- The four land/water use categories used to give a breakdown of *Landscape ET* were used initially as they make sense as a means of showing where consumption in the form of ET could potentially be managed to some degree. However, in practice it was found that it was not always clear which one of these categories to assign to each land cover use class. For example, in some regions of the Kruger National Park the natural vegetation is heavily over utilised even though it is in a conservation area. Five very broad land cover/use classes (*Natural*, *Cultivated*, *Urban*, *Mining* and *Waterbodies*) representing broad water use sectors have been used in place of these four categories. As it is not possible to show water use in more detail for a greater number of land cover/use classes in the Resource Base Sheet, this data is included in an accompanying table in which land use, water inputs and water use for each individual land cover/use class within a catchment is summarised.
- The *Non-utilizable* flow component has been omitted as this is difficult to quantify. Karimi *et al.* (2013a) describe *Non-utilizable flow* as being flows during flood events that need to be released from a catchment to prevents inundation by flood and Molden and Sakthivadivel (1999) describe *Non-utilizable flow* as flows which leave a

catchment due to there being insufficient storage infrastructure or inefficient management of existing infrastructure to capture the outflow for use within the catchment.

- The flow quantities in WA+ are typically expressed as volumes, which are useful, but do not enable catchments of different sizes to be easily compared. In large catchments the volumes can be large, a volume multiplier and units of measure are specified in the top right-hand corner of the sheet. Also precipitation and total evaporation are conventionally expressed as depths, which make it difficult to compare precipitation and total evaporation values in the accounts with other measurements or estimates. To resolve this all flows are also expressed as a percentage of the *Net Inflow* component and, where it makes sense to do so, flows are also expressed as depths in millimeters (based on total catchment area). Flow depths are shown for precipitation and total evaporation, but not for surface water flows into the catchment as these inflows were generated on upstream catchment areas and could result in large flow depth numbers if the receiving catchment is small.
- Additional components showing the partitioned interception evaporation, transpiration, soil water evaporation and open water evaporation components of total evaporation have also been included. This will enable the effect of changes in vegetation and cultivation practices, and the influence of new water bodies to be more clearly reflected in the accounts. These additional components are included in the WA+ Evapotranspiration Sheet, but it was decided that it would be useful to show these values in the Resource Base Sheet and negate the need for the Evapotranspiration Sheet. The only additional information displayed in the Evapotranspiration Sheet is the separation of water use into beneficial versus non-beneficial uses and it was decided that this was not a useful part of the accounting framework and its application is in some cases subjective. For example, soil water evaporation could be seen as beneficial as it is a necessary part of growing a crop and can't be avoided, but it could also be argued that only transpiration is useful as this is related to the production of biomass.

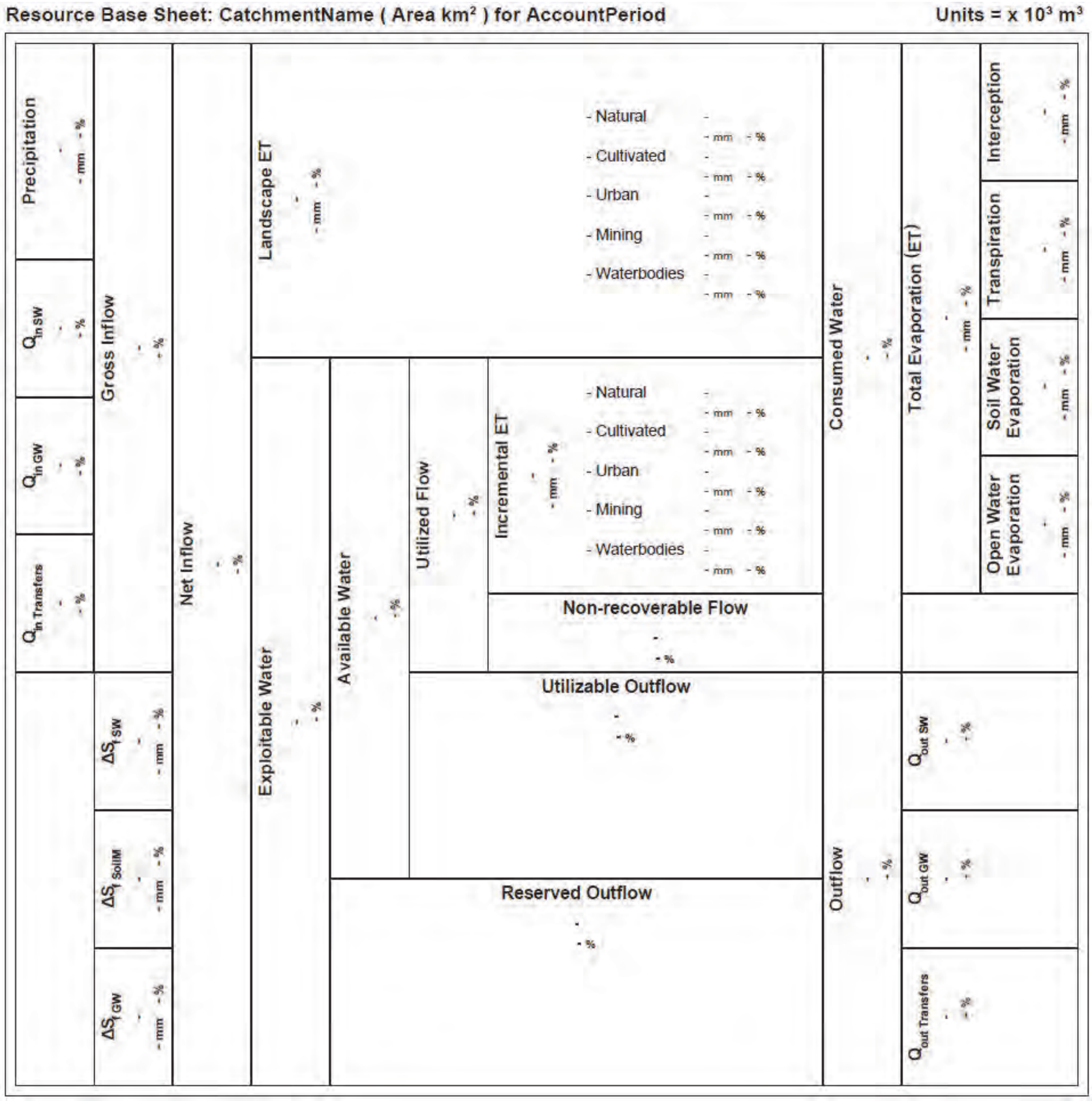


Figure 4.3 Schematic representation of the WA+ Resource Base Sheet modified for the water use quantification and accounting system

Although the Resource Base Sheet provides a very useful overview of water use in a catchment, it is an aggregation of the water balances for each of the individual land cover/use classes existing within the represented catchment, and the detail of these individual water balances is lost. Therefore, a land and water use summary table was developed to accompany the Resource Base Sheet, an example of which is shown in Table 4.1. This summary is in the form of a pivot table summarising areal extent, water availability and use by land cover/use class. The first column contains a nested hierarchical list of all the land cover/use classes within a catchment, with the five broad land cover/use classes displayed in the Resource Base Sheet forming the first level of the hierarchy each potentially containing a number of sub-classes depending on the level of detail required. The second column shows the area of each class, and values could be displayed as percentages or actual areas in square kilometres. The third and fourth column shows the precipitation an irrigation received by each class. The remaining columns show the total evaporation and partitioned components of this for each class. The rainfall, irrigation and evaporation values could be expressed as volumes, depths or percentages. As the values are often large numbers it is recommended that value be shown as depths or percentages. The second row of the table shows the total for each column as a depth or a volume.

Table 4.1 Example of a land and water use summary table using percentages

Land Cover/Use Category	Area (100 km^2)	Precipitation	Irrigation	Total Evaporation	Interception Evaporation	Soil Moisture Evaporation	Transpiration	Open Water Evaporation
Total Water (mm)	-	1000	200	800	190	250	350	10
Natural	70	65	-	60	71	62	68	-
Sub-class N1	55	60	-	58	59	60	59	-
Sub-class N2	45	40	-	42	41	40	41	-
Cultivated	20	25	100	32	26	31	29	-
Sub-class C1	70	72	0	69	71	72	71	-
Sub-class C2	30	28	100	31	29	28	29	-
Sub-class C2.1	25	26	24	28	27	26	27	-
Sub-class C2.2	75	74	76	72	73	74	73	-
Urban	6	6	-	4	3	3	3	-
Sub-class U1	50	50	-	55	52	50	52	-
Sub-class U2	30	29	-	25	28	29	28	-
Sub-class U2	20	21	-	20	20	21	20	-
Mining	3	3	-	3	0	4	0	-
Sub-class M1	100	100	-	100	100	100	100	-
Waterbodies	1	1	-	1	0	0	0	100
Sub-class W1	100	100	-	100	100	100	100	100

A template for the modified Resource Base Sheet shown in Figure 4.3 was created in Scalable Vector Graphics (SVG) format, which serves two purposes, (i) storage of the account data values, and (ii) the graphical display of the accounts using recent versions of most internet browsers. This template can populated with values either (i) automatically using computer code to accumulate and write data values, or (ii) manually if there are values such as reserved flows that are not part of the hydrological modelling process.

4.2 Data Required to Populate the Resource Base Sheet

In Chapter 3 the availability and suitability of datasets and water quantification methodologies for use in compiling water resource accounts in South Africa was investigated. The data requirements and methodology to populate the various components of the Resource Base Sheet are summarised in Table 4.2 and where necessary further details are provided in subsequent sections of this chapter. The components are listed in Table 4.2 in order of calculation starting from the top-left of the Resource Base Sheet with inflows, generally working from top to bottom then left to right, followed by green water use followed by blue water use and finishing with outflows in the bottom-right.

Table 4.2 Summary of data requirements and methodology to populate the Resource Base Sheet

Precipitation	Due to relatively poor availability and accessibility of rain gauge data, and to try and provide better spatial representation of catchment scale rainfall, several remotely sensed rainfall datasets were tested. (Section 4.11)
Surface Water Inflow ($Q_{in\ SW}$)	$Q_{in\ SW}$ was calculated as the sum of the modelled outflow from one or more upstream catchments. In instances where the upstream catchments are not modelled, then measured streamflow would need to be used.
Groundwater Inflow ($Q_{in\ GW}$)	$Q_{in\ GW}$ was assumed to be zero as measurements of groundwater inflow to catchments are not generally available and are not modelled in *ACRU*. This is an area for potential future research.
Transfers In ($Q_{in\ Transfers}$)	$Q_{in\ Transfers}$ was calculated as the sum of the inter-catchment transfers into a catchment which were determined based on measured flow data which was used as an input to the *ACRU* model.
Gross Inflow	Gross Inflow is the sum of Precipitation, $Q_{in\ SW}$, $Q_{in\ GW}$ and $Q_{in\ Transfers}$.
Change in Surface Water Storage ($\Delta S_{f\ SW}$)	$\Delta S_{f\ SW}$ was calculated from modelled surface water storage volumes by subtracting the stored volume at the end of the accounting period from the stored volume at the start. Thus an increase in storage will result in a negative value indicating that a portion of gross inflow has been stored during the accounting period. Surface water storage includes water stored in dams, rivers and also unevaporated intercepted water.
Change in Soil Moisture Storage ($\Delta S_{f\ SoilM}$)	$\Delta S_{f\ SoilM}$ was calculated from modelled soil moisture storage volumes by subtracting the stored volume at the end of the accounting period from the stored volume at the start. Thus an increase in soil moisture will result in a negative value indicating that a portion of gross inflow has been stored during the accounting period.

Table 4.2 (cont.) Summary of data requirements and methodology to populate the Resource Base Sheet

Change in Groundwater Storage ($\Delta S_{f\ GW}$)	$\Delta S_{f\ GW}$ was calculated from modelled groundwater storage volumes by subtracting the stored volume at the end of the accounting period from the stored volume at the start. Thus an increase in storage, if recharge is greater than baseflow plus usage, will result in a negative value indicating that a portion of gross inflow has been stored during the accounting period.
Net Inflow	*Net Inflow* is the sum of *Gross Inflow*, $\Delta S_{f\ SW}$, $\Delta S_{f\ SoilM}$ and $\Delta S_{f\ GW}$.
Landscape ET	Each land use class within a catchment was modelled as a separate Hydrological Response Unit (HRU). *Landscape ET* and the sub-total for each of the five main water use sectors was calculated by aggregating modelled interception evaporation, transpiration, soil water evaporation and open water evaporation from each HRU.
Exploitable Water	*Exploitable Water* is *Net Inflow* minus *Landscape ET*.
Reserved Outflow	*Reserved Outflow* was for most catchments assumed to be zero due to lack of information. Environmental Water Requirements (EWRs), where these have been determined, are for discrete points in the river flow network and thus are not available for each catchment outlet. The potential interpolation of EWRs between points is an area for potential future research. Information on committed outflows is not well documented and varies for each day, month and year and would need to be obtained from water managers on a catchment by catchment basis.
Available Water	*Available Water* is *Exploitable Water* minus *Reserved Outflow*. *Available Water* is overestimated where *Reserved Outflow* is not known.
Incremental ET	To estimate the portion of ET arising from irrigated water a separate soil water balance was kept for irrigated water and irrigated water was assumed to evaporate first. The total Incremental ET and the sub-total for each of the five main water use sectors was calculated by aggregating modelled interception evaporation, transpiration, soil water evaporation and open water evaporation from each HRU, where relevant. The partitioning between *Landscape ET* and *Incremental ET* is an area for potential future research.
Non-recoverable Flow	*Non-recoverable Flow* was assumed to be zero as measurements of non-recoverable flow are not generally available and are not modelled in *ACRU*. This is an area for potential future research.
Utilized Flow	*Utilized Flow* is the sum of *Incremental ET* and *Non-recoverable Flow*.
Utilizable Outflow	Utilizable Outflow is *Available Water* minus *Utilized Flow*. *Utilizable Water* is overestimated where *Reserved Outflow* is not known.
Consumed Water	*Consumed Water* is the sum of *Landscape ET*, *Incremental ET* and *Non-recoverable Flow*.
Total Evaporation	*Total Evaporation* is the sum of *Landscape ET* and *Incremental ET*.

Table 4.2 (cont.) Summary of data requirements and methodology to populate the Resource Base Sheet

Interception	The total interception for a catchment was calculated by aggregating modelled interception evaporation from each HRU.
Transpiration	The total transpiration for a catchment was calculated by aggregating modelled transpiration from each HRU.
Soil Water Evaporation	The total soil water evaporation for a catchment was calculated by aggregating modelled soil water evaporation from each HRU.
Open Water Evaporation	The total open water evaporation for a catchment was calculated by aggregating modelled open water evaporation from each HRU.
Outflow	*Outflow* is *Utilizable Outflow* plus *Reserved Outflow*. The *Outflow* value should equal the sum of $Q_{out\ SW}$, $Q_{out\ SW}$ and $Q_{out\ Transfers}$, which is a useful check that all the modelled values balance.
Surface Water Outflow ($Q_{out\ SW}$)	$Q_{out\ SW}$ was calculated from modelled streamflow leaving a catchment.
Groundwater Outflow ($Q_{out\ GW}$)	$Q_{out\ GW}$ was assumed to be zero as measurements of groundwater outflow from catchments are not generally available and are not modelled in *ACRU*. This is an area for potential future research.
Transfers Out ($Q_{out\ Transfers}$)	$Q_{out\ Transfers}$ was calculated as the sum of the inter-catchment transfers out of a catchment which were determined based on measured flow data which was used as an input to the *ACRU* model.

4.3 Spatial Data Processing Tools

As most of the data requirements for hydrological modelling are spatial in nature the use of GIS software tools is essential. Although the proprietary ESRI ArcView GIS 3.2 and ESRI ArcGIS ArcMap 10.2 software were available to the project team at UKZN, it was decided that the GIS processing should be done using the open source Geospatial Data Abstraction Library (GDAL) [http://www.gdal.org] library of GIS processing tools and the Python scripting language [http://www.python.org/] so that non-availability of proprietary software tools would not prevent the methodology from being applied in other catchments after completion of the project. The Python scripting language was selected as it is supported by several proprietary and free GIS software tools such as ArcGIS, GRASS and QGIS. The details of the GDAL and Python related software tools are provided in Appendix A.

The ESRI shapefile format was selected as the vector GIS file format for use in the project due to its widespread use and the availability of software tools to work with it. For the purpose of the methodology being developed it was decided to standardise on the use of the WGS84 reference spheroid for geographic coordinates, and where it was necessary to project to plane coordinates, to calculate areas, the Transverse Mercator projection was used together with a suitable central meridian for the case study catchment.

During the course of the project several Python scripts were developed to process the spatial data required to configure the *ACRU* hydrological model. A list of the Python modules developed and a short description of these modules is included in Appendix B. A comprehensive data processing software library was not an intended product of this project as the availability and format of datasets are expected to vary for different case study areas and purposes, but the Python scripts developed during the project have been included in the electronic appendices Appendix E.1 for use as a starting point for developing similar scripts for different datasets and study areas.

4.4 Catchment Boundaries

The starting point for setting up a case study catchment using the methodology described in this chapter is to create a shapefile dataset of catchment boundaries at an appropriate spatial scale. Although it was decided to compile the water resource accounts at Quaternary Catchment scale, for modelling purposes it is necessary to subdivide Quaternary Catchments into more hydrologically homogeneous sub-Quaternary catchments in order to be able to better represent the spatial variability of land cover, land use, soil types and climate inputs such as rainfall, temperature and reference potential evaporation. Typically a Quaternary Catchment would be subdivided into sub-Quaternary catchments with topographic watersheds taking into account factors such as altitude, land cover, land use, soils, and also points in the river flow network where flow measurement stations and artificial water transfers in and out occur.

In catchments where sub-Quaternary catchment datasets have been developed by water management bodies such as CMAs and water utilities, it is recommended that these datasets be used to make the water accounts compatible with existing management and hydrological modelling units. The NFEPA (Nel *et al.*, 2011) catchment boundaries are also useful but may need to adjusted by subdividing bigger catchments and making adjustments for large dams that are intersected by catchment boundaries. However, the way in which Quaternary catchments are subdivided should make no difference to the proposed methodology for quantifying water use and compiling accounts, though the modelled water use may vary slightly. It may be necessary to make adjustments to the sub-Quaternary catchments to make sure that they match the boundary of the parent Quaternary catchment.

This catchment boundary dataset is use to clip and query many of the other datasets so it is important that this dataset is topologically clean.

The following fields should be added to the selected sub-Quaternary catchment dataset and populated if they do not already exist:

- a field containing a unique integer ID number (>0) for each sub-Quaternary catchment,
- a field containing a unique integer ID number (>0) for each polygon if different to the catchment polygon features,
- a field containing a text name for each sub-Quaternary catchment,
- a field named *DSQUIN* containing the ID of the downstream sub-Quaternary catchment,
- a field named *Area* (use in *ACRU* and data processing),
- a field named *Latitude* (used in *ACRU*),
- a field named *Longitude* (for completeness),
- a field named *Primary* (used in spatial aggregation),
- a field named *Secondary* (used in spatial aggregation),
- a field named *Tertiary* (used in spatial aggregation), and
- a field named *Quaternary* (used in spatial aggregation).

The hierarchy of Quaternary, Tertiary, Secondary and Primary Catchments to which the case study catchments belong is then determined to enable the water resource accounts to be spatially aggregated up to increasingly larger catchments. The revised set of Primary (SLIM, 2014a), Secondary (SLIM, 2014c), Tertiary (SLIM, 2014d) and Quaternary(SLIM, 2014b) Catchment boundary datasets obtained from the DWS were selected for use in the methodology for the following reasons:

- The revised boundaries are an improvement on the previous boundaries and are accepted by DWS.
- The methodology developed in this project is intended for application nationally in the future, so it would be useful for the catchment boundaries used for the two case studies to fit with future studies in neighbouring catchments.
- These catchment boundaries are compatible with the DEM and other products developed by Weepener *et al.* (2011a), some of which will also be used in this project.
- The revised catchment boundary datasets include portions of catchments that are outside the borders of South Africa, Lesotho and Swaziland.

For each case study catchment, depending on the size of the catchment, separate shapefiles containing only the relevant Primary, Secondary, Tertiary, and Quaternary Catchment boundaries are created.

The Python scripts in the following modules were used to process the catchment boundary data:

- *cwrr.Catchments*, for adjusting sub-Quaternary catchment boundaries to match the Quaternary Catchment boundaries, and
- *cwrr.General.ShapefileTools* for general shapefile processing such as clipping and adding attribute fields.

4.5 Representation of the River Flow Network

A representation of the river flow network between catchments is required so that surface water inflows to catchments and surface water outflows from catchments can be modelled and included in the Resource Base Sheet for each catchment. A simple river flow network could be modelled by specifying a downstream catchment for each catchment as indicated in Section 4.4. For this methodology a better representation of the river flow network was adopted to include confluence nodes and nodes where abstractions, return flows, inter-catchment transfers and streamflow measurements occur. This more detailed river flow network enables better sub-Quaternary representation of water availability for abstraction and in the future will enable river flow routing to be implemented.

The shapefile of flow paths Weepener *et al.* (2011c) developed by (Weepener *et al.*, 2011a) was used as it is expected to be consistent with the revised Quaternary Catchment boundaries dataset (SLIM, 2014b) also developed by (Weepener *et al.*, 2011a) and it is not too detailed. One disadvantage of using the Weepener *et al.* (2011c) rivers dataset is that it does not include any river names or other river characteristics. However, other river flow datasets could be used in the same manner. A new shapefile containing a clipped set of river features for the case study catchment should be created to reduce the size of the dataset for subsequent processing.

Using the rivers dataset together with the dataset of sub-Quaternary catchment boundaries, a point shapefile of river nodes can be created with a river node where each sub-Quaternary catchment boundary intersects a river segment and at any point where there is a confluence of river reaches between these points. In principle this river node dataset could be created automatically using GIS software, but due to small mismatches between the catchment boundaries and rivers, it is better to create this dataset manually. Information contained in the network diagrams for the WRSM2000 model, available from the WR2012 study website (http://waterresourceswr2012.co.za/), are a useful guide to identifying where inter-catchment transfers, abstractions and return flows occur. The following fields should be added to the river nodes dataset and populated:

- A field named *NodeID* containing a unique ID (text or integer>0) for each river node.
- A field named *NodeName* containing a text name for each river node.
- A field named *DSNodeID* containing the ID of the downstream sub-Quaternary catchment.
- A field named *SCNForCats* containing a comma separated list of sub-Quaternary catchment IDs for which the river node is the exit node. Typically one catchment per node, unless there is a river confluence at the exit of two or more catchments.
- A field named *InCats* containing a comma separated list of sub-Quaternary catchment IDs which either contain the river node at an internal confluence or share a common boundary at the river node.

The rivers and river nodes dataset need not take into account dams as these are represented in the dams dataset discussed in Section 4.6. However, for major dams that interrupt the main river flow network between sub-Quaternary catchments, it is recommended that additional river nodes be created where the rivers enter and exit the dam if such nodes do not already exist.

The Python scripts in the *cwrr.General.ShapefileTools* module were used for general shapefile processing of the river flow network data.

4.6 Representation of Dams

It is necessary to represent both major dams and smaller farm dams in each sub-Quaternary catchment in the hydrological model to estimate water depleted in the catchment due to evaporation from the open water surfaces and so that the regulatory effect of dams on downstream river flows can be represented in the accounts. The land cover/use datasets usually include at least one class representing waterbodies and may even have a specific class representing dams.

A simple way to represent dams is to estimate the total surface area of dams for each sub-Quaternary catchment from the total pixel area of the waterbody or dam class in each sub-

Quaternary catchment. This area is then used, together with an equation, such as Equation 4.1 (Maaren and Moolman, 1985), representing a generic surface area:volume relationship to estimate a combined dam volume. However, some disadvantages of this method are that (i) 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, (ii) 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, (iii) all dams are represented as one lumped dam per sub-Quaternary catchment, and (iv) the generic surface area:volume relationship may not give an accurate estimate of total dam storage volume when applied to the combined surface area of a number of smaller dams.

$$A = 7.2\, S_v^{\,0.77} \tag{4.1}$$

where:

A = surface area (m^2), and

S_v = storage volume (m^3).

For this methodology it was decided that a better representation of dams was required and that the DWS Dam Safety Office (DSO) database of registered dams (DSO, 2014) should be used in conjunction with the land cover/use datasets. The DSO (2014) database was selected as it (i) represents all dams of a significant size, those with a storage capacity of more than 50000 m^3, excluding only very small dams, (ii) includes surface area, volume and other useful information, (iii) seems to be updated regularly, and (iv) is freely available. However, the only spatial information associated with the dataset is the latitude and longitude of each dam and the location of the dams need to be checked against other sources such as Google Earth [http://earth.google.com] and the 1:50000 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 representing the dam is located in the correct sub-Quaternary catchment and not just downstream in the next catchment.

An update of the DSO (2014) database, which is in Microsoft Excel (.xlsx) format was first saved to a file in Comma Separated Value (CSV) format, which was converted into a point shapefile using the latitude and longitude values in the dataset. This shapefile was then clipped to produce a shapefile of registered dams in the case study catchment. The location of the dams in this clipped shapefile of registered dams was then checked against other datasets and the sub-Quaternary catchment boundaries dataset and corrections made where necessary. Although this dataset makes it possible to model individual dams within a sub-Quaternary catchment, this is not practical unless the contributing catchment areas and water users from each dam are also modelled individually. For the purpose of this methodology a shapefile of dam nodes was created based on the following assumptions and rules:

- All the larger dams with a storage volume above a specified threshold are represented as individual dam nodes at their specified location and are assumed to be on the main river channel within a sub-Quaternary catchment.
- For modelling purposes these larger dams are assumed to be at the downstream exit of a sub-Quaternary catchment.
- If there is more than one dam with a storage volume above the threshold per sub-Quaternary catchment, then these dams are modelled in order by storage volume along the main river channel with the smallest at the top and the increasingly larger dams downstream of it.
- All the smaller dams below the threshold are combined as a lumped dam, by summing the individual surface areas and volumes, and represented by a dam node at the centroid of their locations and assumed to be off the main river channel.
- For modelling purposes these lumped dams are assumed to receive runoff from the whole sub-Quaternary catchment but not flow from upstream catchments, and they then flow into any large individual dams in their respective catchments.
- All water users abstracting water within their sub-Quaternary catchment use the lowest and largest dam 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. This assumption means that there may be water in registered dams that would not be modelled as being available for irrigation in HRUs containing irrigated crops. An alternative is set a high enough storage volume threshold such that all registered dams in a sub-Quaternary catchment are lumped together near the exit of a catchment and can act as a water source for all water users in the catchment.

The total surface area of registered dams within a sub-Quaternary catchment was then compared to the total area of dams calculated from the land cover/use dataset. One would expect the total area from the land cover/use dataset to be larger in most cases as not all dams are registered and there may also be natural water bodies. In this case a lumped dam, off the main river channel, representing these smaller unregistered dams is modelled, using the difference in surface area and calculating the volume using Equation 4.1. These small unregistered dams impede runoff generated within a catchment but are assumed to not be used for irrigation. It is possible that the total area estimated from the land cover/use dataset could in some cases be smaller than the total area of registered dams, due to classification errors and the satellite imagery used to create the land cover/use dataset being taken at a time of year when dams are not full. In this case the database of registered dams is assumed to be correct and the area of other land cover/use classes is reduced slightly to accommodate the difference in areas.

Two methods of initialising dams storages at the start of the period covered by water resource account are suggested, (i) using measured data level data and (ii) by running the hydrological model for a year or two prior to the start date of the accounting period. For the larger dams dam level data can be requested from the "*Hydrological Services – Surface Water (Data, Dams, Floods and Flows)*" page of the DWS website (http://www.dwa.gov.za/hydrology/), but for smaller dams the starting storage may need to be estimated taking rainfall and the time of year into account.

The Python scripts in the following modules were used to process the dam data:

- *cwrr.Dams.DWSRegisteredDams*, for processing the DWS DSO database of registered dams, and
- *cwrr.General.ShapefileTools* for general shapefile processing such as clipping and copying shapefiles.

4.7 Altitude

The gap-filled DEM (Weepener *et al.*, 2011d) developed by Weepener *et al.* (2011a) for South Africa was selected for use in the methodology as is compatible with the other datasets developed by Weepener *et al.* (2011a) , several of which have also been selected for use in the methodology. A new raster dataset is first created for the case study catchment area by clipping the Weepener *et al.* (2011d) dataset, as the smaller dataset makes subsequent processing faster. A shapefile dataset containing the mean altitude for each sub-Quaternary catchment is then created for use in the *ACRU* model.

The Python scripts in the following modules were used to process the altitude data:

- *cwrr.Altitude.WRC_SRTM90*, for processing the (Weepener *et al.*, 2011d) altitude dataset to calculate catchment mean altitude, and
- *cwrr.General.RasterTools* for general raster file processing such as clipping the shapefile.

4.8 Land Cover and Land Use

Land cover and land use are key attributes of a catchment with regard to water use. 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. Even within a particular land cover/use different management practices can also have a significant impact on water resources. Consequently, the water use quantification and accounting methodology developed in this project has a strong land cover/use focus.

4.8.1 Classification of actual land cover/use

As discussed in Section 3.3.2 there are several datasets of actual land cover/use available and the selection of a land cover/use dataset should be based on the most suitable dataset for the specific case study catchment, the time domain of the water account and the degree of detail required. If there is no recent land cover/use dataset available for the specific case study catchment, then it is recommended that the updated national dataset of actual land cover (DEA and GTI, 2015) be used.

As land cover databases are compiled for different purposes by different people and organisations, the classification system used varies, as is evident in the discussion in Section 3.3.2. For this reason some form of standard classification of land cover/use is required so that the water use quantification and accounting methodology developed in this project can 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 standard land cover/use classification for use in the water use quantification and accounting methodology was an iterative process during the course of the project. Initially a standard set of 36 land cover/use classes was compiled, largely based on the classes in ARC and CSIR (2005) database and the Ezemvelo KZN Wildlife (2011) land cover database. There were two main criticisms of this set of 36 standard land cover/use classes. First, that the water use by the different classes present in a catchment was not reported in detail in the WA + Resource Base sheet, only summarised according to the four broad four land/water use categories (Protected, Utilized, Modified, Managed) shown in

Figure 4.2. Secondly, that having just 36 standard land cover/use classes would mean that land cover/use datasets with more detail could not be used to their full potential. For example the land cover/use dataset (ICMA, 2012b) compiled for the ICMA in 2010 at a 2.5m resolution includes specific agricultural crops, compared to the more generic *commercial-dryland-annual* and *commercial-irrigated-annual* type classes used in most of the other land cover/use datasets. These criticisms led to a proposal to develop a hierarchy of land cover/use classes representing sectoral water use at different levels of detail, where the detail reported in the water accounts will depend on the land cover/use information available and the audience for which the accounts are created. This hierarchical set of standard land cover/use classes was subsequently developed with the intention that it be as inclusive and as flexible as possible, to hopefully be compatible with most existing land cover/use classifications and to enable future expansion if necessary.

Before the design of the standard land cover/use class hierarchy is described it is necessary to first define a few terms, as they will be used in this methodology:

- A *class* represents a group of entities (in this case, land cover/use instances) which have the same set of attributes and are indistinguishable from each other based on the values assigned to these attributes.
- An *attribute* is a characteristic of a class that is used to describe the entities belonging to it and to differentiate these entities from entities in other classes.
- A *category* is a grouping of classes or subcategories with similar attributes.
- A *hierarchy* is an ordered set of categories of classes, where the most specific categories are at the bottom of the hierarchy and these exist within increasingly more general categories, with the most general category (or categories) being at the top of the hierarchy.
- A *hierarchical category* is a category of classes which clearly fits within a hierarchy of other class categories, that is, there is a clear order.
- An *attribute category* is a category of classes which does not clearly fit within a hierarchy of class categories, that is, there is no clear order.

The starting point for the development of a hierarchical set of standard land cover/use classes was to decide on the first level of classes. The SANBI (2009b) dataset has seven broad land cover/use classes:

- Natural,
- Cultivation,
- Degraded,
- Urban Built-Up,
- Waterbodies,
- Plantations, and
- Mines.

Schulze and Hohls (1993) developed a land cover and land use classification system for application in a water and agrohydrological modelling context. This classification system was used in the development of a database of default land cover/use vegetation variables for use in configuring the *ACRU* model (Schulze *et al.*, 1995). The classification system developed by Schulze and Hohls (1993), shown in Figure 4.4, is a hierarchical four-level system taking into account above-ground, surface and below-ground factors affecting hydrological processes. Level 1 includes a small set of broad land cover/use categories; Level 2 includes functional sub-classes of the Level 1 categories based on general hydrological response characteristics; Level 3 typically includes vegetation species related categories of the Level 2 categories; and Level 4 includes subdivisions for the Level 3 categories based on regional characteristics or different methods of site preparation (Schulze and Hohls, 1993). In this classification system a numbering system was used to identify each class based on the category it belonged to in each level. The Level 1 categories in this classification system are:

- Urban,
- Natural Vegetation,
- Agricultural Crops,
- Aquatic Systems and
- Commercial Forests.

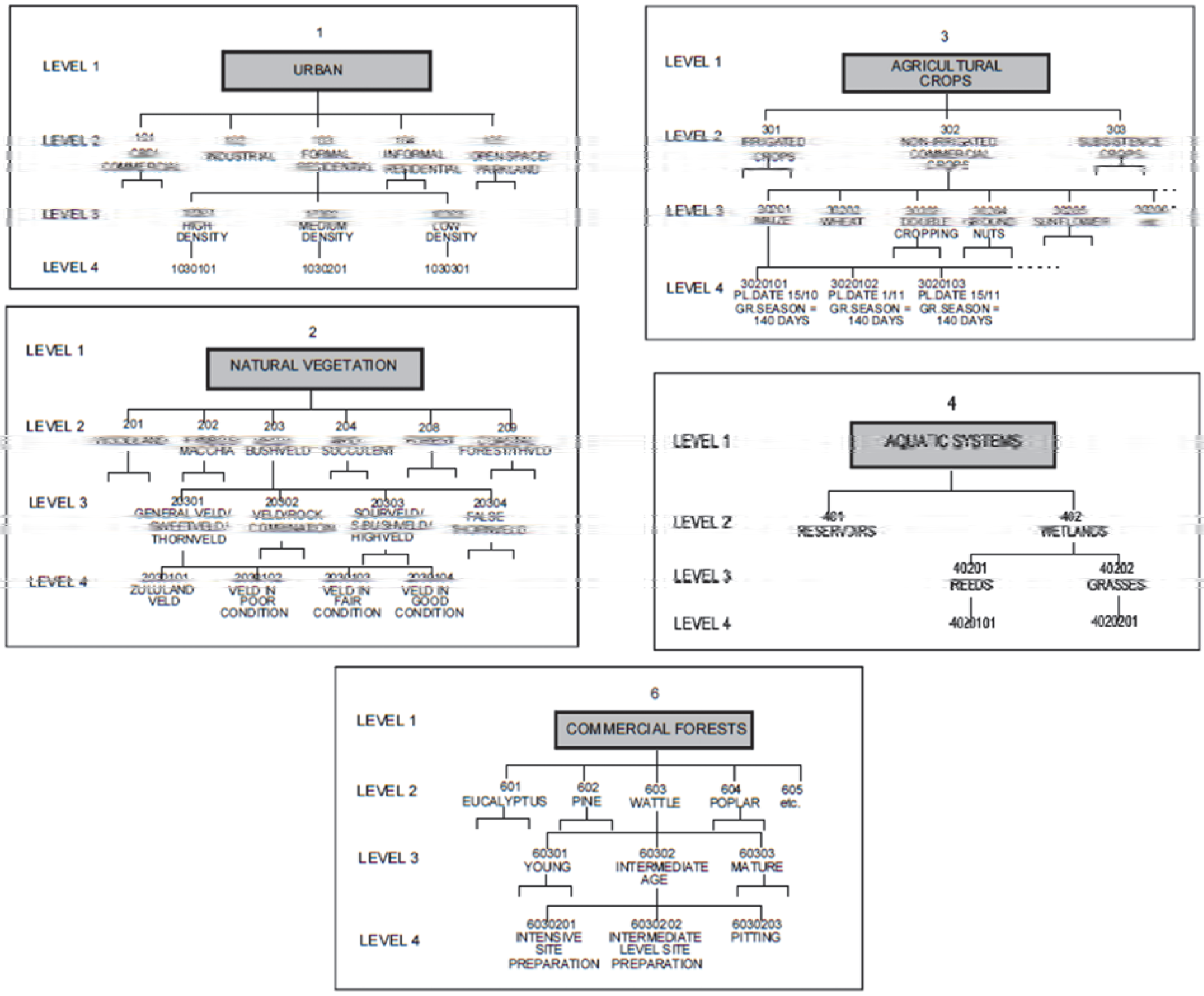


Figure 4.4 The four-level structure of the land cover/use classification system developed by Schulze and Hohls (1993) (Schulze *et al.*, 1995)

In addition Schulze and Hohls (1993) developed a database of hydrologically related land cover/use attributes such as crop coefficient, leaf area index, vegetation interception loss and rooting distribution for use in the *ACRU* model. This *ACRU* land cover/use information database, commonly known as the *Compoveg Database*, is described further by Schulze *et al.* (1995). The *Compoveg Database* is under continual development for use together with the *ACRU* model.

The standard hierarchy of land cover/use classes developed for use in the water use quantification and accounting methodology was based on the Schulze and Hohls (1993) land cover/use classification system, the SANBI (2009b) broad land cover/use classes and the classifications used in the ARC and CSIR (2005) dataset, the Ezemvelo KZN Wildlife (2011) dataset, the ICMA (2012b) dataset and also the classes for the Gauteng and North West provincial datasets documented in SANBI (2009b). The following five Level 1 classes were selected as discussed in Section 4.1 for use in the Resource Base Sheet:

- Natural,
- Cultivated,
- Urban/Built-up,
- Mines and Quarries, and
- Waterbodies.

4.8.1.1 Natural Land Cover/Use Category

The *Natural* category is intended to represent areas covered with natural vegetation or uncultivated bare ground. The first three levels of the *Natural* class hierarchy are shown in Figure 4.5. The *Natural* category has two sub-categories, *Typical* and *Degraded*. The *Typical* category represents areas with natural vegetation in “typical” condition, typical in the sense that they are not considered to be degraded, but may range in condition and degree of utilization. The *Typical* category includes naturally occurring bare (unvegetated) areas. The *Degraded* category represents areas with natural vegetation that are now classified as degraded through activities such as overgrazing, and also areas that are unvegetated due to erosion. The full hierarchy of categories for the *Natural* category is shown in Table 4.3 for the *Typical* sub-category and in Table 4.4 for the *Degraded* sub-category. At Level 3 the distinction between bare and vegetated areas is made and vegetation is represented according to existing systems of classifying natural vegetation. The *General* sub-category includes the very general classes of natural vegetation used in the ARC and CSIR (2005) dataset. The *Acocks* sub-category includes the Acocks Veld Types (Acocks, 1988), with the Acocks Veld Type groups at Level 4 and the 70 Acocks Veld Types at Level 5. The Acocks Veld Types identified by (Acocks, 1988) have been used as they are a generally accepted scientific accepted mapping of natural vegetation (Schulze, 2008a), and have been widely used in South Africa. In addition (Schulze, 2004) proposes a set of hydrological modelling variable values for each Acocks Veld Type, including crop coefficients, interception capacity, rooting fractions and coefficients of initial abstraction required by the *ACRU* model. Similarly, there is the potential to add other natural vegetation classifications to the hierarchy, for example the more recent and more detailed dataset of the vegetation types of South Africa by Mucina and Rutherford (2006). The (Mucina and Rutherford, 2006) classification has not been included in the hierarchy yet, as currently there is no similar set of hydrological variable values describing the hydrological characteristics of these vegetation classes.

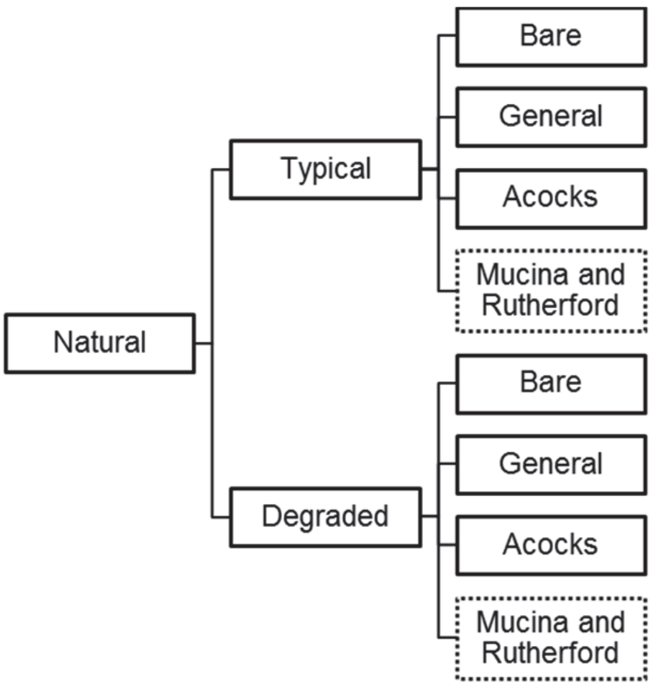


Figure 4.5 The first three levels of the *Natural* class hierarchy

Table 4.3 Hierarchical categories for the *Natural* – *Typical* category

Hierarchical Categories				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Natural	Typical	Bare	Rock	
			Rock and Soil	
			Soil	
			Sand – Inland	
			Sand – Coastal	
		General	Forest (Indigenous)	
			Woodland	
			Thicket, Bushland, Bush Clumps, High Fynbos	
			Shrubland And Low Fynbos	
			Herbland	
			Natural Grassland	
		Acocks	Coastal Tropical Forest	01_Coastal Forest And Thornveld
				02_Alexandria Forest
				03_Pondoland Coastal Plateau Sourveld
				04_Knysna Forest
				05_Ngongoni Veld

Table 4.3 (cont.) Hierarchical categories for the *Natural* – *Typical* category

				06_Zululand Thornveld
				07_Eastern Province Thornveld
			Inland Tropical Forest	08_North-Eastern Mountain Sourveld
				09_Lowveld Sour Bushveld
			Tropical Bush and Savanna (Bushveld)	10_Lowveld
				11_Arid Lowveld
				12_Springbok Flats Turf Thornveld
				13_Other Turf Thornveld
				14_Arid Sweet Bushveld
				15_Mopani Veld
				16_Kalahari Thornveld
				17_Kalahari Thornveld Invaded By Karoo
				18_Mixed Bushveld
				19_Sourish Mixed Bushveld
				20_Sour Bushveld
			False Bushveld	21_False Thornveld Of Eastern Cape
				22_Invasion Of Grassveld By Acacia Karoo
			Karoo and Karroid	23_Valley Bushveld
				24_Noorsveld
				25_Succulent Mountain Scrub(Spekboomveld)
				26_Karroid Broken Veld
				27_Central Upper Karoo
				28_Western Mountain Karoo
				29_Arid Karoo
				30_Central Lower Karoo
				31_Succulent Karoo
				32_Orange River Broken Veld
				33_Namaqualand Broken Veld
				34_Strandveld
			False Karoo	35_False Arid Karoo
				36_False Upper Karoo
				37_False Karroid Broken Veld
				38_False Central Lower Karoo
				39_False Succulent Karoo
				40_False Orange River Broken Veld
				41_Pan Turf Veld Invadedby Karoo
				42_Karroid Merxmuellera Mountain Veld Replaced By Karoo
				43_Mountain Renosterveld

Table 4.3 (cont.) Hierarchical categories for the *Natural* – *Typical* category

			Temperate and Transitional Forest and Scrub	44_Highland Sourveld And Dohne Sourveld
				45_Natal Mist Belt Ngongoniveld
				46_Coastal Renosterveld
				47_Coastal Macchia
			Pure Grassveld	48_Cymbopogon-Themeda Veld
				49_Transitional Cymbopogon-Themeda Veld
				50_Dry Cymbopogon-Themeda Veld
				51_Pan Turf Veld
				52_Themeda Veld Or Turf Highveld
				53_Patchy Highveld To Cymbopogon-Themeda Veld Transition
				54_Turf Highveld To Highland Sourveld Transition
				55_Bankenveld To Turf Highveld Transition
				56_Highland Sourveld To Cymbopogon-Themeda Veld Transition(Eastern Free State Highveld)
				57_North-Eastern Sandy Highveld
				58_Themeda-Festuca Alpine Veld
				59_Stormberg Plateau Sweetveld
				60_Karroid Merxmuellera Mountain Veld
			False Grassveld	61_Bankenveld
				62_Bankenveld To Sour Sandveld Transition
				63_Piet Retief Sourveld
				64_Northern Tall Grassveld
				65_Southern Tall Grassveld
				66_Natal Sour Sandveld
				67_Pietersburg Plateau False Grassveld
				68_Eastern Province Grassveld
			Sclerophyllous Bush	69_Fynbos
			False Sclerophyllous Bush	70_False Fynbos

Table 4.4 Hierarchical categories for the *Natural – Degraded* category

Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Natural	Degraded	Bare	Erosion – Sheet	
			Erosion – Gullies	
		General	Degraded Forest & Woodland	
			Degraded Thicket, Bushland, etc.	
			Degraded Shrubland And Low Fynbos	
			Degraded Unimproved (Natural) Grassland	
		Acocks	Coastal Tropical Forest	01_Coastal Forest And Thornveld
				02_Alexandria Forest
				03_Pondoland Coastal Plateau Sourveld
				04_Knysna Forest
				05_Ngongoni Veld
				06_Zululand Thornveld
				07_Eastern Province Thornveld
			Inland Tropical Forest	08_North-Eastern Mountain Sourveld
				09_Lowveld Sour Bushveld
			Tropical Bush and Savanna (Bushveld)	10_Lowveld
				11_Arid Lowveld
				12_Springbok Flats Turf Thornveld
				13_Other Turf Thornveld
				14_Arid Sweet Bushveld
				15_Mopani Veld
				16_Kalahari Thornveld
				17_Kalahari Thornveld Invaded By Karoo
				18_Mixed Bushveld
				19_Sourish Mixed Bushveld
				20_Sour Bushveld
			False Bushveld	21_False Thornveld Of Eastern Cape
				22_Invasion Of Grassveld By Acacia Karoo
			Karoo and Karroid	23_Valley Bushveld
				24_Noorsveld
				25_Succulent Mountain Scrub(Spekboomveld)
				26_Karroid Broken Veld
				27_Central Upper Karoo
				28_Western Mountain Karoo

Table 4.4 (cont.) Hierarchical categories for the *Natural – Degraded* category

				29_Arid Karoo
				30_Central Lower Karoo
				31_Succulent Karoo
				32_Orange River Broken Veld
				33_Namaqualand Broken Veld
				34_Strandveld
			False Karoo	35_False Arid Karoo
				36_False Upper Karoo
				37_False Karroid Broken Veld
				38_False Central Lower Karoo
				39_False Succulent Karoo
				40_False Orange River Broken Veld
				41_Pan Turf Veld Invadedby Karoo
				42_Karroid Merxmuellera Mountain Veld Replaced By Karoo
				43_Mountain Renosterveld
			Temperate and Transitional Forest and Scrub	44_Highland Sourveld And Dohne Sourveld
				45_Natal Mist Belt Ngongoniveld
				46_Coastal Renosterveld
				47_Coastal Macchia
			Pure Grassveld	48_Cymbopogon-Themeda Veld
				49_Transitional Cymbopogon-Themeda Veld
				50_Dry Cymbopogon-Themeda Veld
				51_Pan Turf Veld
				52_Themeda Veld Or Turf Highveld
				53_Patchy Highveld To Cymbopogon-Themeda Veld Transition
				54_Turf Highveld To Highland Sourveld Transition
				55_Bankenveld To Turf Highveld Transition
				56_Highland Sourveld To Cymbopogon-Themeda Veld Transition(Eastern Free State Highveld)
				57_North-Eastern Sandy Highveld
				58_Themeda-Festuca Alpine Veld
				59_Stormberg Plateau Sweetveld
				60_Karroid Merxmuellera Mountain Veld

Table 4.4 (cont.) Hierarchical categories for the *Natural – Degraded* category

			False Grassveld	61_Bankenveld
				62_Bankenveld To Sour Sandveld Transition
				63_Piet Retief Sourveld
				64_Northern Tall Grassveld
				65_Southern Tall Grassveld
				66_Natal Sour Sandveld
				67_Pietersburg Plateau False Grassveld
				68_Eastern Province Grassveld
			Sclerophyllous Bush	69_Fynbos
			False Sclerophyllous Bush	70_False Fynbos

4.8.1.2 Cultivated Land Cover/Use Category

The *Cultivated* category is intended to represent areas covered with agricultural crops or production forest plantations. The hierarchy and attributes for the *Agriculture* sub-category are shown in Table 4.5, and for the *Forest Plantations* sub-category in Table 4.6. An initial investigation into classifying agricultural land cover/use resulted in several categorisations such as crop types, whether the crop is irrigated, summer vs winter crops, annual vs perennial crops, and whether the crops are grown commercially or on a subsistence basis. However, it was soon apparent that these different categorisations did not fit into a clear hierarchical structure as, for example, one user of the water accounts may be interested in water use by different crops, while another user may be interested in water use by irrigated vs dryland agriculture. The result was that the concept of *attribute categories* was used to allow for user selectable categorisations of agricultural land covers/uses without forcing these categorisations into a particular level in a hierarchy. These attribute categories would enable water use by a variety of agricultural land covers/uses to be summarised using Pivot Tables. Similarly for the *Forest Plantations* category there are attribute categories describing the age of the trees in a plantation and the type of site preparation used. Additional attribute categories could be easily added without any effect on the hierarchy.

Table 4.5 Hierarchical and attribute categories for the *Cultivated – Agriculture* category

Hierarchical Categories		Attribute Categories				
Level 1	**Level 2**	**Irrigated vs Dryland**	**Annual vs Perennial**	**Commercial vs Subsistence**	**Growing Season**	**Crop Type**
Cultivated	Agriculture	Dryland	Annual	Commercial	General	General
		Irrigated	Perennial	Subsistence	Summer	Apples
					Winter	Avocados
					Double	Bananas
					All year	Beans – Dry
						Beans – Green
						Blueberries
						Brassicas
						Cashews
						Citrus
						Citrus – Grapefruit
						Citrus – Lemons
						Citrus – Oranges
						Coffee
						Cotton
						Cucurbits
						Ginger
						Granadillas
						Grapes – Table
						Grapes – Wine
						Groundnuts
						Guavas
						Hay
						Kiwifruit
						Litchis
						Lucerne
						Lupins
						Macadamias
						Maize
						Maize & Wheat
						Mangos
						Onions
						Pasture
						Pawpaws
						Pears

Table 4.5 (cont.) Hierarchical and attribute categories for the *Cultivated – Agriculture* category

						Peas
						Pecan Nuts
						Pineapples
						Pomegranates
						Potatoes
						Sorghum
						Soybeans
						Stone Fruit – Plums, Peaches, Apricots, Nectarines, Cherries, etc.
						Sugarcane
						Sunflowers
						Tea
						Tobacco
						Tomatoes
						Vegetables
						Wheat

Table 4.6 Hierarchical and attribute categories for the *Cultivated – Forest Plantations* category

Hierarchical Categories			**Attribute Categories**	
Level 1	**Level 2**	**Level 3**	**Age**	**Site Preparation**
Cultivated	Forest Plantations	General	General	General
			Young	Intermediate
			Medium	Intensive
			Mature	Pitting
		Pine	General	General
			Young	Intermediate
			Medium	Intensive
			Mature	Pitting
		Eucalyptus	General	General
			Young	Intermediate
			Medium	Intensive
			Mature	Pitting
		Wattle	General	General
			Young	Intermediate
			Medium	Intensive
			Mature	Pitting
		Poplar	General	General
			Young	Intermediate
			Medium	Intensive
			Mature	Pitting
		Clearfelled	-	-

4.8.1.3 Urban/Built-up Land Cover/Use Category

The *Urban/Built-up* category is intended to represent urban and other built-up areas. The hierarchy for the *Urban/Built-up* category is shown in Table 4.7. The Level 2 categories represent the broad types of urban land use, namely residential, commercial, industrial and open spaces. The *Residential* category has sub-categories representing formal and informal areas with different building and population densities within these two groupings. The *Smallholdings* category represents peri-urban plots of land not used for agricultural production. The *Open Spaces* category represents urban open spaces typically used for recreation purposes, such as golf courses, sports fields, parks and botanical gardens. The *Commercial* category represents commercial, non-industrial, areas, the *Mercantile* and *Education, Health and IT*, sub-categories are groupings used in most of the classifications mentioned in Section 3.3.2. The *Agricultural* sub-category represents areas with agricultural structures that are distinct from cultivated agriculture, such as greenhouses, chicken houses, packing facilities and feedlots. The *Industrial/Transport* category represents areas designated for heavy and light industry, but also includes transport infrastructure such as roads, railways, airports and airstrips as some classifications have separate industry and transport classes and some combine these into one class.

Table 4.7 Hierarchical categories for the *Urban/Built-up* category

Hierarchical Categories		
Level 1	**Level 2**	**Level 3**
Urban/Built-up	Residential	Formal – Very High Density (Metro Area)
		Formal – High Density (Formal Townships)
		Formal – Medium Density (Suburbs)
		Formal – Low Density (Peri-Urban)
		Informal – High Density (Informal Townships)
		Informal – High Density (Squatter Camps)
		Informal – Low Density Rural
		Smallholdings (Peri-Urban)
	Open Spaces (Golf Courses and Sports fields. etc.)	-
	Commercial	Mercantile
		Education Health IT
		Agricultural
	Industrial/Transport	Heavy
		Light
		Roads and Railways
		Airports and Airfields

4.8.1.4 Mines and Quarries Land Cover/Use Category

The *Mines and Quarries* category has the simple hierarchy shown in Table 4.8, with a distinction being made between subsurface and surface mining features. The representation of the hydrological impact of these mining related land cover/use classes requires further investigation and may result in changes to the hierarchy.

Table 4.8 Hierarchical categories for the *Mines and Quarries* category

Hierarchical Categories		
Level 1	**Level 2**	**Level 3**
Mines and Quarries	Surface	Opencast Mine/Quarry
		Tailings/Dumps
	Subsurface	Subsurface Mine

4.8.1.5 Waterbodies Land Cover/Use Category

The *Waterbodies* category is intended to represent open bodies of water and wetland areas with aquatic vegetation land cover. The hierarchy for the *Waterbodies* category is shown in Table 4.9. There are three Level 2 categories *General*, *Natural* and *Artificial*. The General sub-category has been included as some classifications do not distinguish between different types of waterbody. The *Natural* sub-category includes naturally occurring waterbodies such as rivers, estuaries, lakes pans and wetlands. The *Artificial* sub-category includes man-made water containment and transfer structures such as dams, sewage ponds and canals.

Table 4.9 Hierarchical categories for the *Waterbodies* category

Hierarchical Categories			
Level 1	**Level 2**	**Level 3**	**Level 4**
Waterbodies	General		
	Natural	Rivers	
		Estuaries	
		Lakes and Pans	
		Wetlands	General
			Grasses
			Reeds
			Mangrove
	Artificial	Canals	
		Dams	
		Sewage Ponds	

4.8.2 Application of the land cover/use hierarchy and classes

The hierarchical set of standard land cover/use classes described in Section 4.8.1 was implemented by creating:

- 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, and

- a set of mapping files relating land cover/use dataset classes to standard land cover/use classes.

4.8.2.1 Land Cover/Use Hierarchy File

The land cover/use hierarchical and attribute categories discussed in Sections 4.8.1.1 to 4.8.1.5 provide a means of grouping similar land covers and uses so that they can be summarised in the water accounts with different degrees of detail. These land cover/use hierarchical and attribute categories were listed in an Extensible Markup Language (XML) formatted file named *LCU_Hierarchy.xml*. The XML format was selected as its structure enables hierarchies to be easily represented. The XML schema used for the *LCU_Hierarchy.xml* file is shown in Figure 4.6. The main *LCU_Hierarchy* element may contain hierarchical category (*HCat*) elements, which in turn may contain child hierarchical category (*HCat*) elements and attribute category (*ACat*) elements. An example of a small portion of the *LCU_Hierarchy.xml* file is shown in Figure 4.7 to show how the structure of the hierarchical and attribute categories is represented. The Python scripts in the *cwrr.LandCover.LCU_ClassHierarchy* module are used to create and read the *LCU_Hierarchy.xml* file.

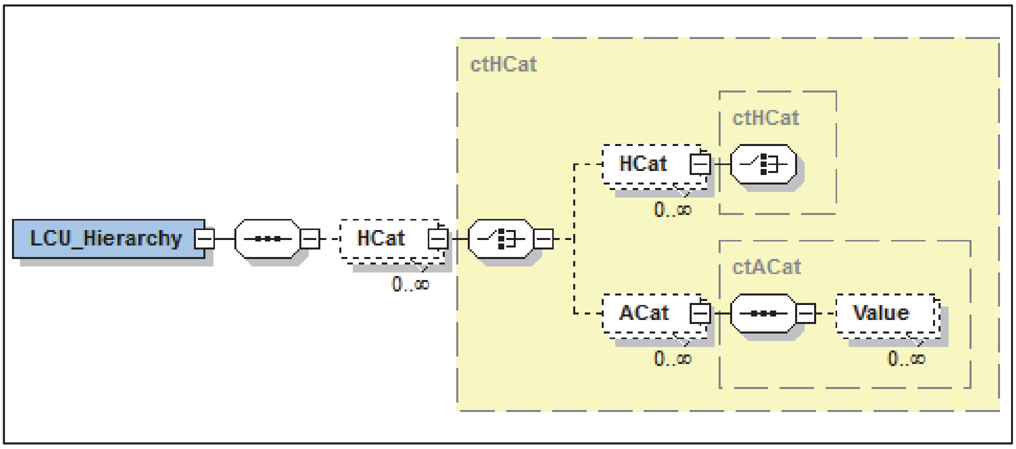


Figure 4.6 Design of the XML schema used for the *LCU_Hierarchy.xml* file

```xml
<HCat Name="Cultivated">
    <HCat Name="Agriculture">
        <ACat Name="CropType">
            <Value>Maize</Value>
            <Value>Wheat</Value>
        </ACat>
        <ACat Name="Irrigated/Dryland">
            <Value>Dryland</Value>
            <Value>Irrigated</Value>
        </ACat>
```

Figure 4.7 Example of a portion of the *LCU_Hierarchy.xml* file

4.8.2.2 Land Cover/Use Classes Database

To represent the different land cover/use classes for the purpose of modelling water use, a database of land cover/use class information was developed. Typically there would be at least one land cover/use class in the database for each hierarchical category and each attribute category value in the *LCU_Hierarchy.xml* file. However, not all permutations of attribute category values make sense, so not all the permutations would have an associated class. It is possible to have more than one class belonging to each hierarchical category or permutation of attribute category values, for example, water use by two maize cultivars could be modelled differently, but grouped together as Cultivated – Agriculture – Maize – Dryland – Summer for the purpose of the water accounts.

The database of land cover/use classes is stored in an XML formatted file named *LCU_Classes.xml*. The database of land cover/use classes has been separated from the *LCU_Hierarchy.xml* file so that different databases of classes, possibly for different models, could be created, but both have reference to the same standard land cover/use class hierarchy. The XML schema used for the *LCU_Classes.xml* file is shown in Figure 4.8. The main *LCU_Classes* element contains *Class* elements, where each *Class* element has a name, a description element (*Desc*), and a hierarchical category element (*HCat)* which contains a comma separated list of hierarchical category names identifying the hierarchical categories to which the class belongs. Each *Class* element may contain one or more *Attribute* elements describing the characteristics of the land cover/use represented by the class. Some of these class attributes relate to the attribute categories in the *LCU_Hierarchy.xml* file and other attributes are used solely to configure the hydrological model. Examples of other attributes are variables describing the vegetated land cover and the fractions of the area that are pervious and impervious. An example of a small portion of the *LCU_Classes.xml* file is shown in Figure 4.9 for commercial, dryland, summer, maize. The *HCat* and *Desc* elements are shown first, followed by the *Attribute* elements. The next few *Attribute* elements, for example *CropType,* are related to the attribute categories shown in Table 4.5 for the *Cultivated – Agriculture* category. The *Attribute* element with *Name=CAY* contains month-of-year mean crop coefficient values for use in hydrological modelling. The Python scripts in the *cwrr.LandCover.LCU_ClassHierarchy* module are used to create and read the *LCU_Classes.xml* file.

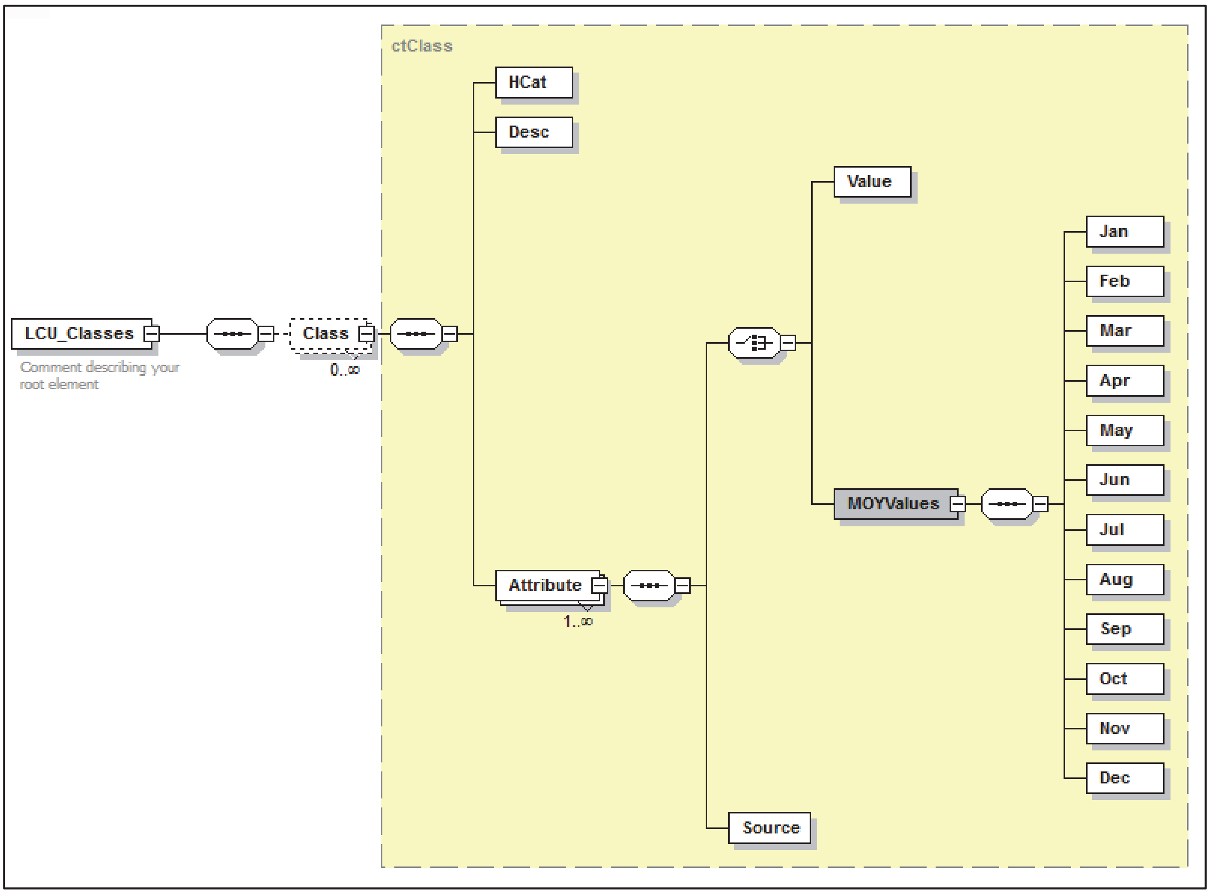


Figure 4.8 Design of the XML schema used for the *LCU_Classes.xml* file

```xml
<Class Name="Agriculture_Commercial_Maize_Dryland_Summer">
  <HCat>Cultivated,Agriculture</HCat>
  <Desc>General commercial dryland summer maize (Based on Compoveg 3020102 –
        MAIZE - ALL AREAS = NOV 1 GROWING SEASON = 140 days)</Desc>
  <Attribute ID="Annual/Perennial">
    <Value>Annual</Value>
    <Source />
  </Attribute>
  <Attribute ID="Commercial/Subsistence">
    <Value>Commercial</Value>
    <Source />
  </Attribute>
  <Attribute ID="CropType">
    <Value>Maize</Value>
    <Source />
  </Attribute>
  <Attribute ID="Growing Season">
    <Value>Summer</Value>
    <Source />
  </Attribute>
  <Attribute ID="Irrigated/Dryland">
    <Value>Dryland</Value>
    <Source />
  </Attribute>
  <Attribute ID="CAY">
    <MOYValues>
      <Jan>1.1</Jan>
      <Feb>0.95</Feb>
      <Mar>0.46</Mar>
      <Apr>0.2</Apr>
      <May>0.2</May>
      <Jun>0.2</Jun>
      <Jul>0.2</Jul>
      <Aug>0.2</Aug>
      <Sep>0.2</Sep>
      <Oct>0.2</Oct>
      <Nov>0.49</Nov>
      <Dec>0.98</Dec>
    </MOYValues>
    <Source>Compoveg 3020102</Source>
  </Attribute>
```

Figure 4.9 Example of a portion of the *LCU_Classes.xml* file

The land cover/use attributes that describe the hydrological characteristics of the land cover/use classes were based on the *Compoveg Database* (Schulze and Hohls, 1993; Schulze, 1995a) for the *ACRU* model which includes attribute values for the Acocks Veld Types based on the values in Schulze (2004). Other sources of information included Schulze (2013), Smithers and Schulze (1995), Allen *et al.* (1998), Chapagain and Hoekstra (2004), Burger *et al.* (2003) and Smith (2006). The database of land cover/use classes is not intended to be a complete database and should be expanded as required to suit different land cover/use datasets and individual case study catchments.

4.8.2.3 Mapping to the Standard Land cover/use Classes

To apply the standard land cover/use classes and hierarchy for use with a specific land cover/use dataset it is necessary to create a mapping table in which one of the standard land cover/use classes is assigned to each class in the land cover/use dataset. If a suitable standard land cover/use class is not found in the database then a new class could be created. These tables are saved in a Comma Separated Value (CSV) file. A simple example of a mapping file is shown in Table 4.10, where *Dataset_ID* is land cover/use dataset class integer ID, *Dataset_Desc* is the land cover/use class text description, and *LCU_Class* is the land cover/use class ID in the *LCU_Classes* database. Tables showing suggested mappings for the ARC and CSIR (2005), Ezemvelo KZN Wildlife and GeoTerraImage (2013) and ICMA (2012a) datasets can be found in Appendix D. A mapping table for the DEA and GTI (2015) land cover/use dataset has not been created as the database was obtained late in the project and further research is required to adequately represent all the classes, especially those where high, medium and low vegetation heights are specified. The Python scripts in the *cwrr.LandCover.LCU_Mapping* module are used to create raster datasets with mapped *LCUClasses* in place of the original classes.

In addition to simple mapping between land cover/use dataset and standard classes it may sometimes be necessary to supplement or improve the accuracy of the land cover/use dataset by superimposing additional or more accurate data for a few specified classes. For example if a land cover/use dataset had a single class representing forest plantations, then if a dataset containing species specific information could be superimposed on the main land cover/use dataset so that forest plantations are then represented by several species specific classes.

Table 4.10 Example of a land cover/use class mapping file

Dataset_ID	**Dataset_Desc**	**LCU_Class**
0	Missing data	UnknownLCU
1	Indigenous Forest	Natural_Typical_IndigenousForest
2	Natural Grassland	Natural_Typical_Grassland
3	Forest Plantations (Pine)	Forest Plantations_Pine_General
4	Forest Plantations (Acacia)	Forest Plantations_Wattle_General
5	Waterbodies	Waterbodies_Artificial_Dams
6	Wetlands	Waterbodies_Natural_Wetlands_General

4.8.3 Natural vegetation types

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 order to be able to represent natural vegetation in more detail, the Acocks Veld Types (Acocks, 1988) dataset was used to determine the spatial location of the different Veld Types and the hydrological characteristics, based on Schulze (2004), from the *LCU_Classes* database. If the natural vegetation is degraded then the hydrological characteristics from Schulze (2004) are adjusted based on recommendations by Schulze (2004).

To use the Acocks Veld Types in place of the natural vegetation classes in a land cover/use dataset then these classes are mapped to the standard class named *Natural_Typical_General*, and similarly degraded natural vegetation classes are mapped to the standard class named *Natural_Degraded_General*. Then when the *ACRU* model is configured, as will be described in Section 0, the appropriate Acocks Veld Types will be used. The Python scripts in the *cwrr.General.ShapefileTools* module were used for general shapefile processing of the Acocks dataset.

As part of this project an initial investigation was done into using the spatial distribution of the Mucina and Rutherford (2006) dataset and assigning equivalent Acocks Veld Types to each Mucina and Rutherford (2006) vegetation type to obtain the hydrological characteristics. However, this approach was not taken further after Schulze (2015) cautioned that though two vegetation types from the two datasets may be botanically compatible they may not be hydrologically compatible. Schulze (2015) explained that when the hydrological characteristics where derived for the Acocks Veld Types, this was done based on climate characteristics for the spatial extent of each particular Acocks Veld Type, which may differ from the spatial extent of the botanically equivalent Mucina and Rutherford (2006) vegetation type. Mr de Winnaar (de Winnaar, 2015) also has reservations about this approach, as in some cases the Acocks Veld Types have grassland and forest represented by a single veld type where Mucina and Rutherford (2006) have them as separate types, which may be a problem in terms of representing hydrological responses. It is recommended that the newer and more spatially detailed Mucina and Rutherford (2006) dataset be used in place of the Acocks (1988) dataset when a similar set of hydrological characteristics for these vegetation types has been developed by the WRC Project K5/2437 titled "*Resetting the baseline land cover against which stream flow reduction activities and the hydrological impacts of land use change are assessed*".

4.8.4 Sugarcane growing regions

In Schulze (2013) different values are provided for vegetation variables for use in the *ACRU* model for four sugarcane growing regions: (i) KwaZulu-Natal South Coast, (ii) KwaZulu-Natal North Coast, (iii) Far North Coast, and (iv) KwaZulu-Natal Inland. Based on Schulze (2013) and the simple rules described in Jewitt *et al.* (2009) a Python script (*cwrr.LandCover.SugarRegions*) was developed to create a shapefile of catchment polygons with sugarcane growing region as an attribute field. The rules used to determine the four sugarcane growing regions based on altitude and latitude were as follows:

- 1 = Far North Coast: altitude<400m and North of Richards Bay (latitude>-28°48'38"),
- 2 = North Coast: altitude<400m and North of Durban (latitude>-29°48'38") and South of Richards Bay (latitude<-28°48'38"),
- 3 = South Coast: altitude<400m and South of Durban (latitude<-29°48'38"), and
- 4 = Inland: altitude>400m.

The Python script in the *cwrr.LandCover.SugarRegions* was used to together with a shapefile of sub-Quaternary catchment boundaries and a shapefile of sub-Quaternary catchment mean altitudes to determine the sugarcane growing region to be used for each sub-Quaternary catchment containing sugarcane as a land cover/use. These regions do not indicate suitability for growing sugarcane or that sugarcane is grown within the entire region.

4.8.5 Urban water use

The water use quantification methodology developed in this project has focused mainly on water use by natural and cultivated land cover/use. This is partly because water use and return flows by urban areas, and especially sectors within the main urban land cover/use class, is difficult to quantify spatially using catchment boundaries, as census and cadastral boundaries often cross catchment boundaries. Also, as discussed in Section 3.8.1, measured urban water use data is not easily accessible. However, quantification of urban water use and return flows are important because not only can urban water use be significant in catchments with large urban area, but also because this use often involves transfers of water between catchments. As an initial attempt to try and quantify residential (domestic household) water use, population data was used together with estimated per capita water use values for different class of urban area. The Census 2011 data available from Statistics South Africa was investigated but it was difficult to associate the tabulated statistics with the spatial boundary datasets. 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 Functional Settlement Typology for South Africa mesozones, developed by the CSIR which takes into account the amount and variety of functions provided by specific urban areas as well as the population density and interconnectivity of these areas. The typology categories are (CSIR, 2013):

- City,
- City Region,
- Regional Centre 1,
- Regional Centre 2,
- Regional Centre 3,
- Service Town,
- Local or Niche Town,
- High Density Rural,
- Dense Rural,
- Sparse Rural,
- Homeland, and
- Non-Homeland.

The first step was 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 subsequently used. These population, per capita water use and return flow values were used to model urban water use in the *ACRU* model.

4.9 Soil Hydrological Properties

The *ACRU* hydrological model requires soil hydrological properties to be specified for each hydrological response unit within a sub-Quaternary catchment. The shapefile dataset of soil hydrological properties described by Schulze and Horan (2008b) and available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\shape_files\soils.shp] was selected for use in the methodology. This dataset was the only readily available South African dataset of soil hydrological properties for *ACRU*. The soil hydrological properties 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. A new shapefile dataset is first created for the case study catchment area by clipping the original dataset, as the smaller dataset makes subsequent processing faster. Soil types could be used together with land cover/use types to determine hydrological response units within a sub-Quaternary catchment. However, this can result is a large number of small HRUs within a catchment. The clipped soils dataset is used to determine the dominant soil type for each land cover/use based HRU within each sub-Quaternary catchment and the hydrological characteristics for the dominant soil types were used in the *ACRU* hydrological model. The Python scripts in the following modules were used to process the soils data:

- *cwrr.General.ShapefileTools* for general shapefile processing such as clipping and adding attribute fields, and
- *cwrr.Soils.Soils_SAAtlas2008*, to add a soil texture field to the shapefile.

It is possible to used remotely sensed estimates of soil moisture near the soil surface to make an estimate of the initial soil moisture store within each HRU at the start of the accounting periods. However, this requires further research for application in this methodology, and so the soil moisture stores were initialised by running the hydrological model for a year or two prior to the start date of the accounting period.

4.10 Subdivision of Catchments into HRUs

Even within a sub-Quaternary catchment there can be a several different types of land cover/use and different soil types. Initially sub-Quaternary catchments were divided into HRUs based on land cover/use, but areal means were calculated for attributes such as soil type, rainfall seasonality and frost occurrence for each whole sub-Quaternary catchment. A visual comparison of the spatial distribution of land cover types and soil types indicated that the spatial distribution of some land cover types, especially natural vegetation and agricultural cultivation, were often closely related and occurred predominantly on certain soil types. Based on this observation, it was decided that it would be better to use the dominant values of attributes such as soil type, rainfall seasonality and frost occurrence per land cover/use based HRU. The process of dividing a sub-Quaternary catchment into land cover/use-based HRUs and assigning attributes to these HRUs is a two stage process, first a raster dataset of *LCUClass* IDs is created and then this *LCUClass* dataset is used together with other raster and vector datasets to determine the vegetation and soil attributes to be used for each HRU.

Land cover/use datasets are compiled for different purposes by different people and organisations, and the land cover/use classes used varies between these datasets. As discussed in Section 4.8.1 this led to the development of a set of standard land cover/use classes called *LCUClasses* organised in a hierarchical structure called the *LCUHierarchy*. The procedure used to develop a raster dataset of *LCUClass* IDs for a study catchment is shown in Figure 4.10, and some Python scripts developed to assist with this are shown in Table 4.11. The steps that would typically be applied are as follows:

(i) Obtain the most recent and comprehensive land cover/use dataset for a study catchment.

(ii) Create a mapping file in Comma Separated Value (CSV) format specifying the *LCUClass* to be used for each land cover/use class.

(iii) Run the script *mapToLandCoverUnits_GeoTiff* to create a raster dataset of *LCUClass* IDs.

(iv) If other raster or vector datasets containing better information for specific land cover/use classes are available then these can be superimposed on the raster dataset of *LCUClass* IDs. The *superimposeShapefileInfoOnLCUClassRaster_Simple* and *superimposeShapefileInfoOnLCUClassRaster_Complex* scripts can be used to superimpose datasets in ESRI shapefile format onto a *LCUClass* ID raster dataset.

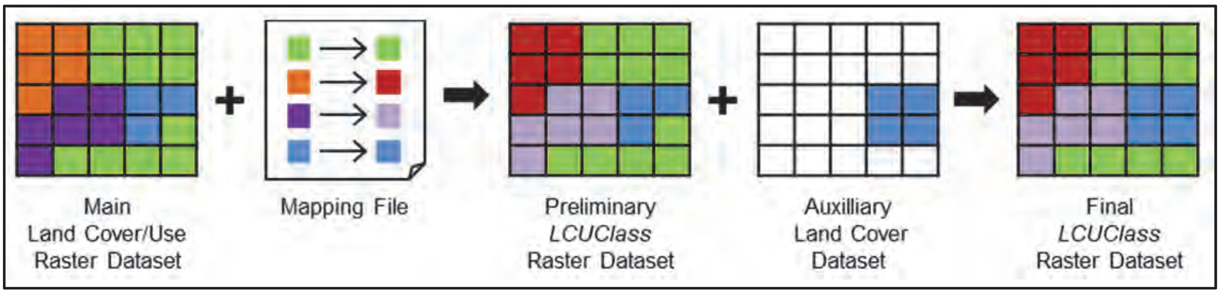


Figure 4.10 Procedure to develop a raster dataset of *LCUClass* IDs

Table 4.11 Scripts for mapping to land cover/use information to *LCUClass* IDs

Module: *cwrr.LandCover.LCU_Mapping*	
Function Name	**Description**
mapToLandCoverUnits_GeoTiff	Takes a land cover/use raster dataset and a mapping file in CSV format as input and creates a mapped raster dataset of *LCUClass* IDs.
superimposeShapefileInfoOnLCUClassRaster_Simple	Does a superimposition of shapefile polygon features onto a mapped *LCUClass* ID raster and sets pixel values to the specified single *LCUClass*. Used to superimpose isolated features such as new dams.
superimposeShapefileInfoOnLCUClassRaster_Complex	Does a superimposition of shapefile polygon features onto a mapped *LCUClass* ID raster and sets pixel values to the *LCUClass* ID specified in a mapping file based on the value in a specified shapefile attribute field.

Within a sub-Quaternary catchment an individual land cover/use type, represented by an *LCUClass* does not typically occur as a single contiguous patch but rather as a number of disjointed patches distributed within the catchment. However, as a simplification for the purpose of modelling, each *LCUClass* within a sub-Quaternary catchment is conceptualised as being one unit and its spatial location within a sub-Quaternary catchment is not known. The procedure used determine the land cover/use-based HRUs to be modelled in each sub-Quaternary catchment and assign soil and other attributes each of these is shown in Figure 4.11 and the Python script developed to assist with is described in Table 4.12.

The following steps are carried out in the *createLCURegionsTables* script:

(i) The shapefile dataset of sub-Quaternary catchment boundaries is re-projected and rasterised to fit the raster dataset of *LCUClass* IDs.

(ii) Any other shapefile datasets, such as Acocks Veld Type, soils and rainfall seasonality are re-projected and rasterised to fit the raster dataset of *LCUClass* IDs.

(iii) Any other raster datasets, such as frost occurrence are re-projected to fit the raster dataset of *LCUClass* IDs.

(iv) All the dataset layers, now in a common raster format and projection, are superimposed and analysed to determine all the unique combinations of layer values and the number of pixels per combination. These combinations and pixel counts are written to a results table called *FullInfo*.

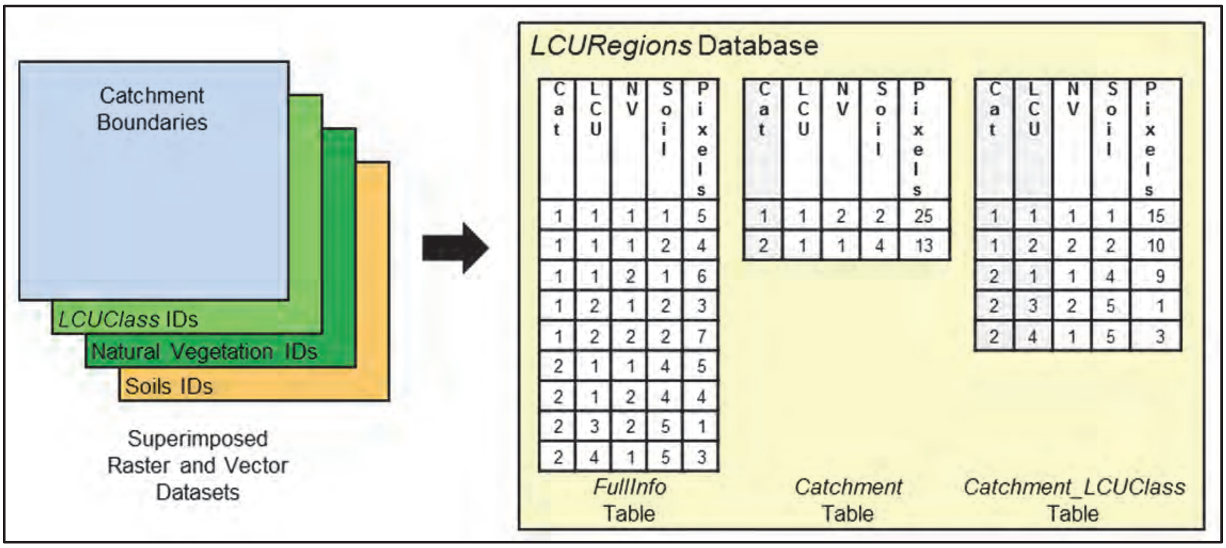
(v) The data in the FullInfo table is analysed to determine the dominant value (by area) of each layer for each sub-Quaternary catchment and the results are saved to a table called *Catchment*.

(vi) The data in the *FullInfo* table is analysed to determine the dominant value (by area) of each layer for each combination of sub-Quaternary catchment and *LCUClass* and the results are saved to a table called *Catchment_LCUClass*.

(vii) If requested by the user further analyses are executed on the *FullInfo* table to determine the dominant value (by area) of each layer for each combination of sub-Quaternary catchment, *LCUClass* and any other layers specified by the user, and the results are saved to an appropriately named table.

(viii) All the results tables are saved to a *LCURegions* spreadsheet in either Microsoft Excel (.xlsx) or Open Data Spreadsheet (.ods) format.

The information in the *LCURegions* spreadsheet can then be used together with information in the *LCUClass* database and other datasets associated with each of the other shapefile and raster layers used in the analysis, to determine the HRUs per sub-Quaternary catchment and their attributes.



Cat	LCU	NV	Soil	Pixels
1	1	1	1	5
1	1	1	2	4
1	1	2	1	6
1	2	1	2	3
1	2	2	2	7
2	1	1	4	5
2	1	2	4	4
2	3	2	5	1
2	4	1	5	3

Cat	LCU	NV	Soil	Pixels
1	1	2	2	25
2	1	1	4	13

Cat	LCU	NV	Soil	Pixels
1	1	1	1	15
1	2	2	2	10
2	1	1	4	9
2	3	2	5	1
2	4	1	5	3

Figure 4.11 Procedure to determine HRUs and assign modelling attributes to them

Table 4.12 Scripts for mapping to land cover/use information to *LCUClass* IDs

Module: cwrr.LandCover.LCURegionsTables	
Function Name	**Description**
createLCURegionsTables	Uses a shapefile of catchment polygons, a raster dataset of *LCUClass* IDs, and a list of other datasets (shapefile and raster) indicating regions such as Acocks Veld Types, Soils, Rain Season, etc. to calculate the area of each combination of regions present in each catchment. At present this script only supports vector datasets in ESRI shapefile format.

4.11 Rainfall

Accurate estimation of areal rainfall is a critical part of the methodology as it is the one of the key inputs required for hydrological modelling and one of the main sources of water in a catchment water resource account.

4.11.1 Daily rainfall

Some of the advantages and disadvantages of daily rain gauge data and remotely sensed were discussed in Sections 3.2.1.4 and 3.2.1.5. As a freely available updated dataset of rain gauge data was not available and given the problems with spatial representation, it was decided that remotely sensed rainfall should be investigated as a potential source of rainfall data for use in water resource accounts.

In addition to evaluating the accuracy of the remotely sensed rainfall estimates the following factors were also considered:

- FTP access to datasets as this enables the download of datasets to be automated and also scheduled for times of day when bandwidth usage is low.
- Daily accumulated rainfall products are convenient to use as modelling is at a daily timestep and sub-daily rainfall data products require additional processing to produce daily rainfall values, also it is more efficient in terms of bandwidth usage and data storage to have one dataset per day rather than several sub-daily datasets per day.
- The data start and end times within a day need to be considered to prevent potential phasing problems.
- The length of product datasets if long term historical accounts are to be generated, or for statistical purposes if using historical rain gauge data to calibrate remotely sensed rainfall data.

- The spatial extent of the datasets, as global datasets are larger than local datasets, affecting bandwidth usage and data storage.
- The file format used for the datasets with respect to the ease and speed with which they can be read and processed.

In the inception phase of the project four remotely sensed daily rainfall data products were identified for evaluation, namely FEWS RFE 2.0, FEWS ARC 2.0, TRMM 3B42 and CMORPH. These four products are briefly described in Sections 4.11.1.1 to 4.11.1.4.

4.11.1.1 FEWS RFE 2.0

The United States' (US) National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) has developed remotely sensed rainfall products to support the humanitarian aid programs of the US Agency for International Development's (USAID) FEWS-NET (Novella and Thiaw, 2012). The CPC developed the Rainfall Estimator (RFE) algorithm in 1998, and subsequently a more advanced algorithm RFE 2.0 in 2001, to provide higher resolution operational daily rainfall estimates (Novella and Thiaw, 2012). RFE 2.0 uses inputs from four sources (i) 24 hour rainfall totals from Global Telecommunications System (GTS) rain gauges, (ii) the Geostationary Operational Environmental Satellite (GOES) precipitation index (GPI) calculated from 3-hourly geostationary EUMETSAT cloud-top infrared (IR) temperatures, (iii) Special Sensor Microwave Imager (SSM/I)-based estimates, and (iv) Advanced Microwave Sounding Unit (AMSU) rainfall estimates (Novella and Thiaw, 2012). Put simply, the bias-corrected satellite measurements are used to define the spatial distribution and extent of rainfall, and the rain gauge measurements are used to determine the magnitude of the rainfall (Novella and Thiaw, 2012). Novella and Thiaw (2012) state that RFE is unique compared to other satellite rainfall products because of its high, 0.1° spatial resolution, and the near real-time blending of rain gauge and satellite measurements to provide daily rainfall estimates for the African continent. Some information about the FEWS RFE 2.0 product is shown in Table 4.13

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Table 4.13 Information for the FEWS RFE 2.0 product

Attribute	Information
Temporal resolution	Daily (06Z-06Z)
Spatial resolution	0.1°×0.1°
File formats	binary, shapefile, GeoTiff
Source	NOAA National Weather Service Climate Prediction Center, Famine Early Warning System Network (FEWS-Net) [http://www.cpc.ncep.noaa.gov/products/fews/data.shtml] [ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/rfe2]
Availability	January 2001 onward with a lag of approximately 2 days
Number of Rows	801
Number of Columns	751
Minimum Longitude	20.05°
Maximum Longitude	55.05°
Minimum Latitude	-40.05°
Maximum Latitude	40.05°

4.11.1.2 FEWS ARC 2.0

The daily remotely sensed precipitation product for Africa called the African Rainfall Climatology, version 2 (ARC 2.0) is described by Novella and Thiaw (2012). The original Africa Rainfall Climatology (ARC1) algorithm was developed based on the RFE2 algorithm but only used the GTS rain gauge and geostationary IR cloud temperature data due to their availability and consistency over time, and their better spatial coverage and reliability compared to passive microwave data from 1983 onwards (Novella and Thiaw, 2012). Novella and Thiaw (2012) state that the main objective of ARC1 was to construct a stable and consistent rainfall dataset, though excluding the microwave inputs may potentially result in lower estimation accuracy, especially for localised heavy rainfall events. The ARC2 algorithm described in Novella and Thiaw (2012) was developed using longer historical rain gauge and IR data to produce a longer and more climatologically stable dataset, and also to remove a processing bias present in ARC1. Novella and Thiaw (2012) report that ARC2 rainfall estimates are an improvement over ARC1 estimates, and that the ARC2 estimates compared favourably in validations against rain gauge measurements relative to TRMM 3B42 and CMORPH products. Novella and Thiaw (2012) investigated a marginal summer dry bias that occurs over West and East Africa, and concluded that both the daily and monthly validations indicated that underestimation of rainfall by ARC2 may be due to the unavailability of some daily GTS data in real time, and to possible deficiencies in the satellite estimates associated with rainfall processes over coastal and orographic areas. Novella and Thiaw (2012) state that the long ARC2 daily rainfall dataset will help in understanding climate variability and change, as it is produced using consistent and reliable data inputs, which is important for continuity and homogeneity, and minimises error and biases. Some information about the FEWS ARC 2.0 product is shown in Table 4.14.

Table 4.14 Information for the FEWS ARC 2.0 product

Attribute	**Information**
Temporal resolution	Daily (06Z-06Z)
Spatial resolution	0.1°×0.1°
File formats	binary, shapefile, GeoTiff
Source	NOAA National Weather Service Climate Prediction Center, Famine Early Warning System Network (FEWS-Net) [http://www.cpc.ncep.noaa.gov/products/fews/data.shtml] [ftp://ftp.cpc.ncep.noaa.gov/fews/fewsdata/africa/arc2]
Availability	January 1983 onward with a lag of approximately 2 days
Number of Rows	801
Number of Columns	751
Minimum Longitude	20.05°
Maximum Longitude	55.05°
Minimum Latitude	-40.05°
Maximum Latitude	40.05°

4.11.1.3 TRMM 3B42 Daily

The Tropical Rainfall Measuring Mission (TRMM) satellite was launched in 1997, its instruments, rainfall estimation algorithms and related products are described by Kummerow *et al.* (2000). Dinku *et al.* (2007) explain that the TRMM 3B42 product algorithm uses the following main data inputs: infrared (IR) data from geostationary satellites, passive microwave (PM) data from the TRMM microwave imager (TMI), Special Sensor Microwave Imager (SSM/I) data, Advanced Microwave Sounding Unit (AMSU) data and Advanced Microwave Sounding Radiometer-Earth Observing System (AMSR-E) data. The post-real-time TRMM 3B42 Daily product also uses rain gauge data (Dinku *et al.*, 2008). Some information about the TRMM 3B42 Daily product is shown in Table 4.15.

Table 4.15 Information for the TRMM 3B42 Daily product

Attribute	Information
Temporal resolution	Daily (00Z-00Z)
Spatial resolution	0.25°×0.25°
File formats	binary, HDF, NetCDF
Source	Goddard Earth Sciences Data and Information Services Center Binary: [ftp://disc2.nascom.nasa.gov/data/TRMM/Gridded/Derived_Products/3B42_V7/Daily/] [http://mirador.gsfc.nasa.gov/] HDF: [http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42_Daily] NetCDF: [http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3B42_Daily] [http://mirador.gsfc.nasa.gov/]
Availability	January 1998 onward with a lag of approximately 3 months
Number of Rows	400
Number of Columns	1440
Minimum Longitude	-180.0° or 0.0° (depending on source)
Maximum Longitude	180.0° or 360.0° (depending on source)
Minimum Latitude	-50.0°
Maximum Latitude	50.0°

4.11.1.4 CMORPH Daily

The Climate Prediction Center Morphing Technique (CMORPH) product is described by Joyce *et al.* (2004). Half-hourly estimates of global precipitation are produced at a spatial resolution of 8km using passive microwave sensor observation which are then spatially propagated using motion vectors derived from geostationary satellite infrared data (Joyce *et al.*, 2004). The shape and intensity of the precipitation features are modified (morphed) for the time period between microwave sensor observation using time-weighted linear interpolation, which results in a spatially and temporally complete microwave-derived precipitation estimate (Joyce *et al.*, 2004).. The daily CMORPH V1.0 product is derived from the half-hourly estimates and is available in two forms (i) bias corrected (CRT) estimates, and (ii) non-bias corrected (RAW) estimates. The bias corrected (CRT) estimates were evaluated in this project. Some information about the product is shown in Table 4.16..

Table 4.16 Information for the CMORPH Daily product

Attribute	Information
Temporal resolution	Daily (00Z-00Z)
Spatial resolution	0.25°×0.25°
File formats	binary
Source	Bias corrected (CRT) data from: http://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/CRT/0.25deg-DLY_00Z Raw (RAW) data from: http://ftp.cpc.ncep.noaa.gov/precip/CMORPH_V1.0/RAW/0.25deg-DLY_00Z
Availability	December 2002 onward, currently available up to December 2013
Number of Rows	480
Number of Columns	1440
Minimum Longitude	0.0°
Maximum Longitude	360.0°
Minimum Latitude	-60.0°
Maximum Latitude	60.0°

4.11.1.5 Data Processing

There are two potential problems related to processing the remotely sensed rainfall products to produce daily timeseries per catchment, (i) the coarse spatial resolution of these raster datasets relative to the size of the sub-Quaternary catchments, and (ii) the amount of processing required to get from large (often global) raster datasets at daily or even sub-daily time steps to a daily time series of area weighted mean rainfall per sub-Quaternary catchments catchment. A common means of determining an area weighted mean value for coarse scale raster pixels overlapping a catchment polygon boundary is to resample the raster dataset to a finer resolution and then using some form of zonal statistics tool to calculate the mean for each catchment polygon. However, this is computer processing intensive when needing to create long time series for hydrological modelling. A solution to these problems was created by writing some Python scripts to perform two operations. The first operation is to assign an ID to each pixel and then determine for each catchment polygon the fractional area of each raster pixel that overlaps it. A table of the fractional areas is created, with one record for each pixel ID – polygon ID pair. This first operation need only be performed once for each case study area, assuming the spatial locations of the pixels in the raster datasets do not change from one time step to another. The second operation is to then read the raster dataset for each time step and for each catchment polygon to multiply the fractional area of each overlapping pixel by the pixel rainfall value and sum the calculated values. This second operation is then repeated for each day and a rainfall timeseries is created for each catchment and saved to a CSV file for use in the *ACRU* model. These Python scripts belong to a module named *cwrr.General.CoarseRasterTimeseriesTools* which contains scripts for working with coarse

resolution raster datasets to create time series. A separate Python module was created for each of the four remotely sensed rainfall data products containing scripts to create time series for modelling. A separate module was created for each product as each is packaged differently and has a different resolution and spatial extent. These four modules are:
cwrr.Rainfall.FEWS_RFE2,
cwrr.Rainfall.FEWS_ARC2,
cwrr.Rainfall.CMORPH_Daily, and
cwrr.Rainfall.TRMM_3B42_Daily.

4.11.2 Mean annual rainfall

The *ACRU* model requires MAP as an input even though it was not strictly required for the model configuration options used for this methodology. To determine MAP for each sub-Quaternary catchment the MAP raster dataset derived by Lynch (2004) was used. This dataset, also described in Schulze and Lynch (2008a), was obtained from the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\gmap]. A new raster dataset was first created for the case study catchment area by clipping the dataset. A shapefile dataset was then created containing an area weighted MAP value for each sub-Quaternary catchment. The Python scripts in the *cwrr.RainMeans.Lynch2004* module are used to process the dataset.

4.11.3 Mean monthly rainfall

To determine the mean monthly rainfall for each sub-Quaternary catchment for use in bias correction of remotely sensed rainfall the dataset of long-term mean monthly rainfall dataset derived by Lynch (2004) was used. This dataset was obtained from the Centre for Water Resources Research (CWRR). For each of the 12 mean monthly rainfall datasets an areal mean value was calculated for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 12 fields containing the calculated mean monthly rainfall values. The Python scripts in the *cwrr.RainMeans.Lynch2004* module are used to process the dataset.

4.11.4 Median monthly rainfall

To determine the mean monthly rainfall for each sub-Quaternary catchment for use in bias correction of remotely sensed rainfall the dataset of long-term median monthly rainfall dataset derived by Lynch (2004) was used. This dataset, also described in Schulze and

Lynch (2008b), was obtained from the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\gmednrfl1 .. D:\GISData\grids\gmednrfl12]. For each of the 12 median monthly rainfall datasets an areal mean value was calculated for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 12 fields containing the calculated median monthly rainfall values. The Python scripts in the *cwrr.RainMedians.Lynch2004* module are used to process the dataset.

4.11.5 Rainfall seasonality

To determine the rainfall seasonality region for each sub-Quaternary catchment the shapefile dataset described in Schulze and Maharaj (2008a) was used. This dataset was obtained from the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\ shape_files\rfl_seasconc.shp]. A new shapefile dataset was first created for the case study catchment area by clipping the dataset. A shapefile dataset was then created containing a rainfall seasonality region number for each sub-Quaternary catchment. The Python scripts in the *cwrr.RainSeasons.SAAtlas2008* module are used to process the dataset.

4.12 Reference Potential Evaporation

The use of direct measurements of ET and the separate interception evaporation, transpiration, soil water evaporation and open water evaporation components of ET is not feasible at a catchment scale. Hence, or the purpose of this methodology it was decided that the approach of using ET_0 as input to the *ACRU* model and modelling total evaporation (ET), rather than using a remote sensing based estimates of ET. 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. WRC Projects K5/1683 and K5/2024 adopted this approach and calculated an ET_0 dataset using the Penman-Monteith equations together with forecast climate data from the SAWS version of the Unified Model and remotely sensed radiation data, as input to the PyTOPKAPI model to estimate ET and soil moisture (Pegram *et al.*, 2010; Sinclair and Pegram, 2010; Pegram and Sinclair, 2013; Sinclair and Pegram, 2013). The ET_0 dataset of hourly values at 0.11° spatial resolution is available on the Satellite Applications Hydrology Group (SAHG) website (http://sahg.ukzn.ac.za/soil_moisture/) for the period 2008 to present. Some information about the SAHG ET_0 product is shown in

.

Table 4.17 Information for the SAHG ET_0 product

Attribute	Information
Temporal resolution	Hourly (0Z-23Z)
Spatial resolution	0.11°×0.11°
File formats	ASCII, GeoTiff
Source	Satellite Applications Hydrology Group (SAHG) [ftp://sahg.ukzn.ac.za/ET0/gtiff/]
Availability	September 2007 onward
Number of Rows	128
Number of Columns	174
Minimum Longitude	14.915°
Maximum Longitude	34.055°
Minimum Latitude	-36.0245°
Maximum Latitude	-21.9445°

The SAHG ET_0 dataset was used together with a shapefile dataset of sub-Quaternary catchment boundaries to create a time series of daily ET_0 data values for each sub-Quaternary catchment. For each sub-Quaternary catchment, for each hour, an areal mean ET_0 value is calculated and added to a time series of hourly values for the catchment. Some problems were experienced with occasional missing hours or days of data. To resolve this problem missing hourly values in each hourly timeseries was then infilled using a median value for the same month-of-year and hour-of-day. Then for each sub-Quaternary catchment, the values in the hourly time series were aggregated to daily ET_0 values in a daily time series which was saved to a CSV file for use in the *ACRU* model. A set of Python scripts in a module named *cwrr.Evaporation.SAHG_ET0* were used for working with SAHG ET_0 hourly raster datasets to create daily time series for modelling.

The *ACRU* model was originally developed to use A-pan reference potential evaporation together with suitable crop factors. The *LCU_Classes* database contains A-pan crop factors for all vegetation classes, but does not yet contain equivalent Penman-Monteith crop factors for all vegetation classes. Therefore, A-pan crop factors were used and a correction factor of 1.2 was applied to the ET_0 values in *ACRU* to calculate A-pan equivalent daily ET_0 values.

4.13 Total Evaporation

Estimation of total evaporation and the partitioned interception evaporation, transpiration, soil water evaporation and open water evaporation components are an important part of the Resource Base Sheet. As discussed in Section 4.12 the approach adopted for this methodology was to use the SAHG estimates of ET_0 as input to the *ACRU* hydrological model which would be used to estimate ET and its partitioned components. The details of how *ACRU* models ET and its partitioned components are described in Schulze *et al.* (1995) and Schulze (1995b). The evaporation of intercepted rainfall is a standard part of *ACRU* and the transpiration and soil water evaporation components are calculated separately if the option *EvapotranspirationOption* (*EVTR*) = 2 is selected. Total ET and its separate components are modelled each day for each HRU in a sub-Quaternary catchment, where each HRU represents a specific *LCU_Class*. The land cover/use hierarchy specified in the *LCU_Hierarchy* file is then used to aggregate the evaporation values for all the HRUs representing each item in the class hierarchy.

4.14 Temperature

The *ACRU* model requires daily maximum and minimum air temperature data as an input even though it was not strictly required for the model configuration options used for this methodology. Hence, for the purpose of this methodology the datasets of long-term mean monthly maximum and minimum air temperature described by Schulze and Maharaj (2008b) and Schulze and Maharaj (2008c) were used. These raster datasets are available on the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the files [D:\GISData\grids\tmaxave01c .. tmaxave12c] and the files [D:\GISData\grids\tminave01c .. tminave12c]. For each of the 12 maximum air temperature datasets and the 12 minimum air temperature datasets an areal mean value was calculated for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 24 fields containing the calculated daily temperature values for each month. The Python scripts in the *cwrr.Temperature.SAAtlas2008* module are used to process the dataset.

To determine which sub-Quaternary catchments receive frost the raster dataset of the mean number of occurrences of heavy frost described in Schulze and Maharaj (2008d) was used. This dataset was obtained from the South African Atlas of Climatology and Agrohydrology DVD-ROM (Schulze *et al.*, 2008b) in the file [D:\GISData\grids\frostnoccc]. A new raster dataset was first created for the case study catchment area by clipping the dataset. A shapefile dataset was then created indicating whether more than half of the pixels in each sub-Quaternary catchment have a mean number of frost occurrences greater than zero. The Python scripts in the *cwrr.Frost.SAAtlas2008* module are used to process the dataset.

4.15 Project Database Spreadsheet

Once all the necessary datasets for a case study catchment have been processed the next step is to combine information and data from all these datasets to configure the *ACRU* model for the case study catchment. Some means was required to simplify this process, make it more transparent, enable the model configuration to be adjusted for special cases and potentially make this data and information accessible to other models. This led to the development of a project database in the form of a spreadsheet in Open Document Spreadsheet (ODS) format. An entity relationship diagram of the project database spreadsheet is shown in Figure 4.12 and each database table is briefly described in Table 4.18. The tables in this database represent the different conceptual spatial entities used to represent a case study catchment. This project database serves the following purposes: (i) to collate and organise all the catchment, HRU, dam and river flow network information, (ii) to enable the configuration information to be adjusted and extended before generating model input files, (iii) provide a more structured data source from which the *ACRU* model, and potentially other models can easily be configured, and (iv) make application of the methodology other catchments easier. This project database structure is not intended to be a complete data repository, it holds catchment configuration information and references to the other required datasets. A Python module named *cwrr.Project.Project* contains scripts to create empty project database spreadsheets and to populate the tables within them.

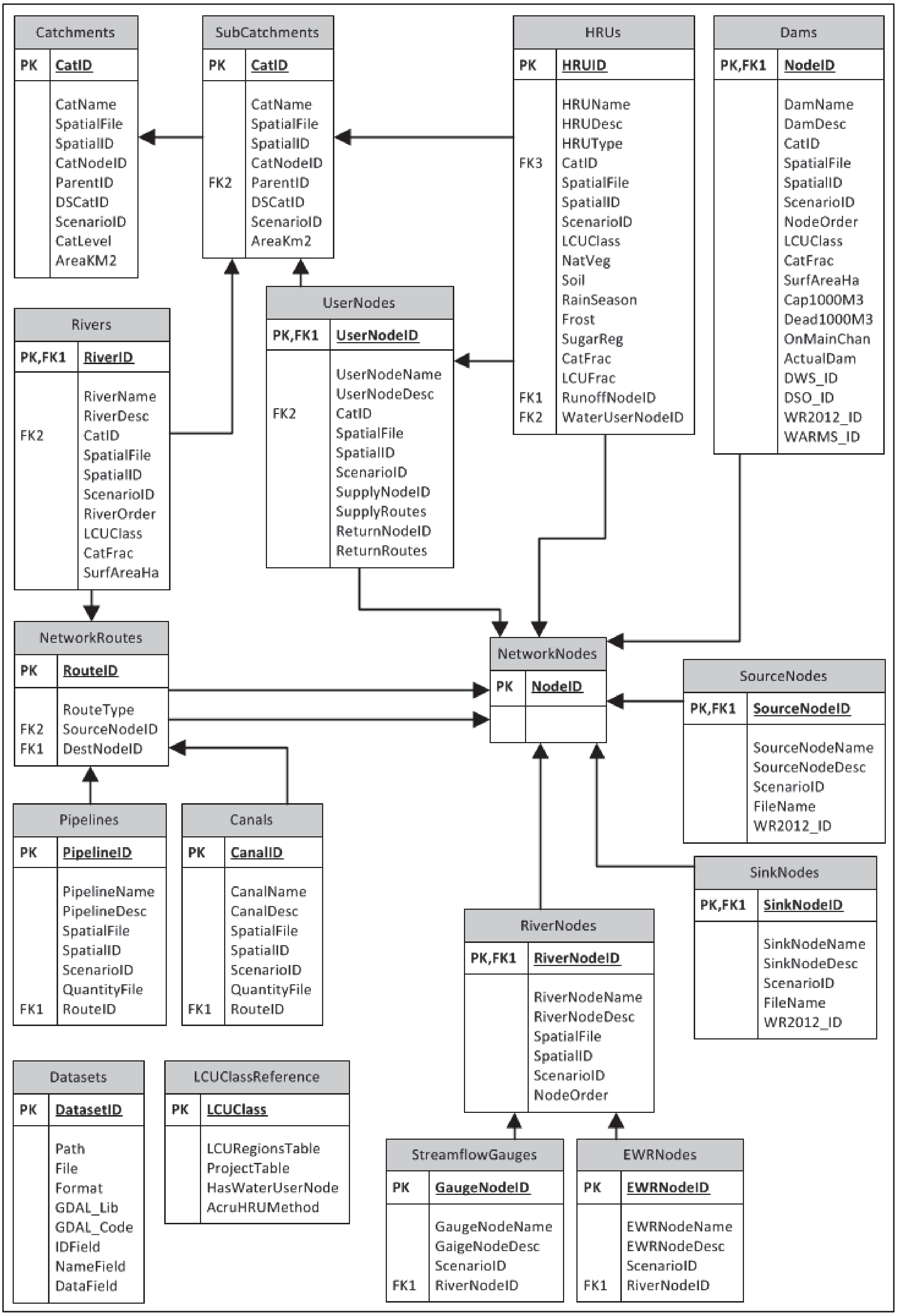

Figure 4.12 Entity-relationship diagram of the project database structure

Table 4.18 Description of the tables in the project database

Datasets	Stores information about the file location and type of datasets used to populated the project database and configure the models (in this case *ACRU*).
Catchments	Stores information about the Primary, Secondary, Tertiary and Quaternary catchments forming a case study catchment, including ID, name, description, area, catchment node ID, parent-child relationships and flow relationships.
SubCatchments	Stores information about the sub-Quaternary level subcatchments forming a case study catchment, including ID, name, description, area, parent catchment, subcatchment node ID, downstream subcatchment and flow relationships.
HRUs	Stores information about the HRUs to be modelled including ID, name, description, area fraction, parent catchment, *LCUClass*, soil type, rainfall seasonality region, frost occurrence region, sugarcane growing region, runoff node and water user node.
LCUClassReference	Contains one record for each *LCUClass* referenced in the *HRUs* table specifying which *LCURegions* table is to be used, which project database table the *LCUClass* relates to, whether the *LCUCLass* should have an associated water user node and which Java code method should be used to configure the *ACRU* model for the *LCUClass*.
NetworkNodes	Contains a list of all the unique river, dam and water nodes forming part of the natural and built flow network within the study catchment.
RiverNodes	Stores information about ID, name and description of the river nodes (representing a point on a 2D line representation of a river flow path) forming part of the natural flow network within the study catchment. River nodes may be “plain” river nodes or may be multifunctional nodes representing catchment exit nodes, subcatchment exit nodes, streamflow gauge nodes and environmental water requirement (EWR) nodes.
StreamflowGauges	Streamflow gauge nodes are special river nodes where streamflow measurements are recorded. Stores the ID of the associated river node and the name of the file specifying a time series of measured streamflow values.
EWRNodes	Environmental water requirement (EWR) nodes are special river nodes at which an environmental water requirement is specified. Stores the ID of the associated river node and information about the environmental water requirements.

Table 4.18 (cont.)	Description of the tables in the project database

Dams	Stores information about ID, name, description, parent subcatchment, *LCUClass*, full surface area and full storage capacity of the dam nodes (representing a dam as a point where the dam wall intersects of a river flow path) forming part of the built flow network within the study catchment. There are also fields specifying whether the node represents an actual or a lumped dam and whether the dam is to be modelled as being on the main river channel or not.
SourceNodes	Sources nodes represent sources of water transferred into the study catchment either via an inter-catchment transfer or from an upstream catchment. Stores information about ID, name, description, and the name of the file specifying a time series of water supply quantities.
SinkNodes	Sink nodes represent sinks of water transferred out of a study catchment via an inter-catchment transfer. Stores information about ID, name, description, and the name of the file specifying a time series of water quantities to be exported.
UserNodes	User nodes represent users of water that extract a water demand from a river or dam node and return some or all of that water to the same node or a different river or dam node.
NetworkRoutes	Contains a list of all the unique river, pipeline, canal and virtual routes of water between two network nodes forming part of the natural and built flow network within the study catchment. Every network route has a source network node and a destination network node. A virtual route simply joins a source node to a destination node without specifying whether the route is a river, pipeline or canal.
Rivers	Stores information about ID, name, description, parent subcatchment, *LCUClass* and surface area of the river routes forming part of the natural flow network within the study catchment.
Pipelines	Stores information about ID, name and description of the pipeline routes forming part of the built flow network within the study catchment, and also a timeseries file containing flow quantities.
Canals	Stores information about ID, name and description of the canal routes forming part of the built flow network within the study catchment, and also a timeseries file containing flow quantities.

4.16 Configuration of the *ACRU* Model

The *ACRU*4 Modelling System includes a graphical user interface called the Configuration Editor with which users of the *ACRU* model can configure model input files. The *ACRU*4 Modelling System also includes a library of software tools named *XmlModelFiles*, described in more detail in Clark (2013), which enables the *ACRU* model to be configured programmatically using either the Java programming language or one of the .Net programming languages. A software module named *cwrr.General.ACRU_Setup.MenuCreator* , written as a Java class, was created in this project to use the Java version of the *XmlModelFiles* library to automate the configuration of the *ACRU* model for a study catchment using data and information contained in a project database spreadsheet and in the datasets referenced within it. A list of the Java modules developed and a short description of these modules is included in Appendix C, and the Java modules have been included in the electronic appendices Appendix E.2.

Translating the information contained in a project database spreadsheet and the datasets associated with it into a model configuration file for the *ACRU* model requires detailed knowledge of the *ACRU* model. This translation is taken care of by the code in *cwrr.General.ACRU_Setup.MenuCreator* but a brief explanation is given here to describe how the spatial configuration of a study catchment in *ACRU* model relates to the configuration information in a project database. The spatial configuration of a study catchment is represented in the *ACRU* model using a set of spatial components, which are described in more detail in Clark (2013). A short description of these spatial components is as follows (Clark, 2013):

- A *Catchment* is a spatial container for other *Catchments, CatchmentNodes* and *Subcatchments*.
- A *CatchmentNode* is a node in the flow network at the outlet of a *Catchment* at which streamflow out of a *Catchment* can be evaluated.
- A *Subcatchment* is a spatial container for other spatial entities including: *HRU*, *IrrigatedArea*, *AdjunctImperviousArea*, *DisjunctImperviousArea*, *River*, *RiverInflowNode*, *Dam*, *DamInflowNode* and *SubcatchmentNode*. A *Subcatchment* may not contain other *Subcatchments*, it is the smallest spatial container representing a surface flow watershed. It is a container for entities representing segments of land and the flow network.
- A *SubcatchmentNode* is a node in the flow network at the outlet of a *Subcatchment* at which streamflow out of a *Subcatchment* can be evaluated.

- A *HRU* (hydrological response unit) is a spatial segment of land for which the soil and land cover are assumed to be homogeneous. A *HRU* is used to represent a spatial segment of land that does not require specialised processes as is the case for *IrrigatedArea*, *AdjunctImperviousArea, DisjunctImperviousArea, Wetland* and *RiparianZone*.
- An *IrrigatedArea* is a spatial segment of land on which irrigation may be applied.
- An *AdjunctImperviousArea* is a spatial segment of land that has an impervious land cover and is adjacent to and flows directly into the flow network.
- A *DisjunctImperviousArea* is a spatial segment of land that has an impervious land cover and is adjacent to a *HRU*, and flows directly onto this *HRU*.
- A *Wetland* is a spatial segment of land adjacent to part of the flow network, it receives excess flow from the flow network and may be modelled together with a dam.
- A *RiparianZone* is a spatial segment of land adjacent to part of the flow network, it receives baseflow from upslope *HRUs* and also excess flow from the flow network.
- A *River* is a spatial river reach and forms part of the flow network.
- A *RiverInflowNode* is a spatial node that flows into a *River*, a *RiverInflowNode* must exist for each *River*.
- A *Dam* is a spatial dam reach and forms part of the flow network.
- A *DamInflowNode* is a spatial node that flows into a *Dam*, a *DamInflowNode* must exist for each *Dam*.

The spatial entity types represented as tables in the project database and their corresponding *ACRU* model spatial entity types is shown in Table 4.19. The spatial entity types for the two systems are quite similar as the project database was to a certain extent designed for use together with the *ACRU* model. However, there is no reason why the project database should not be used to configure other hydrological models.

Table 4.19 Corresponding spatial entity types for the project database and the *ACRU* model

Spatial Entity		**Description**
Project Database	***ACRU* Model**	
Catchment	*Catchment* + *CatchmentNode*	The concept of catchments being spatial containers of other catchments is shared by the project database and the *ACRU* model.
SubCatchment	*SubCatchment* + *SubCatchmentNode*	The concept of the lowest level catchments being spatial containers of response units and flow network components is shared by the project database and the *ACRU* model.
HRU	*HRU* *IrrigatedArea* *AdjunctImperviousArea* *DisjunctImperviousArea* *Wetland* *RiparianZone*	The project database *HRUs* are used to represent any portion of land acting as a response unit and excluding flow network components. These project database *HRUs* are represented in the *ACRU* model either as one of the specialised response units, or as a general *HRU*, or as a combination of response units. Urban areas are an example of where a combination of pervious *HRU* and impervious response units are used. Further details of how different land cover/use classes are configured as response units in the *ACRU* model are described further in Table 4.20.
Dam	*Dam* + *DamInflowNode*	Dams are represented similarly by both systems, except that in *ACRU* each dam has an associated *DamInflowNode* to aggregate inflows from upstream.
River	*River*	Rivers are represented similarly by both systems.
RiverNode	*RiverInflowNode*	River nodes are represented similarly by both systems, except that in *ACRU* and *RiverInflowNode* is associated with the inlet of a specific river reach.
Pipeline	*WaterTransfer* *InterCatchmentWaterTransfer*	The project database *Pipelines* could be represented in *ACRU* as either a *WaterTransfer* if the water source and destination are in the same catchment, or as an *InterCatchmentWaterTransfer* if they are in different catchments.
Canal	*WaterTransfer* *InterCatchmentWaterTransfer*	The project database *Pipelines* could be represented in *ACRU* as either a *WaterTransfer* if the water source and destination are in the same catchment, or as an *InterCatchmentWaterTransfer* if they are in different catchments.
SourceNode	*ExternalWaterSourceNode*	The supply of water from sources outside the represented study catchment is represented similarly by both systems.
SinkNode	*ExternalWaterSinkNode*	The transfer of water to destinations outside the represented study catchment is represented similarly by both systems.

Table 4.19 (cont.) Corresponding spatial entity types for the project database and the *ACRU* model

StreamflowGauge	*RiverInflowNode* *ObsSimNode*	A project database *StreamflowGauge* is currently represented as *RiverInflowNode* in *ACRU* but could also be represented in *ACRU* as an *ObsSimNode* which has an option to replace simulated flow with observed streamflow.
EWRNode	*IFRSite*	Nodes in the river flow network at which EWRs are specified are represented similarly by both systems.
UserNode	*GeneralWaterUser* *IrrigatedArea/System*	Users of water abstracted from groundwater or the flow network are represented differently in *ACRU* depending on the type of user, which could be an *IrrigatedArea* for irrigation users or a *UrbanWaterUser* for urban users. Mining users are not yet represented.

Different *LCU_Classes* are represented differently in the *ACRU* model, some as generic response units (*HRUs*), where there are different parameter values used but they are modelled with the same algorithms, and some as more specialised response units with different parameter values and algorithms. This is done in the *cwrr.General.ACRU_Setup.MenuCreator* module. The module uses the *LCUClassReference* table shown in Figure 4.12 and described in Table 4.18 to determine which method in the *MenuCreator* module should be used to configure the *ACRU* model for each particular *LCU_Class*. Many of the *LCUClasses* are configured in the *ACRU* model in a similar way and so are configured using the same method in the *MenuCreator* module, thus there is a close relationship between these methods and some levels of the *LCU_Hierarchy*. These *LCU_Class* related methods in the *MenuCreator* module are described briefly in Table 4.20. Additional methods can be easily added if required.

Table 4.20 Description of the *LCU_Class* related methods in the *MenuCreator* module

acruHRU_AcocksGeneral In instances where the specific Acocks Veld Type of a response unit with natural vegetation in typical condition is not known, then the Acocks Veld Type is determined from the Acocks dataset and a *HRU* is created using vegetation parameters and variable values from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AcocksGeneralDegraded In instances where the specific Acocks Veld Type of a response unit with natural vegetation in degraded condition is not known, then the Acocks Veld Type is determined from the Acocks dataset and a *HRU* is created using vegetation parameters and variable values from the *LCU_Classes* database which are adjusted to account for the degradation based on recommendations in Schulze (2013). Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AcocksSpecific A *HRU* is created using vegetation parameters and variable values for the specified Acocks Veld Type from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.

Table 4.20 (cont.) Description of the *LCU_Class* related methods in the *MenuCreator* module

acruHRU_AcocksSpecificDegraded A *HRU* is created using vegetation parameters and variable values for the specified Acocks Veld Type from the *LCU_Classes* database which are adjusted to account for the degradation based on recommendations in Schulze (2013). Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AgricCommGeneralDrylandAnnual In instances where the specific type of dryland annual crop growing on a response unit is not known then maize is assumed in summer rainfall regions and wheat is assumed in winter rainfall regions and a *HRU* is created using vegetation parameters and variable values for the assumed crop type from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AgricCommSpecificDrylandAnnual A *HRU* is created using vegetation parameters and variable values for the specified crop type from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AgricCommGeneralIrrigatedAnnual In instances where the specific type of irrigated annual crop growing on a response unit is not known then maize is assumed in summer rainfall regions and wheat is assumed in winter rainfall regions and an *IrrigatedArea* is created using vegetation parameters and variable values for the assumed crop type from the *LCU_Classes* database. The months in which irrigation occurs are also specified based on the rainfall region. The soils variables are modified based on information in Schulze (2013). The depletion scheduling option in *ACRU* is used if more detailed information is not available. Runoff from the *IrrigatedArea* will flow to the *SubcatchmentNode*. Unless more detailed information on water sources is know the source of water for irrigation is a *Dam* in the same *SubCatchment* if there is one, otherwise from run of river at the *SubcatchmentNode*.
acruHRU_AgricCommSpecificIrrigatedAnnual An *IrrigatedArea* is created using vegetation parameters and variable values for the specific crop type from the *LCU_Classes* database. If not specified in the *LCU_Classes* database the months in which irrigation occurs are set based on the rainfall region. The soils variables are modified based on information in Schulze (2013). The depletion scheduling option in *ACRU* is used if more detailed information is not available. Runoff from the *IrrigatedArea* will flow to the *SubcatchmentNode*. Unless more detailed information on water sources is know the source of water for irrigation is a *Dam* in the same *SubCatchment* if there is one, otherwise from run of river at the *SubcatchmentNode*.
acruHRU_AgricCommGeneralIrrigatedPerennial In instances where the specific type of irrigated perennial crop growing on a response unit is not known then an *IrrigatedArea* is created using default vegetation parameters and variable values for a perennial crop from the *LCU_Classes* database. The soils variables are modified based on information in Schulze (2013). The depletion scheduling option in *ACRU* is used if more detailed information is not available. Runoff from the *IrrigatedArea* will flow to the *SubcatchmentNode*. Unless more detailed information on water sources is know the source of water for irrigation is a *Dam* in the same *SubCatchment* if there is one, otherwise from run of river at the *SubcatchmentNode*.
acruHRU_AgricCommSpecificIrrigatedPerennial An *IrrigatedArea* is created using vegetation parameters and variable values for the specific crop type from the *LCU_Classes* database. The soils variables are modified based on information in Schulze (2013). The depletion scheduling option in *ACRU* is used if more detailed information is not available. Runoff from the *IrrigatedArea* will flow to the *SubcatchmentNode*. Unless more detailed information on water sources is know the source of water for irrigation is a *Dam* in the same *SubCatchment* if there is one, otherwise from run of river at the *SubcatchmentNode*.
acruHRU_AgricCommSugarcaneDrylandGeneral A *HRU* is created using vegetation parameters and variable values for sugarcane grown in the relevant sugarcane growing region from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_AgricSubsGeneralDrylandAnnual A *HRU* is created using vegetation parameters and variable values for a default subsistence crop from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.

Table 4.20 (cont.) Description of the *LCU_Class* related methods in the *MenuCreator* module

acruHRU_AgricSubsSugarcaneDrylandGeneral A *HRU* is created using vegetation parameters and variable values for a subsistence sugarcane crop from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_BareCoastalSand A *HRU* is created using parameters and variable values for bare sand from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_BarePervious A *HRU* is created using parameters and variable values for a bare pervious response unit from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_BareRock An *AdjunctImperviousArea* is created. Runoff from the *AdjunctImperviousArea* will flow to the *SubcatchmentNode*.
acruHRU_OpencastMineQuarry An *AdjunctImperviousArea* is created based on the assumption that there will be a small amount of interception, but that drainage structures will result in most rainfall being removed from the site. Runoff from the *AdjunctImperviousArea* will flow to the *SubcatchmentNode*.
acruHRU_Plantation A *HRU* is created using vegetation parameters and variable values for the specified plantation type from the *LCU_Classes* database. Adjustments are made to the default *HRU* configuration to turn on the ACRU forest modelling option for enhanced wet canopy evaporation and to adjust the root colonisation of the subsoil. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_SheetErosion A *HRU* is created using parameters and variable values for an eroded response unit from the *LCU_Classes* database. Runoff from the *HRU* will flow to the *SubcatchmentNode*.
acruHRU_Urban A *HRU* is created to represent the pervious portion. A *DisjunctImperviousArea* and an *AjunctImperviousArea* are also created depending on the characteristics specified in the *LCU_Class*. The *HRU* is currently assumed to be vegetated with the dominant Acocks Veld Type associated with the response unit for which vegetation parameters and variable values from the *LCU_Classes* database are used. Runoff from the *HRU* and *AjunctImperviousArea* will flow to the *SubcatchmentNode*. Runoff from the *DisjunctImperviousArea* will flow onto the *HRU*.
acruHRU_UrbanOpen A *HRU* is created to represent the pervious portion using vegetation parameters and variable values for specified the *LCU_Classes* database. A *DisjunctImperviousArea* and an *AjunctImperviousArea* are also created depending on the characteristics specified in the *LCU_Class*. Runoff from the *HRU* and *AjunctImperviousArea* will flow to the *SubcatchmentNode*. Runoff from the *DisjunctImperviousArea* will flow onto the *HRU*.
acruHRU_Wetland A *Wetland* is created using vegetation parameters and variable values for the specified wetland type from the *LCU_Classes* database. Runoff from the *Wetland* will flow to the *SubcatchmentNode*.

Using the information contained in the project database and the spatial datasets that it references the *ACRU* model is configured for a case study catchment using the *MenuCreator* module. First the *Catchment* and *SubCatchment* components are created. Next, the flow network is created by first creating the network nodes and then the network routes that join them. The flow network is then checked to ensure that all the network nodes are connected. The response units are then created and the flow destinations for runoff are set. Finally the climate data is included in the configuration and the links between this data and the various spatial components are set.

4.17 Compilation of Water Resource Accounts

Most of the data and information required to compile the water resource accounts will be available as output from the *ACRU* model. Given that water resource accounts will need to be compiled at annual, seasonal and possibly even monthly time scales, possibly for a number of years, and for a number of catchments, some means was required to fully or at least partially automate the compilation of accounts.

A new software module named *ACRU.Processes.Accounting* was developed, using the Java programing language, as part of the of the *ACRU* model, to accumulate the relevant *ACRU* output data required to compile water accounts at Quinary to Primary catchment spatial scales for monthly and annual temporal scales. The accounts are compiled in Scalable Vector Graphics (SVG) format using the template for the modified Resource Base Sheet shown in Figure 4.3 and populating it with the relevant data values. Each Resource Base Sheet has an accompanying land and water use summary table in the form of a pivot table, as described in Section 4.1 summarising areal extent, water availability and use by land cover/use class.

4.18 General Workflow

It is difficult to develop a universally applicable workflow for configuring the *ACRU* model and compiling water accounts due to differing degrees of data availability in different catchments, especially updated land cover datasets. However, the aim of this project was to provide a general methodology which is internally consistent, reasonably reproducible, adaptable, and which will greatly ease the process in other catchments. The scripts developed in this project are meant to ease the burden of data processing, but need to be used intelligently and adapted or extended where necessary. A list of suggested processing steps is as follows:

(i) Spatial datasets covering the whole of South Africa need to be processed to use a common spatial reference system. In this project the WGS84 reference has been used. Additional pre-processing may be required to add new attribute fields to some datasets.

(ii) Decide on the extent of the study catchment and create shapefiles of Primary, Secondary, Tertiary, Quaternary and sub-Quaternary catchment boundaries as appropriate for the study catchment.

(iii) Create an empty project database spreadsheet.

(iv) Use the scripts *populateCatchmentsFromShapefile* and *populateSubCatchmentsFromShapefile* from the *cwrr.Project.Project* module to populate the *Catchments* and *SubCatchments* tables in the project database.

(v) Investigate the availability of a recent and suitably detailed land cover/use dataset for the study catchment and select the most suitable dataset for the scale and purpose of the study.

(vi) Create a file specifying a mapping between the land cover/use classes in the land cover dataset and the classes in the *LCUClasses.xml* file.

(vii) Clip spatial datasets of spatial features such as rivers and dams to the extent of the study catchment.

(viii) Create a shapefile of river nodes using the river and sub-Quaternary catchment datasets. At present this has to be done manually.

(ix) Use the *populateRiverNetworkNodesFromRiverNodeShapefile* script from the *cwrr.Project.Project* module to populate the *NetworkNodes*, *RiverNodes*, *RiverRoutes* and *Rivers* tables in the project database.

(x) Use the *createDamNodesShapefile* script in the *cwrr.Dams.DWSRegisteredDams* module to create a shapefile of dam nodes

(xi) Use the *populateDamsFromDamNodesShapefile* script from the *cwrr.Project.Project* module to populate the *NetworkNodes* and *Dams* tables in the project database.

(xii) Clip spatial datasets of HRU related modelling parameters and variables such as altitude, land cover/use, soils, rainfall seasonality, frost occurrence and MAP, to the extent of the study catchment.

(xiii) Use the *mapToLandCoverUnits_GeoTiff* script in the cwrr.LandCover.LCU_Mapping module to create a raster dataset of *LCUClass* IDs using the clipped land cover/use dataset and land cover/use class mapping file.

(xiv) If necessary use the scripts in the *cwrr.LandCover.LCU_Mapping* module to superimpose secondary land cover/use datasets on the raster dataset of *LCUClass* IDs.

(xv) Use the *createLCURegionsTables* script in the *cwrr.LandCover.LCURegionsTables* module to create a *LCURegions* spreadsheet of land cover/use regions using the sub-Quuarternary catchments, *LCUClass* IDs, natural vegetation, soils, rainfall seasonality, frost occurrence and sugarcane growing region datasets.

(xvi) Use the *populateHRUsFromLCURegionsTables* script from the *cwrr.Project.Project* module to populate the *HRUs*, *NetworkNodes* and *UserNodes* tables in the project database.

(xvii) Manually add records to the *StreamflowGauges*, *EWRNodes*, *SourceNodes*, and *SinkNodes* tables in the project database spreadsheet.

(xviii) Check the project database for data processing errors and completeness, and manually make changes to the database where necessary.

(xix) Download and process remotely sensed datasets of climate related modelling variables such as rainfall, reference potential evaporation and temperature to create a separate time series file for each variable for each sub-Quaternary catchment.

(xx) Use the *cwrr.General.ACRU_Setup.MenuCreator* class to generate an *ACRU* model input file.

(xxi) Run the *ACRU* model to compile preliminary water accounts.

(xxii) If necessary update preliminary water accounts using unmodelled data values such as reserved outflows.

(xxiii) Verify water accounts using observed data such as streamflow where this is available.

5 UMNGENI CATCHMENT CASE STUDY

DJ Clark

The uMngeni Catchment forms part of the Pongola-Mtamvuna WMA situated in the summer rainfall region, in the KwaZulu-Natal province of South Africa. The catchment has an area of 4455 km^2 and the altitude ranges from 1913 m in the west to sea level in the east (Warburton, 2011). The mean annual precipitation MAP varies from 1550 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, Albert Falls, Nagle and Inanda) and is augmented with transfers from the Mooi River in the Thukela Catchment. The NWRS (DWAF, 2004) 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, cultivation of sugarcane and commercial forestry plantations (DWAF, 2004). Streamflow in the catchment is largely perennial and there is minimal extraction of groundwater (DWAF, 2004).

The uMngeni Catchment was selected as one of the case study sites as it is an example of a highly developed catchment and is of high economic importance. Other advantages of using this catchment were its proximity to the University of KwaZulu-Natal, that it was familiar to the project team and that this study would other studies taking place in the catchment. The study of this catchment by Warburton (2011) using the National Land Cover (NLC) 2000 land cover map is expected to provide a useful reference point. Another important reason for proposing this catchment was that updated maps of actual land cover at 20 m resolution are available from Ezemvelo KZN Wildlife for 2005, 2008 and 2011, which would potentially enable water accounts based on actual present land cover to be compiled and compared with the 2000 land use used by Warburton (2011). The presence of the bulk water utility Umgeni Water which is responsible for providing potable water within the catchment was another reason for recommending the catchment.

The uMngeni Catchment consists of the U20 Tertiary Catchment and which has the same boundary as the U2 Secondary Catchment. The U20 Tertiary Catchment contains 12 Quaternary Catchments. The Quaternary Catchments within the uMngeni Catchment are shown in Figure 5.1.

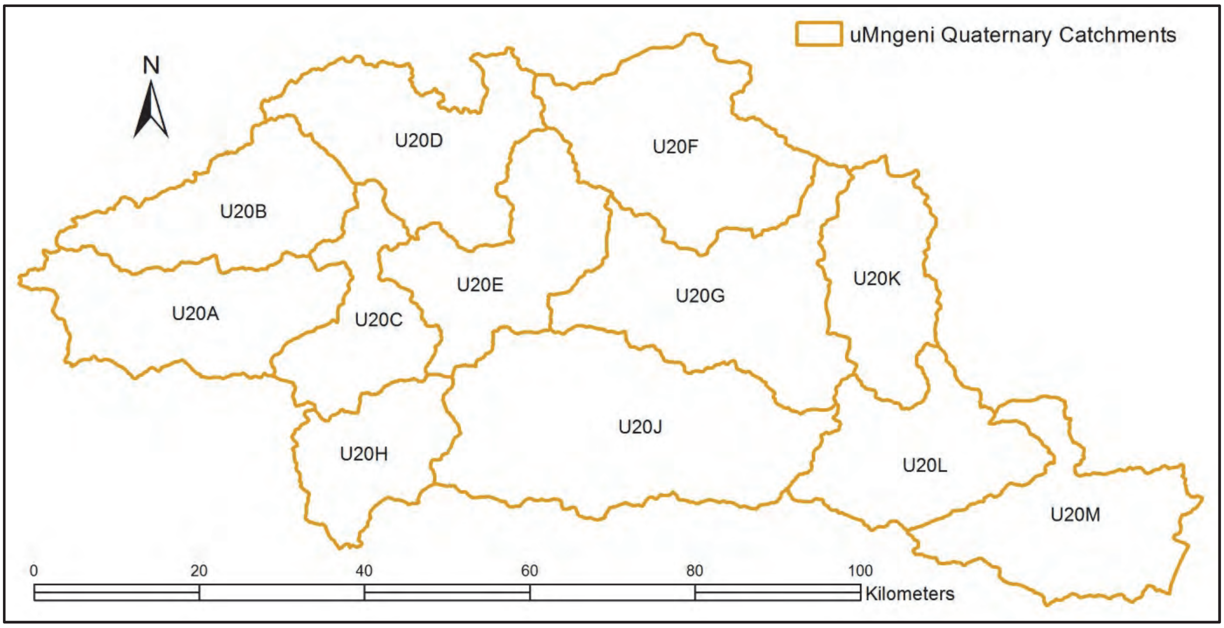

Figure 5.1 The Quaternary Catchments within the uMngeni Catchment (SLIM, 2014b)

5.1 Sub-Quaternary Catchment Boundaries

For the purpose of the uMngeni case study it was decided that the sub-Quaternary catchment boundaries used by Umgeni Water and also Warburton (2011) should be used. This was done so that the results from the case study can be compared to the study by Warburton (2011) and will be compatible with other studies being conducted in the uMngeni Catchment. Although these sub-Quaternary catchment boundaries were similar to the new DWS Quaternary Catchment (SLIM, 2014b) boundaries, they did not match exactly, and the process of adjusting these boundaries was difficult and time consuming. Two sub-Quaternaries, AlbertFalls_40 and Inanda_130, had to be divided as they were split by the new Quaternary catchment boundaries, and a new sub-Quaternary was added in Quaternary U20M to include a missing portion of Durban North. The Durban_145 sub-Quaternary catchment was modified to include the whole coastal section in Quaternary U20M. The sub-Quaternary catchments used for the uMngeni Catchment are shown in Figure 5.2.

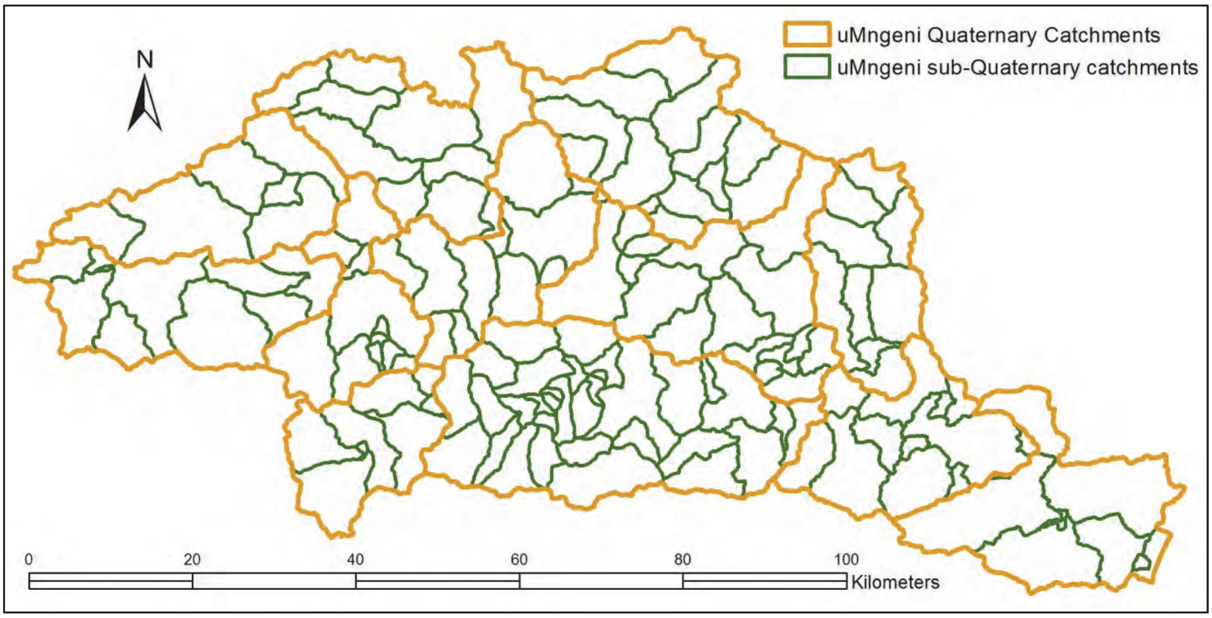

Figure 5.2 The sub-Quaternary catchments for the uMngeni Catchment

5.2 Sub-Quaternary Catchment Altitude

The flow path improved Digital Elevation Model (DEM) (Weepener *et al.*, 2011d) with 90m resolution produced by Weepener *et al.* (2011a) was used to determine the mean altitude for each sub-Quaternary catchment. The DEM altitudes are shown in Figure 5.3 and the mean altitudes for the sub-Quaternary Catchments in the uMngeni Catchment are shown in Figure 5.4.

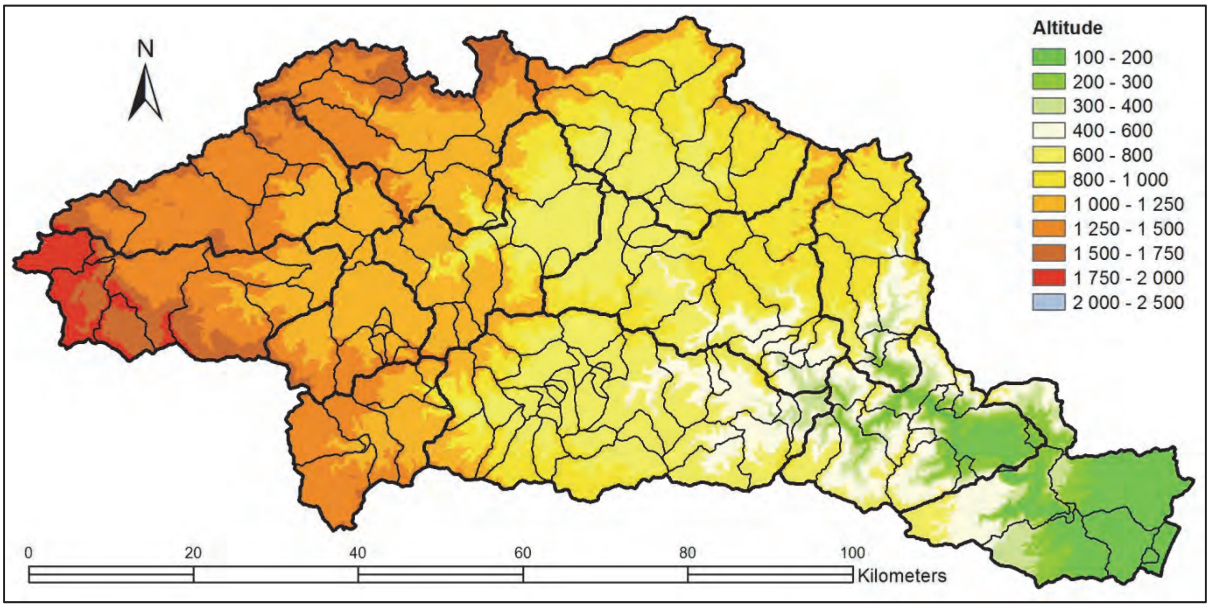

Figure 5.3 DEM altitudes for the uMngeni Catchment (Weepener *et al.*, 2011d)

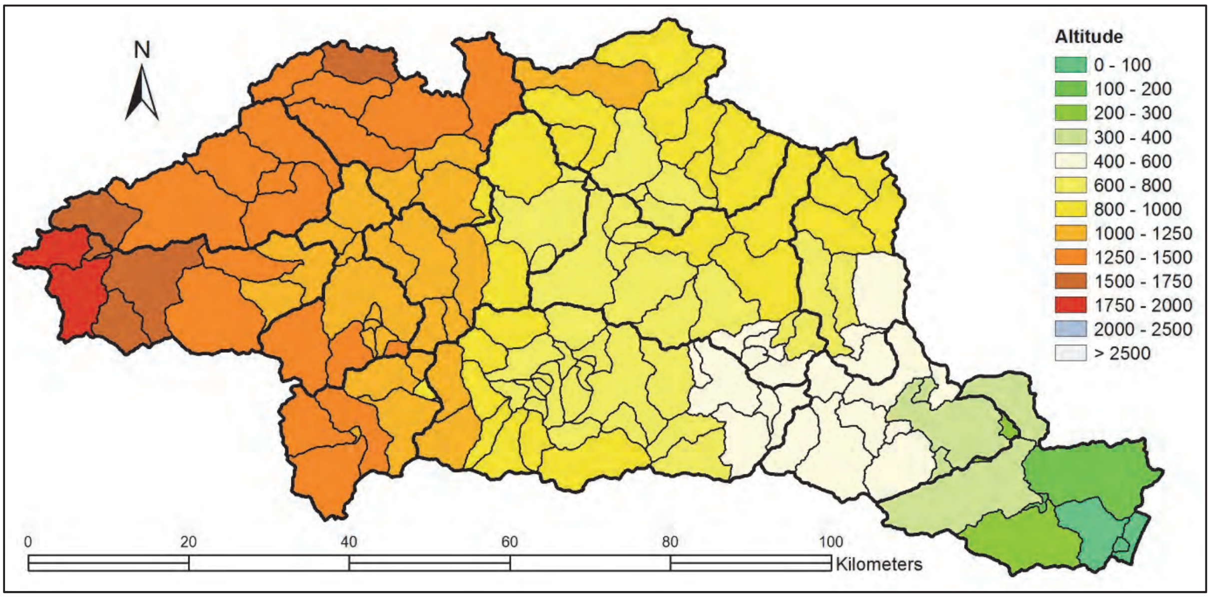

Figure 5.4 Mean altitudes of the sub-Quaternary catchments in the uMngeni Catchment

5.3 Rivers and River Nodes

The shapefile of flow paths (Weepener *et al.*, 2011c) developed in WRC project K5/1908 using the SRTM 90m DEM as described by (Weepener *et al.*, 2011a) was used in this case study. The river features within the uMngeni Catchment were clipped from the Weepener *et al.* (2011c) dataset. As described in Section 4.5, the clipped rivers dataset together with the uMngeni Quaternary Catchment boundaries dataset was used to manually create a point shapefile of river nodes using ArcMap. A river node was created where each sub-Quaternary catchment boundary intersected a river segment and at any points where there was a confluence of river reaches between these points. For each node, attributes were set specifying the downstream node and whether the node was at the exit of a sub-Quaternary catchment. The sub-Quaternary catchment boundaries, rivers and the derived river nodes for the uMngeni Catchment are shown in Figure 5.5.

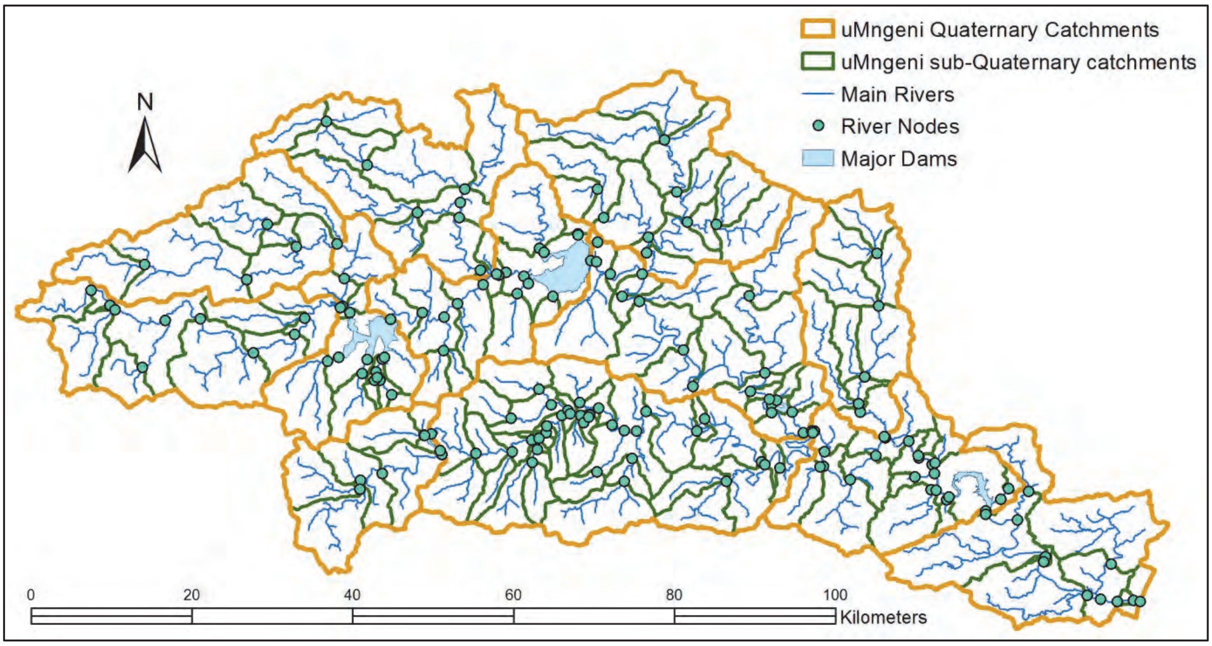

Figure 5.5 Rivers (Weepener *et al.*, 2011c) and derived river nodes

5.4 Dams

For this deliverable the DWS database of registered dams (DSO, 2014) provided in Microsoft Excel (.xlsx) format was used. This database was first saved to CSV format and a shapefile of registered dams was created. This shapefile was then clipped to produce a shapefile of registered dams in the uMngeni Catchment. This shapefile was compared with other dam datasets and Google Earth satellite imagery and the locations of a few large farm dams, located near sub-Quaternary catchment boundaries and which were obviously incorrectly located, were corrected. This clipped dataset was then used to create a shapefile of dam nodes such that all registered dams in a sub-Quaternary catchment are lumped together near the exit of a sub-Quaternary catchment and can act as a water source for all water users in a sub-Quaternary catchment. In sub-Quaternary catchment where the land cover/use dataset indicates a total surface area or dams greater than the total area of registered dams, an additional lumped dam representing unregistered dams is modelled. These small unregistered dams impede runoff generated within a sub-Quaternary catchment but are assumed to not be used for irrigation. The sub-Quaternary catchment boundaries and dam nodes for the uMngeni Catchment are shown in Figure 5.6.

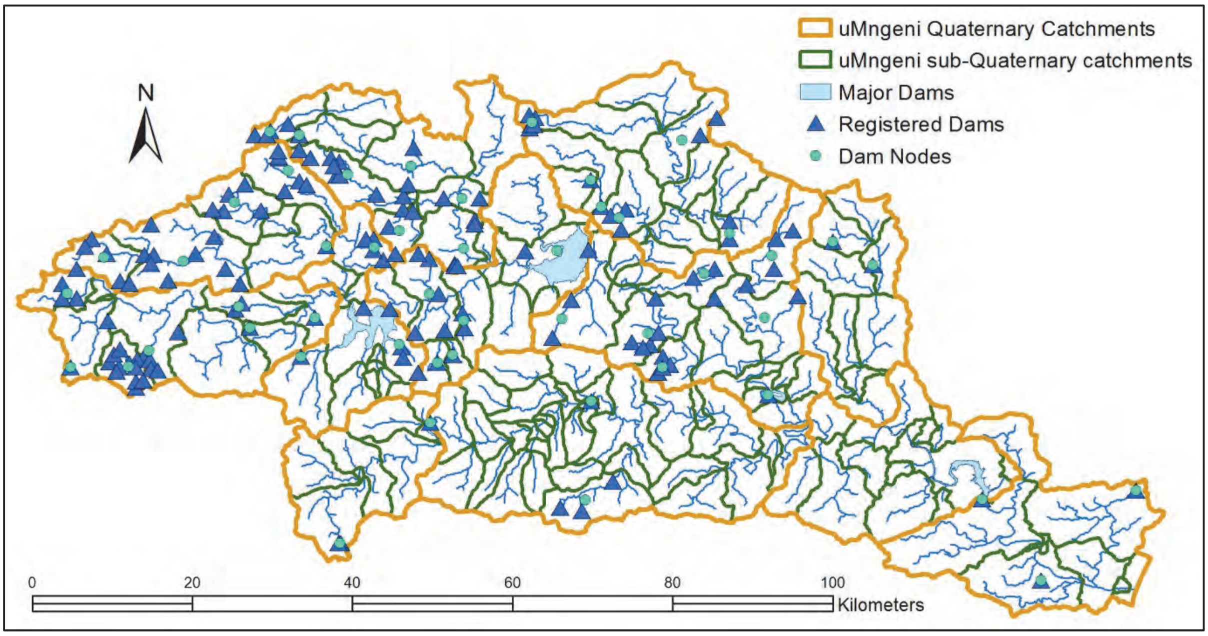

Figure 5.6	Registered dams (DSO, 2014) and derived dam nodes

5.5 Transfers, Abstractions and Return Flows

The only inter-catchment transfer associated with the uMngeni Catchment is the transfer from Mearns Weir on the Mooi River in Quaternary Catchment V20D, to the Mpofana River, a tributary of the Lions River in Quaternary Catchment U20B. Daily average flow data was obtained from DWS for the pumped transfer (gauge V2H015); however, this data was found to include flow rates of up to 328 m^3/s, which exceeds the pumping capacity by a factor of approximately 100. A different dataset of daily flow data was obtained from Umgeni Water, though Umgeni Water pointed out that there were periods when the flow meters were not working, and that during these periods the flows were assumed to be 280 Ml/d when two pumps were operating and 180 Ml/d when one pump was operating, which correspond to the design capacities. Comparing the two datasets there are some months when there is close agreement between the two datasets and other months when the DWS dataset is clearly incorrect. The dataset from DWS was used to estimate the inter-catchment transfer flows for the period October 2011 to December 2011. The dataset from Umgeni Water was used to model the inter-catchment transfer flows for the period January 2012 to December 2014. No flow data could be obtained for the period January 2010 to September 2011, and for the purpose of this case study the flows were assumed to be zero for this period.

5.6 Natural Vegetation

In this case study the Acocks Veld Types (Acocks, 1988) were used to represent all areas with natural vegetation cover for the reasons discussed in Section 4.8.3. The hydrological characteristics of each Acocks Veld Type were based on the values from Schulze (2004). The Acocks Veld Types present in the uMngeni Catchment and their distribution are shown in Figure 5.7.

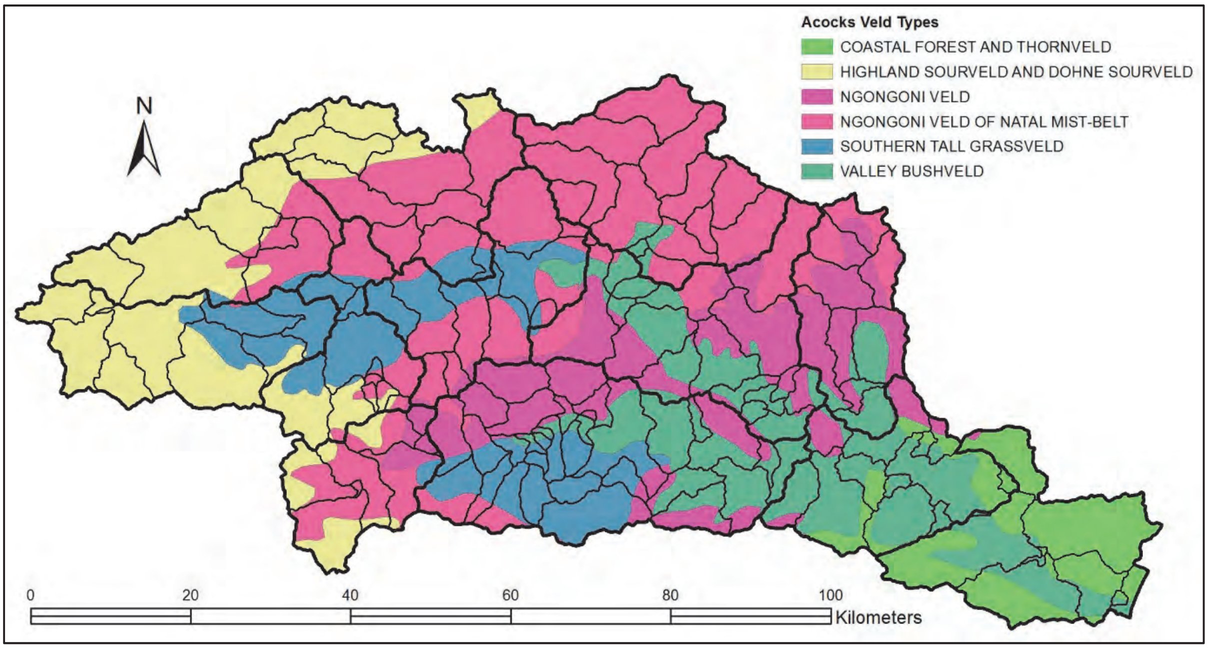

Figure 5.7 Acocks Veld Types in the uMngeni Catchment (after Acocks, 1988)

5.7 Land Cover/Use

The 2011 land cover/use raster dataset for KwaZulu-Natal (Ezemvelo KZN Wildlife and GeoTerraImage, 2013) was used in this case study as it is the most recent and comprehensive dataset available for the uMngeni Catchment. As shown in Figure 5.8, in addition to natural vegetation some of the prominent non-natural land cover classes in the uMngeni Catchment include the greater Pietermaritzburg and Durban urban areas, forest plantations, sugarcane, other commercial crops and four large dams (Midmar, Albert Falls, Nagle and Inanda).

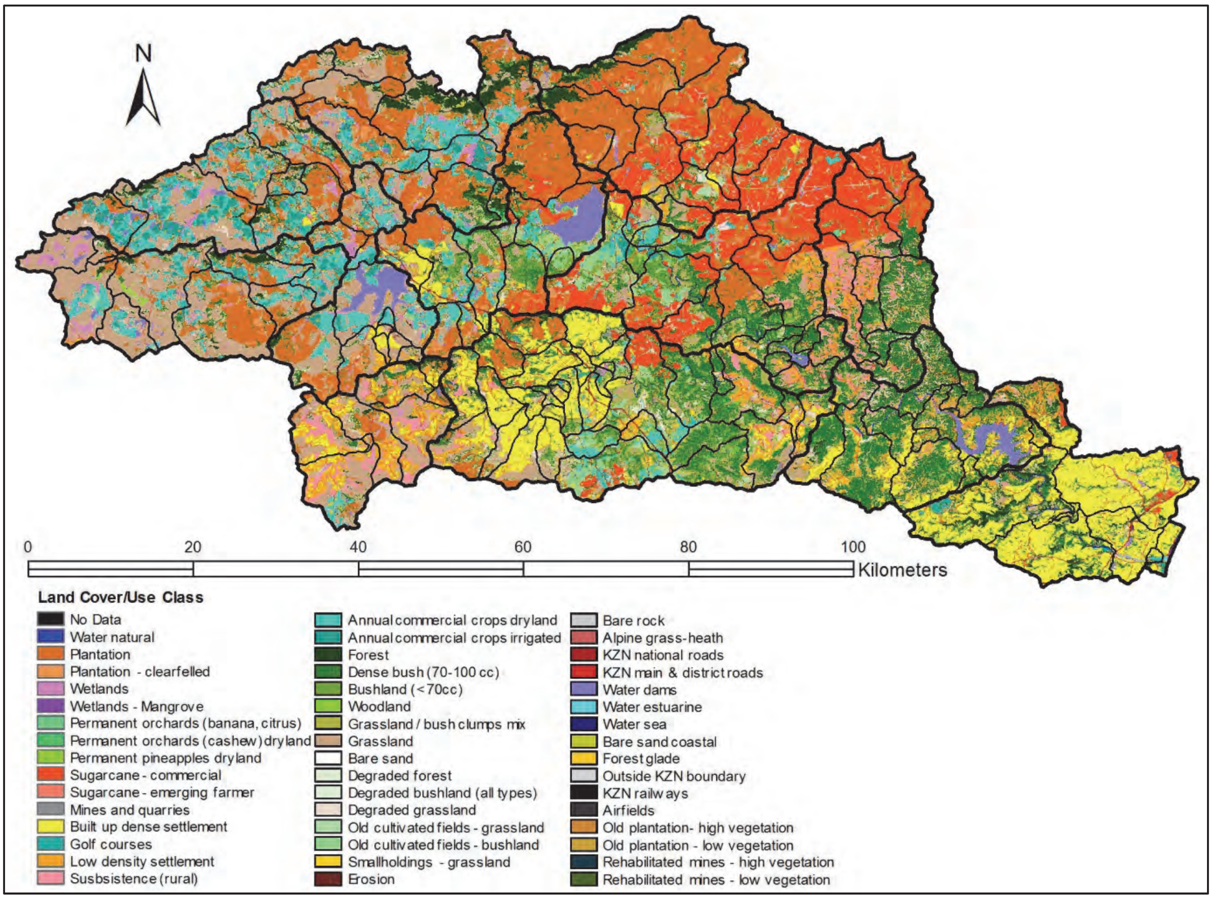

Figure 5.8 Land cover/use classes for the uMngeni Catchment (after Ezemvelo KZN Wildlife and GeoTerraImage, 2013)

A mapping between the Ezemvelo KZN Wildlife and GeoTerraImage (2013) land cover/use classes and classes in the LCUClass database was created, as shown in Appendix D.2. Using the methodology described in Section 4.8.2, the clipped land cover/use file was used to create a raster dataset of *LCUClass* IDs, shown in Figure 5.9. In this case study no other land cover use datasets were superimposed on the raster dataset of *LCUClass* IDs.

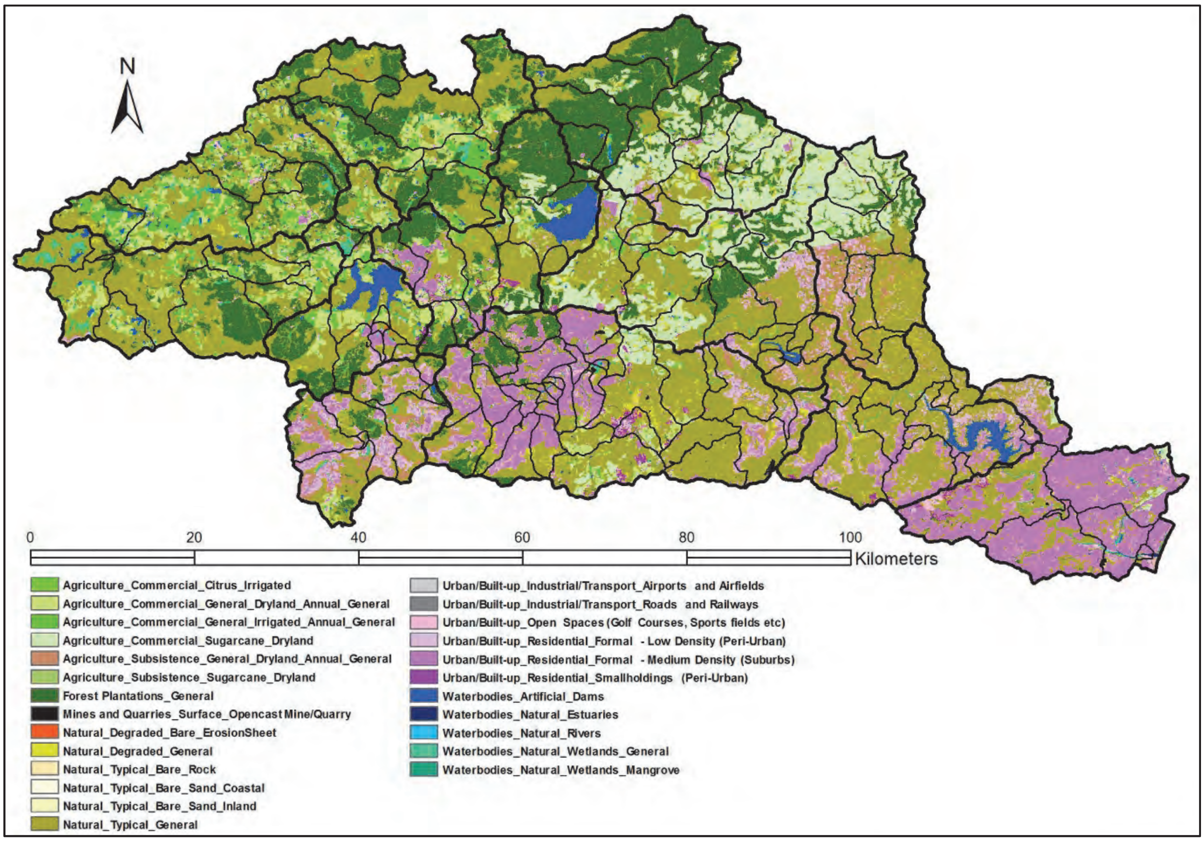

Figure 5.9 Raster dataset of *LCUClasses* for the uMngeni Catchment

In Schulze (2013) different values are provided for vegetation variables for use in the *ACRU* model for four sugarcane growing regions: (i) KwaZulu-Natal South Coast, (ii) KwaZulu-Natal North Coast, (iii) Far North Coast, and (iv) KwaZulu-Natal Inland. Using the methodology described in Section 4.8.4 a shapefile of sugarcane growing regions was created for the uMngeni Catchment, and is shown in Figure 5.10. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet so that a dominant sugarcane growing region could be determined for each HRU with sugarcane as a land cover/use.

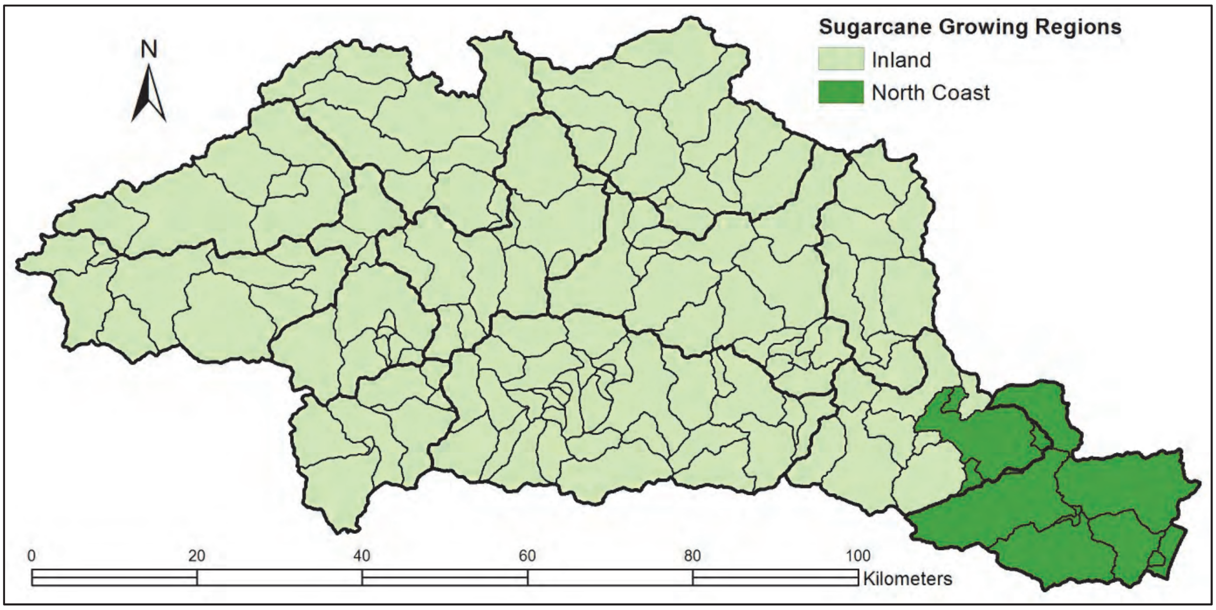

Figure 5.10 Sugarcane growing regions in the uMngeni Catchment

5.8 Soils

The soils dataset developed and described by Schulze and Horan (2008b) was used in this case study. Using the methodology described in Section 4.9, 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.

5.9 Climate

5.9.1 Long-term annual and monthly rainfall

The MAP dataset developed by Lynch (2004) was used in this case study. The MAP for the uMngeni Catchment is shown in Figure 5.11. This dataset was used to create a shapefile containing area weighted mean MAP values for each sub-Quaternary catchment. The MAP value for each sub-Quaternary catchment was then used to configure the *ACRU* hydrological model.

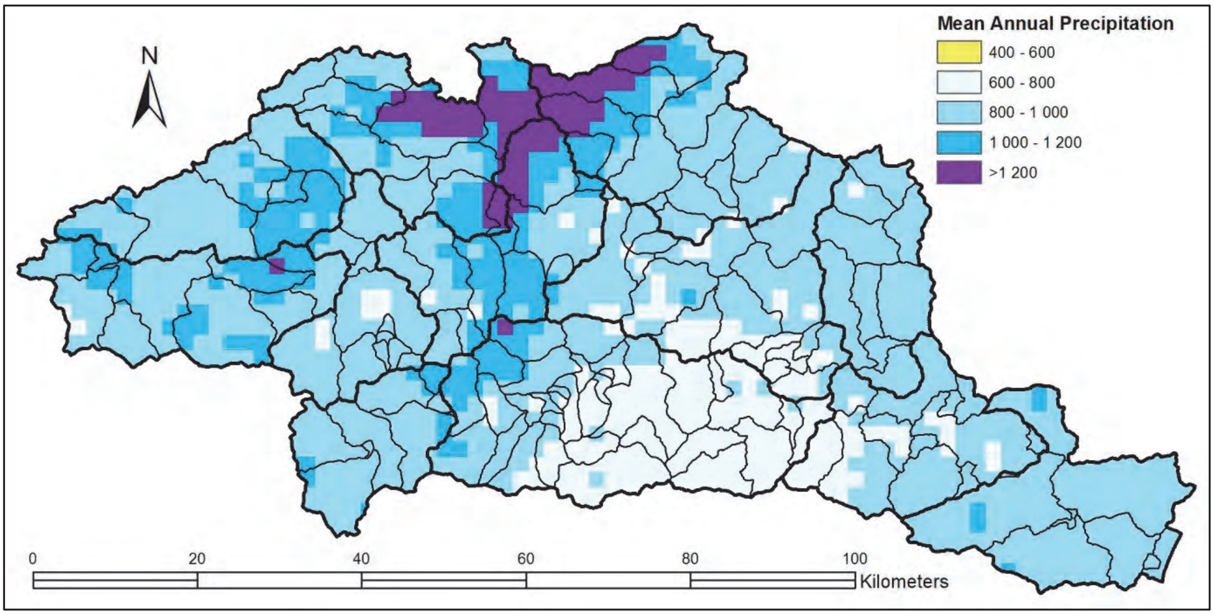

Figure 5.11 Area weighted MAP in the uMngeni Catchment (after Lynch, 2004; Schulze and Lynch, 2008a)

The mean monthly rainfall and median monthly rainfall datasets developed by Lynch (2004) were used in this case study. The mean monthly rainfall datasets were used to calculate areal mean values for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 12 fields containing the calculated mean monthly rainfall values. Similarly, the median monthly rainfall datasets were used to calculate areal mean values for each sub-Quaternary catchment to produce a shapefile dataset containing median monthly rainfall values for each sub-Quaternary catchment. These two shapefiles were then used to calculate bias correction factors to potentially be used as a simple means of bias correction for the remotely sensed daily rainfall data.

5.9.2 Rainfall seasonality

The rainfall seasonality dataset developed and described by Schulze and Maharaj (2008a) was used in this case study. The rainfall seasonality regions for the sub-Quaternary catchments in the uMngeni Catchment are shown in Figure 5.12. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet. The dominant rainfall seasonality region for each land cover/use based HRU within each sub-Quaternary catchment was then used to configure the *ACRU* hydrological model in HRUs where specific types of dryland and irrigated crops were not specified by the land cover/use dataset.

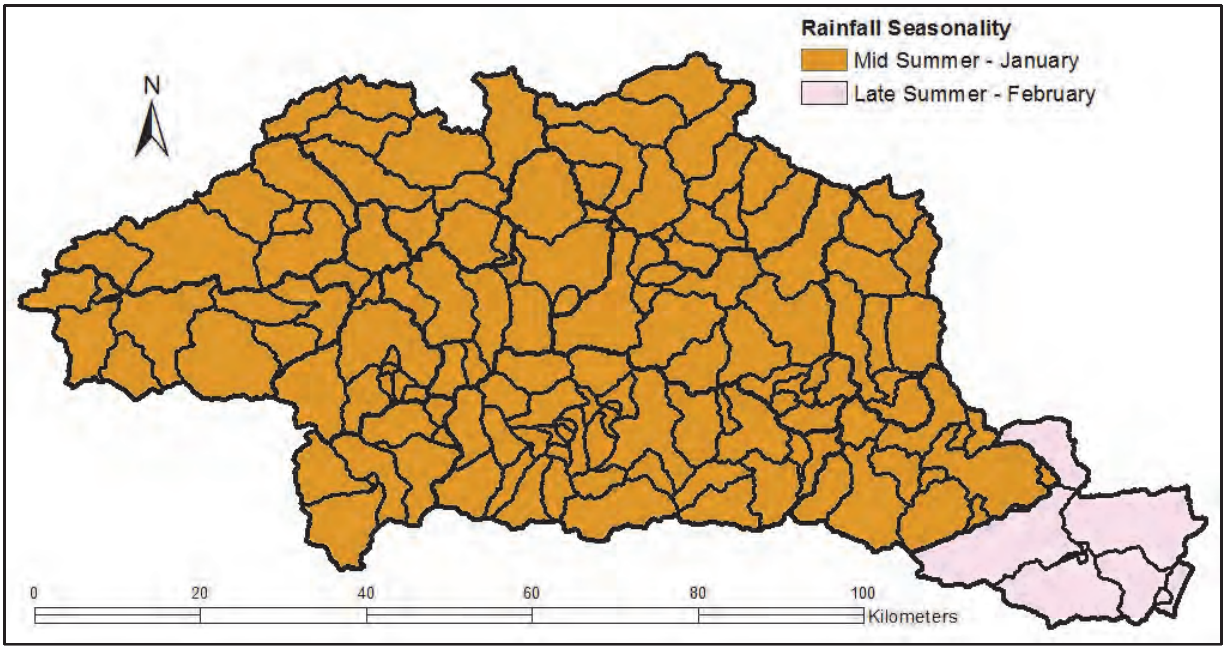

Figure 5.12 Rainfall seasonality regions in the uMngeni Catchment (after Schulze and Maharaj, 2008a)

5.9.3 Daily rainfall

The CMORPH, FEWS ARC 2.0, FEWS RFE 2.0 and TRMM 3B42 remotely sensed daily rainfall datasets described in Section 4.11.1 were compared and evaluated for use in creating water accounts. Although there are many advantages to using remotely sensed data, as discussed in Section 3.2.1.5, the accuracy of these datasets for use in water accounting in the uMngeni Catchment needed to be determined. The first step was to compare the rainfall values in these datasets with rain gauge data from five rain gauges, one situated at Cedara and one at each of the four major dams (Midmar, Albert Falls, Nagle and Inanda) in the uMngeni Catchment. The four remotely sensed datasets had a common data period for the years 2001 to 2013 and were evaluated for this common time period. The rain gauge data was obtained from the "Hydrological Services – Surface Water (Data, Dams, Floods and Flows)" page of the DWS website (http://www.dwa.gov.za/hydrology/). These rain gauges were selected as they were currently operational and their period of record covered the 2001-2013 evaluation period. The details of these rain gauges are shown in Table 5.1 and their locations are shown in Figure 5.13.

Table 5.1 Rain gauges used for verification

Station ID	Location		
	Name	Latitude	Longitude
U2E002	Cedara	29°32'01''	30°16'59''
U2E003	Midmar Dam	29°30'01''	30°11'59''
U2E006	Albert Falls Dam	29°25'46''	30°25'29''
U2E009	Nagle Dam	29°35'01''	30°37'22''
U2E010	Inanda Dam	29°43'30''	30°52'20''

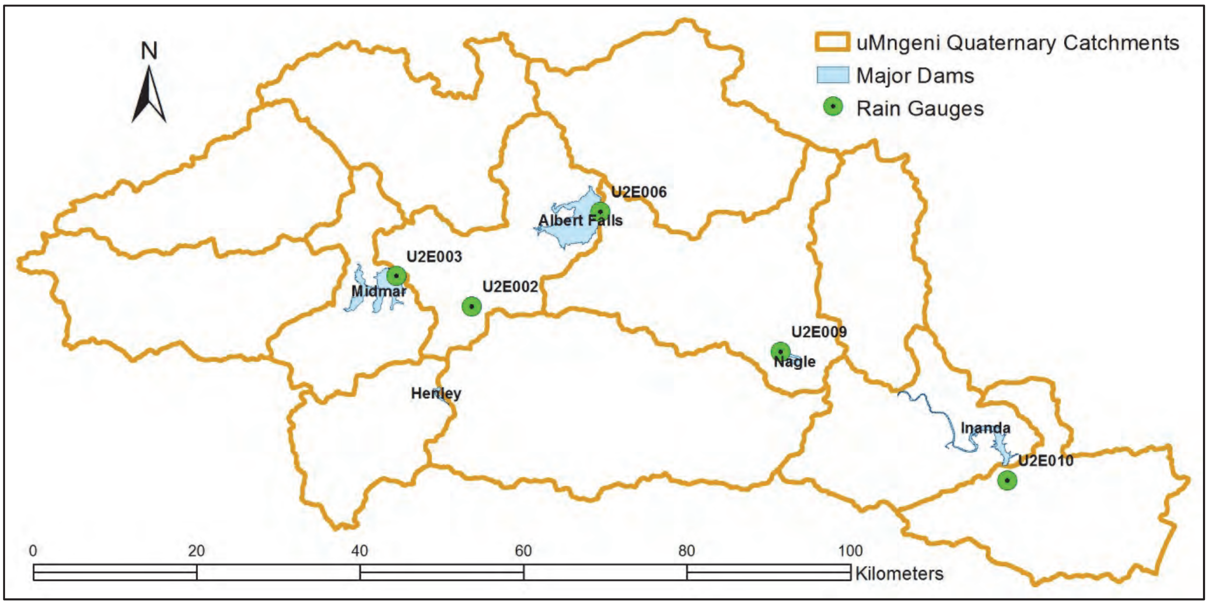

Figure 5.13 Location of rain gauges used for verification

For each of the four remotely sensed datasets a timeseries of daily rainfall was created for each of the rain gauges, using the closest pixel, for the years 2001 to 2013. For each rain gauge the remotely sensed datasets were compared statistically with the rain gauge dataset. In a daily hydrological model, it is important that not only the seasonal or annual rainfall totals are correct, but also that the magnitude and timing of the daily rainfall is correct as this can have a significant impact on the simulation of runoff and total evaporation. It should also be remembered that the rain gauge data is a point estimate while the remotely sensed data is spatially averaged over the area of a pixel which has an area in the order of approximately 100 km^2 to 625 km^2 depending on the dataset. The dataset statistics and comparative statistics for rain gauge U2E002 are shown in Table 5.2 and a graph comparing accumulated daily rainfall is shown in Figure 5.14. All four remotely sensed datasets represent the rainfall for the rain gauge fairly well, with the TRMM 3B42 dataset over estimating relative to the gauge and the others underestimating. The TRMM 3B42 dataset has the lowest bias over the 13 years, but the regression statistics indicate that the two FEWS datasets have a closer association with the daily rain gauge values even though the numbers of rain days are quite different to the rain gauge data.

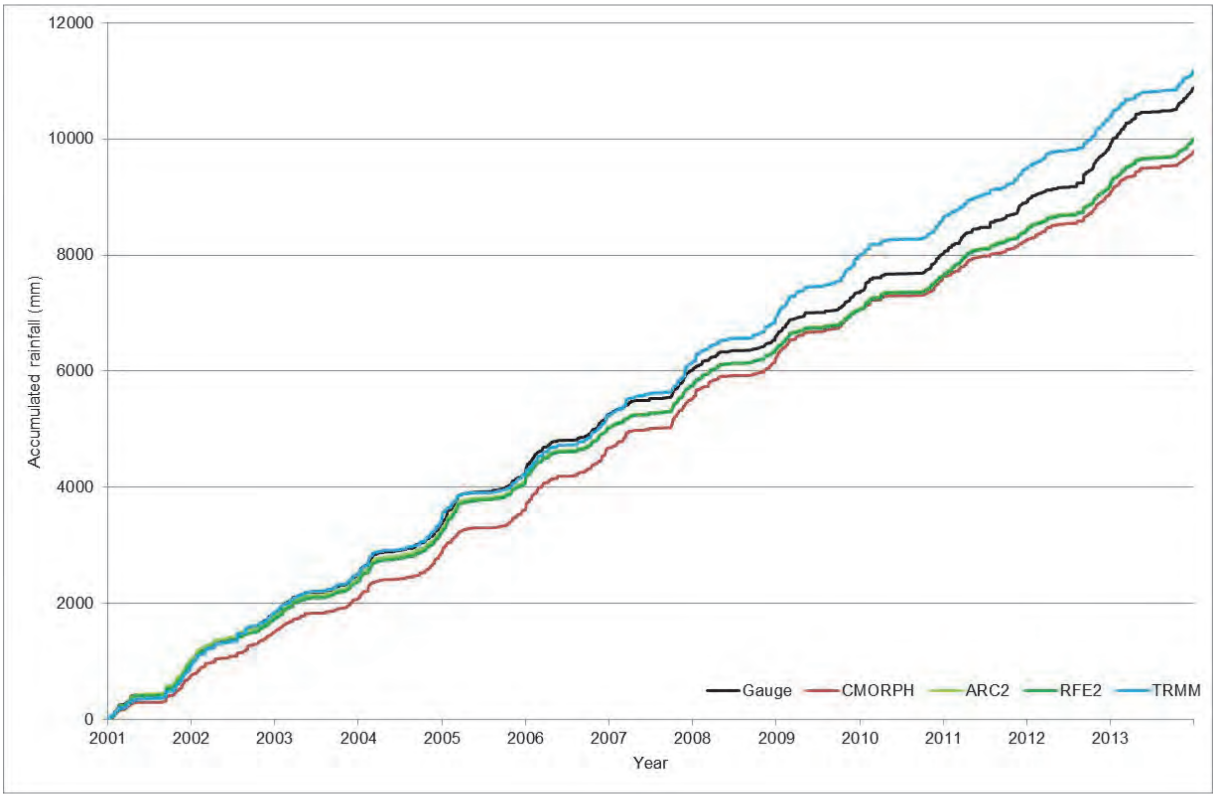

Figure 5.14 Comparison of accumulated rainfall for rain gauge U2E002 (2001 to 2013)

Table 5.2 Comparison of rainfall statistics for rain gauge U2E002 (2001 to 2013)

	Rain Gauge U2E002	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	10878.9	9783	9983.2	9997	11175.4
Max	115.5	72.7	81.2	81.2	92.3
Mean	2.3	2.1	2.1	2.1	2.4
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	6.68	5.87	5.93	5.96	7.31
Variance	44.65	34.46	35.14	35.54	53.47
Std. Error	0.65	0.50	0.51	0.52	0.78
Coef. of Variation	2.90	2.83	2.80	2.81	3.09
Skewness	5.40	5.03	5.08	5.06	5.29
Kurtosis Coef.	44.04	35.45	35.88	35.39	37.17
Sum of Squares	210670.49	162586.56	165788.08	167679.43	252281.29
Count	4718	4718	4718	4718	4718
Count x>0	1664	1692	1848	1821	1434
Count 0<mm<=2	764	810	959	940	593
Count 2<mm<=10	557	545	582	574	481
Count 10<mm<=20	206	233	192	189	199
Count 20<mm<=30	71	64	70	73	86
Count 30<mm<=40	39	20	29	28	37
Count 40<mm<=50	16	10	8	9	14
Count mm>50	11	10	8	8	24
Freq. Non-ex 95%	14.40	12.71	12.80	13.00	15.00
Freq. Non-ex 90%	7.00	7.10	6.11	6.41	7.00
Freq. Non-ex 80%	1.80	1.70	1.90	1.90	1.30
Freq. Non-ex 70%	0.50	0.20	0.60	0.60	0.10
Bias	-	-1095.90	-895.70	-881.90	296.50
RMSE	-	5.93	2.95	2.95	7.04
Correlation (R)	-	0.56	0.90	0.90	0.50
Regression Intercept	-	0.94	0.28	0.27	1.12
Regression Slope	-	0.49	0.80	0.80	0.54
Coef. of Determination (R^2)	-	0.31	0.81	0.81	0.25
Mean % Diff	-	10.07	8.23	8.11	-2.73
t-means	-	2.72	2.20	2.15	-0.59
Variance %Diff	-	22.82	21.30	20.41	-19.75
Std Dev %Diff	-	12.15	11.29	10.78	-9.43
Coef Var % Diff	-	2.31	3.33	2.91	-6.53
Skewness %Diff	-	6.86	5.84	6.33	1.96
Kurtosis %Diff	-	19.50	18.53	19.65	15.59

The dataset statistics and comparative statistics for rain gauge U2E003 are shown in Table 5.3 and a graph comparing accumulated daily rainfall is shown in Figure 5.15. For this rain gauge the CMORPH has the lowest bias over the 13 years and the TRMM 3B42 dataset has the highest bias. However, the regression statistics for both these datasets do not indicate a close association with the daily rain gauge values. Comparing the two FEWS datasets the ARC 2.0 dataset has a lower bias but the regression statistics for the FEWS RFE 2.0 dataset indicate a closer association with the daily rain gauge values.

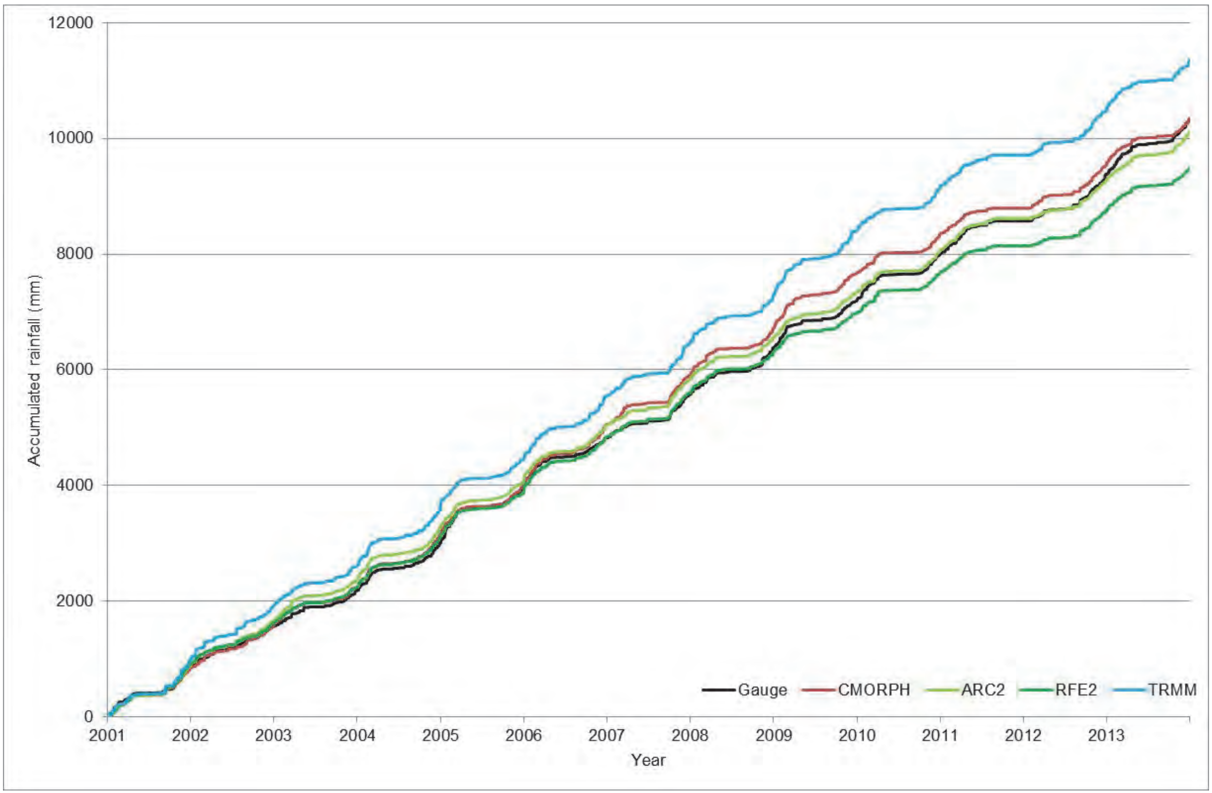

Figure 5.15 Comparison of accumulated rainfall for rain gauge U2E003 (2001 to 2013)

Table 5.3 Comparison of rainfall statistics for rain gauge U2E003 (2001 to 2013)

	Rain Gauge U2E003	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	10316.6	10350.1	10099.8	9481.2	11353.8
Max	78.5	67.8	83.9	84.3	93.4
Mean	2.3	2.3	2.2	2.1	2.5
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	6.36	5.93	5.47	5.31	7.23
Variance	40.47	35.14	29.95	28.15	52.23
Std. Error	0.60	0.52	0.44	0.42	0.77
Coef. of Variation	2.81	2.61	2.47	2.55	2.91
Skewness	4.74	4.36	4.88	5.23	5.13
Kurtosis Coef.	28.95	25.81	36.83	41.19	36.33
Sum of Squares	184732.20	160433.67	136720.77	128516.76	238408.54
Count	4565	4565	4565	4565	4565
Count x>0	1463	1716	1766	1990	1568
Count 0<mm<=2	595	776	707	991	675
Count 2<mm<=10	562	585	763	724	515
Count 10<mm<=20	174	249	205	193	225
Count 20<mm<=30	69	68	60	52	85
Count 30<mm<=40	45	18	21	18	38
Count 40<mm<=50	8	12	4	5	11
Count mm>50	10	8	6	7	19
Freq. Non-ex 95%	13.97	13.80	12.40	11.40	15.37
Freq. Non-ex 90%	6.50	7.90	7.00	6.30	7.60
Freq. Non-ex 80%	2.00	2.20	2.90	2.40	1.90
Freq. Non-ex 70%	0.50	0.40	0.90	1.00	0.20
Bias	-	10.90	-235.60	-856.10	1070.40
RMSE	-	5.50	4.21	3.83	6.77
Correlation (R)	-	0.58	0.74	0.79	0.49
Regression Intercept	-	1.04	0.77	0.59	1.23
Regression Slope	-	0.54	0.64	0.66	0.56
Coef. of Determination (R^2)	-	0.34	0.55	0.62	0.24
Mean % Diff	-	-0.32	2.10	8.10	-10.05
t-means	-	-0.05	0.34	1.34	-1.47
Variance %Diff	-	13.15	25.99	30.43	-29.06
Std Dev %Diff	-	6.81	13.97	16.59	-13.60
Coef Var % Diff	-	7.11	12.12	9.24	-3.23
Skewness %Diff	-	7.90	-2.91	-10.43	-8.23
Kurtosis %Diff	-	10.86	-27.24	-42.29	-25.51

The dataset statistics and comparative statistics for rain gauge U2E006 are shown in Table 5.4 and a graph comparing accumulated daily rainfall is shown in Figure 5.16. For this rain gauge the FEWS ARC 2.0 and CMORPH datasets have a low bias over the 13 years, while the FEWS RFE 2.0 and TRMM 3B42 datasets have higher bias. Again the regression statistics indicate that the two FEWS datasets have a closer association with the daily rain gauge values than the other two datasets.

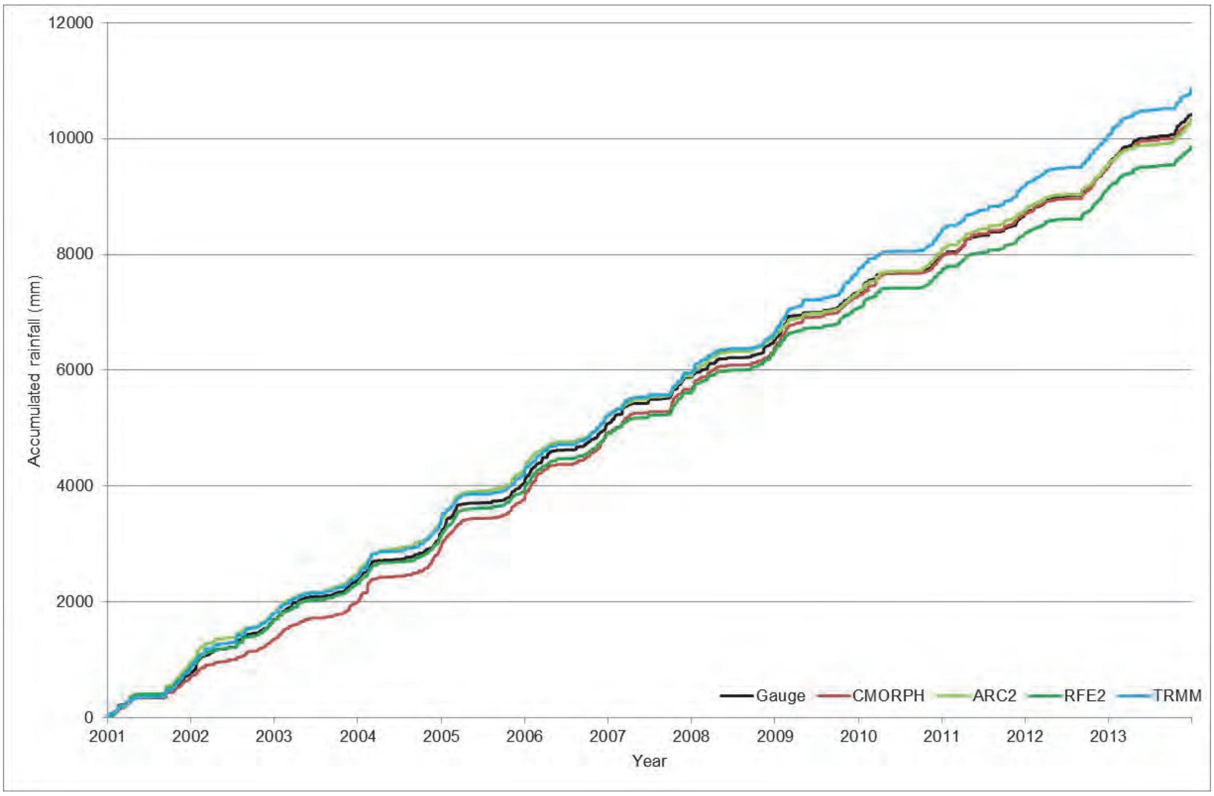

Figure 5.16 Comparison of accumulated rainfall for rain gauge U2E006 (2001 to 2013)

Table 5.4 Comparison of rainfall statistics for rain gauge U2E006 (2001 to 2013)

	Rain Gauge U2E006	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	10418.5	10324.4	10313.8	9858.5	10855.2
Max	105.5	82.1	70.5	73.5	93.6
Mean	2.3	2.2	2.2	2.1	2.4
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	6.89	6.37	5.54	5.67	7.13
Variance	47.54	40.52	30.69	32.14	50.82
Std. Error	0.70	0.60	0.45	0.47	0.75
Coef. of Variation	3.04	2.84	2.47	2.65	3.02
Skewness	5.85	5.21	4.54	5.02	5.11
Kurtosis Coef.	49.28	38.40	28.75	35.18	34.44
Sum of Squares	218674.42	186375.44	141176.70	147848.26	233792.50
Count	4600	4600	4600	4600	4600
Count x>0	1552	1798	1781	1862	1574
Count 0<mm<=2	684	909	713	885	750
Count 2<mm<=10	570	539	770	684	470
Count 10<mm<=20	160	233	199	189	208
Count 20<mm<=30	69	66	64	67	73
Count 30<mm<=40	40	31	20	22	38
Count 40<mm<=50	11	6	6	7	15
Count mm>50	18	14	9	8	20
Freq. Non-ex 95%	13.30	13.80	12.10	12.00	14.60
Freq. Non-ex 90%	6.00	7.10	7.20	6.30	7.10
Freq. Non-ex 80%	1.90	1.80	3.00	2.30	1.40
Freq. Non-ex 70%	0.40	0.30	0.80	0.80	0.20
Bias	-	-134.30	-92.10	-554.90	478.20
RMSE	-	6.04	5.01	4.58	6.61
Correlation (R)	-	0.56	0.67	0.72	0.54
Regression Intercept	-	1.08	1.03	0.80	1.11
Regression Slope	-	0.51	0.54	0.59	0.55
Coef. of Determination (R^2)	-	0.31	0.44	0.52	0.29
Mean % Diff	-	0.90	1.00	5.38	-4.19
t-means	-	0.14	0.16	0.86	-0.61
Variance %Diff	-	14.77	35.44	32.39	-6.91
Std Dev %Diff	-	7.68	19.65	17.77	-3.40
Coef Var % Diff	-	6.84	18.83	13.10	0.76
Skewness %Diff	-	10.89	22.42	14.08	12.63
Kurtosis %Diff	-	22.06	41.66	28.61	30.10

The dataset statistics and comparative statistics for rain gauge U2E009 are shown in Table 5.5 and a graph comparing accumulated daily rainfall is shown in Figure 5.17. For this rain gauge the FEWS RFE 2.0 dataset has the lowest bias over the 13 years, followed by FEWS ARC 2.0, CMORPH and then TRMM 3B42 datasets. The regression statistics indicate that the FEWS RFE 2.0 dataset also has the closest association with the daily rain gauge values.

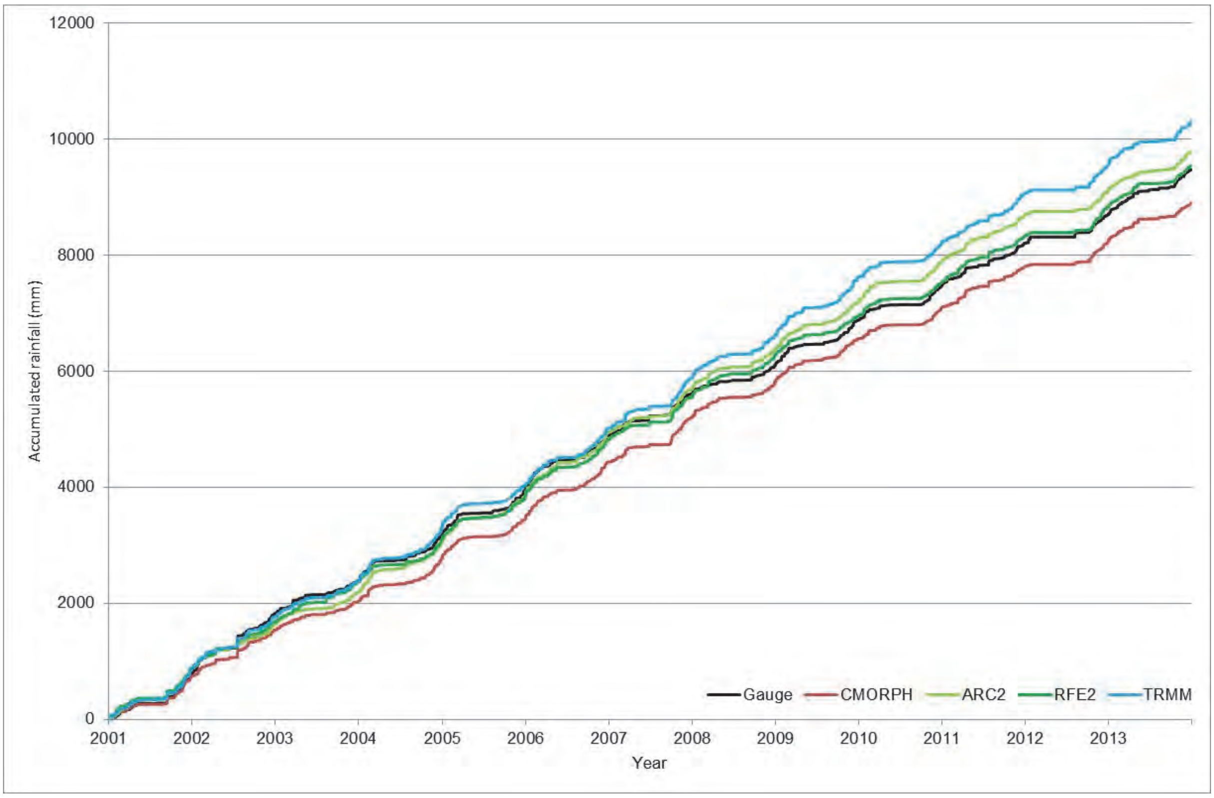

Figure 5.17 Comparison of accumulated rainfall for rain gauge U2E009 (2001 to 2013)

Table 5.5 Comparison of rainfall statistics for rain gauge U2E009 (2001 to 2013)

	Rain Gauge U2E009	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	9467.0	8894.4	9779.6	9534.1	10297.6
Max	146.0	92.0	76.2	86.7	114.8
Mean	2.1	2.0	2.2	2.1	2.3
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	6.71	6.00	5.95	5.90	7.33
Variance	45.08	35.95	35.38	34.76	53.79
Std. Error	0.67	0.53	0.53	0.52	0.80
Coef. of Variation	3.22	3.06	2.76	2.81	3.23
Skewness	6.82	5.44	5.22	5.43	5.60
Kurtosis Coef.	77.97	41.72	37.40	42.02	44.51
Sum of Squares	204565.99	163156.43	160572.37	157725.33	244112.75
Count	4538	4538	4538	4538	4538
Count x>0	1331	1513	1639	1756	1144
Count 0<mm<=2	540	763	704	875	409
Count 2<mm<=10	510	466	649	596	397
Count 10<mm<=20	163	172	180	184	183
Count 20<mm<=30	59	71	66	58	78
Count 30<mm<=40	32	19	19	26	44
Count 40<mm<=50	12	12	7	6	17
Count mm>50	15	10	14	11	16
Freq. Non-ex 95%	12.31	12.11	12.11	12.21	14.10
Freq. Non-ex 90%	5.71	5.90	6.31	6.10	6.91
Freq. Non-ex 80%	1.50	1.12	2.20	1.90	0.80
Freq. Non-ex 70%	0.00	0.10	0.70	0.60	0.00
Bias	-	-593.00	278.30	39.90	822.70
RMSE	-	5.65	5.41	4.83	6.69
Correlation (R)	-	0.59	0.62	0.70	0.53
Regression Intercept	-	0.86	1.01	0.82	1.06
Regression Slope	-	0.53	0.55	0.61	0.58
Coef. of Determination (R^2)	-	0.35	0.39	0.49	0.28
Mean % Diff	-	6.05	-3.30	-0.71	-8.77
t-means	-	0.92	-0.50	-0.11	-1.21
Variance %Diff	-	20.24	21.51	22.90	-19.33
Std Dev %Diff	-	10.69	11.40	12.19	-9.24
Coef Var % Diff	-	4.94	14.24	12.81	-0.43
Skewness %Diff	-	20.14	23.41	20.40	17.91
Kurtosis %Diff	-	46.49	52.03	46.10	42.92

The dataset statistics and comparative statistics for rain gauge U2E010 are shown in Table 5.6 and a graph comparing accumulated daily rainfall is shown in Figure 5.18. For this rain gauge all four remotely sensed datasets overestimated the rainfall. The CMORPH dataset has the lowest bias over the 13 years, followed by FEWS RFE 2.0, FEWS ARC 2.0, and then TRMM 3B42 datasets. The regression statistics indicate that the FEWS RFE 2.0 dataset has the closest association with the daily rain gauge values.

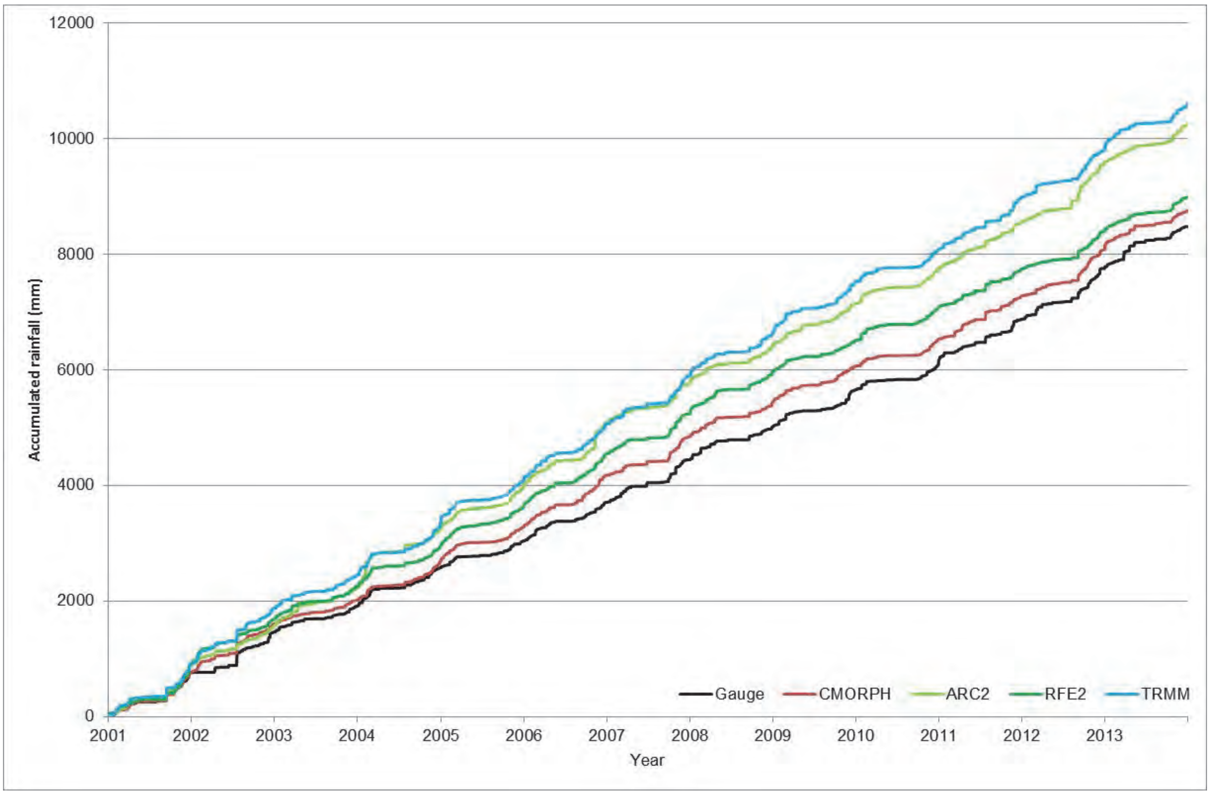

Figure 5.18 Comparison of accumulated rainfall for rain gauge U2E010 (2001 to 2013)

Table 5.6 Comparison of rainfall statistics for rain gauge U2E010 (2001 to 2013)

	Rain Gauge U2E010	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	8471.8	8751.9	10237.2	8980.3	10596.0
Max	143.0	113.9	208.5	79.9	125.7
Mean	1.8	1.8	2.2	1.9	2.2
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	6.85	6.22	7.52	5.76	8.19
Variance	46.96	38.72	56.56	33.22	67.02
Std. Error	0.68	0.56	0.82	0.48	0.97
Coef. of Variation	3.84	3.38	3.49	3.05	3.67
Skewness	7.85	6.48	11.83	5.73	6.43
Kurtosis Coef.	89.41	60.77	244.91	44.78	55.57
Sum of Squares	222986.49	183862.60	268551.85	157733.98	318191.70
Count	4748	4748	4748	4748	4748
Count x>0	1055	1704	1638	1647	1160
Count 0<mm<=2	394	989	725	840	490
Count 2<mm<=10	427	443	629	544	345
Count 10<mm<=20	127	168	180	161	170
Count 20<mm<=30	56	53	55	61	72
Count 30<mm<=40	16	20	23	23	34
Count 40<mm<=50	14	14	9	6	16
Count mm>50	21	17	17	12	33
Freq. Non-ex 95%	10.00	11.10	11.96	11.10	14.20
Freq. Non-ex 90%	4.21	4.80	5.80	5.50	5.20
Freq. Non-ex 80%	0.50	0.90	1.90	1.40	0.50
Freq. Non-ex 70%	0.00	0.20	0.53	0.40	0.00
Bias	-	266.00	1729.00	488.70	2100.00
RMSE	-	6.11	7.04	5.35	7.83
Correlation (R)	-	0.57	0.53	0.65	0.47
Regression Intercept	-	0.92	1.13	0.91	1.22
Regression Slope	-	0.52	0.58	0.55	0.56
Coef. of Determination (R^2)	-	0.32	0.28	0.43	0.22
Mean % Diff	-	-3.31	-20.84	-6.00	-25.07
t-means	-	-0.34	-2.02	-0.63	-2.36
Variance %Diff	-	17.55	-20.43	29.26	-42.70
Std Dev %Diff	-	9.20	-9.74	15.89	-19.46
Coef Var % Diff	-	12.10	9.18	20.66	4.49
Skewness %Diff	-	17.55	-50.61	27.06	18.07
Kurtosis %Diff	-	32.03	-173.93	49.92	37.85

Two simple methods of bias correction for the 4 remotely sensed daily rainfall datasets were tested. In the first method, for each rain gauge and for each month of the year the median monthly rainfall from Lynch (2004) was divided by the median monthly remotely sensed rainfall to calculate a bias correction factor. In the second method the same approach was used as for the first methods, but with mean monthly rainfall values instead of median monthly rainfall. A different set of monthly bias correction factors was calculated for each rain gauge and for each remotely sensed dataset and applied to the daily rainfall values. The results of these bias corrections using both methods were disappointing. In most cases the adjusted rainfall timeseries resulted in poorer estimates of the rain gauge data. Both methods of bias correction were abandoned for this case study catchment.

From these comparisons of the four unadjusted remotely sensed daily rainfall datasets with rain gauge data there is no one dataset that clearly represents rain gauge data better than the others in this study catchment. Although the regression statistics for the two FEWS datasets, especially the FEWS RFE 2.0 dataset, generally seem to be better that the other two datasets the bias and number of rain days seem to be worse. The TRMM 3B42 dataset consistently overestimates the rainfall, but there is no clear trend for the other 3 datasets. It was also not clear whether these comparisons with point rain gauge data would be an accurate representation of how well the remotely sensed datasets would estimate areal rainfall for the catchments. For this reason all four remotely sensed daily rainfall datasets were used in four separate *ACRU* model runs and four sets of water resource accounts were compiled for comparison. For each of these datasets a timeseries of daily rainfall was created for each sub-Quaternary catchment.

5.9.4 Reference potential evaporation

The SAHG ET_0 dataset was used together with a shapefile dataset of sub-Quaternary catchment boundaries to create a time series of daily ET_0 data values for each sub-Quaternary catchment as described in Section 4.12. A correction factor of 1.2 was applied to the ET_0 values in *ACRU* to calculate A-pan equivalent daily ET_0 values.

5.9.5 Air temperature

The datasets of long-term mean monthly maximum and minimum air temperature described by Schulze and Maharaj (2008b) and Schulze and Maharaj (2008c) were used in this case study. For each of the 12 maximum air temperature datasets and the 12 minimum air temperature datasets an areal mean value was calculated for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 24 fields containing the calculated daily temperature values for each month. The monthly values of daily maximum and minimum temperature for each sub-Quaternary catchment were then used to configure the *ACRU* hydrological model.

The frost occurrence dataset developed and described by Schulze and Maharaj (2008d) was used in this case study. The frost occurrence regions for the sub-Quaternary catchments in the uMngeni Catchment are shown in Figure 5.19. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet, from which the dominant frost occurrence region for each land cover/use based HRU within each sub-Quaternary catchment can be determined.

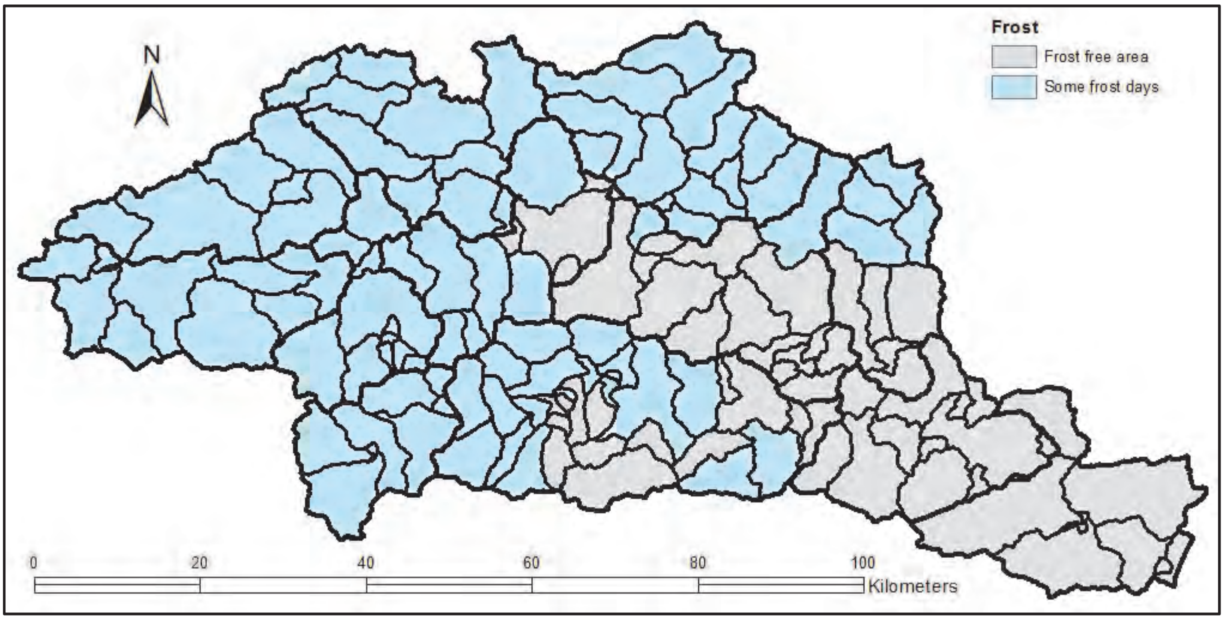

Figure 5.19 Frost occurrence regions in the uMngeni Catchment (Schulze and Maharaj, 2008d)

5.10 Streamflow Gauges

Measured streamflow data was used to verify the simulated streamflow used in the water resource accounts. The measured streamflow data was obtained from the "Hydrological Services – Surface Water (Data, Dams, Floods and Flows)" page of the DWS website (http://www.dwa.gov.za/hydrology/). The streamflow gauges listed in Table 5.7 and shown in Figure 5.20 were selected as they were currently operational and their period of record covered the 2010-2013 period for which water accounts were compiled.

Table 5.7	Streamflow gauges used for verification

Gauge ID	Gauge Description	Sub-Quaternary Catchment
U2H005	Mgeni River @ Table Mountain	Nagle_70
U2H006	Karkloof River @ Shafton	Karkloof_25
U2H007	Lions River@(Mpofana River) @ Weltevreden	Lions River_15
U2H011	Msunduze River @ Henley Dam	Henley_80
U2H012	Sterk River @ Groothoek	New Hanover_60
U2H013	Mgeni River @ Petrus Stroom	Mpendle_7
U2H014	Mgeni River @ Albert Falls	Albert Falls_45
U2H022	Msunduze River @ Inanda Loc.	Table Mountain_116
U2H041	Msunduze River @ Hamstead Park	Pietermaritzburg_105
U2H048	Mgeni River @ Midmar	Midmar_34
U2H054	Mgeni River @ Inanda Mission Res	Durban_138
U2H055	Mgeni River @ Inanda Loc.	Inanda_126
U2H057	Slang Spruit @ Pietermaritzburg	Pietermaritzburg_89
U2H058	Msunduze River @ Masons Mill	Pietermaritzburg_92

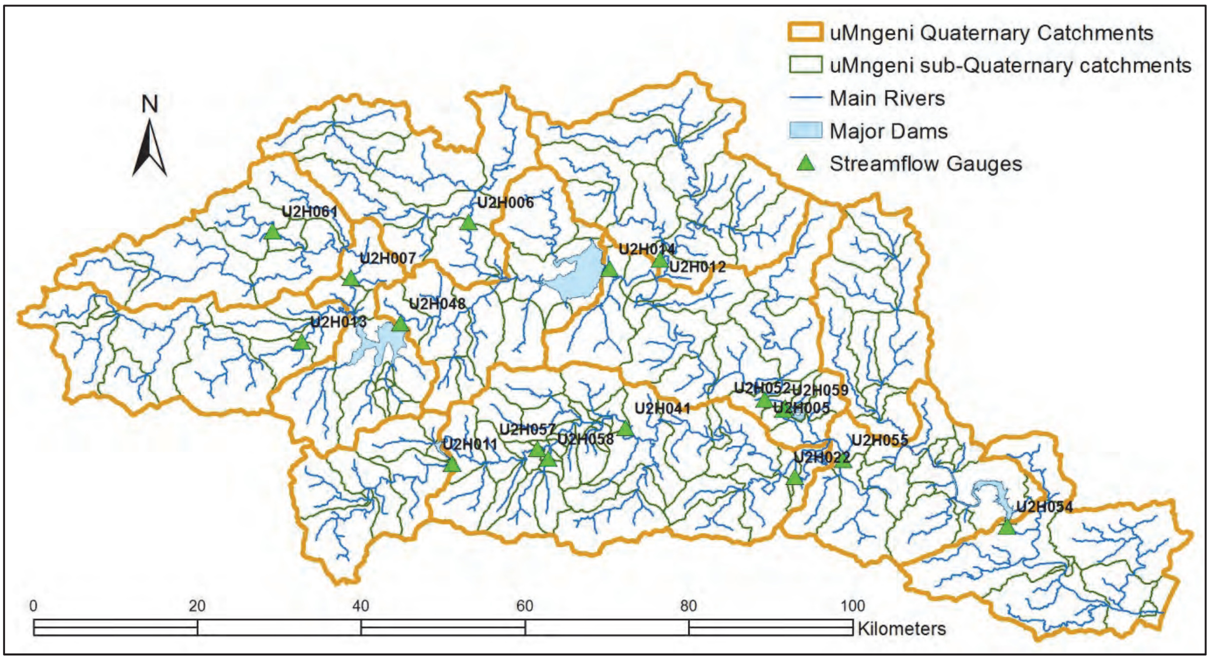

Figure 5.20	Location of streamflow gauges used for verification

5.11 Results

The *ACRU* model was configured for the uMngeni Catchment as described in Section 0 using the datasets described in this chapter. The *ACRU* model was use to simulate four calendar years 2010 to 2013. The first year, 2010, was used as a warm-up period for the model and water accounts were compiled for the three years 2011 to 2013. In Section 5.11.1 the simulated streamflow using each of the four remotely sensed rainfall datasets is compared to observed streamflow. In Section 5.11.2 selected water accounts are discussed.

5.11.1 Streamflow verification

The measured annual streamflow and simulated annual streamflow values for the four remotely sensed rainfall datasets are summarised in Table 5.8 and shown graphically in Figure 5.21 for 2011, Figure 5.22 for 2012 and Figure 5.23 for 2013. For some streamflow gauges for some years there was missing data within a year, and in these instances the measured annual streamflow was omitted from the evaluation. Comparing these measured and simulated annual streamflow values it is difficult to arrive at any definite conclusions as there are no clear trends. Also, because streamflow represents the cumulative result of the hydrological processes upstream it is difficult to determine if one particular remotely sensed dataset performs better in specific parts of the study catchment. For example, the TRMM 3B42 dataset seems to give good results at U2H013, U2H014 and U2H022 in 2011 but does not perform well in other catchments. The results also differ between years. The TRMM 3B42 dataset seems to perform well at U2H013 in 2011, but performs poorly at the same gauge in 2012 and 2013. As seen in the validation of the remotely sensed datasets against rain gauge data the TRMM 3B42 dataset tends to have higer rainfall estimates than the other three datasets and overestimates streamflow at some streamflow gauges, while the other datasets consistently underestimate streamflow at most gauges. It also needs to be remembered that although accurate rainfall measurements or estimates are probably the most important input for hydrological modelling, there are many other inputs such as reference potential evaporation, soil characteristics, land cover/use characteristics and operation of large dams that could also have an effect on simulated streamflow. Comparing the different remotely sensed rainfall dataset with each other there is also a lot of variability between the streamflows simulated with these different datasets with the rest of the model configuration for the catchment being identical. The streamflow in this study catchment in highly altered by the large dams and by urban water use. It is likely that water abstractions from Inanda Dam have been underestimated as abstractions for urban water use outside the catchment have not been taken into account.

Table 5.8 Comparison of measured and simulated annual streamflow

Gauge ID	Year	Annual Streamflow (10^6 m^3)				
		Gauge	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
U2H005	2011	-	67.0	51.7	35.6	136.7
U2H005	2012	183.6	99.5	56.2	42.8	201.3
U2H005	2013	-	108.0	57.0	33.7	207.3
U2H006	2011	-	15.6	22.9	3.5	18.7
U2H006	2012	76.3	18.0	17.8	7.5	26.5
U2H006	2013	-	21.2	17.3	5.1	31.4
U2H007	2011	85.3	33.3	26.7	11.7	51.7
U2H007	2012	71.5	58.7	55.7	50.3	72.8
U2H007	2013	66.8	31.6	19.8	12.1	48.7
U2H011	2011	-	8.9	19.3	7.9	18.3
U2H011	2012	30.6	14.1	11.5	11.8	23.6
U2H011	2013	32.2	15.1	25.8	11.9	25.0
U2H012	2011	-	26.8	9.1	10.3	23.4
U2H012	2012	45.9	27.5	19.5	15.4	35.4
U2H012	2013	57.6	31.9	13.3	9.5	36.3
U2H013	2011	60.3	12.9	9.4	3.0	56.0
U2H013	2012	66.4	9.3	8.4	6.7	27.0
U2H013	2013	91.6	13.5	7.5	4.6	41.1
U2H014	2011	114.6	17.8	24.1	10.4	87.5
U2H014	2012	124.8	48.2	22.4	10.3	127.8
U2H014	2013	241.6	52.0	28.8	10.5	132.6
U2H022	2011	132.2	57.4	81.9	65.0	107.1
U2H022	2012	161.1	81.8	66.3	67.5	128.3
U2H022	2013	154.9	77.7	84.9	69.0	129.6
U2H041	2011	126.3	40.8	60.1	45.9	74.0
U2H041	2012	186.9	59.1	45.9	46.3	84.4
U2H041	2013	179.0	56.0	67.8	49.7	86.2
U2H048	2011	29.5	8.4	8.2	8.1	66.0
U2H048	2012	51.4	21.4	8.2	8.0	84.0
U2H048	2013	106.4	20.9	8.3	8.0	79.3
U2H054	2011	59.9	42.2	54.4	9.0	181.1
U2H054	2012	148.5	143.0	90.0	51.5	322.4
U2H054	2013	267.2	135.7	88.4	49.0	312.1
U2H055	2011	154.7	126.9	136.6	103.7	248.3
U2H055	2012	189.5	184.2	126.1	115.2	338.3
U2H055	2013	307.2	187.6	143.7	106.3	344.0
U2H057	2011	9.0	17.4	31.9	17.7	36.0
U2H057	2012	-	27.8	22.2	22.1	44.0
U2H057	2013	9.8	27.8	42.0	24.4	46.2
U2H058	2011	58.4	6.0	7.3	7.0	9.7
U2H058	2012	77.1	7.8	6.8	7.0	10.1
U2H058	2013	88.1	7.3	7.4	7.1	10.3
U2H061	2011	-	3.2	2.2	0.8	4.3
U2H061	2012	-	2.7	2.4	1.6	4.5
U2H061	2013	-	3.9	2.0	0.9	5.7

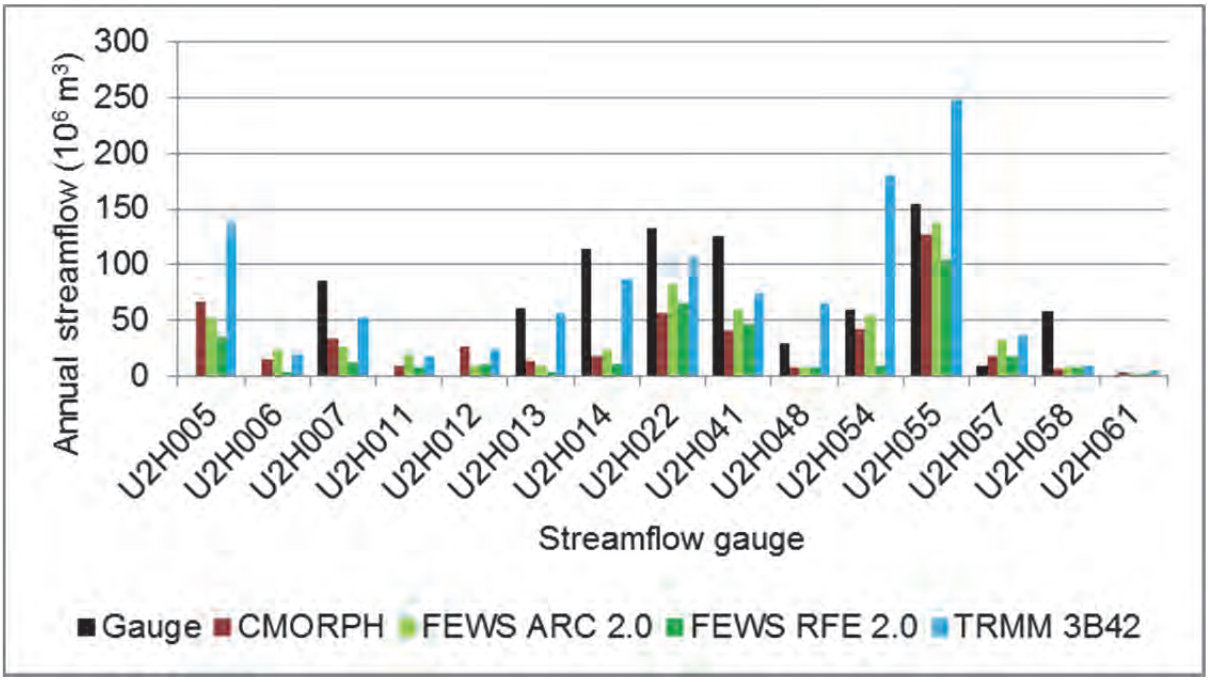

Figure 5.21 Comparison of measured and simulated annual streamflow for 2011

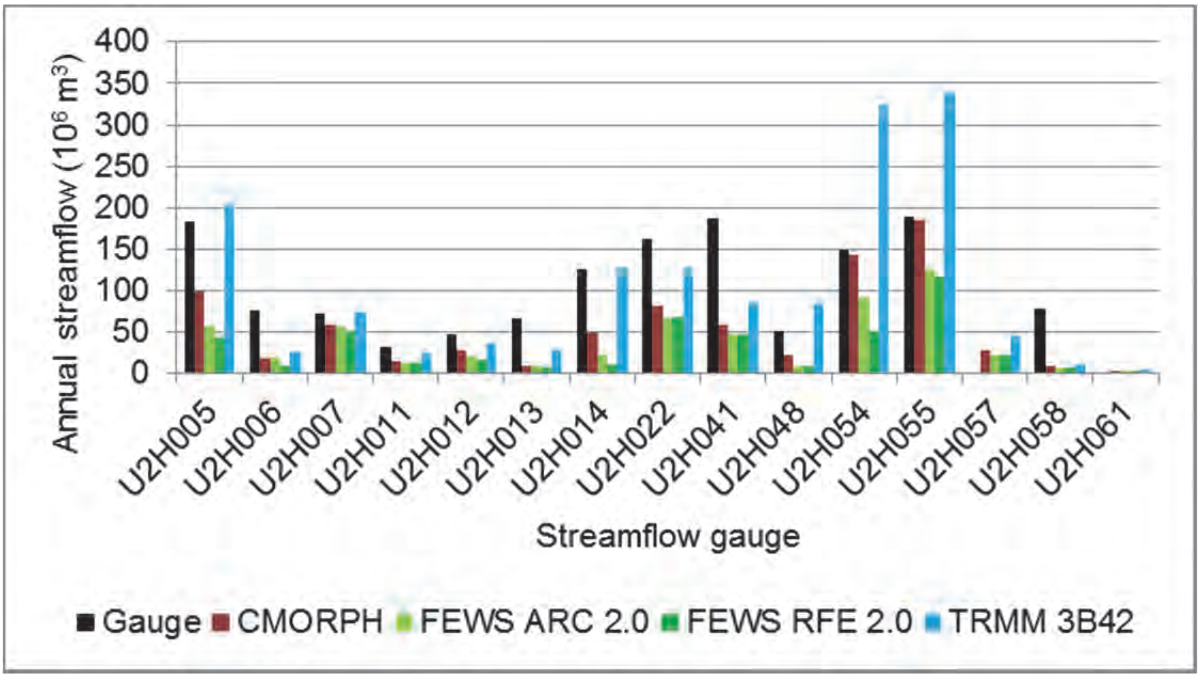

Figure 5.22 Comparison of measured and simulated annual streamflow for 2012

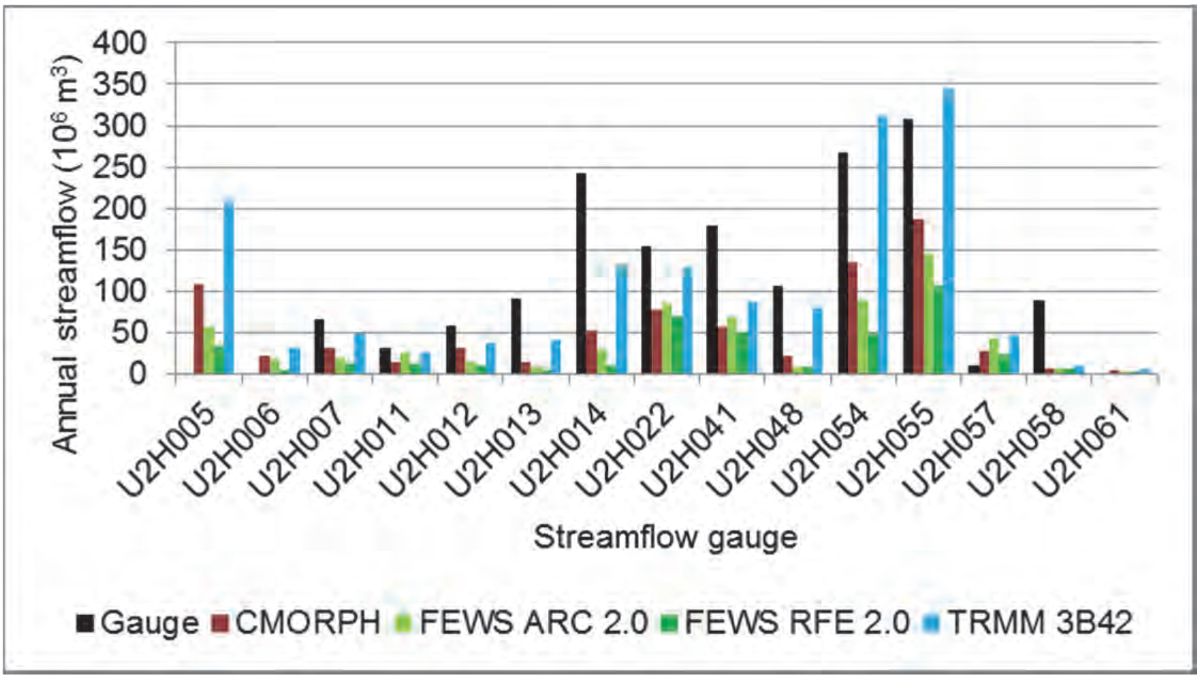

Figure 5.23 Comparison of measured and simulated annual streamflow for 2013

5.11.2 Water resource accounts

For the purpose of demonstrating the water resource accounts the TRMM 3B42 daily rainfall dataset was selected. 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 resource accounts for the whole uMngeni Catchment are shown in Figure 5.24 for 2011, Figure 5.25 for 2012 and Figure 5.26 for 2013. The water volumes shown in the 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.

Apart from artificial transfers from the 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. In 2011 there is a net decrease in the soil moisture store and a net increase in the groundwater store. In 2012, which has higher rainfall than 2011, there is a net increase in both the soil moisture store and in the groundwater store. In 2013, which is a drier year, there is a net decrease in both the soil moisture store and in the groundwater store. 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, with interception evaporation and soil water evaporation contributing similar amounts. Information about reserved flows has not been included into the accounts yet as although there are some values available it is believed that an update of these is currently in progress.

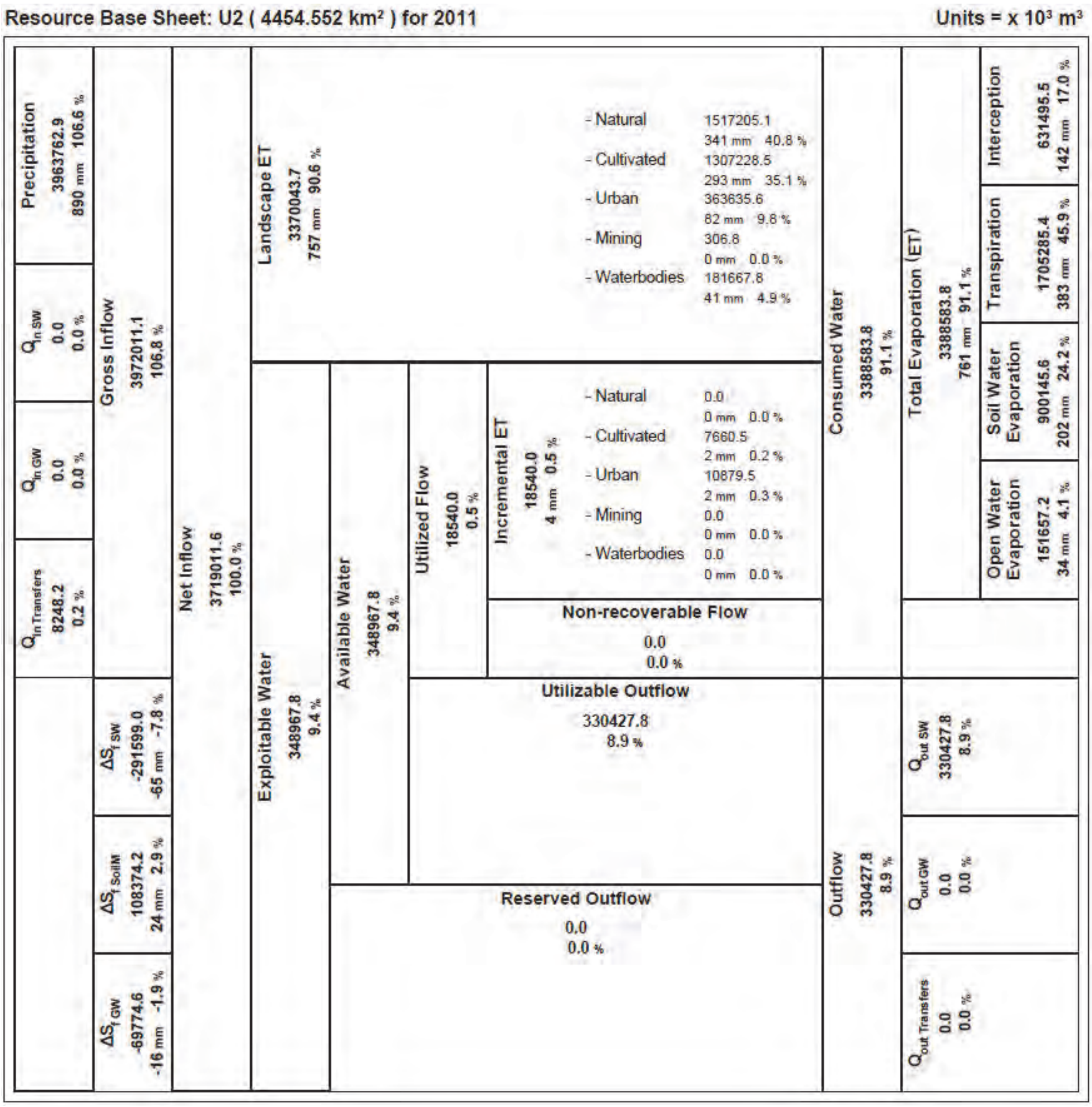

Figure 5.24 Annual water account for the uMngeni Catchment for 2011

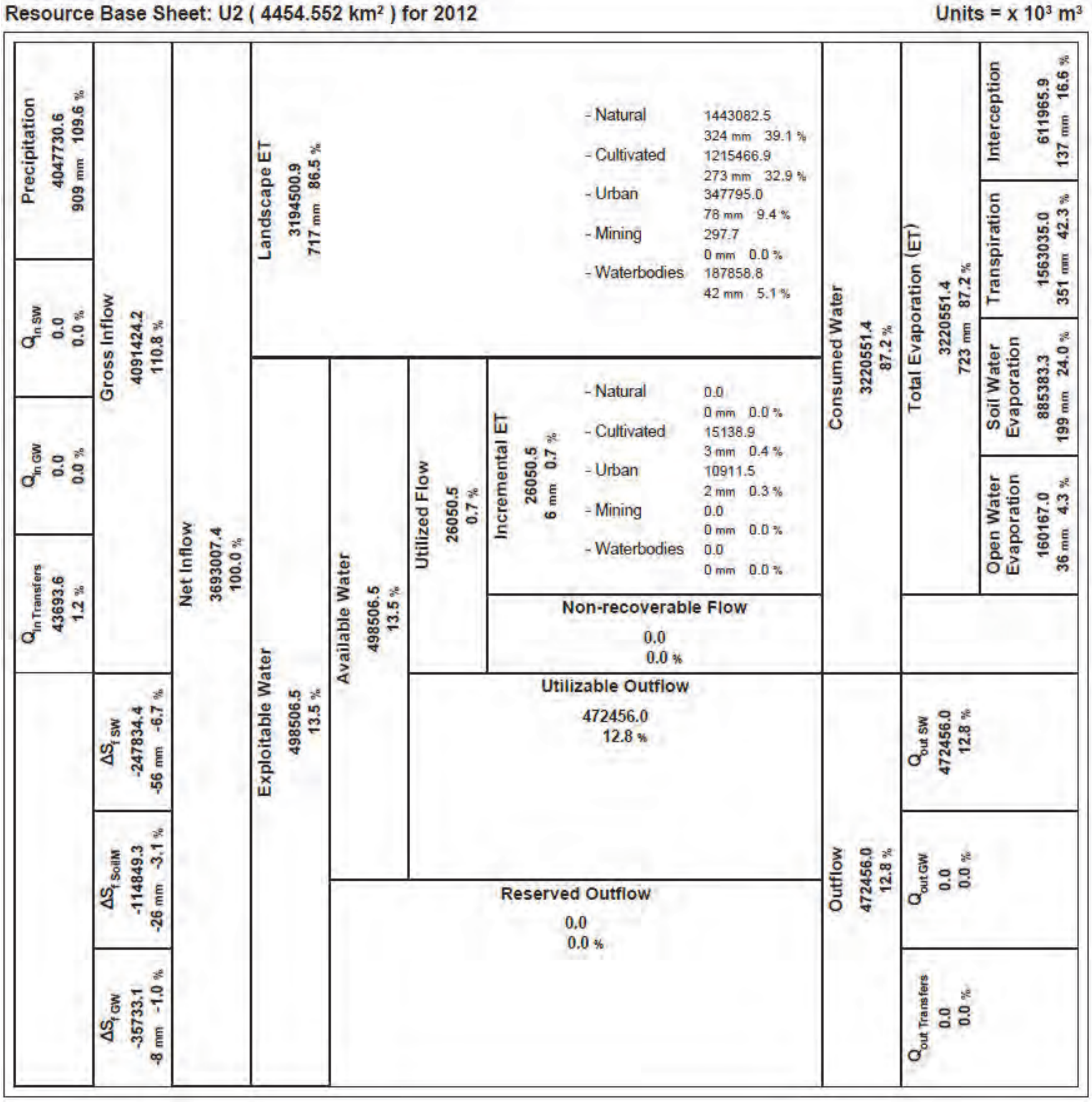

Figure 5.25 Annual water account for the uMngeni Catchment for 2012

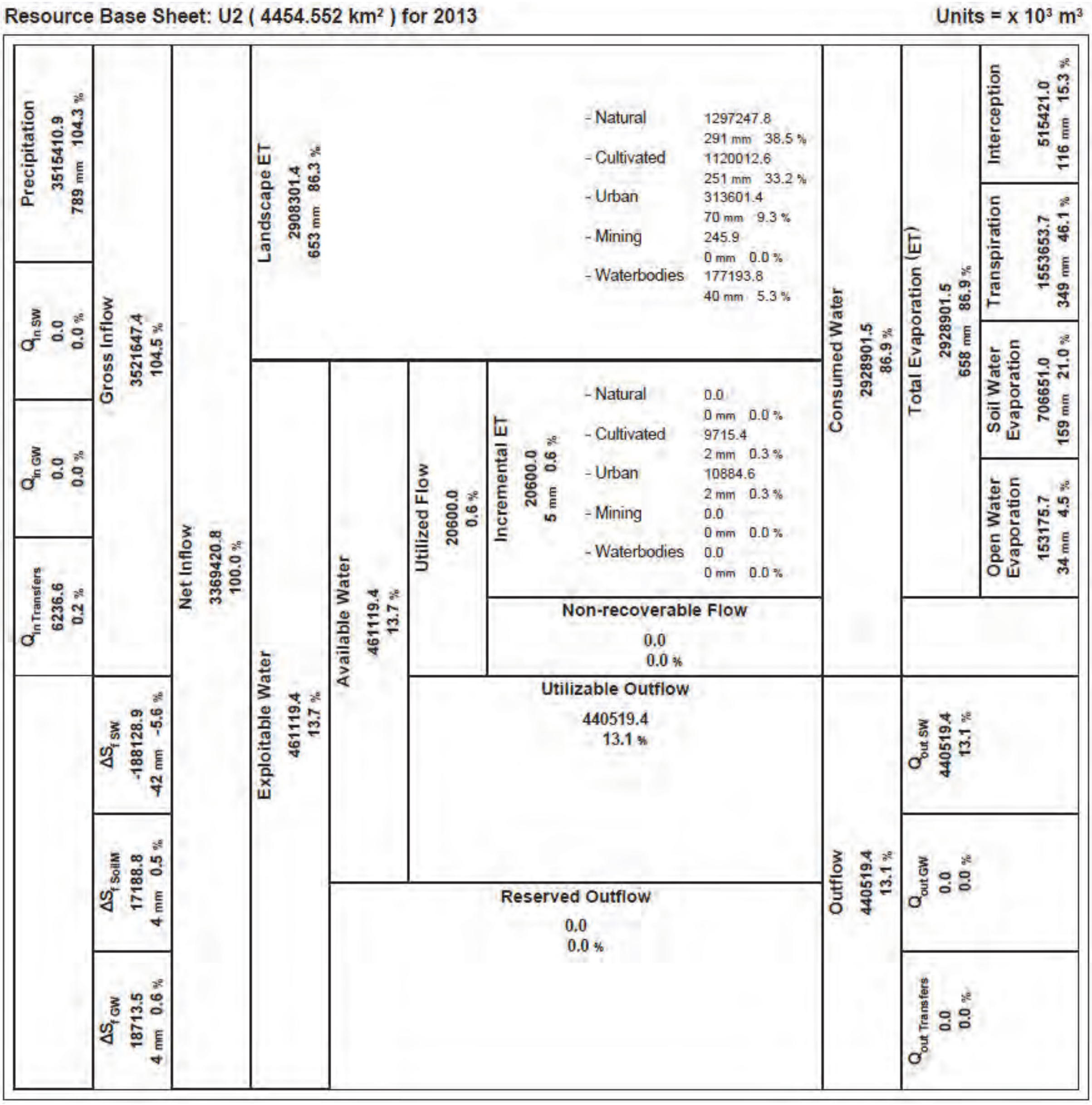

Figure 5.26 Annual water account for the uMngeni Catchment for 2013

Although the Resource Base Sheet provides a very useful overview of water use in a catchment, it is an aggregation of the water balances for each of the individual land cover/use classes existing within the represented catchment, and the detail of these individual water balances is lost. The land and water use summary table for the uMngeni Catchment for 2013 is shown in Table 5.9. This summary is in the form of a pivot table summarising areal extent, water availability and use by land cover/use class. The first column contains a nested hierarchical list of all the land cover/use classes within a catchment. For the *Agriculture* category the *Commercial/Subsistence*, the *Dryland/Irrigated* and the *CropType* attribute categories was also included in the summary, where the crop type *General* indicates that the land cover/use dataset did not specify a specific crop. The second column shows the area of each class as percentages of the preceding level in the hierarchy. The third and fourth column shows the precipitation and irrigation received by each class as percentages of the preceding level in the hierarchy. The remaining columns show the total evaporation and partitioned components of this for each class as percentages of the preceding level in the hierarchy. The advantage of the hierarchy of land cover/use classes and also the attribute categories to help in understanding water use within a catchment can be clearly seen in Table 5.9.

Table 5.9 Land and water use summary table for the uMngeni Catchment for 2013 as percentages

Land Cover/Use Category	Area (4454.552 km^2)	Rainfall	Irrigation	Total Evaporation	Interception Evaporation	Transpiration	Soil Moisture Evaporation	Open Water Evaporation
Total Water (mm)	-	789	2	658	116	349	159	34
Natural	43.20	43.19	0.00	44.29	45.42	44.97	51.59	0.00
Typical	92.10	92.14	-	92.14	95.54	95.70	83.13	-
Acocks	99.86	99.86	-	99.96	99.94	100.00	99.89	-
Coastal Tropical Forest	19.90	18.95	-	18.77	17.83	20.09	16.54	-
Coastal Forest And Thornveld	27.56	27.00	-	24.97	35.57	26.87	11.44	-
Ngongoni Veld	72.44	73.00	-	75.03	64.43	73.13	88.56	-
Karoo and Karroid	25.50	24.01	-	24.57	29.89	24.98	19.73	-
Valley Bushveld	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Temperate and Transitional Forest and Scrub	42.00	44.19	-	43.86	40.17	41.65	51.48	-
Highland Sourveld And Dohne Sourveld	54.09	55.54	-	54.71	56.97	54.15	54.40	-
Natal Mist Belt Ngongoniveld	45.91	44.46	-	45.29	43.03	45.85	45.60	-
False Grassveld	12.60	12.86	-	12.79	12.10	13.27	12.24	-
Southern Tall Grassveld	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Bare	0.14	0.14	-	0.04	0.06	0.00	0.11	-
Rock	64.01	63.44	-	25.79	96.97	0.00	0.00	-
Sand – Inland	35.91	36.48	-	74.02	3.03	99.72	99.73	-
Sand – Coastal	0.08	0.08	-	0.20	0.01	0.28	0.27	-
Degraded	7.90	7.86	-	7.86	4.46	4.30	16.87	-
Acocks	99.51	99.50	-	99.57	99.96	99.99	99.31	-
Coastal Tropical Forest	15.91	15.28	-	14.62	13.86	15.83	14.16	-
Coastal Forest And Thornveld	21.82	21.48	-	16.76	28.19	18.63	13.82	-
Ngongoni Veld	78.18	78.52	-	83.24	71.81	81.37	86.18	-
Karoo and Karroid	22.28	21.07	-	21.51	28.03	22.11	20.10	-
Valley Bushveld	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Temperate and Transitional Forest and Scrub	46.10	47.67	-	47.96	42.86	45.95	49.81	-
Highland Sourveld And Dohne Sourveld	37.15	38.86	-	38.75	40.97	38.26	38.65	-
Ngongoni Veld Of Natal Mist-Belt	62.85	61.14	-	61.25	59.03	61.74	61.35	-
False Grassveld	15.72	15.98	-	15.91	15.24	16.11	15.93	-
Southern Tall Grassveld	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Bare	0.49	0.50	-	0.43	0.04	0.01	0.69	-
Erosion – Sheet	100.00	100.00	-	100.00	100.00	100.00	100.00	-

Table 5.9 (cont.) Land and water use summary table for the uMngeni Catchment for 2013 as percentages

Land Cover/Use Category	Area (4454.552 km^2)	Rainfall	Irrigation	Total Evaporation	Interception Evaporation	Transpiration	Soil Moisture Evaporation	Open Water Evaporation
Cultivated	34.72	35.09	100.00	38.57	38.81	44.20	34.08	1.39
Agriculture	52.12	51.77	100.00	52.09	37.38	48.09	75.28	100.00
Commercial	85.86	86.46	100.00	86.72	90.59	90.95	77.25	100.00
Dryland	85.24	84.62	0.00	83.87	87.24	87.79	75.10	0.00
General	40.27	41.98		40.98	31.58	31.33	70.45	-
Sugarcane – Inland	58.72	57.07		58.66	67.87	68.27	29.43	-
Sugarcane – North Coast	1.01	0.95		0.35	0.56	0.40	0.12	-
Irrigated	14.76	15.38	100.00	16.13	12.76	12.21	24.90	100.00
Citrus	8.38	7.94	40.97	12.48	12.49	16.68	6.32	40.97
General	91.62	92.06	59.03	87.52	87.51	83.32	93.68	59.03
Subsistence	14.14	13.54	0.00	13.28	9.41	9.05	22.75	0.00
Dryland	100.00	100.00	-	100.00	100.00	100.00	100.00	-
General	97.81	97.83	-	97.76	96.24	96.56	98.89	-
Sugarcane	2.19	2.17	-	2.24	3.76	3.44	1.11	-
Forest Plantations	47.88	48.23	0.00	47.91	62.62	51.91	24.72	0.00
General	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Urban/Built-up	18.68	18.27	0.00	11.08	15.19	9.79	11.79	7.11
Industrial/Transport	11.72	11.91	-	2.32	9.52	0.03	0.03	0.00
Roads and Railways	99.82	99.82	-	98.75	99.73	0.00	0.00	-
Airports and Airfields	0.18	0.18	-	1.25	0.27	100.00	100.00	-
Residential	86.88	86.66	-	95.36	89.03	97.21	97.33	100.00
Smallholdings (Peri-Urban)	2.08	2.09	-	3.32	2.68	3.58	3.78	0.31
Formal – Low Density (Peri-Urban)	34.99	35.02	-	55.28	43.32	61.11	61.61	5.52
Formal – Medium Density (Suburbs)	62.93	62.89	-	41.40	54.01	35.30	34.61	94.17
Open Spaces	1.40	1.43	-	2.32	1.45	2.76	2.64	0.00
Waterbodies	3.32	3.38	0.00	6.05	0.54	1.05	2.54	91.50
Artificial	61.39	60.71	-	70.37	0.00	0.00	0.00	88.97
Dams	100.00	100.00	-	100.00	-	-		100.00
Natural	38.61	39.29	-	29.63	100.00	100.00	100.00	11.03
Wetlands	85.49	86.49	-	70.56	100.00	100.00	100.00	0.00
Estuaries	1.20	1.28	-	2.67	0.00	0.00	0.00	9.07
Rivers	13.31	12.23	-	26.77	0.00	0.00	0.00	90.93
Mines and Quarries	0.07	0.07	0.00	0.01	0.05	0.00	0.00	0.00
Surface	100.00	100.00	-	100.00	100.00	-	-	-
Opencast Mine/Quarry	100.00	100.00	-	100.00	100.00	-	-	-

6 SABIE-SAND CATCHMENT CASE STUDY

DJ Clark

The Sabie-Sand Catchment forms part of the Inkomati-Usutu WMA situated in the summer rainfall region, in the Mpumalanga and Limpopo provinces of South Africa. The catchment has an area of 6267 km^2 and the altitude ranges from 1966 m in the south west to 137 m in the east (Schulze *et al.*, 2008b). The mean annual precipitation MAP for the catchment varies from 1368 mm in the west to 509 mm in the east (Schulze *et al.*, 2008b). The catchment includes two main river basins, the Sand River (Tertiary catchment X32) in the northern part of the catchment and the Sabie River (Tertiary catchment X31) in the southern part of the catchment. The Sand River joins the Sabie River within the Kruger National Park where it flows into Tertiary Catchment X33, after which the Sabie River flows into Mozambique. DWAF (2004) states that the Sabie River is ecologically one of the most important rivers in South Africa. There are two large dams in the Sabie Catchment, the Injaka Dam on the Marite River and the Da Gama Dam on the Witwaters River, both tributaries of the Sabie River. There are several small towns in the catchment and economic activity includes tourism, subsistence and commercial farming, with extensive irrigated agriculture, cultivation of sugarcane and commercial forestry plantations. DWA (2013) states that the Sabie River is in better condition than most with the ecological reserve being supplied and water requirements being met, though the limit of water availability has been reached, and in future water currently allocated for irrigation may need to be reallocated to meet water requirements in the domestic sector. However, water availability in the Sand River system is generally poor and already insufficient to meet the requirements of the large semi-rural population which is dependent on transfers from the Injaka Dam in the Sabie River system (DWA, 2013). The ecological Reserve is also not being met in the Sand Catchment which has impacts downstream, including Kruger National Park (DWA, 2013).

The Sabie-Sand Catchment consists of the X3 Secondary Catchment which contains three Tertiary Catchments, X31 (upper Sabie), X32 (Sand) and X33 (lower Sabie) and a total of 25 Quaternary Catchments. The Quaternary Catchments within the Sabie-Sand Catchment are shown in Figure 6.1. The revised set of Primary (SLIM, 2014a), Secondary (SLIM, 2014c), Tertiary (SLIM, 2014d) and Quaternary(SLIM, 2014b) Catchment boundary datasets for South the DWS were used in this configuration of the study catchment.

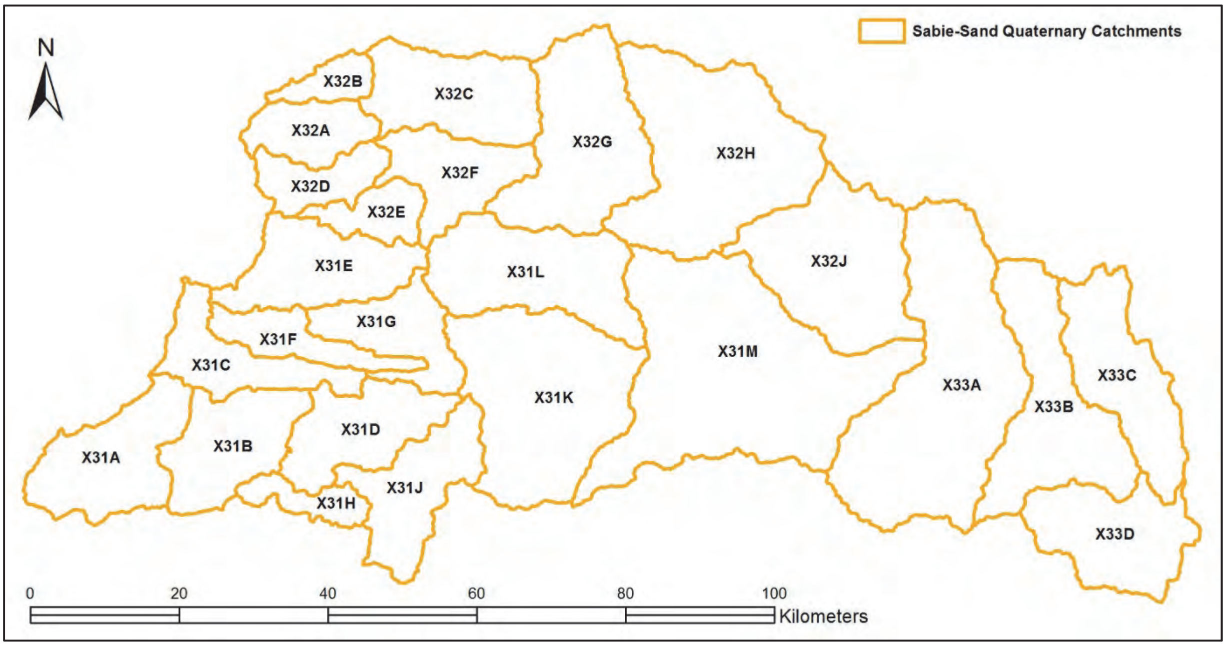

Figure 6.1 The Quaternary Catchments within the Sabie-Sand Catchment (SLIM, 2014b)

6.1 Sub-Quaternary Catchment Boundaries

For the purpose of the Sabie-Sand case study it was decided that the sub-Quaternary catchment boundary dataset (IUCMA, 2014) used by the IUCMA , which includes most of the former Inkomati WMA, should be used. However, this dataset did not include most of the X33 Tertiary catchment and was also not suitably topographically clean for use with many of the raster processing scripts developed in this project. To resolve this problem the NFEPA (Nel *et al.*, 2011) catchment boundaries were used and a few additional sub-Quaternary catchments were added to include catchments from the IUCMA (2014) dataset. A few further changes were made to the boundaries based on anomalies identified using a 90m DEM (Weepener *et al.*, 2011b) and a rivers dataset (Weepener *et al.*, 2011c). Although the resulting sub-Quaternary catchment boundaries were similar to the new DWS Quaternary Catchment (SLIM, 2014b) boundaries, they did not match exactly, and were adjusted computationally using Python scripts to fit the Quaternary Catchment boundaries. The resulting sub-Quaternary Catchments used for the Sabie-Sand Catchment in this case study are shown in Figure 6.2.

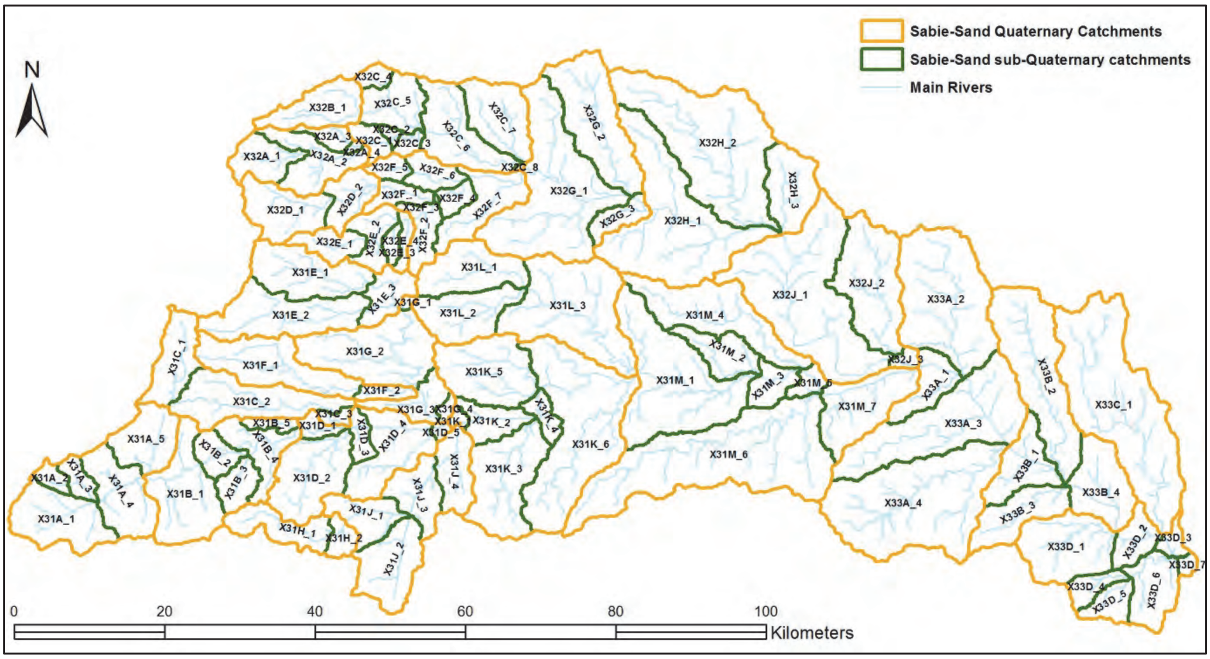

Figure 6.2 The sub-Quaternary catchments for the Sabie-Sand Catchment

6.2 Sub-Quaternary Catchment Altitude

The flow path improved Digital Elevation Model (DEM) (Weepener *et al.*, 2011d) with 90m resolution produced by Weepener *et al.* (2011a) was used to determine the mean altitude for each sub-Quaternary catchment. The DEM altitudes are shown in Figure 6.3 and the mean altitudes for the sub-Quaternary Catchments in the Sabie-Sand Catchment are shown in Figure 6.4.

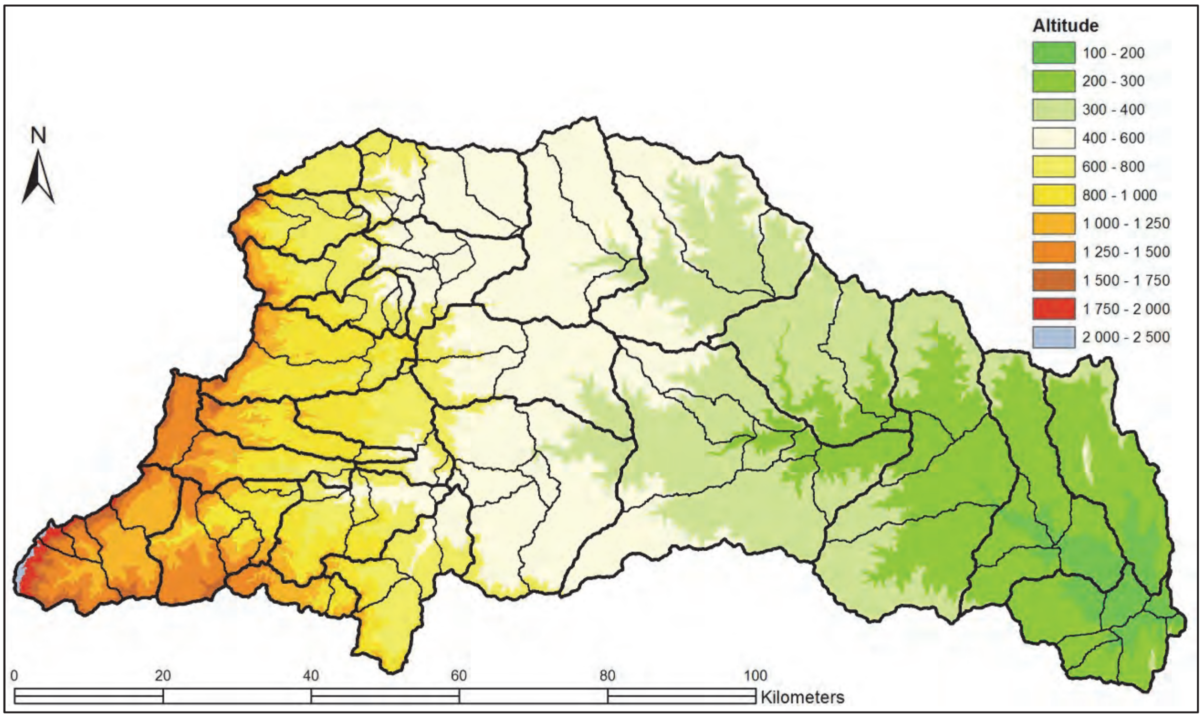

Figure 6.3 DEM altitudes for the Sabie-Sand Catchment (after Weepener *et al.*, 2011d)

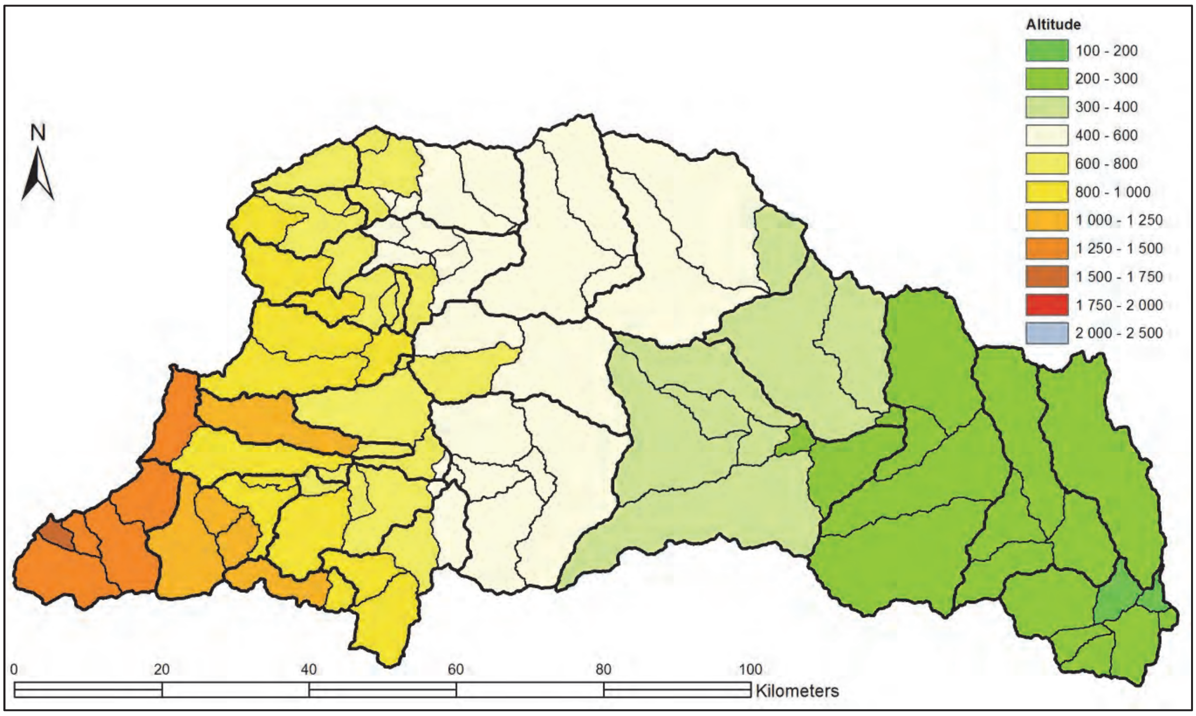

Figure 6.4 Mean altitudes of the sub-Quaternary catchments in the Sabie-Sand Catchment

6.3 Rivers and River Nodes

The shapefile of flow paths (Weepener *et al.*, 2011c) developed in WRC project K5/1908 using the SRTM 90m DEM as described by (Weepener *et al.*, 2011a) was used in this case study. The river features within the Sabie-Sand Catchment were clipped from the Weepener *et al.* (2011c) dataset. As described in Section 4.5, the clipped rivers dataset together with the Sabie-Sand Quaternary Catchment boundaries dataset was used to manually create a point shapefile of river nodes using ArcMap. A river node was created where each sub-Quaternary catchment boundary intersected a river segment and at any points where there was a confluence of river reaches between these points. For each node, attributes were set specifying the downstream node and whether the node was at the exit of a sub-Quaternary catchment. The sub-Quaternary catchment boundaries, rivers and the derived river nodes for the Sabie-sand Catchment are shown in Figure 6.5.

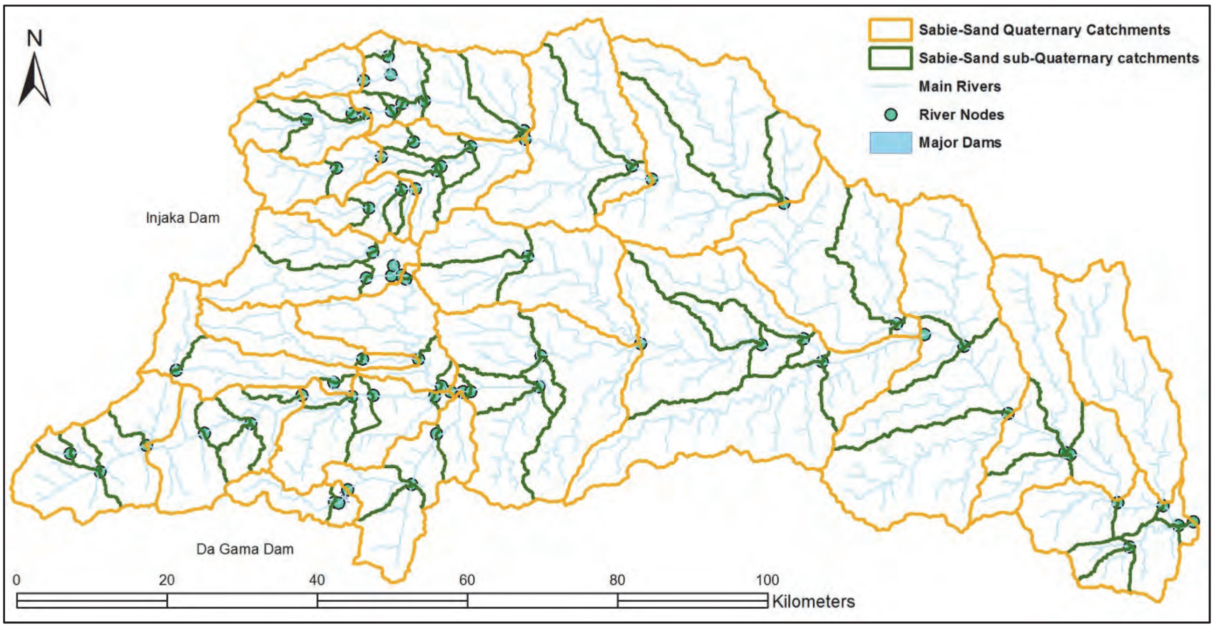

Figure 6.5 Rivers (Weepener *et al.*, 2011c) and derived river nodes

6.4 Dams

For this deliverable the DWS database of registered dams (DSO, 2014) provided in Microsoft Excel (.xlsx) format was used. This database was first saved to CSV format and a shapefile of registered dams was created. This shapefile was then clipped to produce a shapefile of registered dams in the Sabie-Sand Catchment. This shapefile was compared with other dam datasets and Google Earth satellite imagery, and the locations of Da Gama Dam and Injaka Dam were corrected to be within the correct sub-Quaternary catchments.

This clipped dataset was then used to create a shapefile of dam nodes such that all registered dams in a sub-Quaternary catchments were lumped together near the exit of the sub-Quaternary catchments and can act as a water source for all water users in a sub-Quaternary catchments. In sub-Quaternary catchments where the land cover/use dataset indicates a total surface area or dams greater than the total area of registered dams, an additional lumped dam representing unregistered dams was modelled. These small unregistered dams impede runoff generated within a sub-Quaternary catchments but are assumed to not be used for irrigation. The sub-Quaternary catchment boundaries and dam nodes for the Sabie-Sand Catchment are shown in Figure 6.6. The majority of registered farm dams are concentrated in Quaternary Catchments X31D and X31J in the horticultural area upstream of the town of Hazyview. Da Gama Dam is in X31H and Injaka Dam is in X31E.

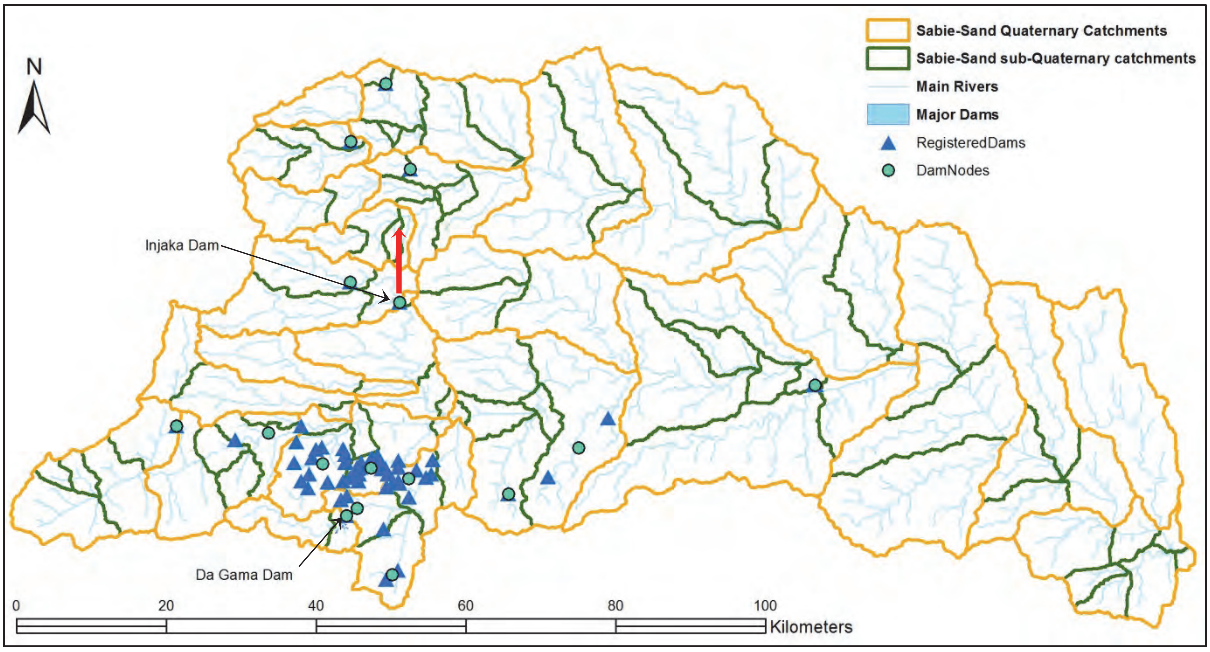

Figure 6.6 Registered dams (DSO, 2014) and derived dam nodes

6.5 Transfers, Abstractions and Return Flows

There are no water transfers into or out of the Sabie-Sand Catchment. The only main inter-catchment transfer within the Sabie-Sand Catchment is from Injaka Dam in X31E to provide water to the town of Dwarsloop and surrounding urban settlements in X32E (shown in red in Figure 6.6). Daily average flow data was obtained from DWS for the pumped transfer (gauge X3H022); which had an average flow rate of approximately 0.038 m^3/s for 2009, 0.053 m^3/s for 2010, 0.045 m^3/s for 2011 and 0.073 m^3/s for 2012. The dataset only included values up to the end of June 2013 and so values for the period July 1013 to December 2013 were estimated based on the mean value for the first 6 months ().

6.6 Natural Vegetation

In this case study the Acocks Veld Types (Acocks, 1988) were used to represent all areas with natural vegetation cover for the reasons discussed in Section 4.8.3. The hydrological characteristics of each Acocks Veld Type were based on the values from Schulze (2004). The Acocks Veld Types present in the Sabie-Sand Catchment and their distribution are shown in Figure 6.7.

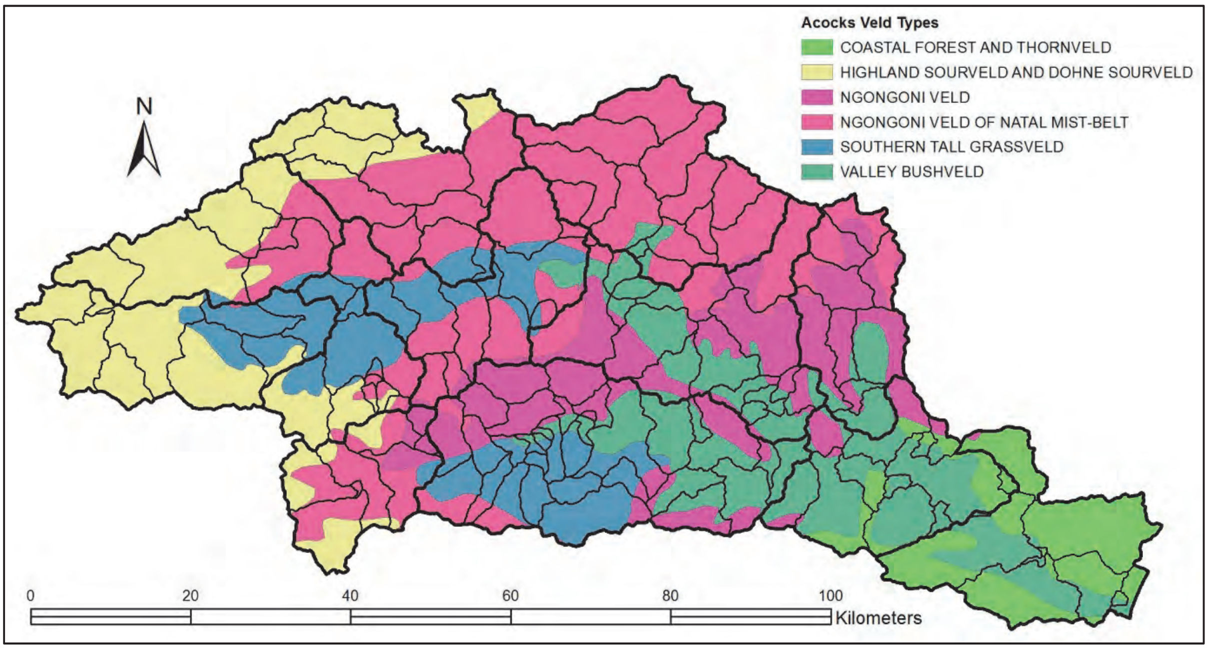

Figure 6.7 Acocks Veld Types the Sabie-Sand Catchment (after Acocks, 1988)

6.7 Land Cover/Use

The 2.5m resolution ICMA (2012b) land cover/use dataset was used in this case study as it is the most recent and comprehensive dataset available for the Sabie-Sand Catchment. As shown in Figure 6.8 some of the prominent non-natural land cover types in the Sabie-Sand Catchment include forest plantations, sugarcane, commercial irrigated and dryland crops. The ICMA (2012b) land cover dataset does not include classification of land cover/use within the Kruger National Park and so land cover within the Kruger National Park was assumed to be natural vegetation based on the Acocks Veld Types. The 2.5m resolution of the ICMA (2012b) land cover/use dataset caused some processing problems and was resampled to

5m resolution for the purpose of calculating the land cover/use regions used to determine the HRUs to be modelled.

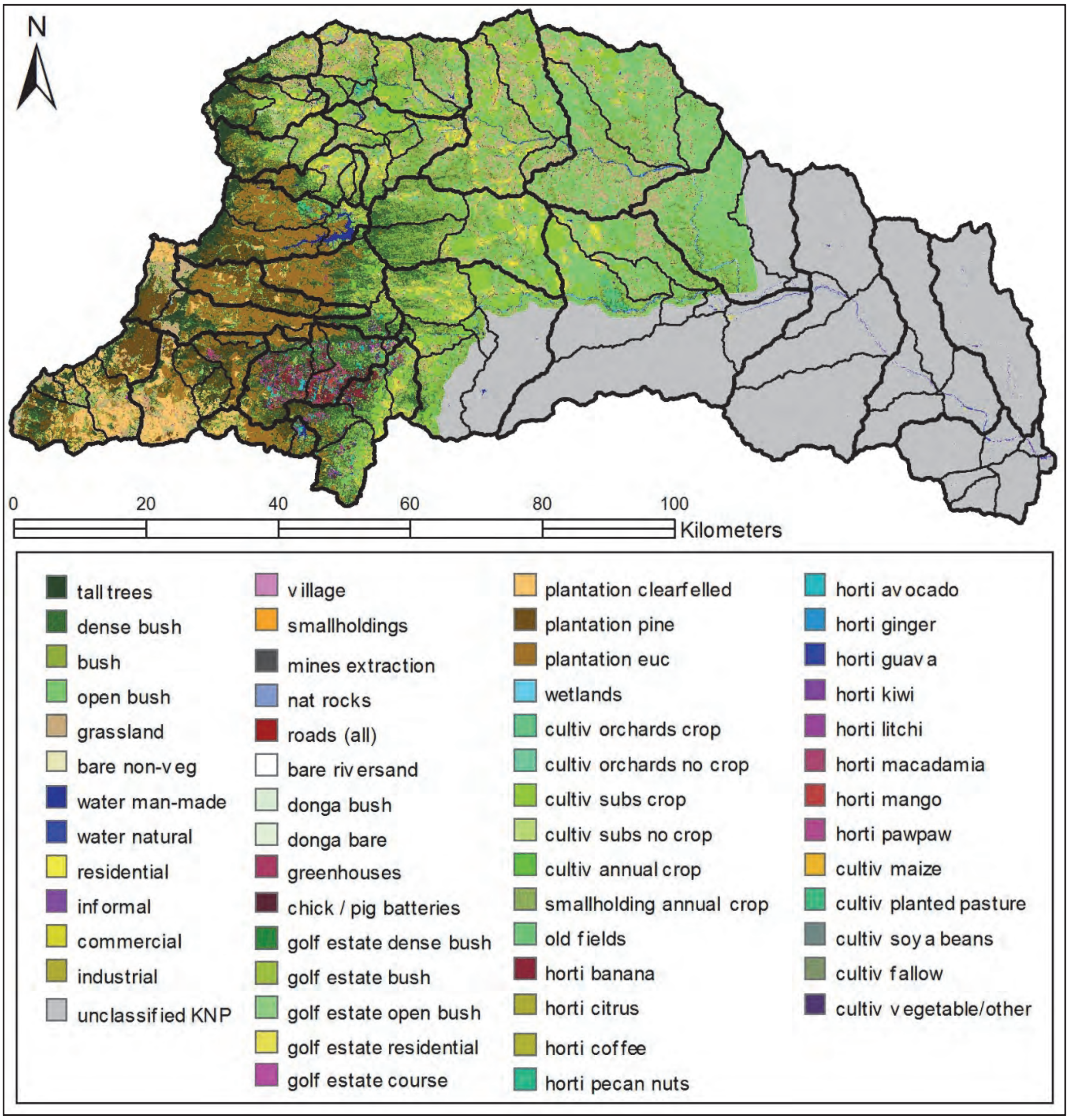

Figure 6.8 Land cover/use of the Sabie-Sand Catchment (after ICMA, 2012b)

A mapping between the ICMA (2012b) land cover/use classes and classes in the LCUClass database was created, as shown in Appendix D.3. Using the methodology described in Section 4.8.2, the clipped land cover/use file was used to create a raster dataset of *LCUClass* IDs, shown in Figure 6.9. In this case study no other land cover use datasets were superimposed on the raster dataset of *LCUClass* IDs.

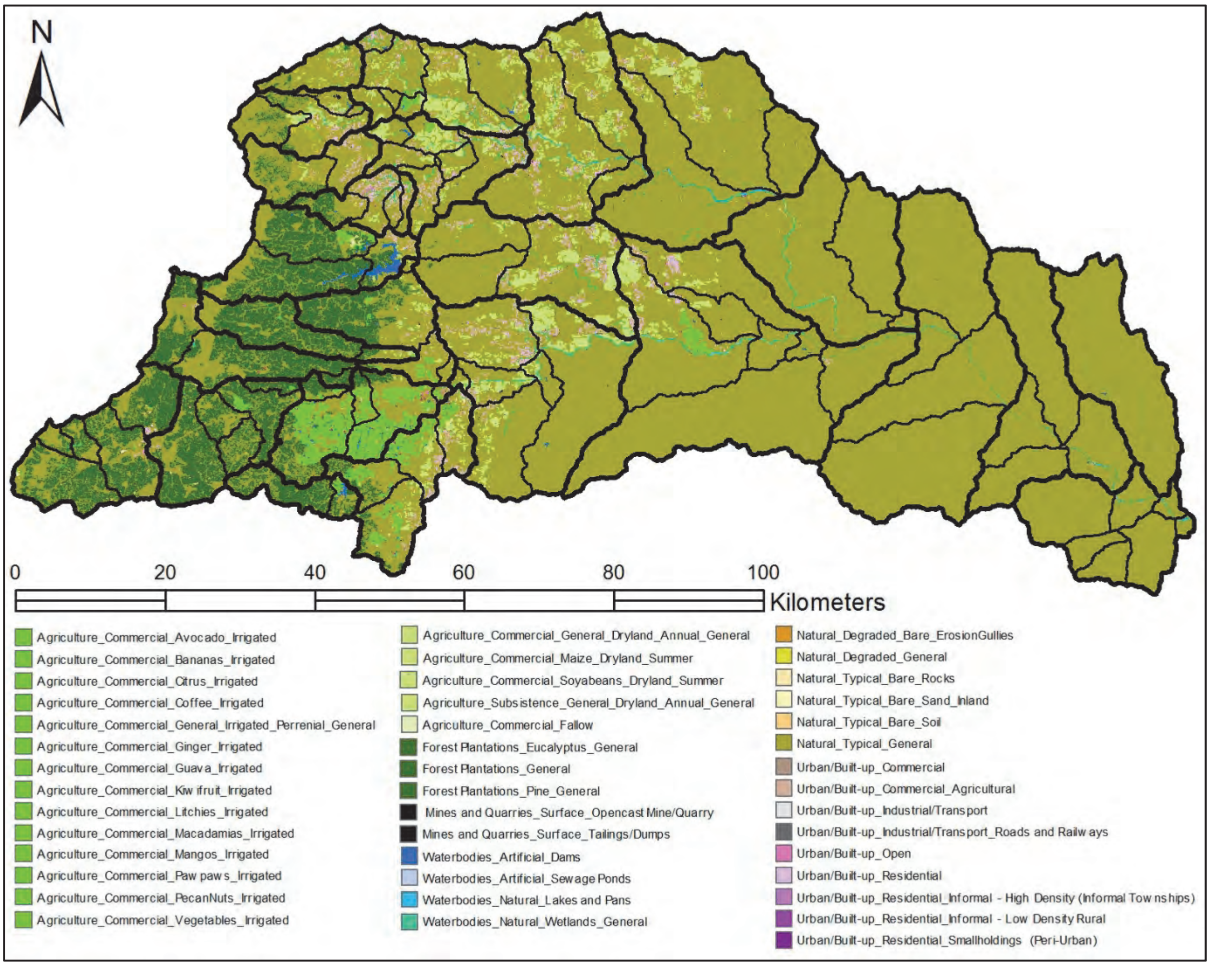

Figure 6.9 Raster dataset of *LCUClasses* for the Sabie-Sand Catchment

In Schulze (2013) different values are provided for vegetation variables for use in the *ACRU* model for four sugarcane growing regions: (i) KwaZulu-Natal South Coast, (ii) KwaZulu-Natal North Coast, (iii) Far North Coast, and (iv) KwaZulu-Natal Inland. Using the methodology described in Section 4.8.4 a shapefile of sugarcane growing regions was created for the Sabie-Sand Catchment, and is shown in Figure 6.10. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet so that a dominant sugarcane growing region could be determined for each HRU with sugarcane as a land cover/use.

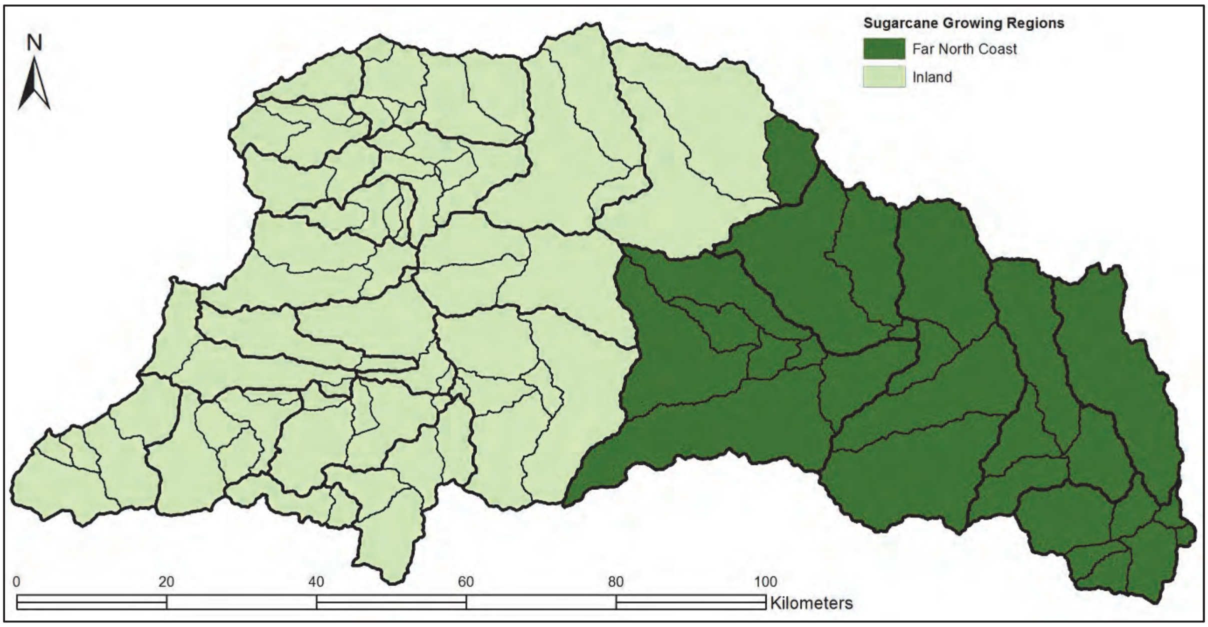

Figure 6.10 Sugarcane growing regions in the Sabie-Sand Catchment

6.8 Soils

The soils dataset developed and described by Schulze and Horan (2008b) was used in this case study. Using the methodology described in Section 4.9, 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.

6.9 Climate

6.9.1 Long-term annual and monthly Rainfall

The MAP dataset developed by Lynch (2004) was used in this case study. The MAP for the Sabie-Sand Catchment is shown in Figure 6.11. This dataset was used to create a shapefile containing area weighted mean MAP values for each sub-Quaternary catchment. The MAP value for each sub-Quaternary catchment was then used to configure the *ACRU* hydrological model.

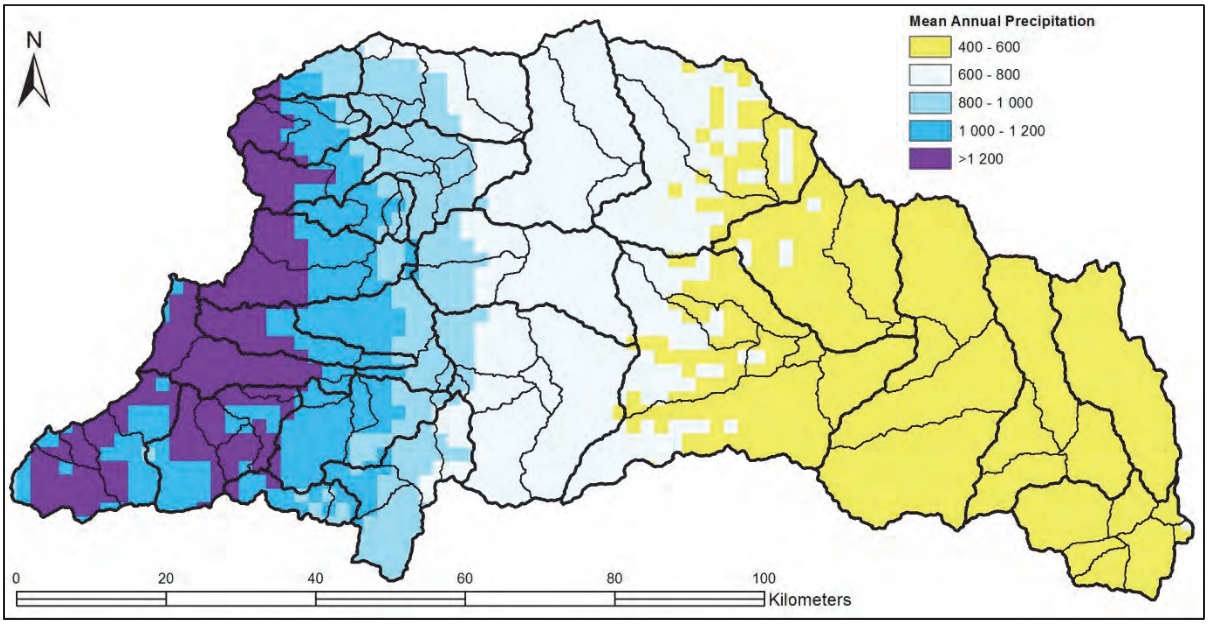

Figure 6.11 Area weighted MAP in the Sabie-Sand Catchment (after Lynch, 2004; Schulze and Lynch, 2008a)

The mean monthly rainfall and median monthly rainfall datasets developed by Lynch (2004) were used in this case study. The mean monthly rainfall datasets were used to calculate areal mean values for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 12 fields containing the calculated mean monthly rainfall values. Similarly, the median monthly rainfall datasets were used to calculate areal mean values for each sub-Quaternary catchment to produce a shapefile dataset containing median monthly rainfall values for each sub-Quaternary catchment. These two shapefiles were then used to calculate bias correction factors to potentially be used as a simple means of bias correction for the remotely sensed daily rainfall data.

6.9.2 Rainfall seasonality

The rainfall seasonality dataset developed and described by Schulze and Maharaj (2008a) was used in this case study. The whole Sabie-Sand Catchment is in the mid-summer (January) rainfall seasonality region. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet. The rainfall seasonality region for each land cover/use based HRU within each sub-Quaternary catchment was then used to configure the *ACRU* hydrological model in HRUs where specific types of dryland and irrigated crops were not specified by the land cover/use dataset.

6.9.3 Daily rainfall

The CMORPH, FEWS ARC 2.0, FEWS RFE 2.0 and TRMM 3B42 remotely sensed daily rainfall datasets described in Section 4.11.1 were compared and evaluated for use in creating water accounts. The first step was to compare the rainfall values in these datasets with rain gauge data from two rain gauges, one situated at Da Gama Dam and the other situated at Injaka Dam, both in the upper catchments of the Sabie-Sand Catchment. The four remotely sensed datasets had a common data period for the years 2001 to 2013 and were evaluated for this common time period. The rain gauge data was obtained from the "Hydrological Services – Surface Water (Data, Dams, Floods and Flows)" page of the DWS website (http://www.dwa.gov.za/hydrology/). The details of these rain gauges are shown in Table 6.1 and their locations are shown in Figure 6.12. Rain gauge X3E004 has data for the periods January 2001 to September 2001 and August 2002 to September 2008. Rain gauge X3E005 has data for the periods August 2002 to December 2013.

Table 6.1 Rain gauges used for verification

Station ID	Location		
	Name	Latitude	Longitude
X3E004	Da Gama Dam	25°08'02''	31°01'59"
X3E005	Injaka Dam	24°53'06"	31°05'10

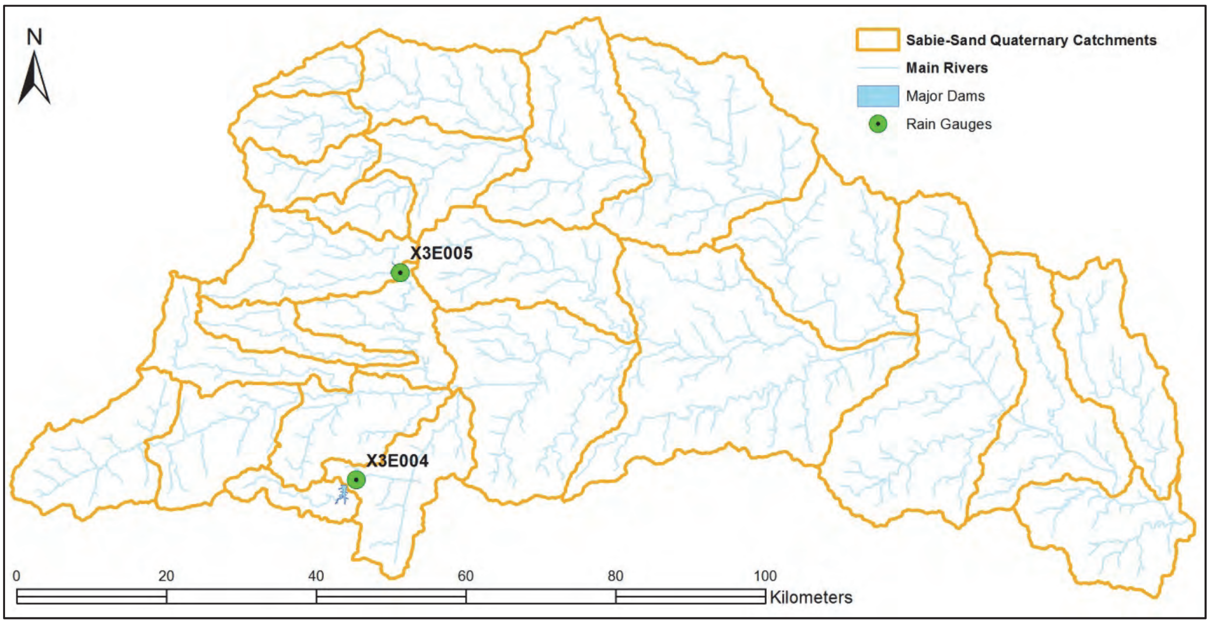

Figure 6.12 Location of rain gauges used for verification

For each of the four remotely sensed datasets a timeseries of daily rainfall was created for each of the rain gauges, using the closest pixel, for the years 2001 to 2013. For each rain gauge the remotely sensed datasets were compared statistically with the rain gauge dataset.

The dataset statistics and comparative statistics for rain gauge X3E004 are shown in Table 6.2 and a graph comparing accumulated daily rainfall is shown in Figure 6.13. None of the four remotely sensed datasets represent the rainfall for the rain gauge well, all substantially underestimating the rainfall. All four remotely sensed datasets have a larger number of rain-days with low rainfall amounts, compared to the rain gauge, and fewer rain-days with high rainfall amounts.

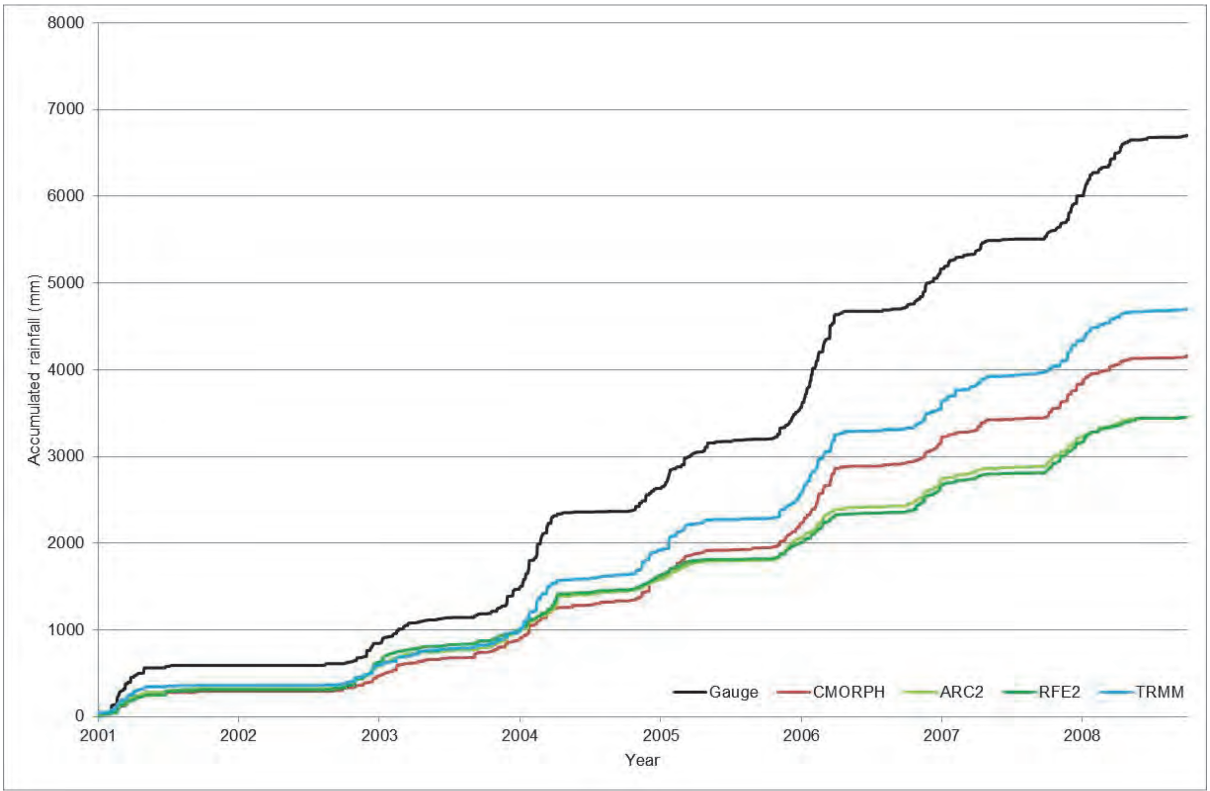

Figure 6.13 Comparison of accumulated rainfall for rain gauge X3E004 (2001 to 2013)

Table 6.2 Comparison of rainfall statistics for rain gauge X3E004 (2001 to 2013)

	Rain Gauge X3E004	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	6699.3	4162.0	3451.9	3455.5	4697.7
Max	148.4	83.7	40.6	88.0	118.3
Mean	2.7	1.6	1.4	1.4	1.9
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	9.42	5.92	3.90	4.42	6.97
Variance	88.82	35.04	15.22	19.55	48.54
Std. Error	1.77	0.70	0.30	0.39	0.97
Coef. of Variation	3.55	3.59	2.85	3.23	3.75
Skewness	6.15	6.54	4.60	7.09	6.88
Kurtosis Coef.	52.33	56.72	26.71	83.59	65.62
Sum of Squares	224363.72	88506.16	38447.48	49390.84	122623.30
Count	2526	2526	2526	2526	2526
Count x>0	500	720	720	616	759
Count 0<mm<=2	84	381	334	229	414
Count 2<mm<=10	219	212	282	300	205
Count 10<mm<=20	92	80	76	60	78
Count 20<mm<=30	50	22	21	14	27
Count 30<mm<=40	16	11	6	9	13
Count 40<mm<=50	13	7	1	3	13
Count mm>50	26	7	0	1	9
Freq. Non-ex 95%	17.00	10.17	8.40	8.70	11.07
Freq. Non-ex 90%	6.20	3.90	4.30	4.20	3.93
Freq. Non-ex 80%	0.00	0.50	1.10	0.90	0.60
Freq. Non-ex 70%	0.00	0.00	0.00	0.00	0.10
Bias	-	-2537.30	-3247.40	-3243.80	-2001.60
RMSE	-	6.24	6.30	6.48	6.68
Correlation (R)	-	0.47	0.43	0.38	0.42
Regression Intercept	-	0.87	0.90	0.89	1.05
Regression Slope	-	0.29	0.18	0.18	0.31
Coef. of Determination (R^2)	-	0.22	0.18	0.14	0.17
Mean % Diff	-	37.87	48.47	48.42	29.88
t-means	-	8.53	16.56	14.60	5.72
Variance %Diff	-	60.55	82.86	77.99	45.35
Std Dev %Diff	-	37.19	58.60	53.08	26.07
Coef Var % Diff	-	-1.10	19.66	9.04	-5.43
Skewness %Diff	-	-6.27	25.18	-15.19	-11.80
Kurtosis %Diff	-	-8.40	48.95	-59.75	-25.40

The dataset statistics and comparative statistics for rain gauge X3E005 are shown in Table 6.3 and a graph comparing accumulated daily rainfall is shown in Figure 6.14. The four remotely sensed datasets also perform badly relative to the X3E005 rain gauge data, again substantially underestimating the rainfall. As with rain gauge X3E005 the four remotely sensed datasets have a larger number of rain-days with low rainfall amounts and fewer rain-days with high rainfall amounts.

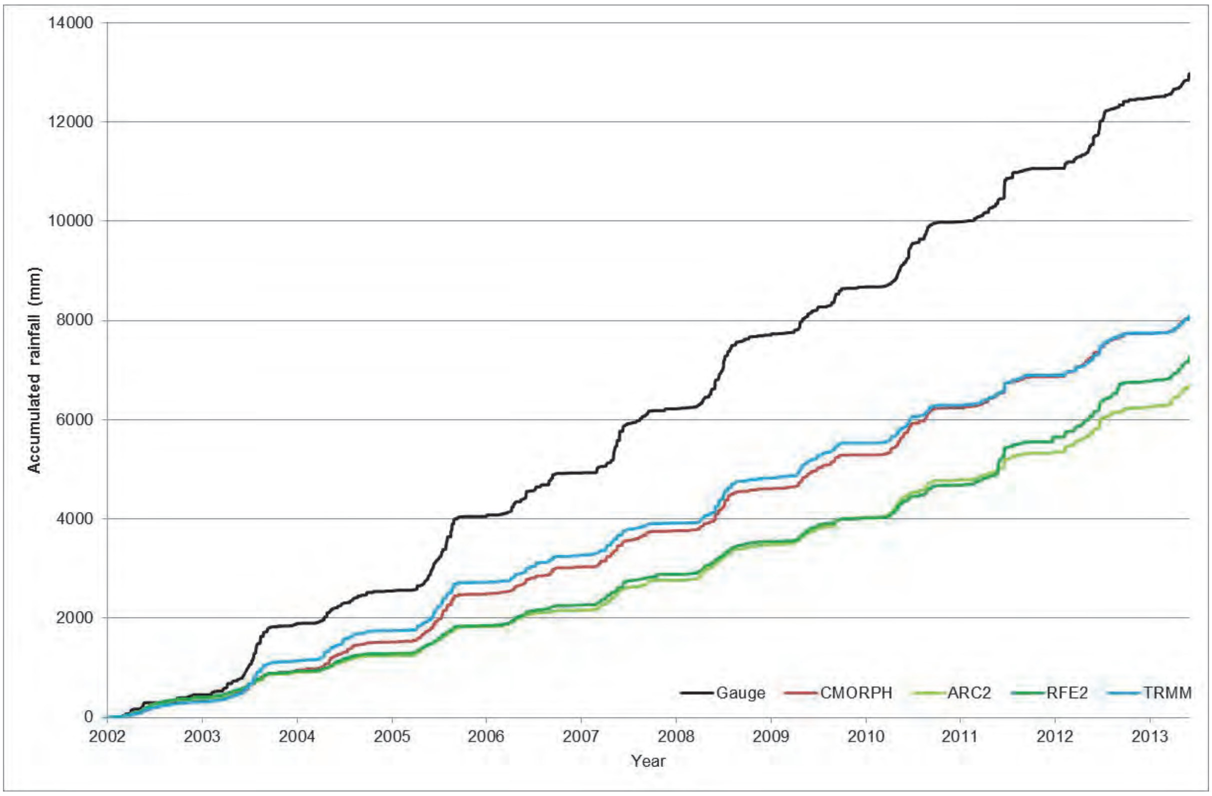

Figure 6.14 Comparison of accumulated rainfall for rain gauge X3E005 (2001 to 2013)

Table 6.3 Comparison of rainfall statistics for rain gauge X3E005 (2001 to 2013)

	Rain Gauge X3E005	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	12970.7	8079.1	7270.6	6692.9	8091.2
Max	190.2	104.5	123.0	91.8	104.0
Mean	3.1	1.9	1.7	1.6	1.9
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	11.08	6.88	5.77	5.11	7.08
Variance	122.66	47.39	33.32	26.10	50.13
Std. Error	1.90	0.73	0.52	0.40	0.78
Coef. of Variation	3.56	3.55	3.31	3.18	3.65
Skewness	7.32	5.99	7.94	6.03	6.34
Kurtosis Coef.	78.25	46.63	101.52	55.17	54.53
Sum of Squares	511618.74	197666.34	138972.07	108879.02	209082.18
Count	4171	4171	4171	4171	4171
Count x>0	1024	1184	1247	1031	1136
Count 0<mm<=2	275	589	559	381	566
Count 2<mm<=10	393	350	476	439	331
Count 10<mm<=20	165	134	142	145	119
Count 20<mm<=30	75	46	40	37	56
Count 30<mm<=40	45	26	14	17	28
Count 40<mm<=50	25	21	7	8	18
Count mm>50	46	18	9	4	18
Freq. Non-ex 95%	18.60	12.14	10.14	10.14	12.10
Freq. Non-ex 90%	8.60	4.60	5.10	5.00	4.30
Freq. Non-ex 80%	1.40	0.50	1.20	0.80	0.50
Freq. Non-ex 70%	0.00	0.00	0.00	0.00	0.00
Bias	-	-4869.20	-5609.00	-6186.70	-4838.40
RMSE	-	8.77	8.53	8.48	9.34
Correlation (R)	-	0.55	0.59	0.61	0.48
Regression Intercept	-	0.87	0.79	0.73	0.99
Regression Slope	-	0.34	0.31	0.28	0.31
Coef. of Determination (R^2)	-	0.30	0.34	0.37	0.23
Mean % Diff	-	37.71	43.95	48.40	37.62
t-means	-	11.00	15.29	19.03	10.67
Variance %Diff	-	61.36	72.84	78.72	59.13
Std Dev %Diff	-	37.84	47.88	53.87	36.07
Coef Var % Diff	-	0.21	7.02	10.60	-2.48
Skewness %Diff	-	18.23	-8.42	17.60	13.43
Kurtosis %Diff	-	40.41	-29.74	29.50	30.32

The same two simple methods of bias correction using long-term mean and median monthly rainfall from Lynch (2004) that were tested in the uMngeni case study were tested for this catchment. The results of these bias corrections using both methods were much better than in the uMngeni case study. The bias correction factors calculated using the median monthly rainfall values gave better results than the bias correction factors calculated using the mean monthly rainfall values. The bias correction factors used to adjust the remotely sensed datasets at rain gauge X3E004 are shown in Table 6.4. The dataset statistics and comparative statistics for the bias corrected data at rain gauge X3E004 are shown in Table 6.5 and a graph comparing accumulated daily rainfall is shown in Figure 6.15. None of the four remotely sensed datasets represent the rainfall for the rain gauge well, all substantially underestimating the rainfall. All four remotely sensed datasets have a larger number of rain-days with low rainfall amounts, compared to the rain gauge, and fewer rain-days with high rainfall amounts.

Table 6.4 Bias correction factors used at rain gauge X3E004

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CMORPH	1.28	1.90	1.43	1.74	4.32	0.82	2.23	2.33	1.55	1.32	1.10	1.18
FEWS ARC 2.0	1.70	1.76	2.02	1.55	2.00	1.06	0.88	3.27	1.49	0.83	1.17	1.35
FEWS RFE 2.0	1.45	2.36	1.82	1.63	5.22	1.04	0.88	3.08	2.75	0.87	1.12	1.31
TRMM 3B42	0.98	1.88	1.42	1.25	3.04	0.74	0.87	1.72	1.62	1.11	1.00	1.13

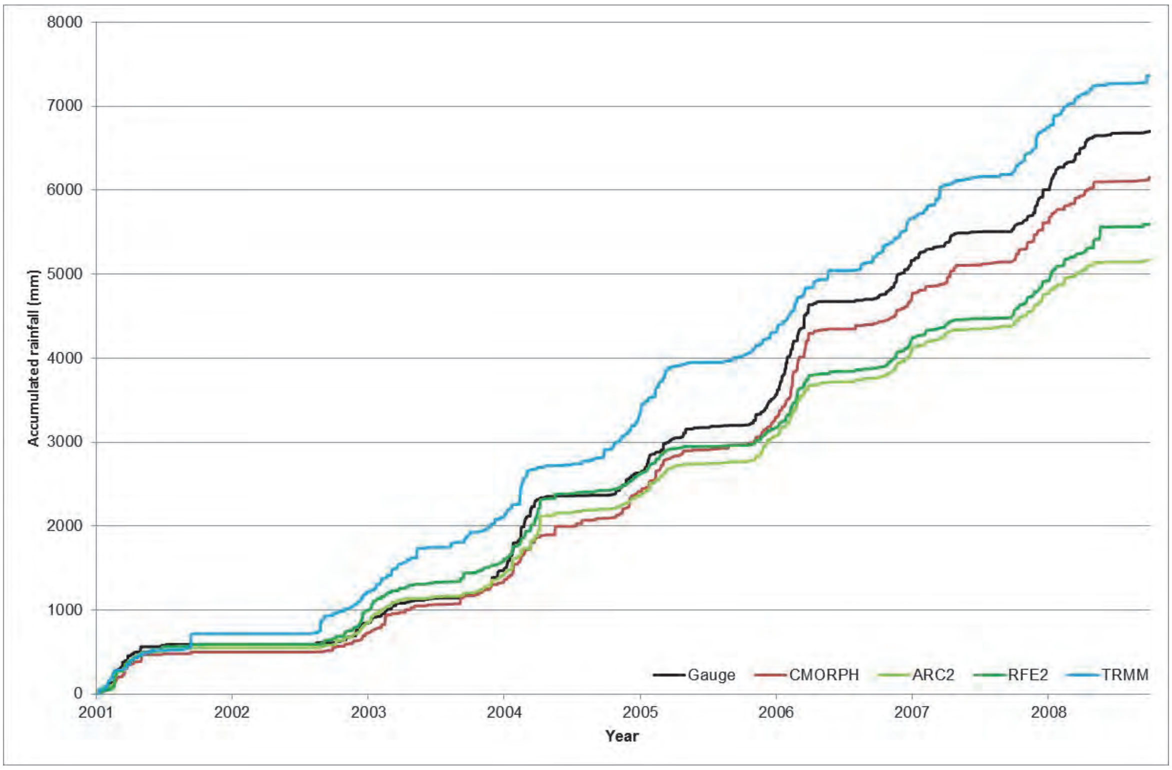

Figure 6.15 Comparison of accumulated bias corrected rainfall for rain gauge X3E004 (2001 to 2013)

Table 6.5 Comparison of bias corrected rainfall statistics for rain gauge X3E004 (2001 to 2013)

	Rain Gauge X3E004	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	6699.3	6148.9	5594.5	5169.1	7361.0
Max	148.4	135.6	104.3	136.0	130.9
Mean	2.7	2.4	2.2	2.0	2.9
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	9.42	8.77	6.77	6.82	9.41
Variance	88.82	76.87	45.81	46.57	88.46
Std. Error	1.77	1.53	0.91	0.93	1.76
Coef. of Variation	3.55	3.60	3.06	3.33	3.23
Skewness	6.15	6.51	5.98	7.49	6.09
Kurtosis Coef.	52.33	56.81	53.21	90.71	51.94
Sum of Squares	224363.72	194183.64	115722.53	117634.78	223449.88
Count	2526	2526	2526	2526	2526
Count x>0	500	720	720	616	771
Count 0<mm<=2	84	328	242	169	298
Count 2<mm<=10	219	203	298	283	248
Count 10<mm<=20	92	105	115	112	108
Count 20<mm<=30	50	31	36	26	57
Count 30<mm<=40	16	22	15	8	26
Count 40<mm<=50	13	10	6	10	14
Count mm>50	26	21	8	8	20
Freq. Non-ex 95%	17.00	14.80	13.59	12.01	18.66
Freq. Non-ex 90%	6.20	5.92	6.85	6.12	8.46
Freq. Non-ex 80%	0.00	0.87	1.63	1.29	1.55
Freq. Non-ex 70%	0.00	0.00	0.00	0.00	0.10
Bias	-	-550.42	-1104.80	-1530.17	661.74
RMSE	-	6.97	6.63	6.69	9.30
Correlation (R)	-	0.45	0.41	0.41	0.09
Regression Intercept	-	1.31	1.43	1.27	2.68
Regression Slope	-	0.42	0.30	0.29	0.09
Coef. of Determination (R^2)	-	0.21	0.17	0.16	0.01
Mean % Diff	-	8.22	16.49	22.84	-9.88
t-means	-	1.25	3.25	4.46	-1.40
Variance %Diff	-	13.45	48.42	47.57	0.41
Std Dev %Diff	-	6.97	28.18	27.59	0.20
Coef Var % Diff	-	-1.36	14.00	6.16	9.18
Skewness %Diff	-	-5.82	2.78	-21.85	1.06
Kurtosis %Diff	-	-8.58	-1.69	-73.35	0.73

The dataset statistics and comparative statistics for rain gauge X3E005 are shown in

Table 6.3 and a graph comparing accumulated daily rainfall is shown in Figure 6.14. The four remotely sensed datasets also perform badly relative to the X3E005 rain gauge data, again substantially underestimating the rainfall. As with rain gauge X3E005 the four remotely sensed datasets have a larger number of rain-days with low rainfall amounts and fewer rain-days with high rainfall amounts.

Table 6.6 Bias correction factors used at rain gauge X3E005

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CMORPH	1.29	1.99	1.84	1.53	3.19	1.57	1.70	1.65	1.50	1.18	0.93	1.11
FEWS ARC 2.0	2.06	2.31	2.34	2.82	3.15	1.00	2.47	10.77	1.72	0.82	1.18	1.47
FEWS RFE 2.0	1.67	2.38	2.09	1.98	5.13	2.05	0.58	4.90	1.79	0.91	1.06	1.40
TRMM 3B42	1.21	2.03	1.74	1.22	2.47	1.67	1.41	1.71	1.96	1.15	0.93	1.10

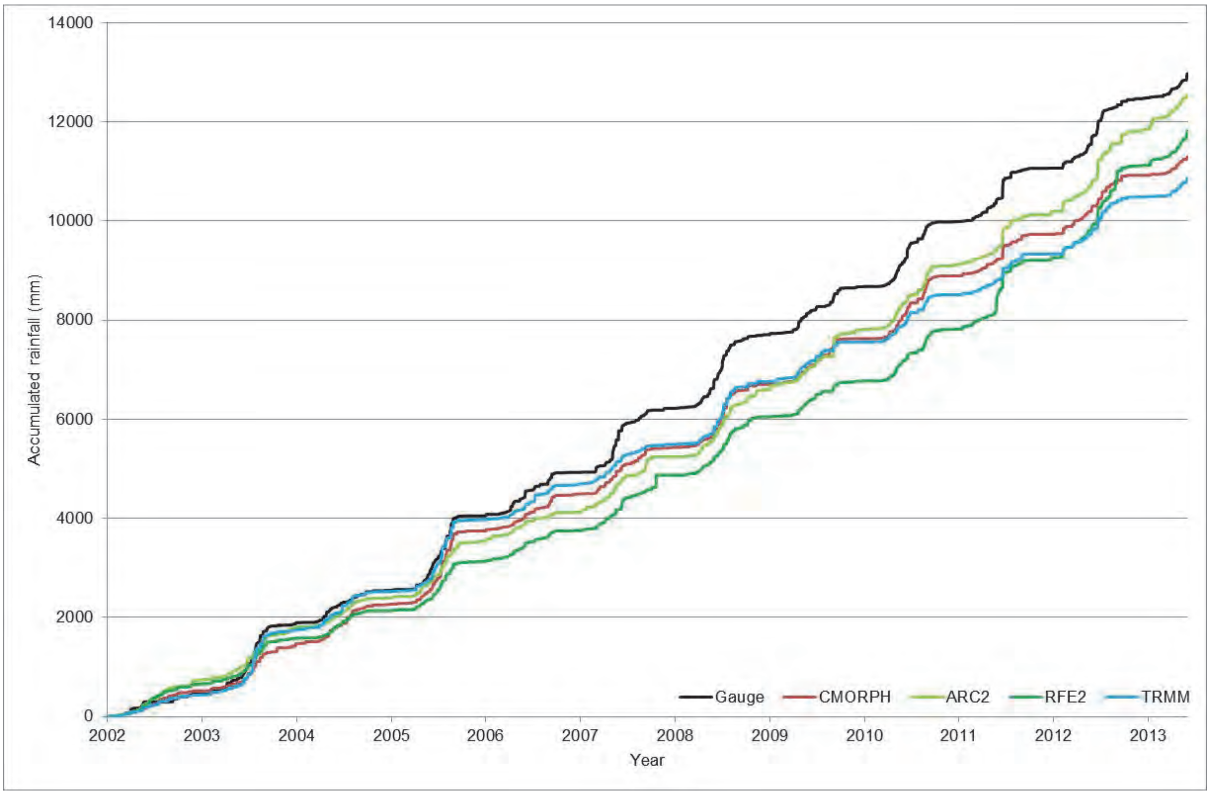

Figure 6.16 Comparison of accumulated bias corrected rainfall for rain gauge X3E005 (2001 to 2013)

Table 6.7 Comparison of bias corrected rainfall statistics for rain gauge X3E005 (2001 to 2013)

	Rain Gauge X3E005	**CMORPH**	**FEWS ARC 2.0**	**FEWS RFE 2.0**	**TRMM 3B42**
Sum	12970.7	11294.6	11810.1	12552.3	10860.1
Max	190.2	157.2	232.3	189.1	153.4
Mean	3.1	2.7	2.8	3.0	2.6
Min	0.0	0.0	0.0	0.0	0.0
Std. Deviation	11.08	9.90	10.12	10.25	9.81
Variance	122.66	97.93	102.40	105.13	96.33
Std. Error	1.90	1.52	1.59	1.63	1.49
Coef. of Variation	3.56	3.65	3.57	3.41	3.77
Skewness	7.32	6.38	9.90	6.90	6.61
Kurtosis Coef.	78.25	54.47	157.29	69.85	57.55
Sum of Squares	511618.74	408460.90	427108.73	438491.32	401780.92
Count	4171	4171	4171	4171	4171
Count x>0	1024	1184	1247	1031	1128
Count 0<mm<=2	275	538	433	237	499
Count 2<mm<=10	393	334	463	425	336
Count 10<mm<=20	165	143	193	199	126
Count 20<mm<=30	75	69	69	68	66
Count 30<mm<=40	45	32	47	41	31
Count 40<mm<=50	25	20	13	21	31
Count mm>50	46	48	29	40	39
Freq. Non-ex 95%	18.60	16.06	16.09	17.23	15.83
Freq. Non-ex 90%	8.60	6.42	7.95	8.44	5.56
Freq. Non-ex 80%	1.40	0.67	1.84	1.57	0.68
Freq. Non-ex 70%	0.00	0.00	0.00	0.00	0.00
Bias	-	-1711.35	-1069.49	-327.30	-2019.52
RMSE	-	9.44	9.45	9.21	10.14
Correlation (R)	-	0.54	0.55	0.58	0.47
Regression Intercept	-	1.20	1.27	1.34	1.31
Regression Slope	-	0.48	0.50	0.54	0.42
Coef. of Determination (R^2)	-	0.29	0.30	0.33	0.22
Mean % Diff	-	12.92	8.95	3.23	16.27
t-means	-	2.62	1.78	0.63	3.33
Variance %Diff	-	20.16	16.52	14.29	21.47
Std Dev %Diff	-	10.65	8.63	7.42	11.38
Coef Var % Diff	-	-2.61	-0.35	4.34	-5.84
Skewness %Diff	-	12.83	-35.22	5.72	9.68
Kurtosis %Diff	-	30.39	-101.00	10.74	26.46

From these comparisons of the four unadjusted remotely sensed daily rainfall datasets with rain gauge data there is no one dataset that clearly represents rain gauge data better than the others in this study catchment. Although the regression statistics for the two FEWS datasets, especially the FEWS RFE 2.0 dataset, generally seem to be better that the other two datasets the bias and number of rain days seem to be worse. The TRMM 3B42 dataset consistently overestimates the rainfall, but there is no clear trend for the other 3 datasets. It was also not clear whether these comparisons with point rain gauge data would be an accurate representation of how well the remotely sensed datasets would estimate areal rainfall for the catchments. For this reason all four remotely sensed daily rainfall datasets were used in four separate *ACRU* model runs and four set of water resource accounts were compiled for comparison. For each of these datasets a timeseries of daily rainfall was created for each sub-Quaternary catchment.

6.9.4 Reference potential evaporation

The SAHG ET_0 dataset was used together with a shapefile dataset of sub-Quaternary catchment boundaries to create a time series of daily ET_0 data values for each sub-Quaternary catchment as described in Section 4.12. A correction factor of 1.2 was applied to the ET_0 values in *ACRU* to calculate A-pan equivalent daily ET_0 values.

6.9.5 Air temperature

The datasets of long-term mean monthly maximum and minimum air temperature described by Schulze and Maharaj (2008b) and Schulze and Maharaj (2008c) were used in this case study. For each of the 12 maximum air temperature datasets and the 12 minimum air temperature datasets an areal mean value was calculated for each sub-Quaternary catchment to produce a shapefile dataset containing sub-Quaternary catchments as features and 24 fields containing the calculated daily temperature values for each month. The monthly values of daily maximum and minimum temperature for each sub-Quaternary catchment were then used to configure the *ACRU* hydrological model.

The frost occurrence dataset developed and described by Schulze and Maharaj (2008d) was used in this case study. The frost occurrence regions for the sub-Quaternary catchments in the Sabie-Sand Catchment are shown in Figure 6.17. This dataset was used as one of the region datasets used to generate the *LCURegions* spreadsheet, from which the dominant frost occurrence region for each land cover/use based HRU within each sub-Quaternary catchment can be determined.

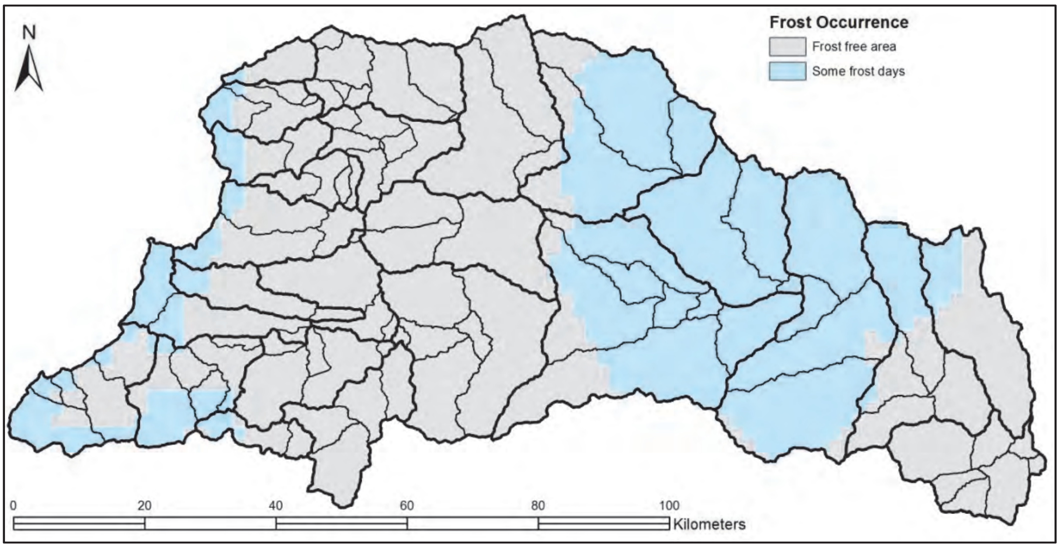

Figure 6.17 Frost occurrence regions in the Sabie-Sand Catchment (Schulze and Maharaj, 2008d)

6.10 Streamflow Gauges

Measured streamflow data was used to verify the simulated streamflow used in the water resource accounts. The measured streamflow data was obtained from the "Hydrological Services – Surface Water (Data, Dams, Floods and Flows)" page of the DWS website (http://www.dwa.gov.za/hydrology/). The streamflow gauges listed in Table 6.8 and shown in Figure 6.18 were selected as they were currently operational and their period of record covered the 2010-2013 period for which water accounts were compiled.

Table 6.8 Streamflow gauges used for verification

Gauge ID	Gauge Description	Sub-Quaternary Catchment
X3H001	Sabie River @ Sabie	X31A_4
X3H002	Klein Sabie River @ Sabie	X31A_5
X3H003	Mac-Mac River @ Geelhoutboom	X31C_1
X3H004	Noordsand River @ De Rust	X31J_3
X3H008	Sand River @ Exeter	X32G_3
X3H011	Marite River @ Injaka	X31G_1
X3H015	Sabie River @ Lower Sabie Rest Camp	X33B_4
X3H020	White Waters River @ Etna	X31H_2
X3H021	Sabie River @ Kruger Gate	X31M_1, X31M_2
X3H023	Sabie River @ Emmet	X31C_3, X31D_1, X31D_2

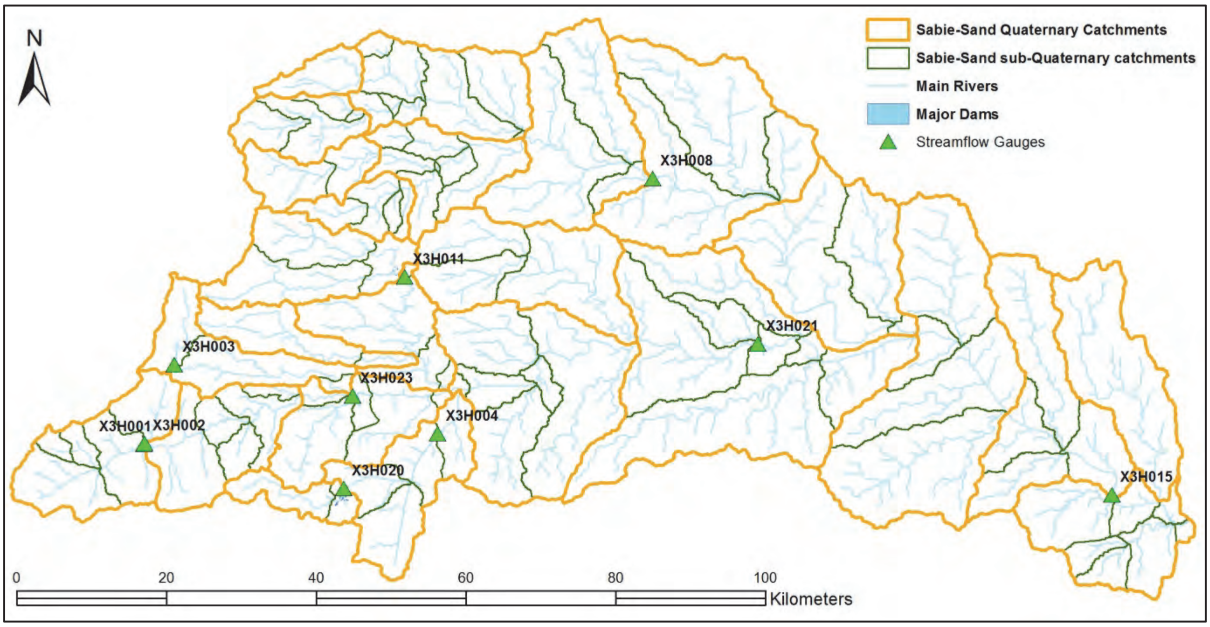

Figure 6.18 Location of streamflow gauges used for verification

6.11 Results

The *ACRU* model was configured for the Sabie-Sand Catchment as described in Section 0 using the datasets described in this chapter. The *ACRU* model was used to simulate four calendar years 2010 to 2013. The first year, 2010, was used as a warm-up period for the model and water accounts were compiled for the three years 2011 to 2013. In Section 6.11.1 the simulated streamflow using each of the four remotely sensed rainfall datasets is compared to observed streamflow. In Section 6.11.2 selected water accounts are discussed.

6.11.1 Streamflow verification

The measured annual streamflow and simulated annual streamflow values for the four remotely sensed rainfall datasets are summarised in Table 6.9 and shown graphically in Figure 6.19 for 2011, Figure 6.20 for 2012 and Figure 6.21 for 2013. It should be noted that the bias corrected versions of the remotely sensed rainfall datasets, as discussed in Section 6.9.3, were used for these simulations. For some streamflow gauges for some years there was missing data within a year, and in these instances the measured annual streamflow was omitted from the evaluation. As with the uMngeni case study, comparing these measured and simulated annual streamflow values it is difficult to arrive at any definite conclusions, although the CMORPH dataset seems to perform well for several streamflow gauges and years. Despite the poor verification of the remotely sensed rainfall datasets against rain gauge data and the need to try and bias correct the datasets, the results in the Sabie-Sand were more encouraging that the results for the uMngeni catchment. Part of the reason for this may be that the Sabie-Sand Catchment is less developed than the uMngeni Catchment in terms of general land use and the effect of large dams. The bias corrected TRMM 3B42 dataset does not appear to oversimulate rainfall in this catchment as it did in the uMngeni catchment. There also seems to be less variability between the simulated streamflow from the remotely sensed rainfall datasets in this catchment.

Table 6.9 Comparison of measured and simulated annual streamflow

Gauge ID	Year	Annual Streamflow (10^6 m^3)				
		Gauge	CMORPH	FEWS ARC 2.0	FEWS RFE 2.0	TRMM 3B42
X3H001	2011	-	75.6	39.4	50.8	41.7
X3H001	2012	87.4	80.7	57.5	67.7	61.1
X3H001	2013	102.4	64.6	112.1	99.4	61.8
X3H002	2011	18.7	27.8	16.5	19.0	26.5
X3H002	2012	13.8	24.7	18.9	20.4	23.3
X3H002	2013	18.9	23.5	35.8	41.3	21.8
X3H003	2011	41.8	36.9	16.9	22.5	20.6
X3H003	2012	23.9	31.3	15.8	21.0	35.6
X3H003	2013	30.0	32.8	42.6	54.7	25.5
X3H004	2011	-	41.7	23.2	7.0	26.3
X3H004	2012	34.8	33.5	36.2	37.1	33.3
X3H004	2013	44.8	22.7	59.4	69.7	24.7
X3H008	2011	-	131.6	92.3	81.0	65.0
X3H008	2012	-	202.3	181.8	192.4	156.6
X3H008	2013	222.3	217.8	285.5	289.6	132.8
X3H011	2011	84.8	66.4	19.9	6.1	27.4
X3H011	2012	-	66.1	21.4	44.3	73.8
X3H011	2013	64.7	62.0	141.9	157.9	42.6
X3H015	2011	-	998.1	417.3	323.2	489.6
X3H015	2012	-	877.8	1004.2	945.5	1206.7
X3H015	2013	-	886.0	1455.4	1491.8	706.8
X3H020	2011	-	13.4	9.4	1.3	20.6
X3H020	2012	13.8	13.6	12.7	10.1	12.2
X3H020	2013	10.3	9.4	22.1	24.7	8.7
X3H021	2011	-	601.0	292.7	227.9	406.9
X3H021	2012	836.9	550.9	421.6	578.2	631.0
X3H021	2013	1102.6	488.9	978.4	1058.9	425.4
X3H023	2011	303.1	294.0	191.1	174.1	299.7
X3H023	2012	-	298.1	211.5	241.4	278.0
X3H023	2013	298.7	251.0	469.5	466.9	230.3

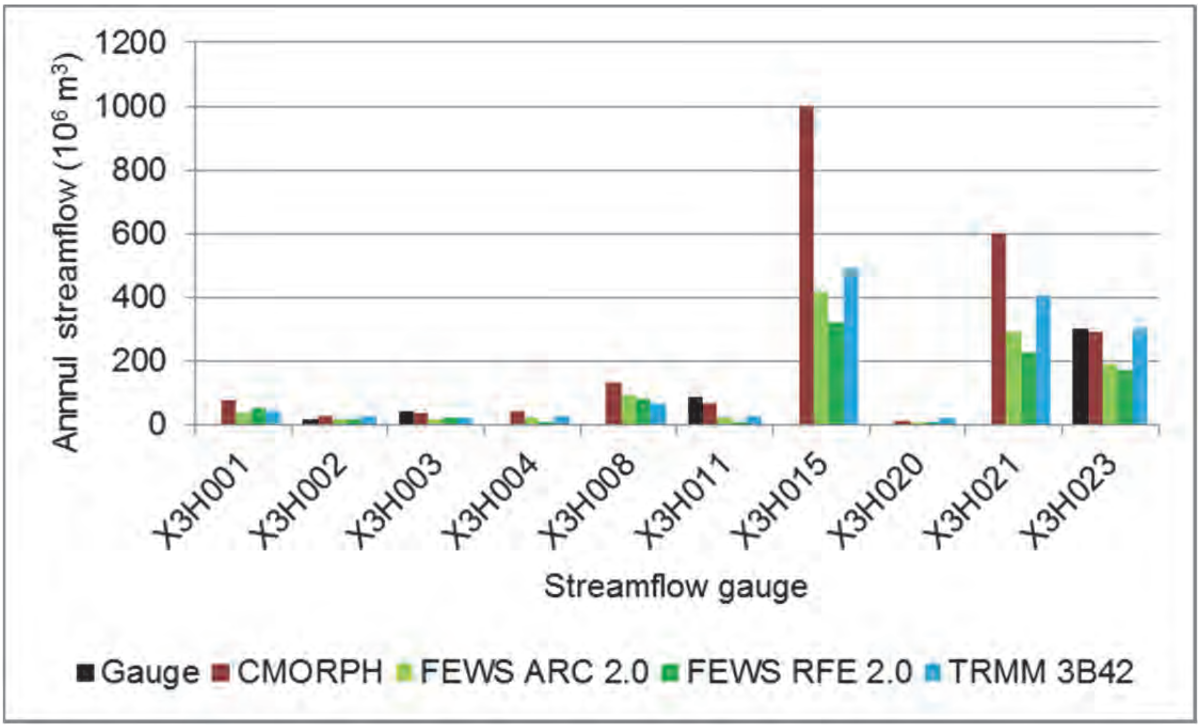

Figure 6.19 Comparison of measured and simulated annual streamflow for 2011

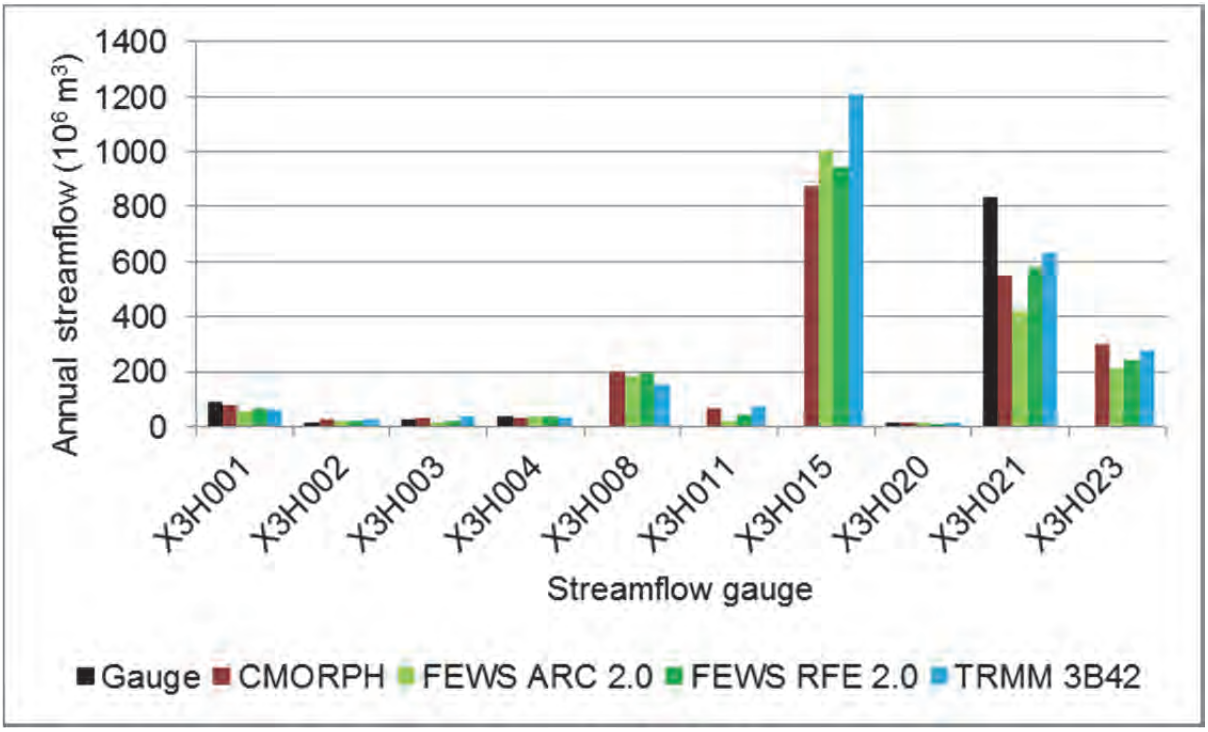

Figure 6.20 Comparison of measured and simulated annual streamflow for 2012

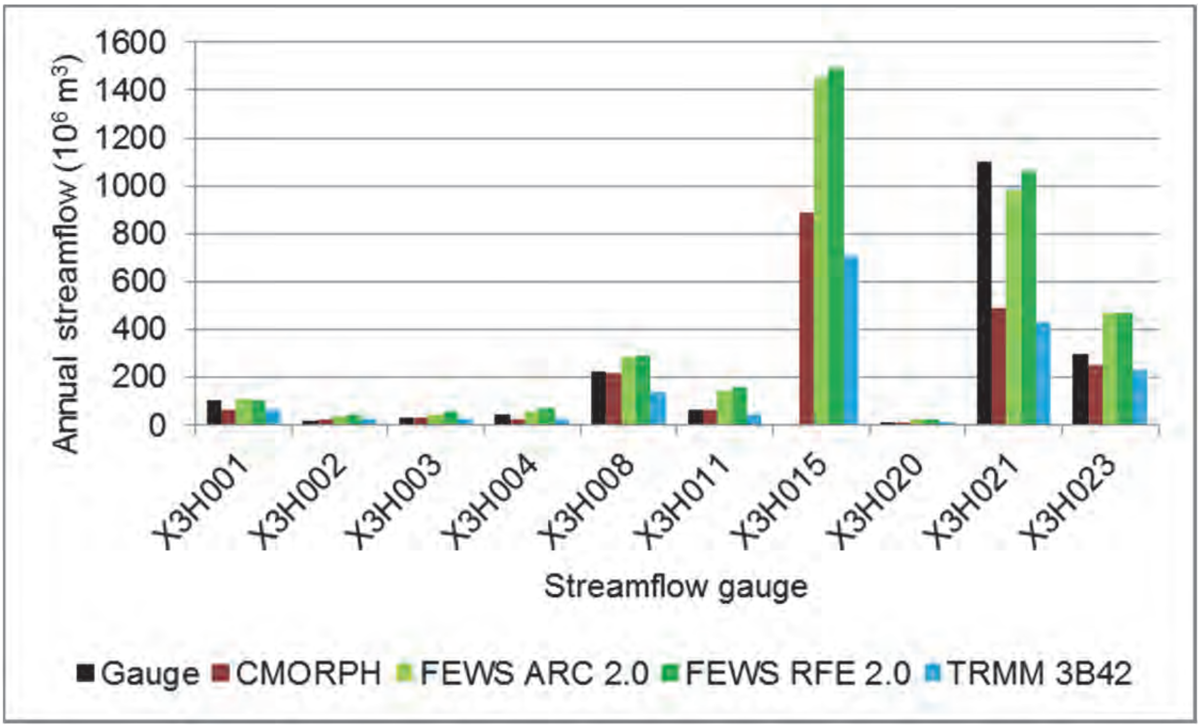

Figure 6.21 Comparison of measured and simulated annual streamflow for 2013

6.11.2 Water resource accounts

For the purpose of demonstrating the water resource accounts the CMORPH data was selected. 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 Sabie-Sand Catchment. The annual water resource accounts for the whole Sabie-Sand Catchment are shown in Figure 6.22 for 2011, Figure 6.23 for 2012 and Figure 6.24 for 2013. The water volumes shown in the 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.

The only source of water to the catchment is rainfall as there is no flow into the Sabie-Sand Catchment from any upstream catchments. In 2011 there is a net decrease in both the soil moisture store and in the groundwater store. In 2012, which has higher rainfall than 2011, there is a net increase in both the soil moisture store and in the groundwater store. In 2013, there is a net increase in the soil moisture store and a net decrease in the groundwater store. Looking at the *Landscape ET* section of the account, the majority of total evaporation occurs in the *Natural* and *Cultivated* categories. Irrigated agriculture represents only about 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 occurs through transpiration, with interception evaporation and soil water evaporation contributing similar amounts. Information about reserved flows has not been included into the accounts yet, because, although some data on environmental water requirements has been obtained the sites do not generally coincide with Quaternary Catchment boundaries and there is no EWR site at the exit of the Sabie-Sand Catchment.

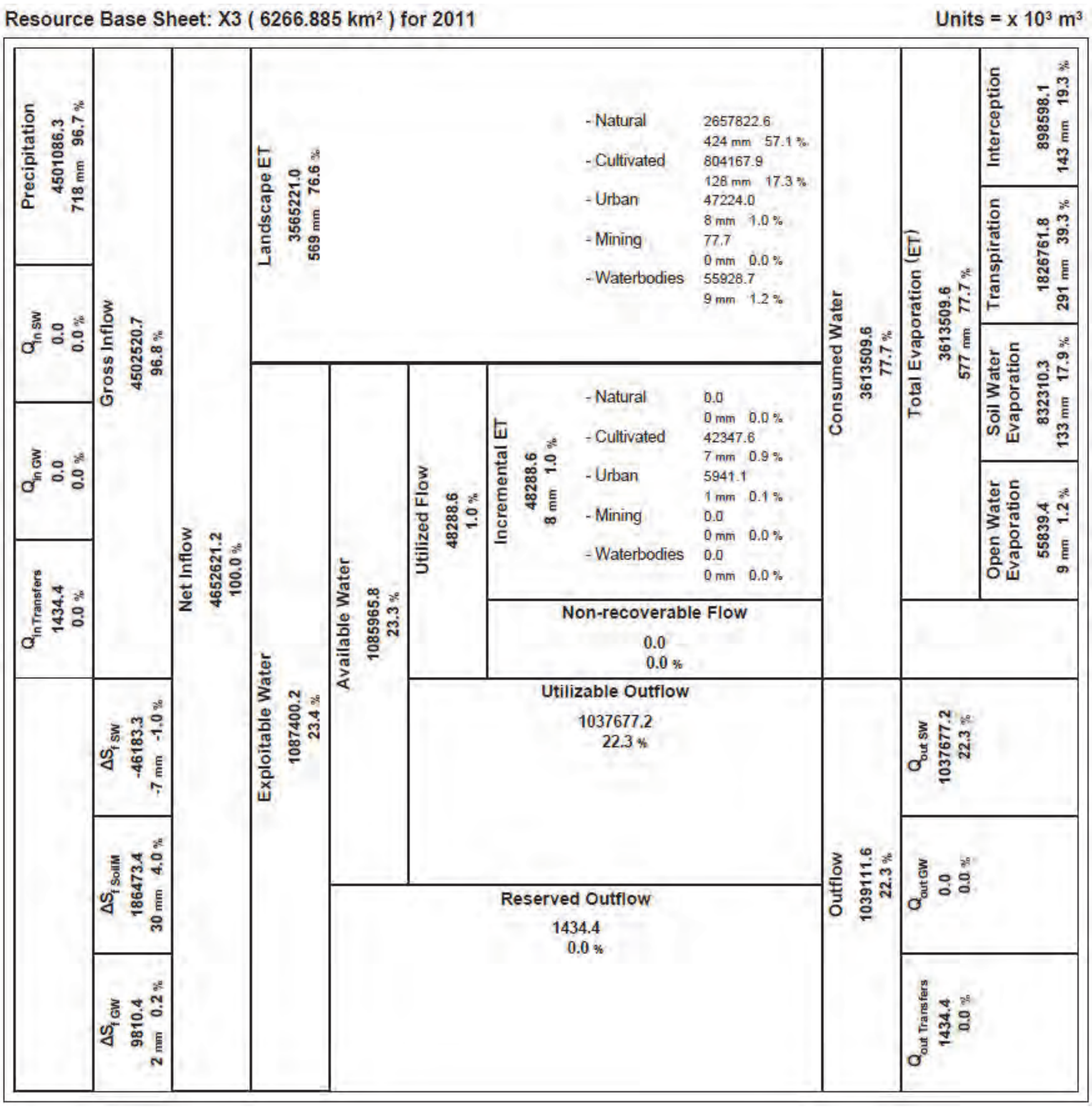

Figure 6.22 Annual water account for the Sabie-Sand Catchment for 2011

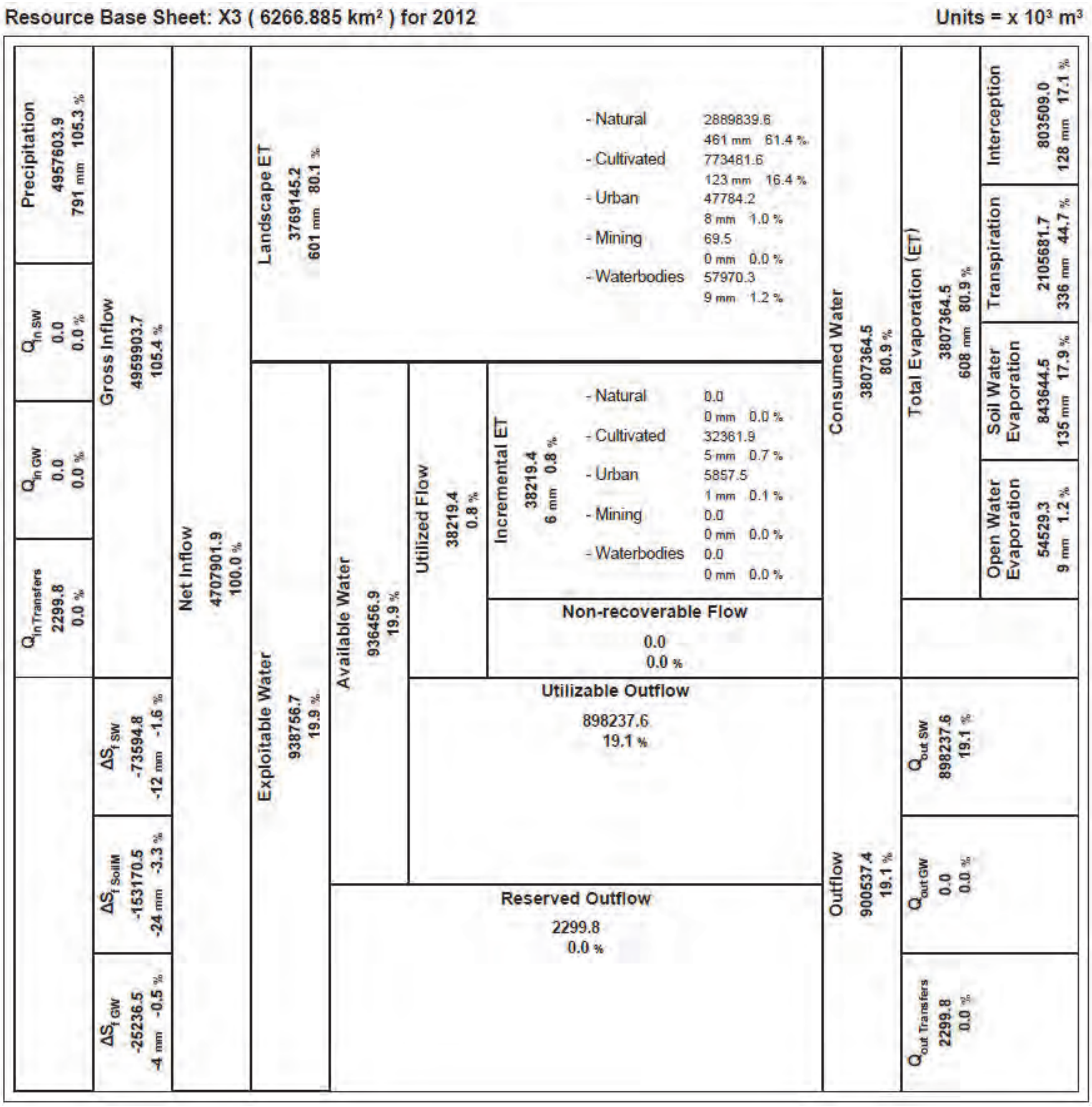

Figure 6.23 Annual water account for the Sabie-Sand Catchment for 2012

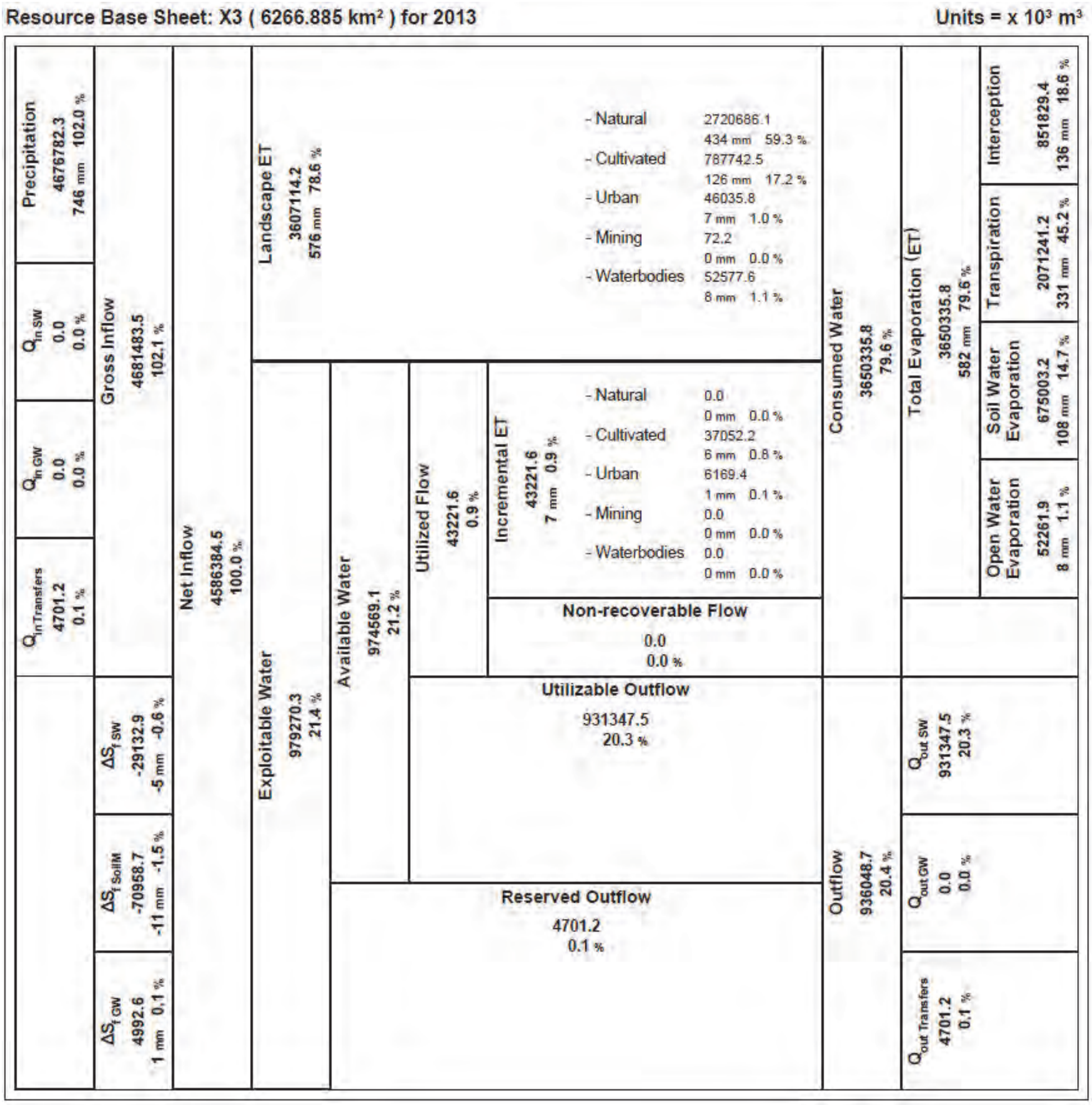

Figure 6.24 Annual water account for the Sabie-Sand Catchment for 2013

Although the Resource Base Sheet provides a very useful overview of water use in a catchment, it is an aggregation of the water balances for each of the individual land cover/use classes existing within the represented catchment, and the detail of these individual water balances is lost. The land and water use summary table for the Sabie-Sand Catchment for 2013 is shown in Table 6.10. This summary is in the form of a pivot table summarising areal extent, water availability and use by land cover/use class. The first column contains a nested hierarchical list of all the land cover/use classes within a catchment. For the *Agriculture* category the *Commercial/Subsistence*, the *Dryland/Irrigated* and the *CropType* attribute categories was also included in the summary, where the crop type *General* indicates that the land cover/use dataset did not specify a specific crop. The second column shows the area of each class as percentages of the preceding level in the hierarchy. The third and fourth column shows the precipitation and irrigation received by each class as percentages of the preceding level in the hierarchy. The remaining columns show the total evaporation and partitioned components of this for each class as percentages of the preceding level in the hierarchy. The advantage of the hierarchy of land cover/use classes and also the attribute categories to help in understanding water use within a catchment can be clearly seen in Table 6.10.

Table 6.10 Land and water use summary table for the Sabie-Sand Catchment for 2013 as percentages

Land Cover/Use Category	Area (6266.885 km^2)	Rainfall	Irrigation	Total Evaporation	Interception Evaporation	Transpiration	Soil Moisture Evaporation	Open Water Evaporation
Total Water (mm)	-	746	5	582	136	331	108	8
Natural	68.08	73.18	0.00	74.53	79.71	74.97	72.42	0.00
Typical	99.81	99.85	-	99.87	99.95	99.93	99.58	-
Acocks	99.45	99.46	-	99.67	99.93	99.99	98.29	-
Inland Tropical Forest	28.13	21.29	-	18.79	17.09	18.94	20.74	-
North-Eastern Mountain Sourveld	33.41	37.54	-	34.67	35.96	33.52	36.56	-
Lowveld Sour Bushveld	66.59	62.46	-	65.33	64.04	66.48	63.44	-
Tropical Bush and Savanna (Bushveld)	71.87	78.71	-	81.21	82.91	81.06	79.26	-
Lowveld	100.00	89.84	-	90.80	91.09	91.08	89.46	-
Arid Lowveld	0.00	10.16	-	9.20	8.91	8.92	10.54	-
Bare	0.55	0.54	-	0.33	0.07	0.01	1.71	-
Rock	36.23	22.80	-	4.34	82.85	0.00	0.00	-
Sand – Inland	5.30	8.98	-	11.65	2.22	12.62	12.17	-
Soil	58.48	68.22	-	84.01	14.93	87.38	87.83	-
Degraded	0.19	0.15	-	0.13	0.05	0.07	0.42	-
Acocks	79.89	79.26	-	83.01	98.62	99.50	72.03	-
Inland Tropical Forest	19.80	19.91	-	19.39	19.90	18.68	19.75	-
North-Eastern Mountain Sourveld	2.99	3.37	-	3.17	3.23	3.12	3.19	-
Lowveld Sour Bushveld	97.01	96.63	-	96.83	96.77	96.88	96.81	-
Tropical Bush and Savanna (Bushveld)	80.20	80.09	-	80.61	80.10	81.32	80.25	-
Lowveld	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Arid Lowveld	0.00	0.00	-	0.00	0.00	0.00	0.00	-
Bare	20.11	20.74	-	16.99	1.38	0.50	27.97	-
Erosion – Gullies	100.00	100.00	-	100.00	100.00	100.00	100.00	-

Table 6.10 (cont.) Land and water use summary table for the Sabie-Sand Catchment for 2013 as percentages

Land Cover/Use Category	Area (6266.885 km^2)	Rainfall	Irrigation	Total Evaporation	Interception Evaporation	Transpiration	Soil Moisture Evaporation	Open Water Evaporation
Cultivated	27.19	22.91	100.00	22.60	18.15	23.82	24.99	15.36
Agriculture	27.90	26.24	100.00	33.28	15.84	24.74	71.08	100.00
Commercial	39.26	32.78	100.00	41.93	47.54	44.44	34.34	100.00
Fallow	1.26	1.42	0.00	0.67	0.06	0.01	1.85	0.00
Dryland – General	0.78	0.88	0.00	0.54	0.44	0.59	0.59	0.00
Dryland – Maize	1.31	1.31	0.00	0.87	0.76	0.97	0.95	0.00
Dryland – Soybeans	0.33	0.42	0.00	0.23	0.16	0.17	0.37	0.00
Irrigated – General	17.19	16.77	39.79	23.89	15.84	26.95	19.07	39.63
Irrigated – Avocado	5.88	6.03	7.16	6.59	7.42	6.20	6.77	7.18
Irrigated – Bananas	29.58	29.07	28.71	29.90	31.18	27.85	32.46	28.78
Irrigated – Citrus	0.51	0.48	0.78	0.59	0.55	0.75	0.35	0.78
Irrigated – Coffee	0.36	0.40	0.50	0.42	0.40	0.41	0.44	0.50
Irrigated – Ginger	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Irrigated – Guava	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02
Irrigated – Kiwifruit	0.06	0.06	0.07	0.07	0.06	0.07	0.06	0.07
Irrigated – Litchis	3.10	3.04	3.03	3.13	3.42	3.46	2.64	3.04
Irrigated – Macadamias	28.29	29.31	9.47	22.85	31.58	23.64	21.94	9.49
Irrigated – Mangos	4.46	4.49	4.39	4.49	4.95	4.45	4.42	4.40
Irrigated – Pawpaws	0.97	0.84	1.11	0.98	0.84	1.02	0.93	1.11
Irrigated – Pecan Nuts	0.39	0.39	0.19	0.32	0.40	0.34	0.31	0.19
Irrigated – Vegetables	5.44	4.99	4.72	4.36	1.85	3.02	6.77	4.74
Subsistence	60.74	67.22	0.00	58.07	52.46	55.56	65.66	0.00
Dryland – General	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Forest Plantations	72.10	73.76	0.00	66.72	84.16	75.26	28.92	0.00
Eucalyptus	54.91	53.26	-	56.70	50.52	61.89	33.68	-
General	20.65	21.30	-	21.03	20.07	20.66	26.40	-
Pine	24.44	25.45	-	22.27	29.42	17.45	39.91	-
Urban/Built-up	3.67	3.10	0.00	1.43	2.01	0.88	1.58	11.80
Commercial	2.30	1.91	-	1.08	1.66	1.00	0.92	0.00
General	92.22	90.09	-	90.52	90.80	90.01	90.67	-
Agricultural	7.78	9.91	-	9.48	9.20	9.99	9.33	-
Industrial/Transport	16.54	19.39	-	5.60	14.70	1.43	1.40	0.00
General	5.82	5.74	-	20.92	7.95	100.00	100.00	-
Roads and Railways	94.18	94.26	-	79.08	92.05	0.00	0.00	-
Residential	80.71	78.36	-	92.49	83.26	96.24	96.52	100.00
General	95.73	95.81	-	80.23	94.51	90.63	90.79	0.00
Informal – High Density (Informal Townships)	0.69	0.64	-	3.12	0.54	0.61	0.53	20.55
Informal – Low Density Rural	3.21	3.24	-	15.84	4.51	7.93	7.91	77.76
Smallholdings (Peri-Urban)	0.37	0.31	-	0.81	0.43	0.83	0.78	1.69
Open Spaces (Golf Courses and Sports fields, etc.)	0.45	0.34	-	0.82	0.37	1.33	1.15	0.00
Waterbodies	1.03	0.79	0.00	1.44	0.12	0.32	1.01	72.84
Artificial	56.11	53.82	-	72.40	0.00	0.00	0.00	100.00
Dams	100.00	100.00	-	100.00				100.00
Natural	43.89	46.18	-	27.60	100.00	100.00	100.00	0.00
Wetlands	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Mines and Quarries	0.02	0.02	0.00	0.00	0.01	0.00	0.00	0.00
Surface	100.00	100.00	-	100.00	100.00	100.00	100.00	-
Opencast Mine/Quarry	99.74	99.65	-	98.12	99.99	0.00	0.00	-
Tailings/Dumps	0.26	0.35	-	1.88	0.01	100.00	100.00	-

7 DISCUSSION AND CONCLUSIONS

DJ Clark

This project was based on the recognition that water resource accounts were a potential tool that could be used to describe and communicate information about water availability and use in South Africa to facilitate better management of water resources and better communication between water managers and water users. A review of the literature describing existing water accounting frameworks provided a better understanding of water accounting and lead to the selection of WA+ as a suitable framework for compiling catchment scale water accounts in South Africa. 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 to guide the development of a methodology for estimating water availability and use at a catchment scale. It was decided that hydrological modelling was the best way to develop an integrated and internally-consistent methodology for estimating water availability and water use based on a water balance approach, and to enable quantification of all water fluxes in the hydrological cycle and to distinguish between use by different sectors. The methodology was designed to have a strong land cover/use focus and aimed to produce annual water resources accounts at Quaternary Catchment scale. A guiding principle behind the design of the methodology was that it should be suitable for compiling water accounts for the whole of South Africa and thus should, as far as possible, use readily available datasets covering the whole of South Africa to ensure consistency in its application for different catchments across the country.

It was recognised that although the accounts were to be at a Quaternary Catchment scale it would be necessary to do the hydrological modelling at a finer spatial scale to enable the quantification of water use by different sectors within a Quaternary Catchment and also to account for variability in climate and soil characteristics within a Quaternary Catchment. One unexpected hurdle in the project was the difficulty in developing datasets of sub-Quaternary catchment boundaries for the two case study catchments. A suitable sub-Quaternary catchment boundary does not exist for South Africa, though the NFEPA catchment boundary dataset is a good starting point. The development of a sub-Quaternary catchment dataset for South Africa that takes major dams, weirs and major water abstraction points into account would be useful for more spatially detailed hydrological modelling in South Africa. In both case study catchments, existing catchment specific sub-Quaternary catchment boundary datasets were used.

As already stated, the methodology was intended to have a strong land cover/use focus. When the project started the most recent detailed national land cover/use dataset for South Africa was the National Landcover 2000 dataset, though more recent datasets were available for some provinces and catchments. A further complication was that all these datasets used 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 to enable water resource accounts 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 describing the hydrological characteristics of these classes. In this project the Acocks Veld Types (Acocks, 1988) dataset and associated hydrological characteristics from Schulze (2004) were used to represent natural vegetation, but the more detailed Mucina and Rutherford (2006) dataset can be used once a corresponding dataset of hydrological characteristics have been developed. The methodology developed for determining HRUs for modelling using catchment boundaries, land cover/use, natural vegetation and soils datasets was also a useful development.

Four remotely sensed daily rainfall datasets 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. Further work is required to evaluate the datasets at other locations in South Africa and to investigate methods for downscaling these datasets and methods for bias correction.

This project focused on the quantification of water use by *Natural*, *Cultivated* and *WaterBody* 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, but further work needs to done to include the relationship between water use and stand size. Industrial and commercial water use was not included in the water use estimates in the case study catchments.

The project database spreadsheet, in which the spatial configuration of catchments, subcatchments, HRUs, river flow network, dams and other water infrastructure is specified, provides 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, though implementation by individual models will require different model specific assumptions. The library of Python scripts developed in this project to process datasets and populate the project database spreadsheet will be invaluable for configuring other catchments and compiling water accounts.

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 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.

In conclusion, this project has successfully (i) reviewed existing water accounting frameworks, (ii) demonstrated the application of a water resource accounting framework to help in understanding water availability and use at a catchment scale, and (ii) 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 has 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 aggregation of results from finer to coarser spatial and temporal scales, and also at different levels of land cover/use detail. Although there is still much work to be done to refine the methodology, a good foundation has been set for the development of a system that in future will enable annual Quaternary Catchment scale water resource accounts to be compiled for the whole country.

8 RECOMMENDATIONS

DJ Clark

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

Rainfall is a critical input for water resource assessments, but good quality rain gauge data are difficult to obtain and the sparse network leads to poor spatial representation. There are many advantages to using remotely sensed rainfall datasets including accessibility and spatial representation of rainfall, but bias errors in the rainfall estimates can be a problem in some regions. There are South African research projects currently in progress to infill national rainfall datasets and to develop methodologies to correct bias in remotely sensed rainfall data. In particular the products from WRC Project K5/2241 should be evaluated once these have been completed. The products from these projects need to be applied and tested when they have been completed. The remotely sensed rainfall datasets also have a coarse spatial resolution relative to the scale at which modelling is undertaken and methods of downscaling need to be investigated. The Level 3 data products from the new Global Precipitation Mission (GPM) satellite need to be evaluated.

Sub-Quaternary Catchments and Response Regions

It is desirable to model at sub-Quaternary catchment scale due to variations in climate, soils, topography and land cover/use within a Quaternary Catchment and to represent important water abstraction and return flow points within a Quaternary Catchment. Surprisingly, one of the biggest problems encountered in this project was the development of a suitable set of sub-Quaternary Catchment boundaries as there is no nationally accepted dataset and catchment specific datasets in the case study catchments were of poor quality. The use of digital elevation model (DEM) based methods of catchment delineation should be investigated further. In addition, methods of subdividing catchments into homogeneous response regions using methods such as altitudinal breaks, climate regions and the KwaZulu-Natal Department of Agriculture's system of Bioresource Units need to be investigated further.

Land Cover Datasets and Classes

The new 2013/2014 national land cover dataset from 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.

Land cover/use datasets are a valuable source of information, but have each been developed for a specific purpose and use different sets of land cover/use classes. 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". Additional datasets need to be sourced to enable modelling of more specific agricultural crop types. Where possible, land management practices need to be represented in the assessments as these can often have a more significant hydrological impact than land use.

Irrigation is a major use of blue water. Additional datasets need to be sourced to identify and enable modelling of different irrigation systems and scheduling methods. The WARMS database is one potential source of such information.

Mucina and Rutherford Natural Vegetation Dataset

In 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 of naturally vegetated areas. 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 titled "*Resetting the baseline land cover against which stream flow 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.

Water Sources

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. The WARMS database is one potential source of such information.

Urban Industrial and Residential Water Use

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.

Initialisation of Water Stores

A common problem when modelling water resources over short time spans is the initialisation of water stores at the start of a simulation. In this project this was done in a simple manner by means of running the hydrological model for a warm-up period prior to the start of the accounting period. Sources of information to initialise dam storage volumes and soil moisture at the start of a simulation period need to be investigated.

Include Additional Accounting Sheets

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. Further sheets showing information about water abstractions, return flows and water stocks should be considered.

Testing the Methodology in the Winter Rainfall Region of South Africa

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 reference potential evaporation estimates and parameterisation of the hydrological model.

Engaging With Potential Users of Water Accounts

The water use quantification methodology and the resulting accounts appear to be highly relevant in the catchment management context, as well as making a contribution to the overall strategic development of the water sector, including the national scale. However, 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 to make management decisions with regard to current water use, redress of water allocations, projections of demand in the short-term (e.g. forecasting) and mid-term (e.g. climate change), as well as overall strategic planning for infrastructure and adaptation. This engagement on the other hand should also aim to establish the decision maker's needs, and thus how the water accounts might need to be adjusted and further developed, to meet their needs.

9 CAPACITY BUILDING

DJ Clark

Several forms of capacity building have taken place as a result of the project including: supervision of post-graduate students, staff development, institutional (CWRR and UKZN) development, a workshop and submission of a paper for publication.

There was one post-graduate student, Ms Cletah Shoko, whose studies were fully funded by the project. Ms Shoko was awarded her MSc degree in May 2015 and her dissertation was titled "*The effect of spatial resolution in remote sensing estimates of total evaporation in a heterogenous uMngeni catchment*" (Shoko, 2014). Ms Shoko prepared two papers based on her MSc dissertation. The paper titled "*Estimating spatial variations of total evaporation using multispectral sensors within the uMngeni catchment, South Africa*" was published in Geocarto International (Shoko *et al.*, 2015b). The paper titled "*Effect of spatial resolution on remote sensing estimates of total evaporation in the uMngeni catchment, South Africa*" is under review for possible publication in the Journal of Applied Remote Sensing (Shoko *et al.*, 2015a).

In addition, there are several other students whose post-graduate studies have contributed to some extent or who have benefited from advice from members of the project team paid from this project, as shown in Table 9.1.

Table 9.1 Post-graduate students contributing to project or receiving assistance from the project team

Person	**Degree**	**Contribution / Assistance Received**
Mr David Clark	PhD	Project leader. Hydrological modelling and compiling water accounts. Studies partially funded from project.
Ms Tinisha Chetty	PhD	Remotely sensed rainfall estimates
Ms Cletah Shoko	MSc	Remotely sensed ET and ET_0 estimates
Mr Shaeden Gokool	MSc	Remotely sensed ET estimates Assistance from Mr Clark regarding the use of ET estimates in the *ACRU* model
Ms Sibusizwe Majozi	BSc Hons	Urban water use
Mr Predarshan Naidoo	BSc Hons	Remotely sensed rainfall estimates
Mr Predarshan Naidoo	MSc	Remotely sensed rainfall estimates
Mr Jermaine Nathanael	MSc	Assistance from Mr Clark regarding Python scripting
Mr Thomas Rowe	MSc	Land cover/use classes and parameters

As part of this project a paper titled "*A Review of water accounting frameworks for potential application in South Africa*" (Clark *et al.*, 2015) was submitted to WaterSA for publication and is currently under review. This paper is expected to be of interest to the South African and also the broader international water community as an introduction to the concept of water resource accounting which has matured considerably in the last few years. There is potential to publish other papers describing the methodology developed in this project and the case studies.

Mr Clark who is the responsible researcher on the project attended a three-day workshop (10-12 November 2014) on the United Nations' System of Environmental-Economic Accounting (SEEA) organised by Statistics South Africa. This workshop was invaluable in providing a better understanding of SEEA, how it is being implemented in South Africa and the current status of water accounting in South Africa. The workshop also provided Mr Clark with an opportunity to meet members of the Environmental Accounts section of Statistics South Africa and a representative from the United Nations responsible for promoting and providing advice on the implementation of SEEA.

Mr Clark also attended a one day workshop (21 April 2015) organised as part of a project titled "*Advancing Experimental Ecosystem Accounting*" by Statistics South Africa and SANBI. This workshop provided valuable insight into research related to the SEEA Experimental Ecosystem Accounts, land cover/use change and SEEA Land Accounts.

Most of the members of the CWRR at UKZN receive funding from the WRC and are involved in the teaching of hydrology courses at both undergraduate and postgraduate levels as well as in the supervision of postgraduate research projects. The CWRR also employs both undergraduate and postgraduate students in research projects during the long 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 successful in later attracting students to postgraduate studies.

Due to the nature of the project, requiring a wide range of expertise in water resources, several staff within the CWRR at UKZN have been involved with the project to some extent and in the process have increased their knowledge of water accounting. Professor Pegram and Dr Sinclair, of Pegram and Associates, were also members of the project team and have provided capacity within the project team as a result of their experience in the use of remote sensing together with hydrological modelling. This project also provided capacity within UKZN, which recognises the need for expertise in water resources in South Africa.

The Inception Workshop provided Reference Group members the project team and invited students with an introduction to water accounting and existing water accounting frameworks. Deliverable 11 for the project is expected to take place in October or November 2015 in conjunction with the Inception Workshop for WRC Project K5/2419 and is expected to inform delegates about the WA+ framework, a comparison with other existing frameworks and how WA+ was applied in this project.

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APPENDICES:

Appendix A – GDAL and Python Software Tools

The following are the details of the GDAL and Python related software tools used in the project including where these tools can be obtained and addresses of websites that were useful in helping to install these tools.

A.1 Python Scripting Language

Version 2.7 of the Python scripting language was used as this had already been installed as part of the ESRI ArcGIS ArcMap 10.2 software. Installers for Python can be downloaded from the website [http://www.python.org/]

A.2 Geospatial Data Abstraction Library (GDAL)

The open source Geospatial Data Abstraction Library (GDAL) is a software library of GIS processing tools for working with geospatial vector and raster data and supports a variety of data file formats. The main GDAL website [http://www.gdal.org] includes information on where versions of the library for different programming languages and different computer operating systems can be found. The website also includes links to documentation for the library and tutorials.

The gdal-110-1600-core.msi installer for the GDAL Core software library and the GDAL-1.10.1.win32-py2.6.exe installer for the Python bindings were downloaded from the GISInternals webpage [http://www.gisinternals.com/sdk/] for use on a 64-bit version of the Microsoft Windows 7 Enterprise operating system. The webpage [http://pythongisandstuff.wordpress.com/2011/07/07/installing-gdal-and-ogr-for-python-on-windows/] was useful in explaining where to obtain the required GDAL Core library and the associated Python bindings and how to install them.

A.3 NumPy Numerical Processing Library

NumPy is software library that is useful for scientific computing with Python and more information can be found at the NumPy website [website [http://www.numpy.org]. The installer for the 32-bit Version 1.9.1 of NumPy was downloaded from the SourceForge website [http://sourceforge.net/project/files/NumPy/1.9.1/]. The installer for the 64-bit Version 1.9.1 of NumPy was downloaded from website [http://www.lfd.uci.edu/~gohlke/pythonlibs/] as SourceForge only had a 32 bit binary installation.

A.4 Eclipse and PyDev Integrated Development Environment

The open source Eclipse Integrated Development Environment (IDE), together with the PyDev plugin for Python, was used for writing and running the Python scripts developed as part of this project. The Eclipse IDE can be downloaded from the Eclipse website [https://eclipse.org]. The PyDev plugin can be downloaded from the PyDev website [https://pydev.org]. The webpage [http://augusttown.blogspot.com/2011/02/configure-gdalogr-python-debug.html] was useful for information to help in setting up PyDev as some new system environment variables may need to be created.

Appendix B – Python Modules Developed

The Python modules containing scripts developed in this project to process the spatial data required to configure the *ACRU* hydrological model are summarised in Table B.1. These Python modules were not intended to be a comprehensive data processing software library but are provided as a starting point for other studies. Neither the Water Research Commission nor the Centre for Water Resources Research makes any warranties or representations with regard to the correctness or accuracy of these code libraries. Neither the Water Research Commission nor the Centre for Water Resources Research assumes any liability or responsibility for any errors or omissions in these code libraries.

Table B.1 Summary of Python modules developed in project

cwrr.Altitude.SAAtlas2008	Python scripts to process the Schulze and Horan (2008a) altitude raster (in ESRI binary grid format).
cwrr.Altitude.WRC_SRTM90	Python scripts to process the Weepener *et al.* (2011d) and Weepener *et al.* (2011b) altitude raster (in ESRI binary grid format).
cwrr.Catchments.AdjustBoundaries	Python script to adjust sub-Quaternary catchment boundaries to the revised SLIM (2014b) Quaternary Catchment boundaries dataset.
cwrr.Dams.DWSRegisteredDams	Python scripts to process the DSO (2014) database of registered dams from the DWS Dam Safety Office.
cwrr.Evaporation.SAGH_ET0	Python scripts to process the SAHG ET_0 dataset to create time series files for modelling.
cwrr.Frost.SAAtlas2008	Python scripts to process the Schulze and Maharaj (2008d) frost occurrence raster (in ESRI binary grid format).
cwrr.General.CoarseRasterTimeseriesTools	General purpose Python scripts for working with coarse resolution raster datasets (e.g. remotely sensed rainfall) and extracting data for gauge points and catchment polygons.
cwrr.General.KMLTools	Python scripts for converting between KML and other GIS file formats.
cwrr.General.RasterTools	General purpose Python scripts for working with raster datasets.

Table B.1 (cont.) Summary of Python modules developed in project

cwrr.General.ShapefileTools	General purpose Python scripts for working with vector datasets in ESRI shapefile format.
cwrr.General.ZonalStatistics	General purpose Python script for calculating zonal statistics.
cwrr.LandCover.LCU_ClassHierarchy	Python scripts for creating and reading *LCU_Hierarchy.xml* and *LCU_Classes.xml* files.
cwrr.LandCover.LCU_Mapping	Python scripts for mapping values in raster datasets based on values in a shapefile or pairs specified in a CSV file.
cwrr.LandCover.RegionsTables	Python scripts for creating LCURegions tables using catchment boundaries, a land cover/use raster dataset and other raster and vector datasets.
cwrr.LandCover.SugarRegions	Python script to create a shapefile of sugarcane growing regions.
cwrr.MAP.Lynch2004	Python scripts to process the Lynch (2004) MAP raster (in ESRI binary grid format).
cwrr.Population.General	Python script to estimate population per urban residential area.
cwrr.Procedures.SabieSand.Workflow	Python scripts representing the tasks forming a workflow to process the datasets for the Sabie-sand case study.
cwrr.Procedures.uMngeni.Workflow	Python scripts representing the tasks forming a workflow to process the datasets for the Sabie-sand case study.
cwrr.Project.Project	Python scripts used to create a new project database spreadsheet with empty tables and populate these tables.
cwrr.Rainfall.CMORPH_Daily	Python scripts to process CMORPH daily rainfall datasets.
cwrr.Rainfall.FEWS_ARC2	Python scripts to process FEWS Arc 2.0 daily rainfall datasets.
cwrr.Rainfall.FEWS_RFE2	Python scripts to process FEWS RFE 2.0 daily rainfall datasets.
cwrr.Rainfall.TRMM_3B42_Daily	Python scripts to process TRMM 3B42 daily rainfall datasets.
cwrr.RainMeans.Lynch2004	Python scripts to process the Lynch (2004) mean monthly rainfall rasters (in ESRI binary grid format).

Table B.1 (cont.) Summary of Python modules developed in project

cwrr.RainMeans.Lynch2004	Python scripts to process the Lynch (2004) median monthly rainfall rasters (in ESRI binary grid format).
cwrr.RainSeasons.SAAtlas2008	Python scripts to process the Schulze and Maharaj (2008a) rainfall seasonality shapefile.
cwrr.Soils.SAAtlas2008	Python scripts to process the Schulze and Horan (2008b) shapefile of soil characteristics.
cwrr.Temperature.SAAtlas2008	Python scripts to process the Schulze and Maharaj (2008b) mean monthly maximum air temperature and Schulze and Maharaj (2008c) mean monthly minimum air temperature rasters (in ESRI binary grid format).

Appendix C – Java Modules Developed

The Java modules developed in this project to create the model configuration files for the *ACRU* hydrological model are summarised in Table C.1. These Java modules include case study specific assumptions, but are provided as a starting point for other studies. Neither the Water Research Commission nor the Centre for Water Resources Research makes any warranties or representations with regard to the correctness or accuracy of these code libraries. Neither the Water Research Commission nor the Centre for Water Resources Research assumes any liability or responsibility for any errors or omissions in these code libraries.

Table C.1 Summary of Java modules developed in project

cwrr.General.ACRU_Setup.MenuCreator	Java module used to create the model configuration files for the *ACRU* hydrological model from the project database spreadsheet and other datasets.
cwrr.General.LCU_Classes	Java module for creating and reading *LCU_Classes.xml* files.
cwrr.General.LCU_Hierarchy	Java module for creating and reading *LCU_Hierarchy.xml* files.

Appendix D – Suggested Land Cover/Use Mappings

The tables in this appendix show some suggested mappings from land cover/use dataset classes to standard land cover/use classes as discussed in Section 4.8.2.3. 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.

D.1 Mapping for ARC and CSIR (2005)

Table D.1 Land cover/use mapping for the ARC and CSIR (2005) dataset

Dataset_ID	**Dataset_Desc**	**LCU_Class**
0	Missing data	UnknownLCU
1	Forest (indigenous)	Natural_Typical_General
2	Woodland	Natural_Typical_General
3	Thicket, Bushland, Bush Clumps, High Fynbos	Natural_Typical_General
4	Shrubland and Low Fynbos	Natural_Typical_General
5	Herbland	Natural_Typical_General
6	Natural Grassland	Natural_Typical_General
7	Planted Grassland	Urban/Built-up_Open Spaces (Golf Courses and Sports fields, etc.)
8	Forest Plantations (Eucalyptus spp)	Forest Plantations_Eucalyptus_General
9	Forest Plantations (Pine spp)	Forest Plantations_Pine_General
10	Forest Plantations (Acacia spp)	Forest Plantations_Wattle_General
11	Forest Plantations (Other / mixed spp)	Forest Plantations_General
12	Forest Plantations (clearfelled)	Forest Plantations_General
13	Waterbodies	Waterbodies_Artificial_Dams
14	Wetlands	Waterbodies_Natural_Wetlands_General
15	Bare Rock and Soil (natural)	Natural_Typical_Bare_RockAndSoil
16	Bare Rock and Soil (erosion: dongas / gullies)	Natural_Degraded_Bare_ErosionGullies
17	Bare Rock and Soil (erosion: sheet)	Natural_Degraded_Bare_ErosionSheet
18	Degraded Forest & Woodland	Natural_Degraded_General
19	Degraded Thicket, Bushland, etc.	Natural_Degraded_General

Table D.1 (cont.) Land cover/use mapping for the ARC and CSIR (2005) dataset

20	Degraded Shrubland and Low Fynbos	Natural_Degraded_General
22	Degraded Unimproved (natural) Grassland	Natural_Degraded_General
23	Cultivated, permanent, commercial, irrigated	Agriculture_Commercial_General_Irrigated_Perrenial_General
24	Cultivated, permanent, commercial, dryland	Agriculture_Commercial_General_Dryland_Perrenial_General
25	Cultivated, permanent, commercial, sugarcane	Agriculture_Commercial_Sugarcane_Dryland
26	Cultivated, temporary, commercial, irrigated	Agriculture_Commercial_General_Irrigated_Annual_General
27	Cultivated, temporary, commercial, dryland	Agriculture_Commercial_General_Dryland_Annual_General
28	Cultivated, temporary, subsistence, dryland	Agriculture_Subsistence_General_Dryland_Annual_General
29	Cultivated, temporary, subsistence, irrigated	Agriculture_Subsistence_General_Irrigated_Annual_General
30	Urban / Built-up	Urban/Built-up
31	Urban / Built-up (rural cluster)	Urban/Built-up_Residential_Informal – Low Density Rural
32	Urban / Built-up (residential, formal suburbs)	Urban/Built-up_Residential_Formal – Medium Density (Suburbs)
33	Urban / Built-up (residential, flatland)	Urban/Built-up_Residential_Formal – High Density (Formal Townships)
34	Urban / Built-up (residential, mixed)	Urban/Built-up_Residential_Formal – Medium Density (Suburbs)
35	Urban / Built-up (residential, hostels)	Urban/Built-up_Residential_Formal – High Density (Formal Townships)
36	Urban / Built-up (residential, formal township)	Urban/Built-up_Residential_Formal – High Density (Formal Townships)
37	Urban / Built-up (residential, informal township)	Urban/Built-up_Residential_Informal – High Density (Informal Townships)
38	Urban / Built-up (residential, informal squatter camp)	Urban/Built-up_Residential_Informal – High Density (Squatter Camps)
39	Urban / Built-up (smallholdings, forest & woodlands)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
40	Urban / Built-up (smallholdings, thicket, bushland, etc.)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
41	Urban / Built-up (smallholdings, shrubland, etc.)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
42	Urban / Built-up (smallholdings, grassland, etc.)	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
43	Urban / Built-up (commercial, mercantile)	Urban/Built-up_Commercial_Mercantile

Table D.1 (cont.) Land cover/use mapping for the ARC and CSIR (2005) dataset

44	Urban / Built-up (commercial, education, health, IT)	Urban/Built-up_Commercial_Education Health IT
45	Urban / Built-up (industrial / transport: heavy)	Urban/Built-up_Industrial/Transport_Heavy
46	Urban / Built-up (industrial / transport: light)	Urban/Built-up_Industrial/Transport_Light
47	Mines and Quarries (underground / subsurface mining)	Mines and Quarries_Subsurface_Subsurface Mine
48	Mines and Quarries (surface-based mining)	Mines and Quarries_Surface_Opencast Mine/Quarry
49	Mines and Quarries (mine tailings, waste dumps)	Mines and Quarries_Surface_Tailings/Dumps

D.2 Mapping for Ezemvelo KZN Wildlife and GeoTerraImage (2013)

Table D.2 Land cover/use mapping for the Ezemvelo KZN Wildlife and GeoTerraImage (2013) dataset

Dataset_ID	**Dataset_Desc**	**LCU_Class**
0	No Data	UnknownLCU
1	Water (natural)	Waterbodies_Natural_Rivers
2	Plantation	Forest Plantations_General
3	Plantation – clearfelled	Forest Plantations_General
4	Wetland	Waterbodies_Natural_Wetlands_General
5	Wetland – mangrove	Waterbodies_Natural_Wetlands_Mangrove
6	Orchards – permanent, irrigated, banana's and citrus	Agriculture_Commercial_Citrus_Irrigated_TransvaalNatal
7	Orchards – permanent, dryland, cashew nuts	Agriculture_Commercial_CashewNuts_Dryland
8	Orchards – permanent, dryland, pineapples	Agriculture_Commercial_Pineapples_Dryland
9	Sugarcane, commercial, irrigated & dryland	Agriculture_Commercial_Sugarcane_Dryland
10	Sugarcane, semi-commercial, emerging farmer, irrigated & dryland	Agriculture_Subsistence_Sugarcane_Dryland
11	Mines & Quarries	Mines and Quarries_Surface_Opencast Mine/Quarry
12	Built-up / dense settlement	Urban/Built-up_Residential_Formal – Medium Density (Suburbs)
13	Golf courses	Urban/Built-up_Open Spaces (Golf Courses and Sports fields, etc.)
14	Low density settlements	Urban/Built-up_Residential_Formal – Low Density (Peri-Urban)

Table D.2 (cont.) Land cover/use mapping for the Ezemvelo KZN Wildlife and GeoTerraImage (2013) dataset

15	Cultivation, subsistence, dryland	Agriculture_Subsistence_General_Dryland_Annual_General
16	Cultivation, commercial, annual crops, dryland	Agriculture_Commercial_General_Dryland_Annual_General
17	Cultivation, commercial, annual crops, irrigated	Agriculture_Commercial_General_Irrigated_Annual_General
18	Forest (indigenous)	Natural_Typical_General
19	Dense thicket & bush (70-100 % cc)	Natural_Typical_General
20	Medium bush (< 70% cc)	Natural_Typical_General
21	Woodland & Wooded Grassland	Natural_Typical_General
22	Bush Clumps / Grassland	Natural_Typical_General
23	Grassland	Natural_Typical_General
24	Bare Sand	Natural_Typical_Bare_Sand_Inland
25	Degraded Forest	Natural_Degraded_General
26	Degraded Bushland (all types)	Natural_Degraded_General
27	Degraded Grassland	Natural_Degraded_General
28	Old Fields (previously grassland)	Natural_Typical_General
29	Old Fields (previously bushland)	Natural_Typical_General
30	Smallholdings	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
31	Erosion	Natural_Degraded_Bare_ErosionSheet
32	Natural Bare Rock	Natural_Typical_Bare_Rock
33	Alpine Grass – Heath	Natural_Typical_General
34	KZN National Roads	Urban/Built-up_Industrial/Transport_Roads and Railways
35	KZN Main & District Roads	Urban/Built-up_Industrial/Transport_Roads and Railways
36	Water (dams)	Waterbodies_Artificial_Dams
37	Water (estuarine)	Waterbodies_Natural_Estuaries
38	Water (sea)	UnknownLCU
39	Bare Sand (coastal)	Natural_Typical_Bare_Sand_Coastal
40	Forest glade	Natural_Typical_General
41	Outside KZN Province	UnknownLCU
42	KZN Railways	Urban/Built-up_Industrial/Transport_Roads and Railways
43	Airfields	Urban/Built-up_Industrial/Transport_Airports and Airfields
44	Old plantations – high vegetation	Natural_Typical_General
45	Old plantations – low vegetation	Natural_Typical_General
46	Rehabilitated mines – high vegetation	Natural_Typical_General
47	Rehabilitated mines – low vegetation	Natural_Typical_General

D.3 Mapping for ICMA (2012a)

Table D.3 Land cover/use mapping for the ICMA (2012) dataset

Dataset_ID	Dataset_Desc	LCU_Class
0	No Data	UnknownLCU
1	TALL TREES	Natural_Typical_General
2	DENSE BUSH	Natural_Typical_General
3	BUSH	Natural_Typical_General
4	OPEN BUSH	Natural_Typical_General
5	GRASSLAND	Natural_Typical_General
6	BARE NON-VEGETATED	Natural_Typical_Bare_Soil
7	WATER MAN-MADE	Waterbodies_Artificial_Dams
8	WATER SEWAGE	Waterbodies_Artificial_Sewage Ponds
9	WATER NATURAL	Waterbodies_Natural_Lakes and Pans
10	PANS – WATER	Waterbodies_Natural_Lakes and Pans
11	PANS – BARE	Natural_Typical_Bare_Soil
12	PANS – VEGETA-TED	Waterbodies_Natural_Lakes and Pans
13	RESIDENTIAL	Urban/Built-up_Residential
14	INFORMAL	Urban/Built-up_Residential_Informal – High Density (Informal Townships)
15	COMMERCIAL	Urban/Built-up_Commercial
16	INDUSTRIAL	Urban/Built-up_Industrial/Transport
17	VILLAGE	Urban/Built-up_Residential_Informal – Low Density Rural
18	SMALLHOLDINGS	Urban/Built-up_Residential_Smallholdings (Peri-Urban)
19	MINES TAILINGS	Mines and Quarries_Surface_Tailings/Dumps
20	MINES EXTRACTION	Mines and Quarries_Surface_Opencast Mine/Quarry
21	NAT ROCKS	Natural_Typical_Bare_Rock
22	ROADS (ALL)	Urban/Built-up_Industrial/Transport_Roads and Railways
23	BARE RIVERSAND	Natural_Typical_Bare_Sand_Inland
24	DONGA BUSH	Natural_Degraded_General
25	DONGA BARE	Natural_Degraded_Bare_ErosionGullies
26	GREENHOUSES	Urban/Built-up_Commercial_Agricultural
27	FEEDLOTS	Urban/Built-up_Commercial_Agricultural
28	CHICK / PIG BATTERIES	Urban/Built-up_Commercial_Agricultural
29	GOLF ESTATE TALL TREES	Natural_Typical_General
30	GOLF ESTATE DENSE BUSH	Natural_Typical_General
31	GOLF ESTATE BUSH	Natural_Typical_General
32	GOLF ESTATE OPEN BUSH	Natural_Typical_General

Table D.3 (cont.) Land cover/use mapping for the ICMA (2012) dataset

33	GOLF ESTATE GRASSLAND	Natural_Typical_General
34	GOLF ESTATE BARE	Natural_Typical_Bare_Soil
35	GOLF ESTATE RESIDENTIAL	Urban/Built-up_Residential
36	GOLF ESTATE COURSE	Urban/Built-up_Open Spaces (Golf Courses and Sports fields, etc.)
37	PLANTATION CLEARFELLED	Forest Plantations_General
38	PLANTATION PINE	Forest Plantations_Pine_General
39	PLANTATION EUC	Forest Plantations_Eucalyptus_General
40	PLANTATION WATTLE	Forest Plantations_Wattle_General
41	PLANTATION OTHER	Forest Plantations_General
42	WETLANDS	Waterbodies_Natural_Wetlands_General
43	CULTIVATED ORCHARDS CROP COVER	Agriculture_Commercial_General_Irrigated_Perrenial_General
44	CULTIVATED ORCHARDS NO CROP COVER	Agriculture_Commercial_General_Irrigated_Perrenial_General
45	CULTIVATED SUBSISTENCE CROP COVER	Agriculture_Subsistence_General_Dryland_Annual_General
46	CULTIVATED SUBSISTENCE NO CROP COVER	Agriculture_Subsistence_General_Dryland_Annual_General
47	CULTIVATED ANNUAL CROP COVER	Agriculture_Commercial_General_Dryland_Annual_General
48	CULTIVATED ANNUAL NO CROP COVER	Agriculture_Commercial_General_Dryland_Annual_General
49	CULTIVATED ANNUAL PIVOT CROP COVER	Agriculture_Commercial_General_Irrigated_Annual_General
50	CULTIVATED ANNUAL PIVOT NO CROP COVER	Agriculture_Commercial_General_Irrigated_Annual_General
51	CULTIVATED SUGARECANE	Agriculture_Commercial_Sugarcane_Dryland
52	CULTIVATED CANE NO CROP COVER	Agriculture_Commercial_Sugarcane_Dryland
53	CULTIVATED CANE PIVOT CROP COVER	Agriculture_Commercial_Sugarcane_Irrigated
54	CULTIVATED CANE PIVOT NO CROP COVER	Agriculture_Commercial_Sugarcane_Irrigated
55	CULTIVATED SCATTERED RURAL CROP COVER	Agriculture_Subsistence_General_Dryland_Annual_General

Table D.3 (cont.) Land cover/use mapping for the ICMA (2012) dataset

56	CULTIVATED SCATTERED RURAL NO CROP COVER	Agriculture_Subsistence_General_Dryland_Annual_General
57	SMALLHOLDING ANNUAL CROP COVER	Agriculture_Commercial_General_Dryland_Annual_General
58	SMALLHOLDING ANNUAL NO CROP COVER	Agriculture_Commercial_General_Dryland_Annual_General
59	OLD FIELDS	Natural_Typical_General
60	CULTIVATED SUBSISTENCE SUGARCANE	Agriculture_Subsistence_Sugarcane_Dryland
61	CULTIVATED SUBSISTENCE CANE NO CROP COVER	Agriculture_Subsistence_Sugarcane_Dryland
62	tmp horti banana	Agriculture_Commercial_Bananas_Irrigated
63	tmp horti blueberries	Agriculture_Commercial_Blueberries_Irrigated
64	tmp horti citrus	Agriculture_Commercial_Citrus_Irrigated_TransvaalNatal
65	tmp horti coffee	Agriculture_Commercial_Coffee_Irrigated
66	tmp horti granaat	Agriculture_Commercial_Pomegranates_Irrigated
67	tmp horti passion fruit	Agriculture_Commercial_Granadillas_Irrigated
68	tmp horti pecan nuts	Agriculture_Commercial_PecanNuts_Irrigated
69	tmp horti stone fruit	Agriculture_Commercial_StoneFruit_Irrigated
70	tmp horti avocado	Agriculture_Commercial_Avocado_Irrigated
71	tmp horti ginger	Agriculture_Commercial_Ginger_Irrigated
72	tmp horti guava	Agriculture_Commercial_Guava_Irrigated
73	tmp horti kiwi	Agriculture_Commercial_Kiwifruit_Irrigated
74	tmp horti litchi	Agriculture_Commercial_Litchies_Irrigated
75	tmp horti macadamia	Agriculture_Commercial_Macadamias_Irrigated
76	tmp horti mango	Agriculture_Commercial_Mangos_Irrigated
77	tmp horti pawpaw	Agriculture_Commercial_Pawpaws_Irrigated
78	tmp cultiv maize	Agriculture_Commercial_Maize_Dryland_Summer
79	tmp cultiv planted pasture	Agriculture_Commercial_General_Irrigated_Perrenial_General
80	tmp cult soya beans	Agriculture_Commercial_Soyabeans_Dryland_Summer
81	tmp cultv fallow	Agriculture_Commercial_Fallow
82	tmp cult wheat	Agriculture_Commercial_Wheat_Dryland_Winter
83	tmp cult vegetable/other	Agriculture_Commercial_Vegetables_Irrigated
98	unclassified KNP	Natural_Typical_General

Appendix E – Electronic Appendix

Appendix E is an electronic appendix on the CD accompanying this report. Appendix E includes (i) the Python and Java code modules developed as part of the project, (ii) the data and *ACRU* configuration files for the two case studies. These Python and Java code modules are provided subject to the BSD licence packaged as part of the electronic appendices. Neither the Water Research Commission nor the Centre for Water Resources Research makes any warranties or representations with regard to the correctness or accuracy of these code libraries or the case studies. Neither the Water Research Commission nor the Centre for Water Resources Research assumes any liability or responsibility for any errors or omissions in these code libraries or the case studies.

E.1 Python Modules

See folder *Appendix E\E.1_PythonModules* on the CD accompanying this report.

E.2 Java Modules

See folder *Appendix E\E.2_JavaModules* on the CD accompanying this report.

E.3 uMngeni Case Study

See folder *Appendix E\E.3_uMngeniCaseStudy* on the CD accompanying this report.

E.4 Sabie-Sand Case Study

See folder *Appendix E\E.4_SabieSandCaseStudy* on the CD accompanying this report.