SETTING UP ARCSWAT HYDROLOGICAL MODEL FOR THE VERLORENVLEI CATCHMENT

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AUTHOR'S DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any other university for a degree.

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ABSTRACT

Agricultural production has become vital to the Sandveld, of which Verlorenvlei is a part, in terms of both economic growth and food security. It is well documented as an area under threat of severe natural resource depletion if it is not well managed with sustainability in mind. Agricultural production, other human-driven development and the survival of the local ecosystems compete for the limited water resources.

This study uses the SWAT hydrological model to simulate the transport of water through the catchment area. ArcSWAT, a third-party software extension to ArcGIS, is used as an interface between ArcGIS and the SWAT model. Spatial data (DEM, soil and landuse) is used in the pre-processing phase and fed into the SWAT model through the interface.

Daily climate data were sourced and prepared according to the SWAT model's input requirements. Considerable effort was required to fill temporal and spatial gaps in available climate data, and to infer certain unmeasured climate variables from other measurements (e.g. infer solar radiation from daylight hours, time of the year and latitude).

The SWAT hydrological model was then run. The model results compared favourably to measured flow data. The study recommends building on from this first step using the SWAT hydrological model to simulate future land use scenarios for the catchment area.

Key Words: hydrological modelling, geographic information systems, surface water, land use, Sandveld

OPSOMMING

Landbouproduksie het toenemend noodsaaklik geword in die Sandveld, insluitend Verlorenvlei, in terme van beide ekonomiese groei en voedselsekuriteit. Die area is deeglik gedokumenteer as 'n gebied wat bedreig word deur erge uitputting van die natuurlike hulpbronne, indien dit nie verantwoordelik bestuur word met die oog op volhoubaarheid nie. Landbouproduksie, ander menslik-gedrewe ontwikkeling en die oorlewing van die plaaslike ekosisteme, kompeteer vir die beperkte water hulpbronne.

Hierdie studie gebruik die SWAT hidrologiese model om die beweging van water deur die opvang-gebied te simuleer. ArcSWAT, ’n derde-party sagteware uitbreiding wat vir ArcGIS geskryf is, word gebruik as ’n tussenvlak vir kommunikasie tussen ArdGIS en die SWAT model. Ruimtelike data (DEM, grond-tipe and grondgebruik) word gebruik in die data-voorbereidings-fase en word dan ingevoer in die SWAT model deur middel van die tussenvlak.

Daaglikse klimaat-data is opgespoor en voorberei volgens die SWAT model se invoer-data vereistes. Daar was aansienlike moeite verbonde daaraan om temporale and ruimtelike gapings in die klimaat-data in te vul, en om sekere ongemete veranderlikes af te lei van ander metings (bv. lei bestraling af van aantal dagligure, tyd van die jaar, en lengtegraad).

Die SWAT hidrologiese model het toe sy berekeninge gedoen. Die model se resultate het goed vergelyk met gemete vloei-data. Die studie beveel aan om voort te bou op hierdie eerste stap om die SWAT hidrologiese model te gebruik om toekemstige grondgebruik scenarios te simuleer vir die opvang-gebied.

Sleutelwoorde: hidrologiese modellering, geografiese inligtingstelsels, oppervlakwater, grondgebruik, Sandveld.

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CHAPTER 1: INTRODUCTION

1.1. GENERAL BACKGROUND

This study focuses on the Sandveld and its unique problems. More specifically it looks at the Verlorenvlei and an ephemeral river system which falls within the quaternary catchments G30B, G30C, G30D, G30E, G30F and G30G. Low & Pond (2003) refer to as the Verlorenvlei, the Langvlei and Jakkalsvlei of the Sandveld as longitudinal wetlands. The Sandveld is a colloquial term for an inexactly defined area, overlapping mostly with the G30 tertiary catchment that has a definite ecological and agricultural character. It is a naturally arid region with (relatively) low agricultural productivity. The Department of Agriculture Western Cape (DAWC) initially defined subregions for use as homogenous management units where similar agricultural industries and practices exist within the province. These units are defined according to topography, soil characteristics and climate. The Sandveld forms part of the Graafwater/Sandveld homogenous farming area as defined by DAWC. Figure 1.1 and Figure 1.2 on the following pages give an overview of the Sandveld area and the homogenous farming areas.

The Sandveld is part of the Winter Rainfall area. Rainfall, being generally low, unpredictable and unevenly distributed, varies from as low as 75 mm per annum to 250 mm per annum according to DAWC (1991), whereas Munch et al (2004) estimate rainfall varying between 100 - 400mm per annum. The area is known for warm, dry summers with high evaporation rates and regular, long periods of low rainfall. Grazing shortages for livestock are experienced During summer. Low rainfall is the single greatest limiting factor for the Sandveld in terms of agricultural potential, setting the production patterns for the area. Strong winds prevail in the summer, increasing the danger of wind erosion (Heydenrych 1993) and heightening evaporation and evapo-transpiration losses.

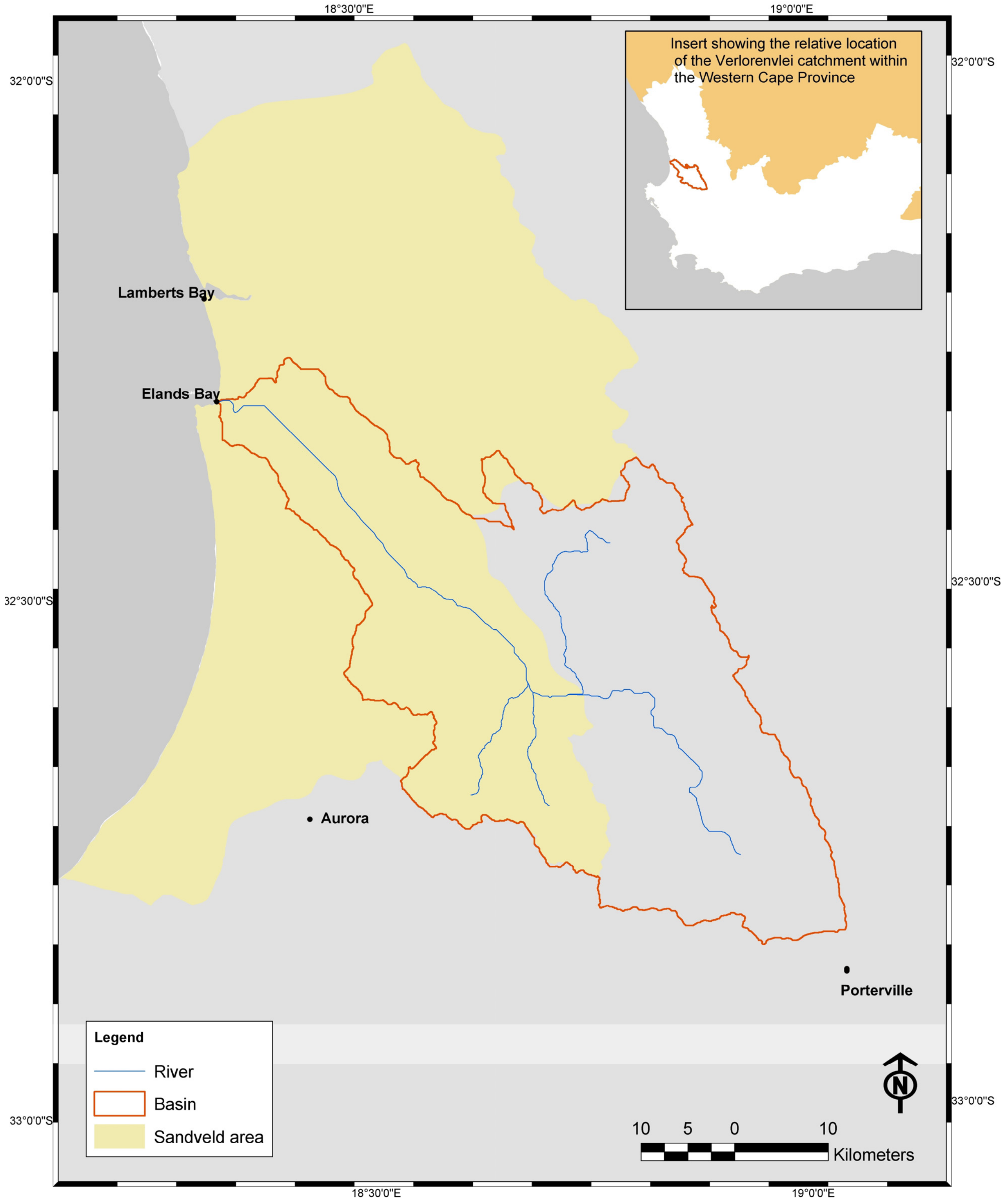


Figure 1.1 The Sandveld area and the Verlorenvlei Catchment

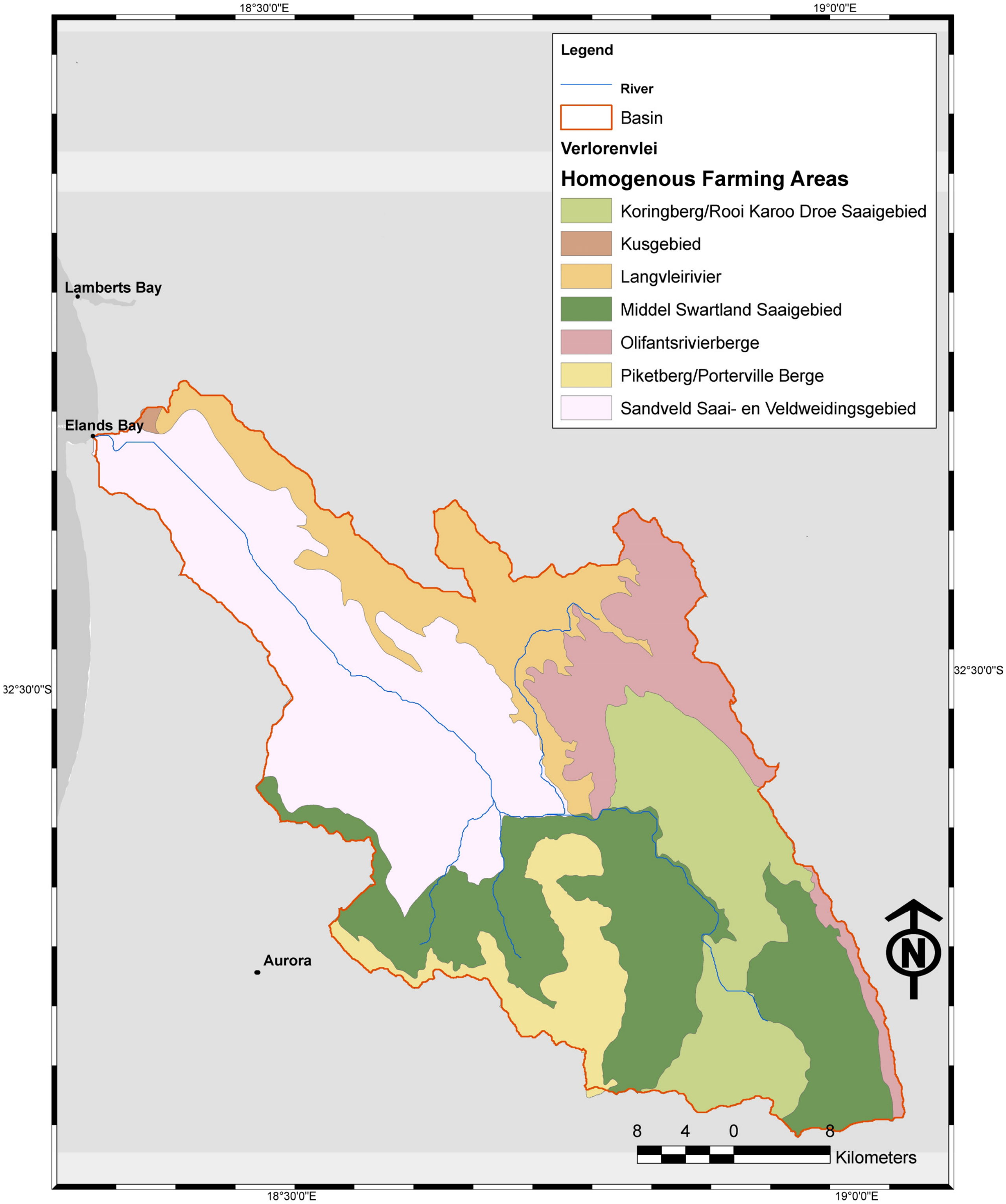


Figure 1.2 Homogenous farming areas in the Verlorenvlei catchment

Historically, farming in the Sandveld has reflected these limiting physical conditions. Prior to the 1980s stock farming provided the main agricultural income in the area. The typical stocking rate was one large stock units per 30 ha (Olivier 2007, pers com) indicating that the veld has a low carrying capacity due to the climate, soil and veld type. According to the regional agricultural report for the Sandveld (DAWC 1991), limited areas of dry land wheat and rooibos production existed prior to 1980. There were also a few seed potato farmers driving centre pivot irrigation on expensive generator power. Homogenous farming areas were demarcated according to landtype zones and climate data (DAWC 1991), where each area was considered suitable for specific farming practices within the homogenous zone. For instance the “Middel Swartland Saaigebied” was good for cultivating wheat due to the climatic and physio-graphic features, and so most producers would have farmed wheat in the area.

Large-scale potato farming escalated in the 1980s when bulk electricity, through Eskom, became readily available in the area. This made two things possible that facilitated large scale potato production; firstly, bulk electrical power could drive large centre pivot irrigation systems as well as pump large quantities of groundwater for irrigation into the arid landscape. Secondly the old Lamberts Bay fish factory was converted to a potato processing factory and cannery, and the Sandveld was set to become a centre for table potato production, now possessing the means and the market for profitable business.

The increase in potato production, particularly table potatoes, in the Sandveld has led to wide ranging ecological and sustainability problems. The natural resources are under severe pressure due to land clearing and groundwater abstraction for, inter alia, agricultural production. Often the ground is left bare, leaving valuable topsoil exposed to wind erosion. The sandy soil requires special land management planning (Valentin et al. 2004) and is inherently less suited to intensive farming. Notwithstanding the natural vegetation was cleared at a rate of 2.5 hectares per day according to Burger (2005, pers com) of CapeNature. Consequently groundwater quality has deteriorated in certain parts of the Sandveld (Conrad 2005) due to over abstraction and contamination from chemicals used for agricultural production.

Watson & Burnett (1995) recommend particular attention to managing coastal aquifers as a rule, and Conrad (2005) in this regard refers to the Wadrif well field (to the North of Verlorenvlei, near Lamberts Bay) where the aquifer is vulnerable to salt water intrusion as over abstraction occurs. Low & Pond (2003) indicate almost irrevocable damage to the Wadrif wetland as a result of a fire that broke out when the wetland was very dry. A railway line built across the wetland has also reduced its ability to provide ecological services. The vegetation indicates a shift over time from permanently wet species to seasonally dry types.

Surveys by the DAWC in the Langvlei River area between 1984 and 1990 (DAWC 1991) indicate a decline in table potato production in this area from 705 hectares to 543 hectares, although seed potato production increased from zero to 734 hectares during this time. Between 1984 and 1990 the production of high quality seed potatoes was profitable. The Sandveld was considered an excellent area for growing potatoes as the soil was sandy, groundwater quality was good, and wind and high temperatures were not considered limiting factors. It was also largely free of diseases, a prerequisite for the seed production industry. In the past potato related diseases have necessitated the fallowing of fields for between three and four years after cultivation for table potato production. Seed potato production requires a fallow period of up to seven years. Diseases in recent years have increasingly become a serious threat to the seed potato industry, which has more stringent anti-disease requirements. These are not as important to the table potato industry.

1.1.1. Technical background

1.1.1.1 Hydrological model

In choosing hydrological models as the vehicles for studying the relationship between water and agricultural land use, the focus is on water, the limiting factor for social and economic development and agricultural production in the Sandveld (DAWC 1991). Hydrological models have been created specifically for the purpose of investigating the water cycle, as water interacts with soil, plants, atmosphere, chemical residues and physical elements. Hydrological studies do however require expert knowledge (Watson & Burnett 1995) that should be conducted by specialists.

1.1.1.2 Related GIS software

Geographical Information Systems (GIS) provide a visual-spatial analytical tool that compliments and enhances the value of results from hydrological models. Using the GIS medium, the relationships between agricultural land use, soil, and water resources are explored spatially and graphically. To this end, the ArcSWAT hydrological model was selected for this study in conjunction with the ESRI ArcView 9.1 or 9.2 GIS software (ESRI 2005). This hydrological model was envisioned as part of a possible toolkit for visualising and assisting planning decisions for various land use scenarios for the catchment.

1.1.2. The multi-disciplinary nature of this study

The skills required to run the ArcSWAT model are firstly of a technical nature. The problems that the technical framework reveal are however usually of a complex, interactive nature. To apply the tool effectively for management alternatives for the area, specialist collaboration between farmers, scientists and economists would be ideal. Not only is the amount of water abstracted an issue for concern, but its deteriorating quality affects all who must use it to survive. This study looks only at the amount of water flowing at a gauged point in the catchment. Expert input from a GIS perspective was required as well as hydrological and programming expertise. It would be desirable to run scenarios for various management options based on the results of this flow study. It would require a further suite of experts on particular crops, irrigation regimes, chemical applications for crop improvement etc. The idea is that the flow results form a basis from which more effective management of natural and economic resources can be made using water quality results at various points in the catchment.

1.2. OBJECTIVES AND AIMS

This study aims to test whether the ArcSWAT model is a useful tool to obtain modelled surface water flow results. The modelled results should be accurate in comparison to measured flow results. The measured flow gauge data from the Het Kruis gauge in the Verlorenvlei (see Figure 4.4) should compare favourable to the model's cumulative flow results of the channel reach closest to it.

The relative usefulness of the software is determined by the successes or shortcomings experienced in the setup and running of the model as well as the accuracy of the results. The study could serve as a future informant for hydrological model choices for modelling in terms of agricultural and natural resource management.

1.3. THESIS LAYOUT

In Chapter 1, the reader is introduced to the study area and the inter-disciplinary combination of GIS and hydrological modelling for agricultural use. Historical and current agriculture and land use trends relating to the Verlorenvlei and the Sandveld are discussed.

Chapter 2 informs the reader about hydrology, its relevance to the study and hydrological modelling and explains the necessary terminology and concepts. A glossary of hydrological terms is attached as an appendix and can be used if necessary in the reading of this chapter.

Chapter 3 begins with a description of methods and data. Data issues insofar as populating the model for South Africa are discussed. A section on model criteria for selection is included. This is followed by a description of ArcSWAT, its requirements and work flow processes, including the different parts of the hydrological cycle as the SWAT software has modelled and interpreted them.

Chapter 4 accounts the results from testing the SWAT model. Descriptions and graphic interpretations of the results are shown.

In Chapter 5 the final discussion of the model results are given and it includes recommendations for use of the model and looks at future research and applications.

CHAPTER 2: HYDROLOGY AND HYDROLOGICAL MODELLING

2.1. HOW IS HYDROLOGY IMPORTANT TO THIS STUDY?

To answer this question, it is necessary to take a closer look at what hydrology is and what opportunities it affords the regional geographer and agricultural development planner to understand events at the human and natural environment interface. Assuming that a fuller understanding incorporating insights from various disciplines is necessary for a comprehensive and sustainable solution to a problem; then complexity and holistic approaches are necessary to develop them. The following explanation of hydrology encompasses many relevant aspects investigating complex social-environmental-economical issues as they are found in the Sandveld.

2.1.1. What is IWRM?

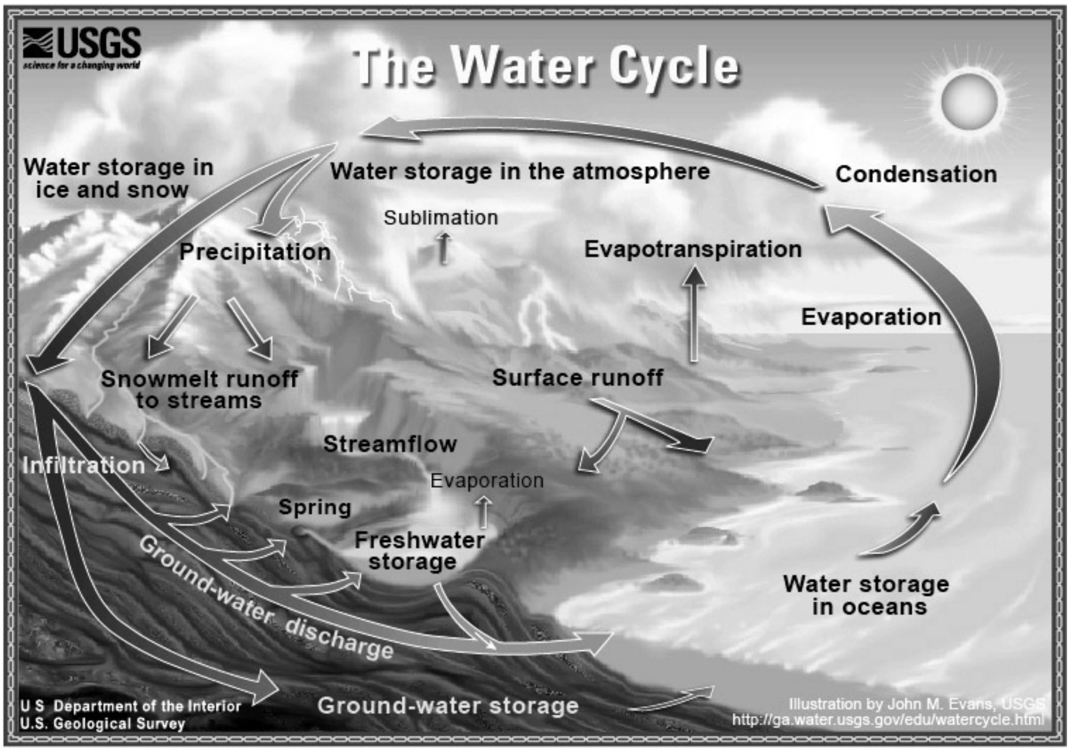
Dent (2007) recommends the Integrated Water Resource Management (IWRM) approach to catchment management. He argues that "almost all actions in a catchment have consequences for water". He further suggests that IWRM should seek as its goal cooperative governance between individuals, groups and organisations. A comprehensive plan should be made by the people of the catchment concerning the sustainable management of the natural resources, focusing on water, to the profit of the community and without damaging the environment. Dent (2007) explains that it requires regular interaction between individuals, disciplines and organisations to effect wise and timeous management of the consequences of our actions of the past, present and future.

2.1.2. What is hydrology?

In COHS (1991) hydrology is described as a distinct geoscience with a strong interdisciplinary flavour. The current understanding of hydrology encompasses a mixture of natural and altered physical, chemical and biological systems and incorporates engineering and social sciences. Although the focus of hydrology is on water and its cyclical movement through the environment, it provides for an holistic approach which may more closely investigate how water, the environment and human activities are mutually dependent and interactive (Watson & Burnett 1995) . Hydrology can be used as a scientific analysis and research tool within IWRM and catchment management.

2.1.3. The hydrological cycle

It is the natural system in which water moves between land, atmosphere and the ocean cyclically as depicted in Figure 2.1. Our actions as human beings can interrupt these cycles, the consequences of which could threaten our existence. Watson & Burnett (1995) refer to the hydrological cycle as a dynamic, water transport and filtering system.



Source: Uhlenbrook (2006a: 10)

Figure 2.1 The hydrological cycle

The hydrological cycle consists of a series of interactive, iterative processes which can be simplified and represented mathematically in a model. They are according to Uehlenbrook (2006a):

- precipitation,
- interception (including, utilisation by ecosystems, utilisation by man and irrigation),
- absorption into earth materials and uptake by plants (including percolation),
- water movement from a shallow aquifer to a deep aquifer,
- surface flow and runoff,
- subsurface flow, and
- water losses in the form of evaporation, transpiration, and seepage.

Subsurface flow can be described as flow of water through earth materials. Most earth materials are non-homogenous and then the flow path is dictated by the path of least resistance, determined by the properties of these earth materials. Mass permeability of these materials determines resistance to flow.

Traditionally groundwater and surface water hydrology are two separate areas of scientific study. Groundwater models are seldom used together with surface water models and vice versa. Models depict a simplification of this configuration and distribution of the materials creating a flow pattern.

2.2. TYPES OF MODELS

The hydrological models discussed here are mathematical models, meaning that they are abstract and use mathematics to describe the behaviour of hydrological systems. Mathematical models can take many forms, and can overlap as they may incorporate a variety of abstract structures. Wikipedia (2007) describes the following polar classifications of mathematical models:

- Models can be classified as *linear* or *non linear* where non linearity is associated with chaos and irreversibility, making it more difficult to study;
- The next classification category is *deterministic* or *probabilistic*, the latter also known as stochastic. Deterministic models are uniquely defined and parameterised, with a given set of initial conditions. On the other hand, stochastic models represent randomness, and probable outcomes;
- Models can be either *static* or *dynamic* depending on whether the element of time is excluded or included in the model. Dynamic models often make use of difference equations or differential equations. Artificial neural networks (ANN) are dynamic system models which mimic simple biological nervous systems. In their current form they have the capacity to extract relationships in data and can represent highly complex, multi dimensional and non linear relationships well, but do not spatially distribute watershed modelling systems;
- Models can also be classified as either *lumped parameter* or *distributed parameter* models. Lumped models apply to homogenous states throughout the system, where distributed models signify varying states throughout the system, in which case parameters are in part represented by differential equations. Domenico (1972) discusses the uses of lumped or distributed parameter models, each applicable to situations where detailed accuracy and scale will determine which should be used. The SWAT model uses a combination of both lumped (rainfall per sub basin) and distributed parameters for example, HRU combinations of unique soil, topography and landuse characteristics. Lumping serves to reduce complexity and promote expediency and the distributed parameters are chosen to increase accuracy;
- A model is *physically based* if its parameters can be measured in the field. Physically based models use equations in a modular way to replicate physical processes in the hydrological cycle. They can partly contain linear regression models, where constant, linear relationships are assumed between elements. Conceptual models, in contrast, do not require empirical measurements.

Complexity and accuracy stand opposed to simplicity and generalisation in modelling. Where complexity may improve fit of a model, it can also make it computationally inefficient and difficult to understand. And simplicity can lead to uncertainty being more than desired.

2.3. HYDROLOGICAL MODELS

An hydrological transport model is a mathematical model used to simulate river or stream flow and calculate water quality parameters. These models generally came into use in the 1960s and 1970s when demand for numerical forecasting of water quality was driven by environmental legislation in the United States and the United Kingdom. At about this time computers became more widely accessible, and powerful enough to significantly assist in modelling processes. There are numerous hydrological models and they can be grouped by pollutants addressed, complexity of pollutant sources, whether the model is steady state or dynamic, and the time period modeled. Also important in determining the selection of model is whether it is distributed (i.e. capable of predicting multiple points within a river) or lumped. Simple models may only address a single pollutant, whereas a complex model could have multiple runoff and point sources for pollution for more than one chemical, as well as sediment data. It could further divide the channel flow into strata in which various biota are modeled in relation to chemical and sediment transport. The groundwater component may also be present in a model (Kim et al 2007).

Models often address individual steps modularly in the simulation process. Typically subroutines for surface runoff include components for a land use type, topography, soil type, vegetation cover, precipitation and land management practice (regular agricultural activities e.g. pesticide or fertiliser application).

2.3.1. Physical ‘real world’ models

Physical, deterministic or comprehensive models use mathematical process descriptions to represent the observed physical processes of the real world. They may consider the processes for surface runoff, subsurface flow, evapotranspiration, and channel flow or can become much more complex.

Système Hydrologique Européen (SHE) ACRU, SWAT and VTI share the description of being semi-distributed, quasi-physically based daily time step models for watershed-scale modelling. It allows for spatially distributed water flow and sediment transport modelling. Processes are represented by either finite difference sub models of partial differential equations or by derived empirical equations. They simulate the interaction between land use and climate changes as they impact on in-stream water quality, with varying consideration of groundwater interactions. Other similar international models include RORB, Xinanjiang, Tank model, ARNO, TOPMODEL, UBC, HBV, AGNPS, GWLF, HSPF and MohidLand.

2.3.2. Stochastic models

Stochastic, or data based models use mathematics and statistics to relate model inputs to model outputs. Neural networks, regression, transfer and system identification techniques are often used in this kind of model. Flood forecasting is the main use for data based models where rainfall and runoff are related to one another, and antecedent moisture conditions are considered, in real-time replication of real world hydrological systems.

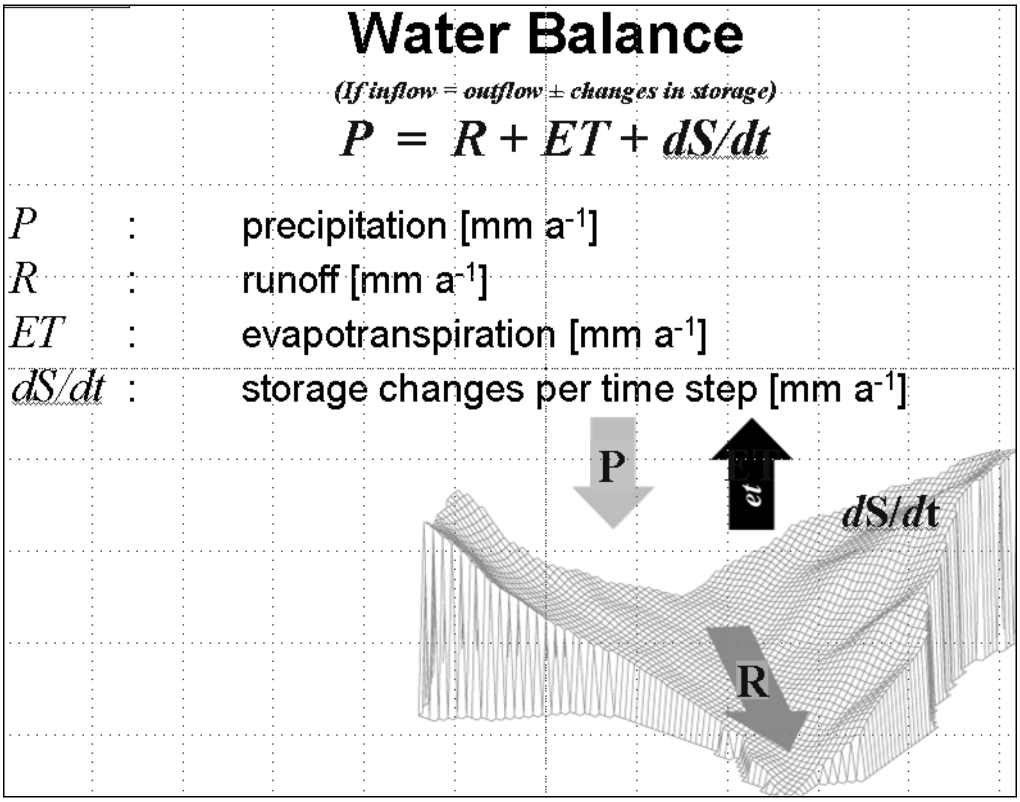
2.3.3. Surface runoff contaminant models

These models have not been given as much attention by the hydrological community as the pure hydrology models. A hydrological transport model forms the surface runoff element, but the focus is on the sediment, and chemical contaminants in the runoff.

2.4. STANDARD EQUATIONS

Hydrological models consist of a vast number of equations, each representing a different part of the hydrological cycle in mathematical simplification. The surface energy balance and the water balance equations are the back bone supporting hydrological models. As with the actual hydrological cycle, each part is built on the next and mistakes in any part may affect the accurate simulation of the complete cycle.

Models are simplified imitations of real hydrological systems and must conform to what is happening in the watershed. The hydrological equation forms the basis of hydrological studies and models. Matthewson (1981) discusses the principle underlying hydrological equation which assumes that water is not created or destroyed, but remains somewhere in the hydrological cycle, therefore the equation must balance. A catchment is the hydrological base unit for water balance estimations. The simplified version of the water balance equation in Figure 2.2 demonstrates this concept:



Water Balance

(If inflow = outflow ± changes in storage)

$$P = R + ET + dS/dt$$

P : precipitation [mm a^{-1}]
R : runoff [mm a^{-1}]
ET : evapotranspiration [mm a^{-1}]
dS/dt : storage changes per time step [mm a^{-1}]

Source: Uhlenbrook (2006a: 13)

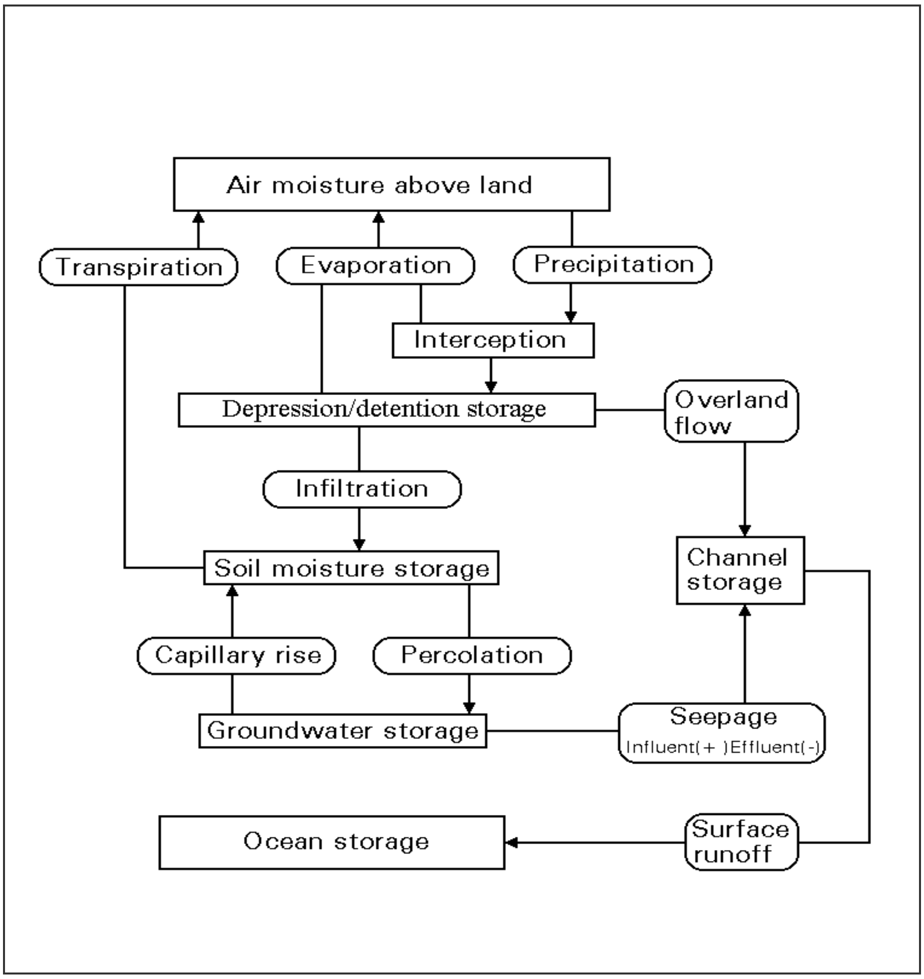
Figure 2.2 The water balance

The water balance equation: P = R + ET + ΔS/Δt is normally solved for catchments. Where P is precipitation, R is runoff, ET is evapotranspiration and ΔS/Δt is change in storage over time.

Uhelenbrook (2006a) lists the following storages in the hydrological cycle:

- Atmosphere
- Soil water / groundwater
- Oceans
- Ice caps, glaciers, snow
- Rivers, lakes
- Surface storage (interception)
- Biosphere

The diagram in Figure 2.3serves to illustrate the movement and storage of water through various systems from water vapour to surface runoff.



Source: Uhlenbrook (2006a: 18)

Figure 2.3 Schematization of storages and processes of the terrestrial part of the hydrological cycle

Water storage fluctuations are influenced by precipitation, evaporation, transpiration, plant water uptake, discharge, interactions between surface water and groundwater, snow and ice melt. These water fluxes between storages are of primary interest to hydrological studies.

According to Uhlenbrook (2006a) the water balance does not stand in isolation for hydrological studies, and is used in conjunction with the surface energy balance equation which represents evapotranspiration processes more accurately:

$R_n = \lambda E + H + G + \Delta S/\Delta t$

where

R_n: Net radiation

λE: Latent heat (= evapotranspiration; ET)

H: Sensible heat

G: Soil heat flux
$\Delta S/\Delta t$: Change in storage
Assuming G and $\Delta S/\Delta t$ to be negligible: the equation can be further simplified to
$R_n = \lambda E + H$ or also expressed as: Incoming Energy = Outgoing Energy + D Storage

The following sub models and equations from Uhelenbrook (2006a), Watson & Burnett (1995) and Neitsch et al (2002) are some examples of more specific sub routines which have been used to flesh out the bones of the hydrological model:

Table 2.1 Other equations often used in hydrological models

Equation	**What it is used for**
The Soil Conservation Service (SCS) curve number method	It is a correlation between rainfall and runoff
Penman-Monteith formalism (Monteith 1965)	This equation simulates evapotranspiration
The Modified Universal soil loss equation (MUSLE)	Erosion can be studied using detachment equations for raindrop and overland flow
Manning's roughness coefficient	Used for overland and channel flow and to calculate time of concentration
Overland Flow Sediment Transport sub routines	These may make use of the 2D total sediment load conservation equation
The Richards equation	It has been used to calculate unsaturated flow
The Green & Ampt (1911) equation	This method simulates infiltration
Lane's method	It is used to calculate transmission losses through leaching channel beds
Darcy's law and the mass conservation of 2D laminar flow	They are used for groundwater saturated flow

The following extract from Uhlenbrook (2006b: 18) sets out the detailed workings of the SCS curve number:

"

The SCS curve number equation is (SCS, 1972):

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

where Q_{surf} is the accumulated runoff or rainfall excess (mm H_2O), R_{day} is the rainfall depth for the day (mm H_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm H_2O), and S is the retention parameter (mm H_2O). The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. The retention parameter is defined as:

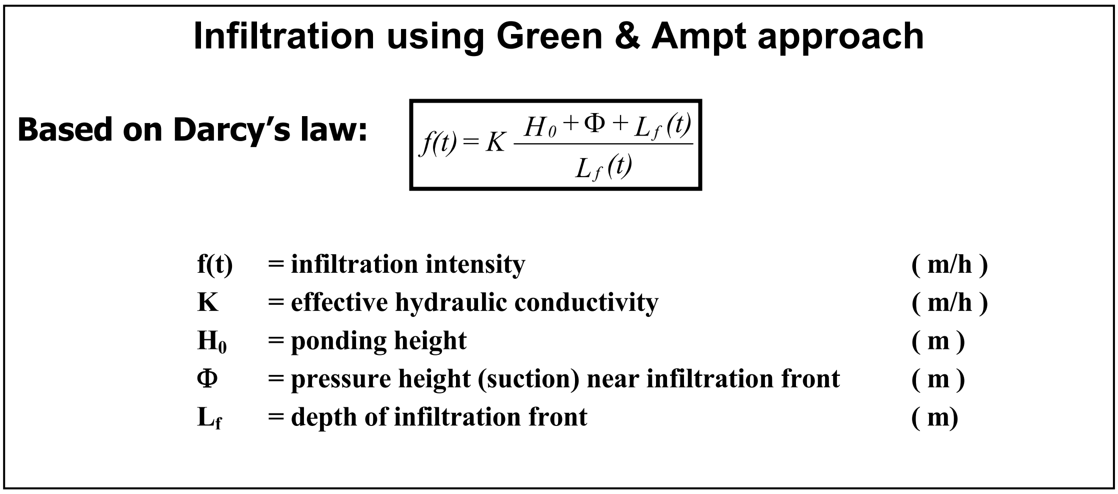
$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

where CN is the curve number for the day. The initial abstractions, I_a, is commonly approximated as $0.2S$ and the previous equation becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)}$$

Runoff will only occur when $R_{day} >$ Ia"

Uhlenbrook also provides us with the following description of the Greem Ampt equation based on Darcy's law:



Infiltration using Green & Ampt approach

Based on Darcy's law: $$\boxed{f(t) = K\,\frac{H_0 + \Phi + L_f(t)}{L_f(t)}}$$

f(t)	**= infiltration intensity**	**(m/h)**
K	**= effective hydraulic conductivity**	**(m/h)**
H_0	**= ponding height**	**(m)**
Φ	**= pressure height (suction) near infiltration front**	**(m)**
L_f	**= depth of infiltration front**	**(m)**

Source: Uhlenbrook (2006b: 23)

Figure 2.4 The Green Ampt infiltration method

Darcy's Law describes the relationship between groundwater velocity, hydraulic gradient and permeability as a volumetric discharge of water through an aquifer. It is only valid for laminar flow in which flow lines remain distinct and adhere to the general vector of flow direction.

2.5. THE USE OF VARIOUS MODELS

In his report on suitable hydrological models for use across Southern Africa, Hughes (1997) describes the conceptual and deterministic models applied (Pitman, VTI and empirical reservoir models) for hydrological studies for the Water Research Commission (WRC) in Southern Africa. ANN models were tested against the SWAT model by Srivastava et al (2006) with favourable accuracy for stream flow modelling. In their hydrological model for the Mgeni catchment, Schulze & Tarboton (1992) decided on ACRU, a distributed parameter model because of the complexity of climatic and physiographic variables in area of study. ACRU is a South African model which is designed specifically for challenges faced in this region which includes a lack of data. The CSIR in Pietermaritzburg have successfully used both the ACRU (Everson 2001) and SWAT (Savage 2006; Govender 2006, pers com; Govender & Everson 2005) for hydrological studies in KwaZulu Natal.

2.6. GOOD HYDROLOGICAL PRACTICE

Schulze (1995) cautions the hydrological practitioner to consider the system in its entirety instead of isolating details, which might skew perspective. In the real world it is not feasible to test what if scenarios physically. It is here that a well constructed model may predict responses for all combinations of land uses, land treatments and climate regimes (Watson & Burnett 1995).

Hydrologists and modellers warn against using models without the necessary knowledge. They can only anticipate possibilities and are a means to an end (Pereira 1984), not the solution to problems, although they may provide insight to these. De Coursey (1991) highlights the synthesising function of good hydrological modelling which is important in facilitating knowledge pooling from all components of the system. In so doing, creating a more coherent view of the behaviour of the entire soil-plant-atmosphere-and water continuum.

Scaling is a pertinent issue to modelling the hydrological cycle – the smaller the unit of measurement (for example time step, spatial resolution) the higher the cost of input, not necessarily increasing the accuracy or value of the results. Accurate data for specific physical processes is not well represented in South Africa (Hughes, 1997).

CHAPTER 3: METHODS

3.1. STUDY AREA

The study area, namely the Verlorenvlei catchment, is depicted in below in Figure 3.1.

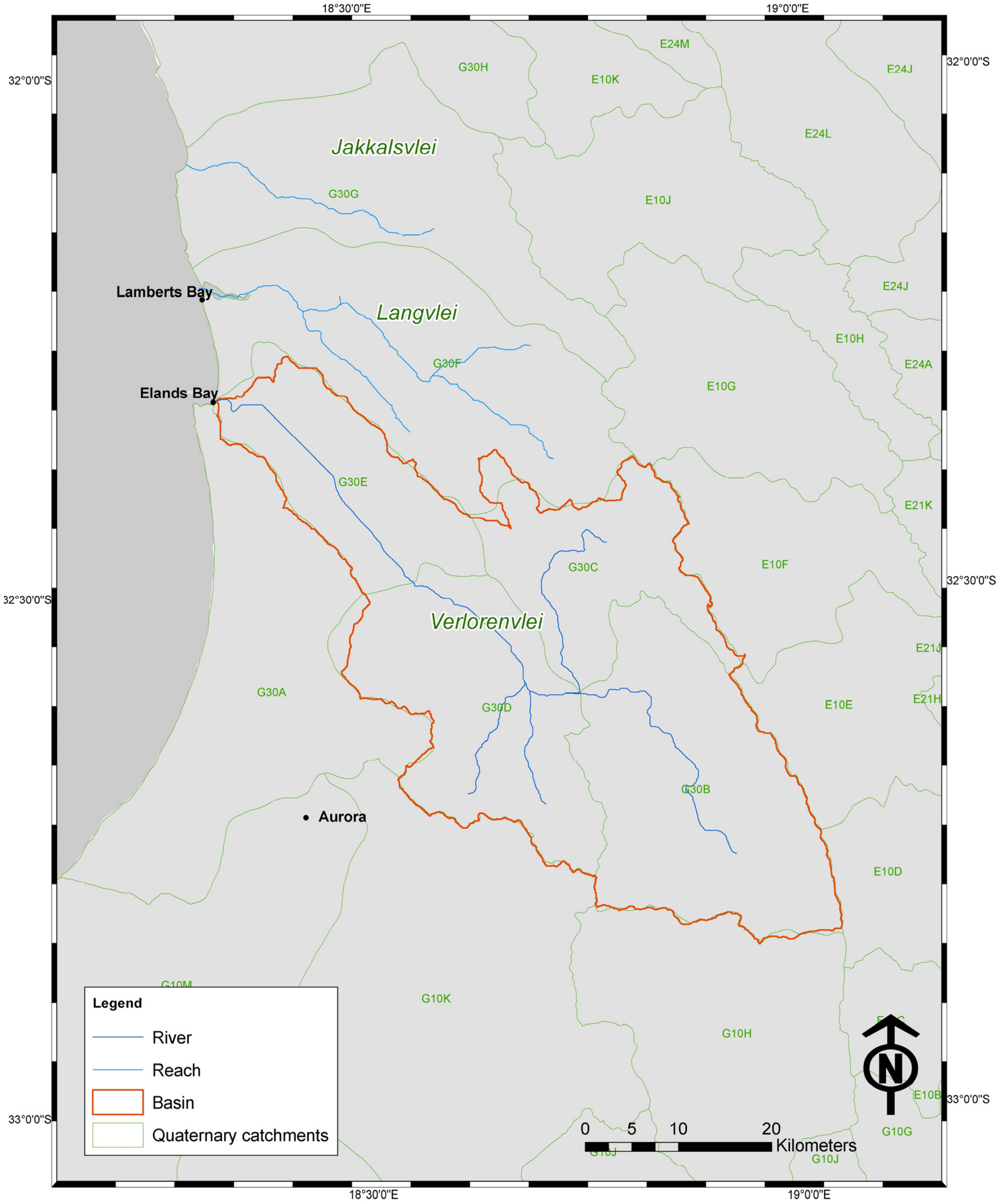


Figure 3.1 Study area consisting of the Jakkalsvlei (G30G), Langvlei (G30F) and Verlorenvlei (G30B, C, D and E) quaternary catchments.

The Verlorenvlei catchment falls within the arid Sandveld region on the West Coast of the Western Cape Province. The watershed area encompasses 186510 ha, which forms part of the Olifants-Doorn Water Management Area. Three ephemeral rivers flow from east to west in parallel sub catchments i.e. the Jakkalsvlei is in the north, south if which lies the Langvlei and further south of that the Verlorenvlei as seen in. The model was tested on the Verlorenvlei catchments.

The Verlorenvlei catchment was chosen as it is the only of the three rivers with a flow gauge, (see Figure 4.4). Measured data from a flow gauge is essential in calibrating the model. These catchments function similarly as they have similar topography, soils and land use and are essentially groundwater driven (Conrad 2005). This could prove useful if the other two catchments (Langvlei and Jakkalsvlei) were to be incorporated into the study area at a later stage. Some interpolation and extrapolation of Verlorenvlei's results could provide relevant input.

Elevation varies from 0 - 1445 m at the highest elevation, (see Figure 3.6), making it a relatively flat slope compared to other catchments in South Africa. Elevation bands may be used in ArcSWAT to emulate the orographic effects on both precipitation and temperature. The elevation band option was not implemented in this study.

Lane (1980) describes the sandy soils as very loose and nutrient poor. Parker et al (2004) refer to young and semi unconsolidated aeolian and alluvial deposits on the coastal geology, originating from the ocean and redistributed by the wind. These sands also contain calcrete and ferricrete deposits. Underlying the sands are Cape, Gariep and Malmesbury Super Group palaeolithic deposits. Gariep and Malmesbury Groups weather quickly and tend towards the formation of clay loams and clays. In the east, the Cederberg Group forms part of the Cape Super Group that weathers to coarse quartzitic sands.

The climate of the study area is best described as a low winter rainfall area with rainfall varying between 100 - 400mm per annum (Munch et al 2004). The rainfall follows a statistically skewed normal tendency (Beuster 2007, pers com) with rainfall events concentrated over short periods. The Sandveld is situated on the West Coast along the Atlantic Ocean where the cold Benguela current influences the climate dramatically. Preston-Whyte & Tyson (1988) describe the polar water imparting very little heat to the air mass abutting it and so reducing the potential for uplift and instability associated with rainfall. The winter months deliver the most rainfall as the size and turbulence in westerly waves create cold fronts that result in rain (Preston-Whyte & Tyson 1988). It is an arid area where Chittenden Nicks (1993) report that for most of the year evaporation exceeds precipitation and winds are typically strong north west in winter and south east during summer months (Maclear 1994).

Low & Pond (2003) describe how the study area vegetation type has a large range in variability from mountain fynbos (dominated by Cederberg Sandstone Fynbos and Graafwater Sandstone Fynbos) to lowland fynbos (Leipoldtville Sand Fynbos) (see Figure 3.2 and Table 3.1).

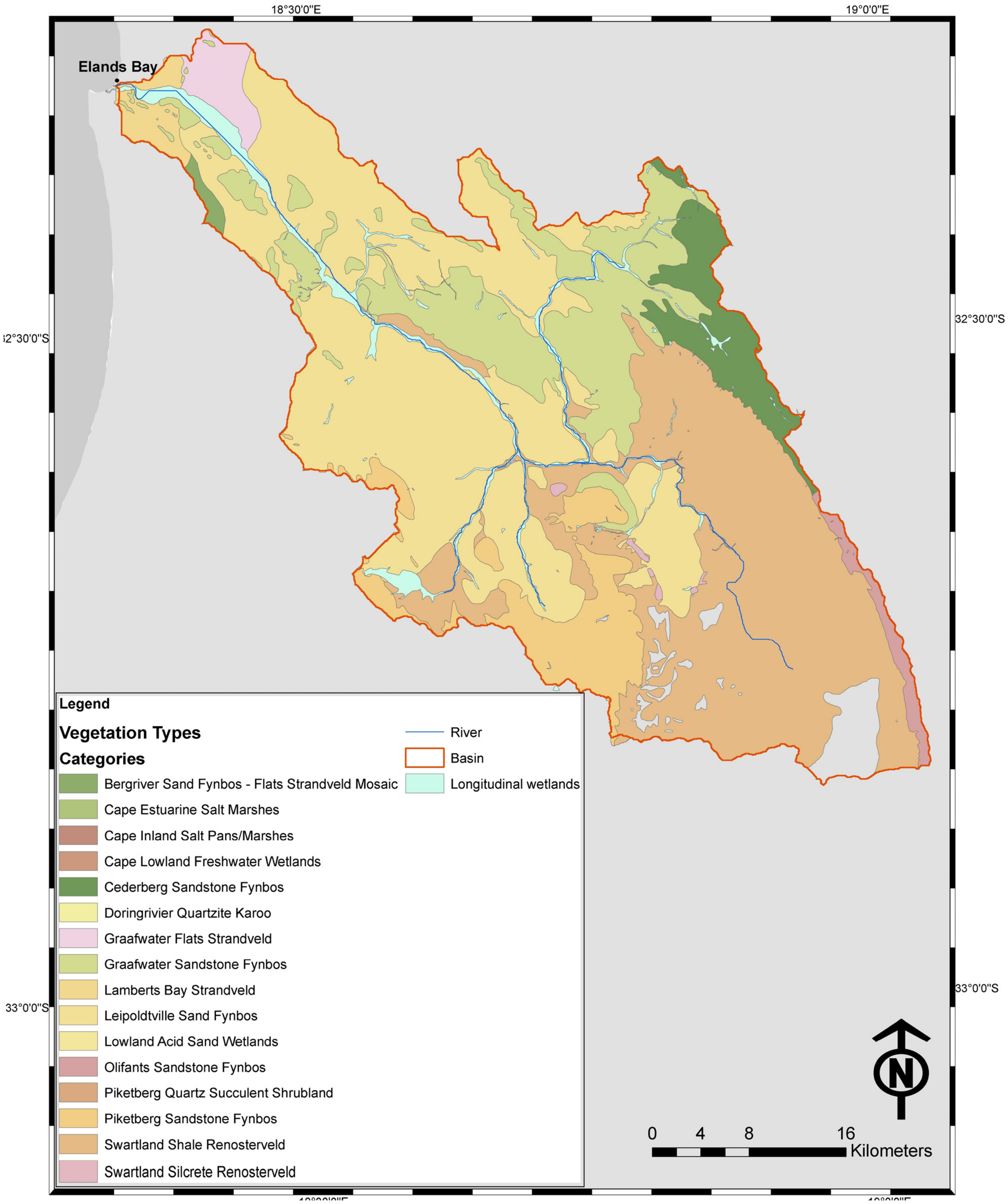


Figure 3.2 Vegetation types in the Verlorenvlei catchment area

In the South-eastern parts of the Sandveld, Swartland Shale Renosterveld dominates but other shales are included. Mesic fynbos and Renosterveld tend to change to succulent and thicket types towards the coast. These include Lambert's Bay Succulent Karoo and Langebaan Dune Thicket. Low & Pond (2003) also refer to the steep rainfall gradient, between 100 and 400 mm per annum (Munch et al 2004) which facilitates the transition from inland to coastal vegetation. Substrate influences the vegetation gradient too, where the inland parts are dominated by sandstones and shales of the Table Mountain Group and the coastal regions tend towards deep calcareous, as well as acid sands.

Table 3.1 lists the vegetation types found in the Sandveld area and indicates the original extent of the vegetation type in hectares. The land cover map created by the same project separates the disturbed area from the less disturbed or pristine area. The combined information from these maps was used to identify the area of what remains of the original vegetation types.

Table 3.1 Area of different vegetation types in the study area

Vegetation Types	**Hectares**
Leipoldtville Sand Fynbos	71535
Swartland Shale Renosterveld	54498
Graafwater Sandstone Fynbos	27323
Piketberg Sandstone Fynbos	12495
Cederberg Sandstone Fynbos	8717
Cape Lowland Freshwater Wetlands	4552
Lambert's Bay Strandveld	2613
Olifants Sandstone Fynbos	2369
Cape Estuarine Salt Marshes	1670
Hopefield Sand Fynbos	728
Swartland Silcrete Renosterveld	701
Piketberg Quartz Succulent Shrubland	255
Doringrivier Quartzite Karoo	194
Cape Inland Salt Pans	35
Cape Vernal Pools	12

Source: Helme & FCG (2007)

The demise of the fishing industry and subsequent refurbishing of the cannery at Lamberts Bay to accommodate potato products, and the arrival of large-scale electricity supply in the 1980's facilitated the use of centre pivot irrigation and thereafter the rapid growth of the potato industry in the Sandveld (Heydenrych 1993; Bonthuys 2005). This led to larger volumes of water being necessary to irrigate these areas. The high profits made from potato farming encouraged farmers to establish ever more centre pivots for potato production (Burger 2005; Theron 2006, pers com).

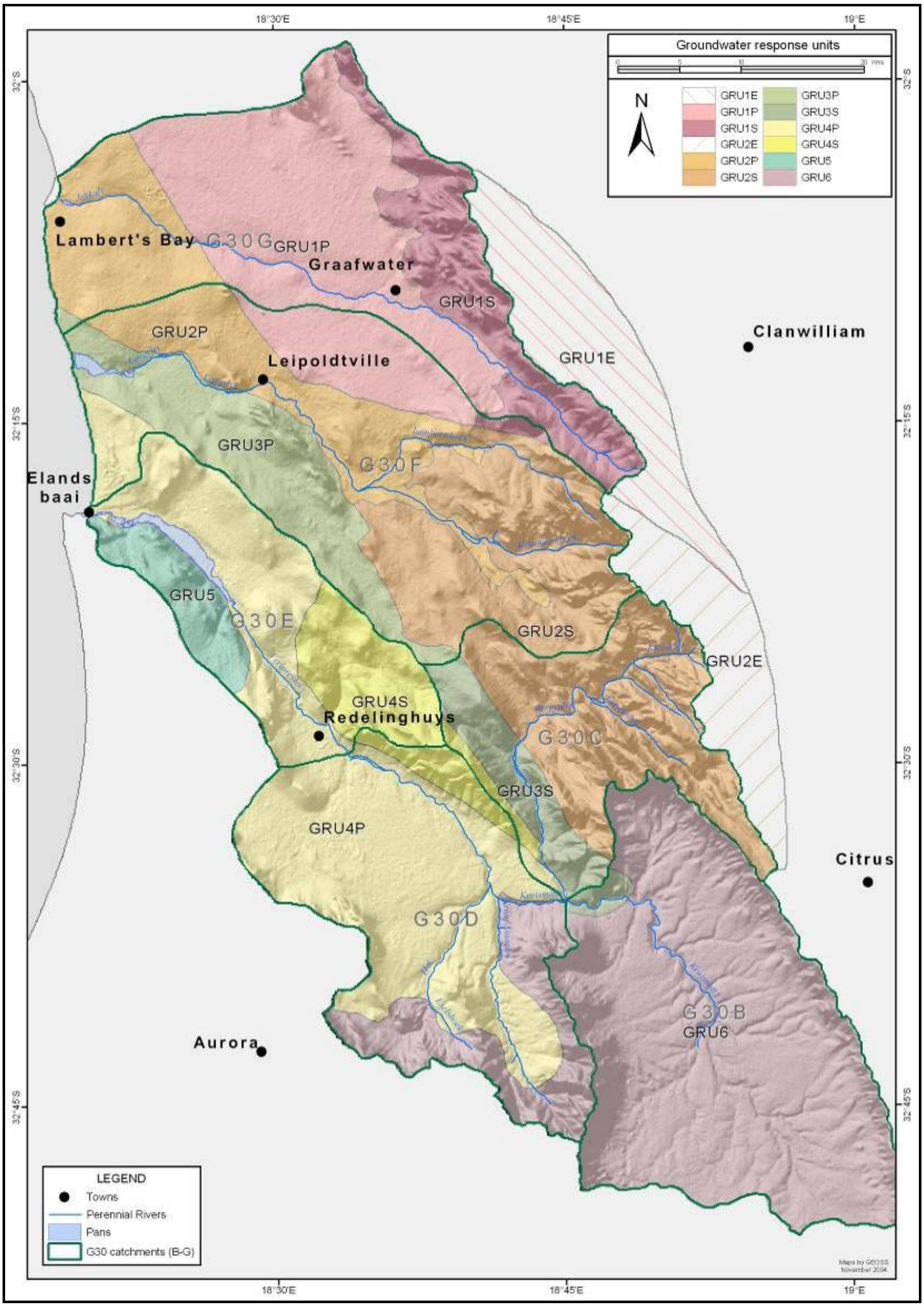
Potato related diseases required the fallowing of fields for between three and four years after cultivation. This practice left the ground bare, and vulnerable to wind erosion and the loss of valuable topsoil. The soil, being mostly sand, requires special land management planning as described by Valentin et al (2004), and is inherently less suited to agricultural intensification in semi-arid areas like the Sandveld. Natural vegetation was nevertheless being cleared at a rate of 2.5 hectares per day according to Burger (2005, pers com) of CapeNature. Duncan (2004) lists several natural systems or species as threatened or near collapse due to the current land use circumstances.

The groundwater resource has become a contentious topic in the Sandveld (Bonthuys 2005). During the last five years this has lead to numerous studies focusing on groundwater and the dependent ecosystems (DWAF 2003; Low & Pond 2003; Duncan 2004; Munch 2004; Conrad 2005; Conrad & Munch 2006). These studies resulted in several groundwater related maps which are depicted in Figure 3.3, Figure 3.4 and Figure 3.5 below.

Figure 3.3 shows the groundwater response units. They differ significantly from the surface water drainage boundaries created by the SWAT model in Figure 4.1. The Sandveld is an environment where surface water and groundwater are intricately connected and their relationship is not well understood scientifically.

Parker et al (2004) describe the groundwater of the Sandveld as having both primary (sand) and secondary (bedrock) aquifers (see Figure 3.4). The primary aquifers occur along the coast in the coarse sand, deeper than 100m in places depending on the water holding capacity and thickness (see Figure 3.5) of the sand.

Groundwater is influenced by a wider area and its contributing area may not conform to particular catchment management boundaries, but may fall outside the surface water management area. In the case of the Verlorenvlei it is thought that the Cederberg Mountains are the most likely source of groundwater (Conrad 2006, pers com).

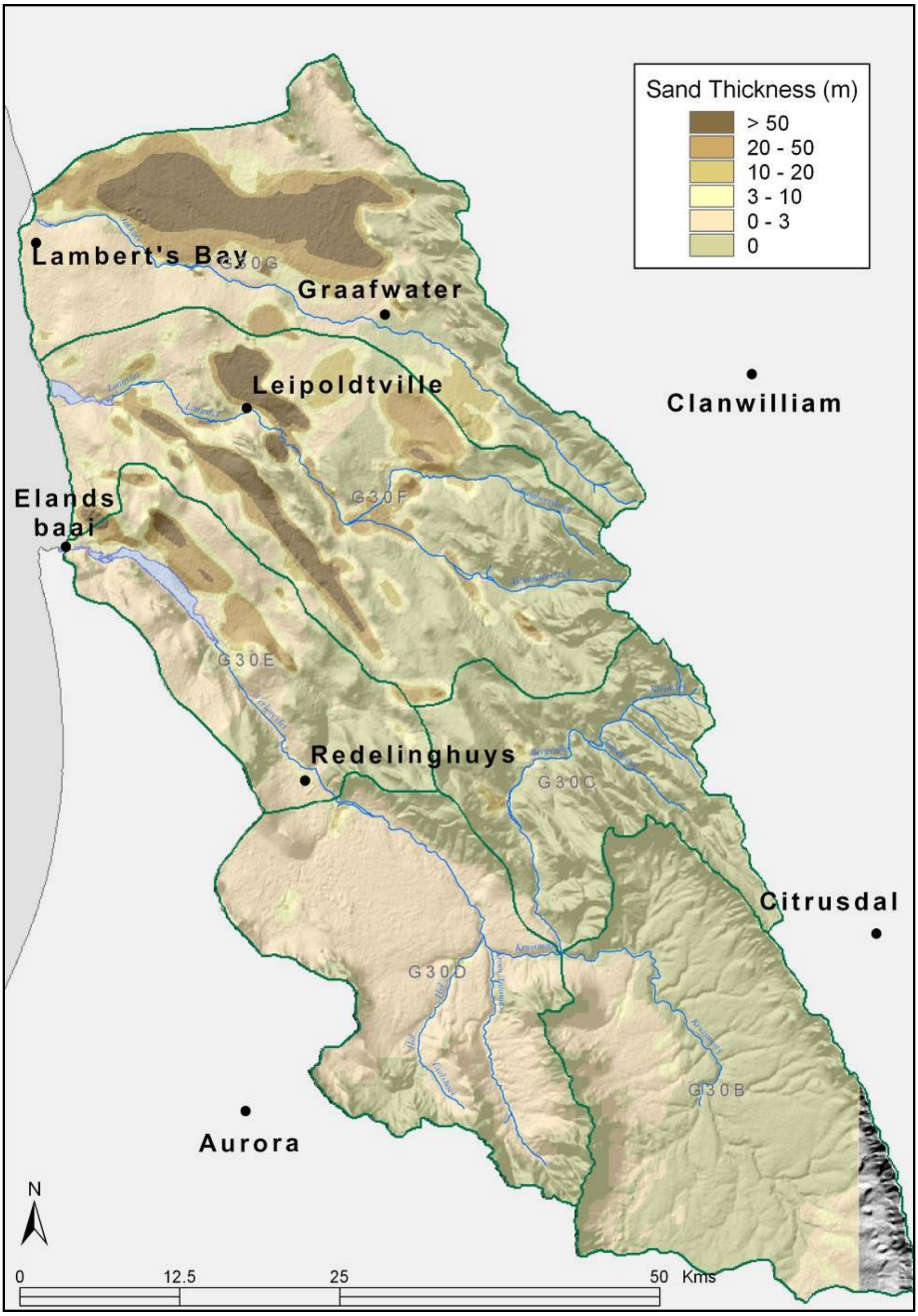


Source: DWAF (2003)

Figure 3.3 Groundwater response units for the study area

Source: DWAF (2003)

Figure 3.4 Sand and bedrock aquifers in the study area



Source: DWAF (2003)

Figure 3.5 Sand thickness in the study area

3.2. DATA

Hydrological models require large amounts of data, depending on the scale and accuracy requirements of the model. Data collection and preparation for the model formed the most time consuming and challenging component of the study. Since the start of the study, new and improved data sets have been produced for example the CAPE Finescale Planning Project's (FSP) land cover (Thompson, 2007) and vegetation layers (Helme & Freshwater Consulting Group, 2007) for the Sandveld. These were finalised in time for the final steps of setting up the model, providing a high level of accuracy with the latest available land cover data. Most of the data required by the model was spatial data. Climate data, acquired in tables were also linked to climate station locations, proving the usefulness of the GIS for spatial representation of the data.

3.2.1. Projection

All spatial data sets were projected to UTM 34 South and WGS84 datum. Reprojections were done using ArcGIS 9.1's raster and vector standard world reproject tool. ArcSWAT requires all data to be in the same projection before any GIS processing can take place. The UTM projection was chosen as it is widely used in the Western Cape Province.

3.2.2. Digital Elevation Model

This study used the Digital Elevation Model (DEM) for Western Cape created from 20m contours to produce 20 x 20m pixels (CGA, 2001). It is a grid layer where each pixel contains an X and Y location value as well as a Z value indicating height above sea level. It was produced for finer application scales than the current project but it was resampled to 40 x 40m pixel size, making it a coarse enough resolution in order to use less space and memory resources. Processing becomes memory intensive in proportion to the level of detail (i.e. resolution) of the data. The nearest neighbour assignment resampling technique was recommended (ESRI, 2005) for resampling the DEM. It is applicable to both discrete and continuous value types such as the DEM.

The topography varies little over the study area (see Figure 3.6), making it less important to identify flatter slopes as they have little effect on rainfall and runoff. The steeper variations in elevation are still easily identified at 40m resolution. The resampling was conducted in a two step process. First a nine-cell shifting window, averaging filter was applied which updates the average Z value of the surrounding eight cells to the central ninth one. These generalised and smoothed values were then put through the second process, a nearest neighbour resampling which generalised the grid to 40 x 40m pixel size.

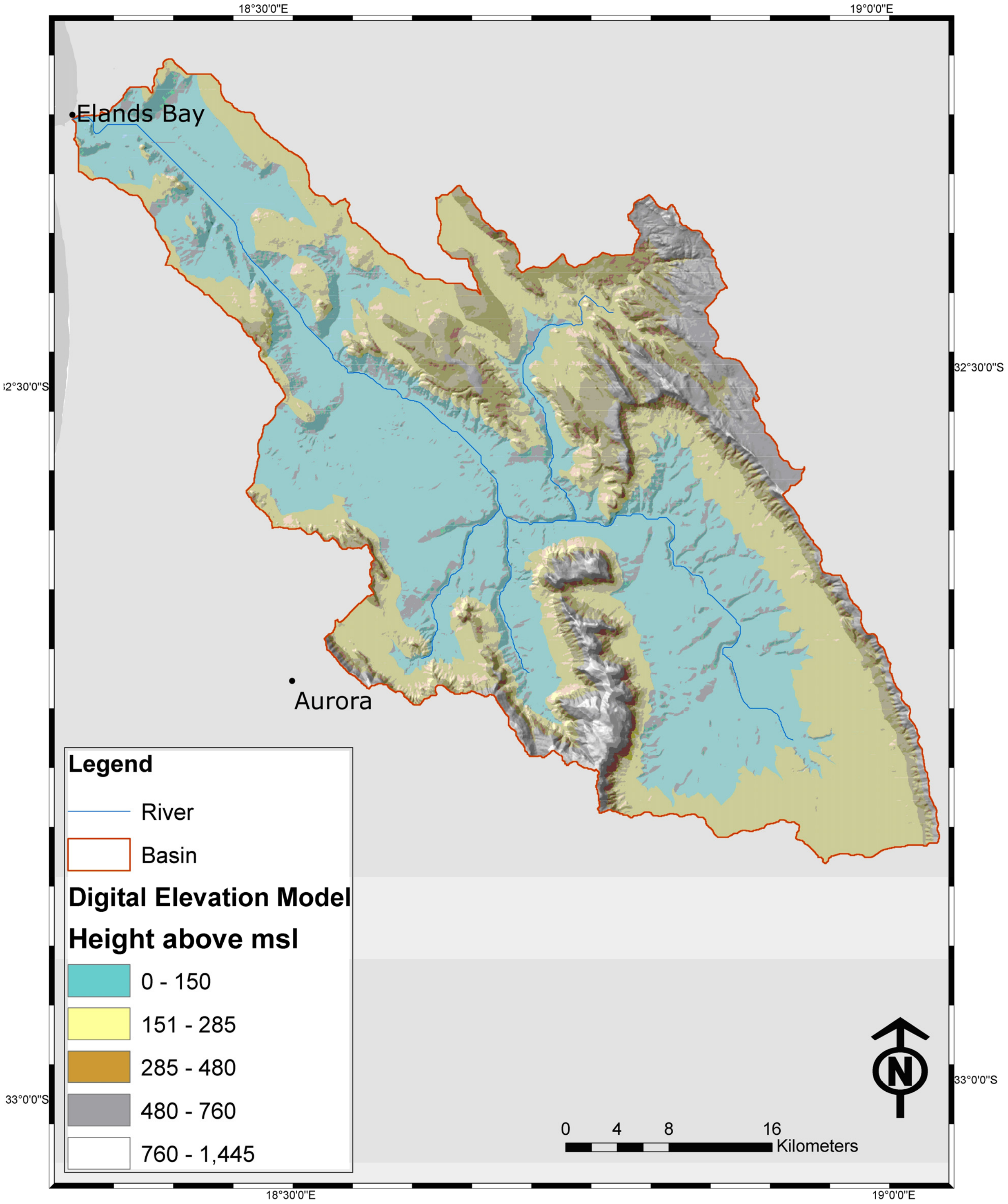


Figure 3.6 Topography of the study area

3.2.3. Soils

The soil map seen in Figure 3.7 was sourced from the Food and Agriculture Organisation of the United Nations (FAO, 1995).The data is provided at 10km spatial resolution along with a database of soil properties for two soil layers. The top layer is created at a default of 0-30cm, and the subsequent layer is set at 30-100cm (effective plant root depth). Soil properties for particle size distribution, bulk density, organic carbon content and available water capacity were obtained using Reynolds et al (1999) by Schuol & Abbaspour (2007). Soils input data are important because they affect hydrological results where granular or cohesive soils behave very differently in the presence of water.

The course scale and lack of local detail necessitated by a map covering a continent or the world is not ideal for a local hydrological study. It could be argued that the accuracy and resolution on this input layer are insufficient for fine scale modelling as in this study. Expert input for soil physical and chemical properties would require extensive empirical research and re-calculation as many of the variables required by the model are not readily available in South African datasets, and need to be derived from other properties. For example some chemical soil qualities can be derived from the soil texture classes (Hoffman 2008, pers com). Mr H Schloms (2007, pers com) of the Department of Agriculture Western Cape advised that the C horizon may be much deeper than 100cm, even up to 20m in some of the sandy soils.

The clay percentages provided in the data are also too high for most of the soil types actually found in the area. Soil is one of the key variables in hydrological modelling, and may have a large impact on the accuracy of flow and water quality results. Alternative data sets for this feature might be required in future runs of the SWAT model. The specific requirements of the ArcSWAT model are not easy to obtain however, and specialised fine scale mapping as well as laboratory test results would be needed. The current study did not allow for the inclusion of such data at present, so the FAO data was used for the sake of obtaining immediate results, possibly at the cost of some accuracy.

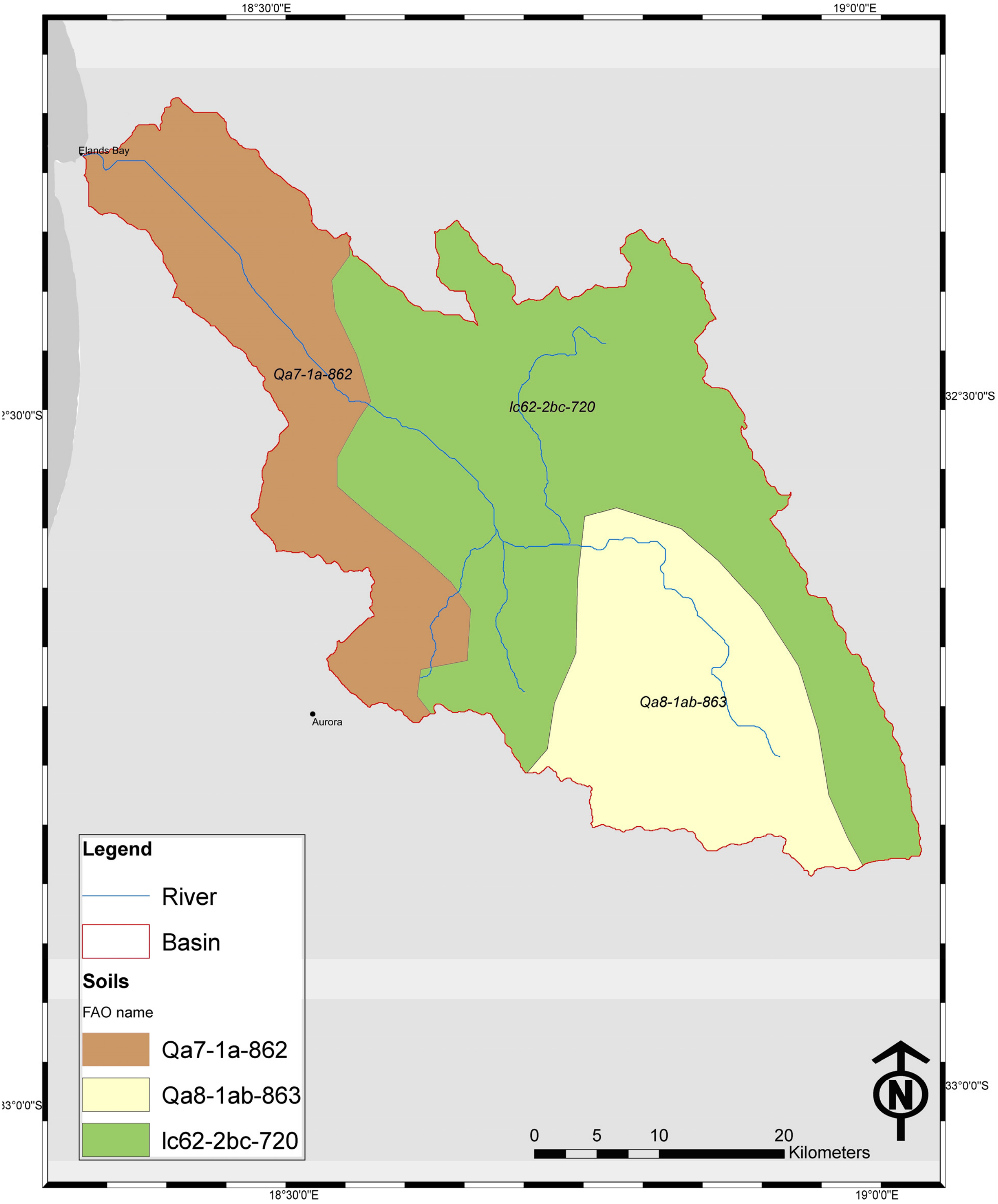


Figure 3.7 Soils of the study area

3.2.4. Land cover to land use

The land use dataset was derived from land cover data acquired from the C.A.P.E Fine Scale Planning Initiative, managed by CapeNature. Thompson & Forsythe (2006) describe the land use data acquisition process used in creating the final product.

3.2.4.1 The original land cover data

Satellite (SPOT 5) images taken in December 2005 were used to create the land cover dataset. SPOT 5 panchromatic band (2.5m pixel size) was orthorectified using a good cadastral layer in ERDAS software. The 10 x 10m spectral bands were then orthorectified against the panchromatic band. A twenty metre Digital Elevation Model (DEM) was used to correct topography. The two image layers were then merged together using the "Resolution Merge" function in ERDAS. Sensors vary in which band numbers represent the near infra red (NR), middle infra red (MIR) and infra red (R) bands. Each needs to be checked according to that particular product's specifications. In this case, the following bands are used to set up the RGB (red, green, blue) within the image:
Red = Band 1 = NR
Green = Band 4 = MIR
Blue = Band 2 = R

The classification process used, identified each spectral and land cover class individually, starting with the smallest and easiest to identify, as indicated in the left hand column of Table 3.2.

Digitised polygons were used to train the image analysis process, storing templates for each class. Before converting the final raster classifications to vector, the majority 3x3 filter (ESRI, 2005) was used to smooth areas before creating polygons. This is methodology is explained in detail in Thompson & Forsythe (2006).

The original land cover as it was adapted and converted to land use for ArcSWAT appears in Figure 3.8 below. The following paragraph describes the modifications made to the original FSP land cover data to create the SWAT data set depicting land use for the study area.

3.2.4.2 Modifications for use in the hydrological model

The source dataset did not cover the entire study area and a small part in the south eastern corner was manually extended in ArcGIS 9.1 to cover the whole area using the main land cover values adjacent to the uncovered areas. For the purposes of running the hydrological model, this data was clipped to the catchment boundary, resampled from the original 2.5m x 2.5m in four steps. The first was a three by three-cell shifting window, where a majority filter was applied. This updates the central ninth cell to the majority value of the surrounding eight cells. This process smoothed values which were then put through the second process, a nearest neighbour resampling from 2.5m x 2.5m to 7.5m x 7.5m pixel size. The majority filter was then repeated and finally the data was resampled to 22.5m x 22.5m. This method removed odd articles within uniform areas, to give a better aggregated result.

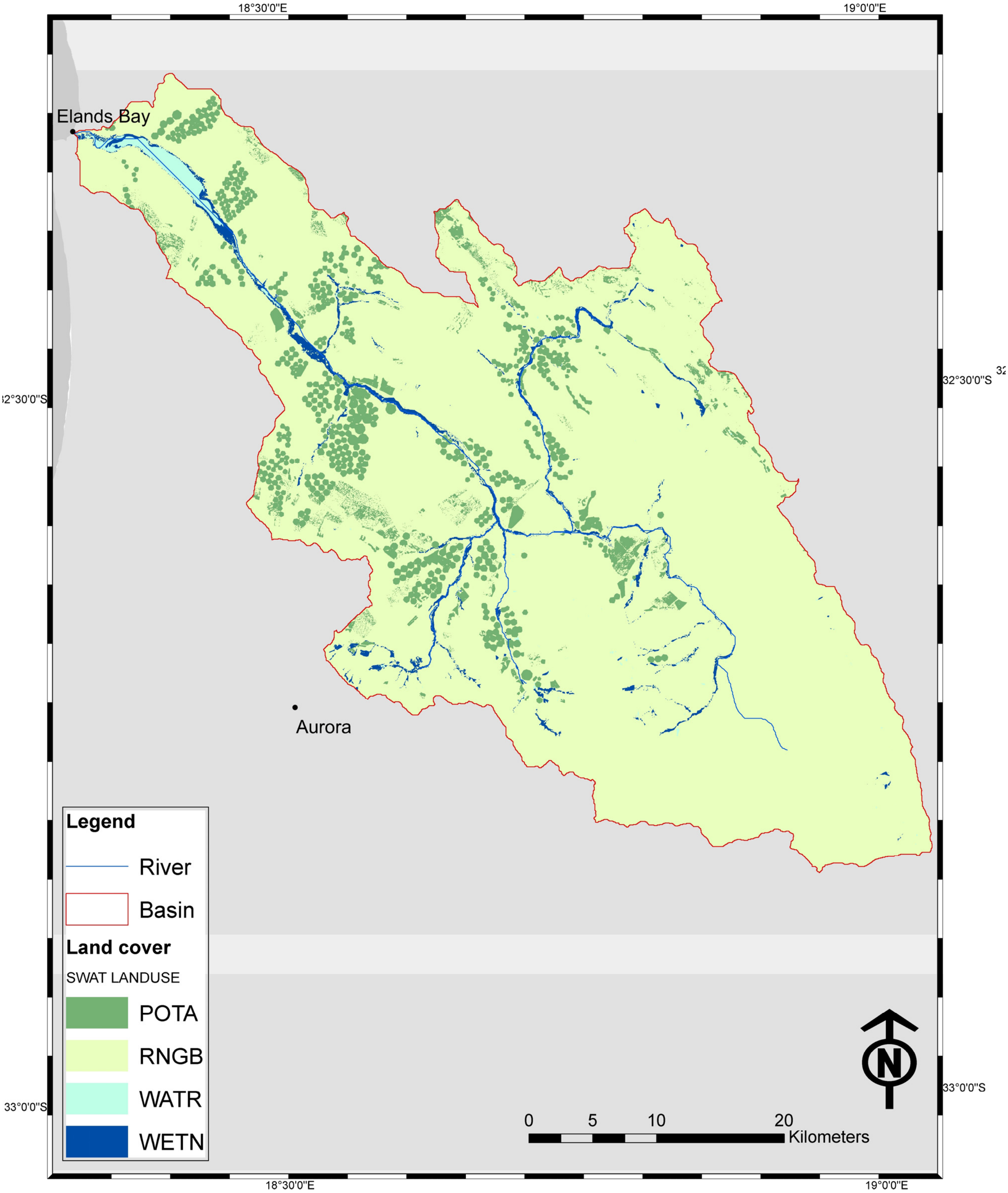


Figure 3.8 Land use map

The original twenty-two land cover classes were simplified into four main land use classes for use in the SWAT model. Table 4.3 lists the original land cover classed from the FSP project and in the right hand column the new values for the SWAT model are indicated.

Table 3.2 Land use conversion from FSP land cover classes to ArcSWAT classes

Fine Scale Planning	**SWAT**
Water	WATR
Wetlands	WETN
Bare rocks – Non coastal	RNGB
Plantations / Woodlots	RNGB
Improved grassland / golf courses	POTA
Farm feedlots	POTA
Hay bales (plastic covered)	RNGB
Mines – Sand	RNGB
Mines – Rock	RNGB
Coastal sand	RNGB
Urban areas / Farmyards	RNGB
Roads / Rails / Tracks	RNGB
Tall fynbos	RNGB
Cultivated – Ploughed (bare soil) (white & blue)	POTA
Bare soil – Non coastal	RNGB
Cultivated – New growth (red)	POTA
Natural fynbos – Disturbed (red)	RNGB
Cultivated – Normal (green)	POTA
Natural fynbos – Disturbed (old fields) (green)	RNGB
Bare soils – Non coastal (blue)	RNGB
Disturbed veld (in fields)	RNGB
Disturbed veld (outside fields)	RNGB

The following SWAT master database values for land cover were used to replace the FSP values from Thompson & Forsythe's (2006) land cover classes in an effort to simplify the land cover into only four classes that were already set up in the SWAT master database. Potatoes (POTA) were chosen to represent agricultural intensification practices where natural veld had been severely altered, as this is the predominant cultivated crop in the study area. This finally comprised approximately 46868ha. Where natural veld was still more or less in tact with some extensive farming practices, the SWAT classification for Rangeland Brush (RNGB) was applied, amounting to a total of 264794ha for this class. Water and wetlands remained in their separate categories, although the corresponding SWAT values were chosen for best fit. Water (WATR) referring to open water, covered the smallest area of 1316ha (less than 1% of the total area), and wetlands (WETN) which are vital in the hydrological processes comprised only 4886ha.

The SWAT master database had more than one type of wetland, and the type with bushes was chosen as opposed to wetlands with mainly grasslands or trees. This simplified classification was intended to set a base line for future modelling where minimal effort on spatial variability and complexity were spent classifying the land use. It was decided to only use land cover types that were already set up in the SWAT master database for the sake of simplicity. The SWAT model requires a vast number of parameters for each land use type and collecting data for these manually would require a large amount of time and effort which was not feasible for this study.

Figure 3.9 and Figure 3.10 show the area for each new land cover category in hectares and as a percentage of the total area respectively.

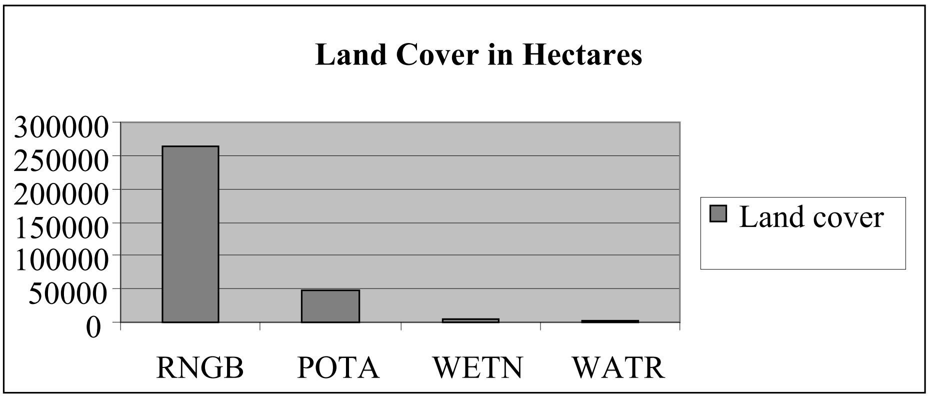


Figure 3.9 Area per land use type

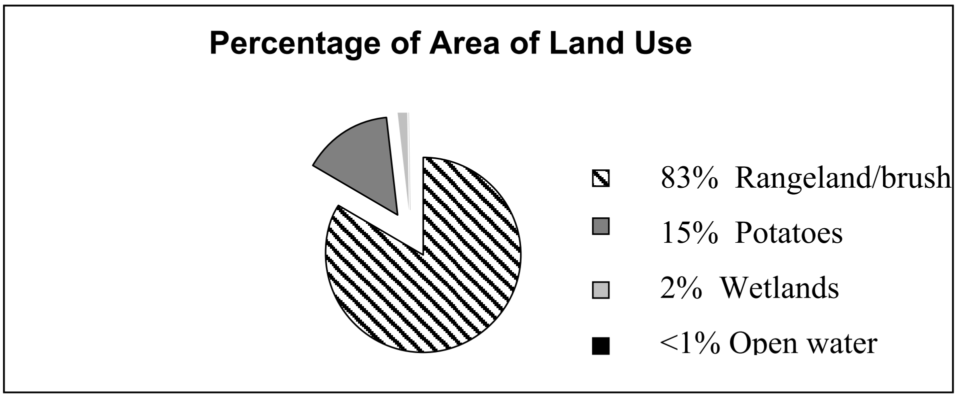


Figure 3.10 Land use percentages in the Sandveld, reclassified with ArcSWAT.

The GIS data are required as inputs to ArcGIS or ArcView 3.2 from which the SWAT model extracts tabular data as inputs into the hydrological modelling process.

3.2.5. Climate

Climate data is slightly different in that the user needs to supply exactly formatted tabular data for climate variables.

3.2.5.1 Daily data

SWAT requires daily variables for precipitation, maximum temperature and minimum temperatures. The remaining necessary climate data can be generated from a statistical climate data matrix provided by the user in the .dbf format, which is stored in the project database as the userwgn file. Creating this dataset is a complicated process and requires expert input from a hydrologist or climatologist. A special programme was written in Delphi programming language to convert the ARC input files into the fixed column format required by the SWAT model (Beuster 2007).

Daily precipitation was obtained from data collated by the Agricultural Research Council (ARC) weather office. Periods for available data vary from station to station, as seen in Table 3.3 and Table 3.4. Missing data for days and in some cases for a number of years adds to data uncertainty and inaccuracy of precipitation measurements, finally affecting the accuracy of output results. Data for only two stations was acquired namely Porterville and Riviera.

Table 3.3 Types of weather stations in the Sandveld, used for precipitation

NAME	START DATE	END DATE	YEARS	STATION TYPE
REDELINGHUYS	1991/01/01	2004/05/01	13.34	MECHANICAL
AFGUNST	1985/07/01	2004/05/31	18.93	MECHANICAL
RIVIERA	2001/05/01	2007/07/31	6.25	AUTOMATIC
PORTERVILLE	1973/01/01	2008/06/31	36.5	AUTOMATIC

The Porterville and Riviera stations are still in working order; however the data for this study was collected at different times which reflect in the date range. Porterville's measured rainfall was incorporated into the model inputs because of it's location against the neighbouring mountains and its tendency for higher rainfall than the stations situated in the coastal floodplain.

This approach was suggested by a hydrologist (Howard 2008, pers com) as typically most of the runoff generated in this catchment would originate in the mountains. The location of the station was manipulated within the GIS to fall on the Northern edge of Sub basin 5, more or less at the same elevation and aspect as the original station location. Figure 3.11 illustrates some of the problems encountered with the available climate data. Redelinghuys and Afgunst were abandoned in 2004, while Riviera was missing data from November 2003 to May 2004. The graph compares the average monthly precipitation for each station.

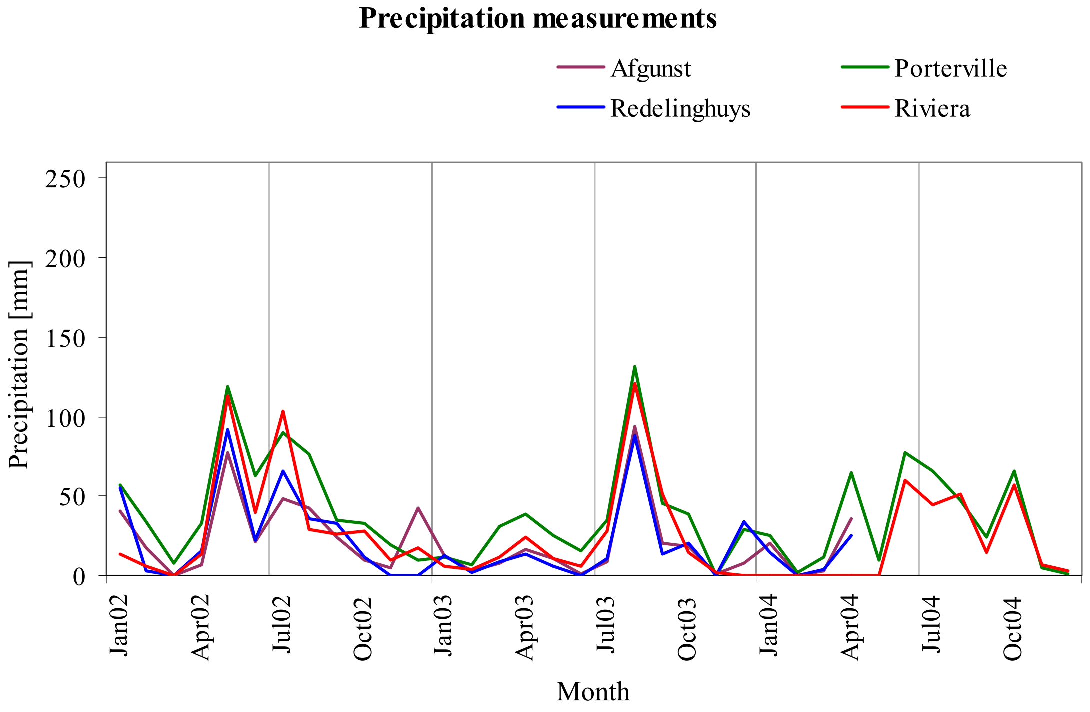


Figure 3.11 Comparison of precipitation measured at the rainfall stations

Only two temperature gauges were used by the model. Their available data is summarised in Table 3.4 below.

Table 3.4 Maximum and minimum temperature stations used in the simulation with start and end dates

NAME	START DATE	END DATE	YEARS	STATION TYPE
AFGUNST	1985/07/01	2004/05/31	18.93	MECHANICAL
RIVIERA	2001/05/01	2007/07/31	6.25	AUTOMATIC

ArcSWAT requires a separate location table for rainfall, temperature and weather generation functions, depending on the data available at each station. The SWAT programme requires the name for each station to be no longer than eight characters, hailing from the FORTRAN programming base. Each station was allocated a basic four letter identification and depending on the purpose, the relevant suffix was added i.e. _WEA for weather station, _TMP for temperature station, and _RAI for a rainfall station. Only automated stations provide the extra weather data in various formats. Compiling and formatting this data is one of the most time-consuming parts of setting up for the model. Directly measured weather data was not available for the following variables; solar radiation, wind speed and relative humidity. These are also required by the model. These values were statistically simulated using the weather generator methodology and data matrix discussed in Section 3.2.5.2

The location of precipitation and temperature gauges is illustrated in Figure 3.12 below.

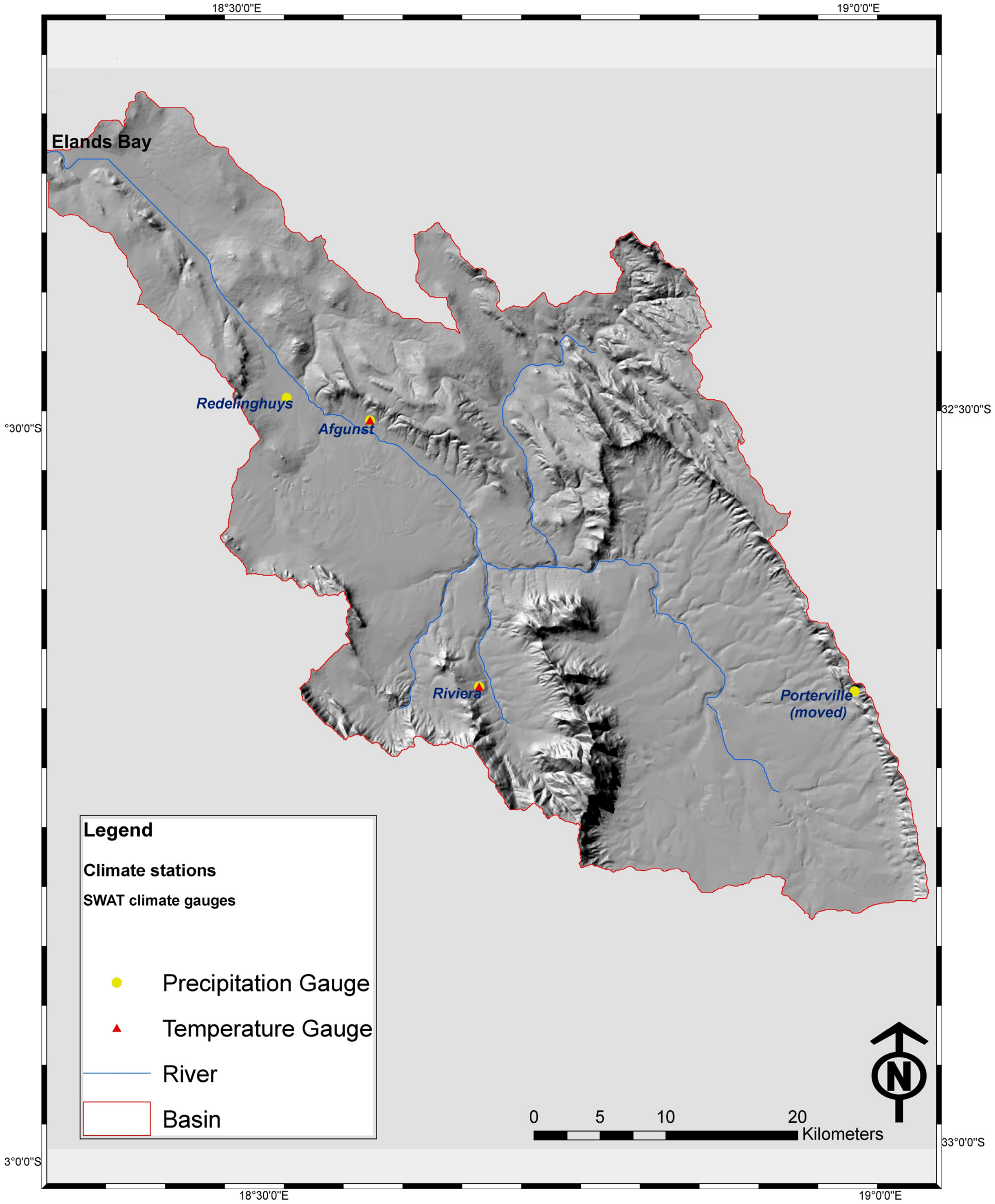


Figure 3.12 Climate station locations in the study area

3.2.5.2 Long term statistical climate data

The statistical data required for the weather generator routine was complex to acquire, with expert processing needed for some values where daily data was not available. SWAT requires daily precipitation and maximum/minimum air temperature to populate the weather matrix with averages for each month of the year over the total period covered by the station. Values are created (where measured data is not available) for solar radiation, wind speed and relative humidity for the weather generator function. Values for all these parameters may be read from daily records of observed data if these exist or they may be statistically generated to patch areas where data is missing; in which case the weather generator (WGN) is used. Ideally, at least 30 years of records are used to calculate parameters in the WGN file. Using a utility (Beuster 2007) especially designed for this purpose, the station data in Table 3.5 were used to create a statistical matrix from existing records.

Table 3.5 Weather station input used to create the WGN file

NAME	START DATE	END DATE	YEARS	STATION TYPE
AFGUNST	1985/07/01	2004/05/31	18.93	MECHANICAL
RIVIERA	2001/05/01	2007/07/31	6.25	AUTOMATIC

Statistical techniques documented in Neitsch et al (2005) were used to calculate the long term climate trends for the study area.

The user input file must contain the following fields in order to generate representative daily climate data for the sub basins. Where calculations were used to obtain statistical data for these fields, original formulas will be found in Neitsch et al, (2005). The 17 fields listed below were populated for each weather station, for each month in a year, creating a large reference table.

The **WLATITUDE** field contains the latitude of the weather station. The approximate value of 32.5 degrees South was used for all stations and for the solar radiation calculations.

WELEV is the elevation of the weather station in meters above mean sea level.

RAIN_YRS is the number of years of maximum monthly half hour rainfall data used to define values for averages per month of the year. The ArcSWAT counts the number of years for which rainfall is available – in this case 83.

TMPMX reflects average or mean daily maximum air temperature for each month in degrees centigrade (ºC). It is calculated by summing the maximum air temperature for every day in the month for all years on record and dividing it by the number of days. There are twelve fields for this dataset, one for each month of the year.

TMPMN represents the average or mean daily minimum air temperature per month of the year in ºC. This value is calculated in the same way as maximum air temperature, only using minimum mean air temperatures. There are twelve fields for this dataset, one for each month of the year.

The field: **TMPSTDMX** contains the standard deviation for daily maximum air temperature in a given month in ºC. It quantifies the variability in maximum temperature for each month of the year.

In the same way as the pervious field represented maximum temperature, **TMPSTDMN** is the standard deviation for daily minimum air temperature per month of the year in ºC, quantifying the variability in minimum temperature for each month.

PCPMM is the average or mean total of monthly precipitation in millimetres (mm) of water.

PCPSTD quantifies the variability in precipitation by using standard deviation for daily precipitation in each month, expressed in mm of water per day.

The skew coefficient for daily precipitation, **PCPSKW** is calculated for each month. This parameter quantifies the symmetry of the precipitation distribution about the monthly mean.

PR_W1 quantifies the probability of a wet day following a dry day in the month of the year over the entire record period. A dry day is a day with 0mm of precipitation. A wet day is a day with more than 0mm precipitation.

Similarly **PR_W2** statistically indicates the probability of a wet day following a wet day in the month.

The **PCPD** indicates the average number of days of precipitation in the month of the year.

The maximum half hour rainfall **RAINHHMX** represents the most extreme 30-minute rainfall intensity recorded in the entire period of record. It is represented in mm of water for each month of the year. In the study the standard value of 55mm was used for all months and all stations failing the availability of measured data (Beuster 2007, pers com).

The **SOLARAV** variable contains the average daily solar radiation for each month. It is calculated by summing the total solar radiation for every day in the month for all years of record and dividing it by the number of days summed. Solar radiation was only available from one station in the study area, Riviera. Other stations had records of the number of daylight hours. These were converted to the required SWAT input using the empirical relation as set out by Glover & McCulloch (1957) in the utility created by Beuster (2007).

DEWPT represents the average daily dew point temperature per month of the year in ºC. The dew point temperature is the temperature at which the actual vapour pressure present in the atmosphere is equal to the saturation vapour pressure. This value is calculated by summing the dew point temperature for every day in the month for all years of record and dividing by the number of days summed.

WNDAV is the average daily wind speed at each station for each month of the year and is measured in meters per second. This value is calculated by summing the average or mean wind speed values for every day in the month for all years of record and dividing by the number of days summed.

Where some stations provided only total wind run, this was converted to wind speed using the Sandveld Weather Utility (Beuster 2007).

3.2.6. Agricultural Data

Although the model can incorporate various land use data, the most problematic to set up is agricultural data. This is because there are lists of scheduled events, applications of chemicals and soil management that add depth and complexity to the functional contribution of agricultural land management to the outputs of the model. The SWAT model requires a number of parameters which can be set for these. The parameters require expert interpretation and value setting by an agronomist who understands how the particular crops are cultivated in the study area. The expertise of fertiliser and pesticide suppliers are required for the chemical breakdown of these products, and SWAT focuses on organic and inorganic nitrogen and phosphorus for water quality results.

The default agricultural data for potato production in the USA (cold season row crop) was used in the model, along with the default values for conventional tillage, and for applications of fertiliser and pesticides. Agricultural management practices were not included in the setting up of the model for this initial run. It will be a very important input when the model is used for water quality and sedimentation modelling.

3.3. CRITERIA FOR MODEL SELECTION

Experienced hydrologists warn against using hydrological models without the necessary discerning expertise. Watson & Burnett (1995) provide guidelines using the following criteria to be considered for model selection:

3.3.1. Is the model appropriate for the study area and the problem being investigated?

- The model should be able to address the hydrologic conditions at hand. For example, in the case of the Sandveld, it has a non-homogenous aquifer with anisotropic conditions, possibly changing boundary conditions, and time-variable precipitation and infiltration rates.
- The model should be suitable for the particular problem(s) being studied. Surface flow results were required for the Sandveld, with the option of iterations for specific problem investigation once flow results are reliable.

3.3.2. What are the input data requirements?

- The availability of measured input data will determine whether a particular model is suitable for use in a particular study area or not.
- How well does the model cope with data gaps either where entire variables are missing or where historical sequential data is incomplete, as experienced in this study?

3.3.3. Computer requirements, ease of use and user support

- Hardware requirements should be checked upfront, as it could be a limiting factor to using particular software.
- Watson & Burnett (1995) suggest initial consideration of the ease of user interface, as this could take up large amounts of time and effort if the model is not well constructed. This is often related to the ease or effort required preparing input data, which could contribute to the generally high investment of setting up time.
- An existing, wide local user community may cut down time spent on setup and output problem solving. The availability and level of expertise and software vendor support are also important to consider.
- There should be hardcopy support in terms of appropriately complex yet understandable documentation.

3.3.4. Output requirements

- It is important to consider how the programme will interpret the output data, and whether this is suitable to the study.
- The availability of graphical pre- and post processing is a great benefit, and this is where the GIS used in conjunction with a hydrological model is of value.
- Does the model provide easy mesh (grid) generation and condensation with enough specificity to the problem focus and is there enough elasticity in terms of presenting results?
- Flexibility regarding units of measure and display both in terms of input and output could be very useful.
- Consideration should be given to the restart capabilities of the software, given the high intensity of data acquisition and manipulation. Hydrological modelling may require a multitude of iterations and scenario changes.

The particular computer model used should be well understood in order to determine if it meets the project specific requirements, the most accurate input data available for the area and the problem being studied. Watson & Burnett (1995) use as an example the question whether measured water levels, transmissivity, storativity and cation exchange capacity already exist as suitable data sets, as interpolated data is seldom detailed enough.

3.4. RATIONALE USED FOR HYDROLOGICAL MODEL SELECTION IN THIS STUDY

Several hydrological software options were investigated for the Sandveld application, including ArcHydro, HECRAS, ACRU and AVSWATX, then finally ArcSWAT, which was selected. Important factors considered for this particular project were GIS capability or interaction with ESRI compatible GIS software, as this is the current industry standard in South African government departments. Added reasons were the cost of software, suitability for agricultural applications, built-in land use scenario functionality and flexibility which were suited to South African circumstances. Most models are produced in the Northern Hemisphere for particular circumstances and they may require adaptation for use in South Africa.

Models commonly used by professional hydrologists in South Africa such as Pitman, a monthly time step, semi-distributed rainfall-runoff catchment hydrology model and the Variable Time Interval (VTI) model which were not investigated as they have no GIS interface.

ArcHydro, an extension for the ESRI software ArcGIS, is not an actual hydrological model, although it can be used to pre-process spatial data for input into an hydrological model. It uses a DEM and has all the necessary subroutines to identify and calculate basin area, slope and direction, as inputs into a model, but it doesn’t model hydrological processes, making it an inappropriate choice for this study.

HECRAS was found to be suitable for modelling inundation area during flood events simulating river hydraulics, but it does not aim to model long term rainfall, or overland processes like vegetation interception of rainfall. It functions off a UNIX platform which requires specialist installation and knowledge. The data format is raster based and uses a DEM which it converts to a Triangulated Irregular Network (TIN). HECRAS uses the ARC/INFO AML language, which is older technology, command-line driven and not user friendly. The final result is a series of inundation polygons along the flow path. This software requires specialist software knowledge that is difficult to acquire. Although its spatiotemporal visualisation abilities are attractive, it would not be able to model long term climate scenarios as required for this study.

The South African based **ACRU** model was an attractive option as it is suited to the local conditions and would require little if any adaptation of local data sources. S or A-pan values corrected for open water evaporation are commonly found in South Africa as Hughes (1997) explains. ACRU uses A-pan evaporation data values, the adapted SCS curve values for South Africa, and Schulze's climate atlas for data input. This is a possible future model for use in the Sandveld. ACRU was not chosen for use in this study as training and support were not readily available at the time of inception of this study.

AVSWATX and ArcSWAT

Both AVSWATX and ArcSWAT are interfaces that use the SWAT2005 model, which was written in FORTRAN programming language. They sit as extensions within ESRI software packages, namely ArcView 3.2 or ArcGIS 9.1 or 9.2. The ArcSWAT and ArcGIS 9.2 combination are the latest release, and were eventually successfully and extensively investigated. It is a highly flexible and comprehensive, physically based model with a strong emphasis on particularly agricultural land use scenarios, which made it the most attractive option for this study.

3.5. INTRODUCING ARCSWAT

This introduction details the reasons for choosing ArcSWAT and preparations necessary to implement it. Soil Water Assessment Tool (SWAT) was developed out of several preceding models (Neitsch et al 2005) by Arnold for the United States Department of Agriculture. It was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large watersheds with varying spatial and temporal conditions. A watershed scale, continuous time model, it was designed to study long term effects on large and complex areas. It is not suited to modelling single flood events. The SWAT model underlies the ArcSWAT interface where ArcGIS is used to provide geographic analyses, which feed into the SWAT model and provide hydrological outputs.

SWAT as described by Bian et al (1996) is a semi-empirical and semi-physically based model. It adopts existing mathematical equations approximating the physical behaviour of the hydrologic system. It is also an advanced lumped or semi-distributed model dividing the catchment into discrete area units for analysis which makes it suitable for integration with a GIS. SWAT divides the watershed into sub basins, functioning as a smaller hydrological unit. Each sub basin is in turn subdivided into Hydrological Response Units (HRU's); discrete areas of similar, slope, soil and land use through which water is expected to flow in a more or less homogenous fashion. Each of these is analysed separately to improve the accuracy of the model, but results are lumped per sub basin and averaged for the entire catchment in the final report.

Model inputs include the physical characteristics of the watershed and its sub basins such as precipitation, temperature, soil type, land slope and slope length, width and slope, Manning's n values and MUSLE K factors. Either simulated or measured precipitation and temperature values may be used in SWAT.

No matter what physical problem is studied using ArcSWAT, water balance is the driving force behind everything that happens in the watershed. Neitsch et al (2005) explain how conceptually, the hydrological cycle is divided into two main sections within the model. The upland processes are emulated in the first part (weather, surface runoff, return flow, percolation, crop growth, groundwater flow and evapotranspiration), where the movement of water on and through earth materials is quantified along with elements which are transported with the flow. The second part considers channel processes (transmission losses, pond and reservoir storage, irrigation water transfer and channel routing). It models the path of the water and substances suspended in it as it travels through the channel (primarily sediment, nitrogen and phosphates) in each sub basin to the watershed outlet.

In terms of water balance storages (see Chapter 2, Section 2.2.4) for each HRU in the watershed, four layered storage possibilities exist. Snow is the first, then a soil profile of up to 2 meters, followed by a shallow aquifer underneath it comprising the next 18 meters up to 20 meters, and a deep aquifer sitting below 20meters underground is the final storage space from which water is ultimately completely lost to the SWAT system. A surface:runoff coefficient is used in the SCS curve number method (SCS 1972). The Modified Universal Soil Loss Equation (MUSLE) of Williams & Berndt (1977) is incorporated into SWAT to represent sediment yield. SWAT's command language defines water movement for each of the sub basins, rivers, ponds, and reservoirs within the watershed.

The SWAT model uses daily time steps and distributed parameters to account for some spatial differences in channel morphology, soils, land use, climate and topography. It treats each homogenous area separately, connecting outflows to inflows through unique, discrete areas. It then lumps the results at the outflow of each unique area; ultimately summarizing them for the whole watershed at the final outlet.

The SWAT model includes eight major components (Neitsch et al. 2005):

- **Hydrology** considers the where, how and why of water moving over or through the earth material.
- **Weather** is the engine for hydrology and all the following processes, and is a key input into the model.
- The **sedimentation** component investigates the movement of sediment with water through the catchment. This becomes increasingly important with extreme weather events.
- **Soil temperature** is a key factor for the general movement of water through soil and plants, influencing it's speed and losses to the soil and plants.
- The focus in SWAT is on **agricultural crops**, so crop growth is an important module in yield considerations. For hydrological purposes, biomass, canopy storage, rooting depth and uptake of nutrients and water are essential to quantify within the hydrological cycle.
- In the case of **nutrients**, particularly Nitrogen and Phosphorus are of importance in estimating levels of pollution.
- Similarly to nutrients, **pesticides** are broken down into their Nitrogen and Phosphorus content for routing through the catchment. Other elements are not included in the default setting, but may be included with expert assistance from the software developers.
- Agricultural management brings together a calendar of applications (pesticide and nutrients), tillage, irrigation, crop rotation and other events that influence the availability and quality of water.

3.5.1. Preparation prior to installing SWAT

The software itself is available on the internet (http://www.brc.tamus.edu/swat/arcswat.html) free of cost. The user downloads and extracts the .zip file containing the interface and SWAT installation files.

3.5.1.1 System requirements

The minimum system requirements for ArcSWAT are a personal computer using a Pentium IV processor or higher, running at 2 gigahertz or faster. A minimum of 1 gigabyte of RAM, a minimum of 500 megabytes of free memory should be available on the hard drive, but a two gigabyte hard drive is recommended.

3.5.1.2 Software requirements

To run ArcSWAT, the following list of software modules is required to be installed on the computer: SWAT2005/ArcSWAT 1.0 Interface, Microsoft Windows XP or Windows 2000, ArcGIS

9.2 with SP2 (build 766), ArcGIS Spatial Analyst 9.1, ArcGIS Developer Kit (usually found in: C:\ProgramFiles\ArcGIS\DeveloperKit), ArcGIS Dot Net support (usually found in: C:\ProgramFiles\ArcGIS\DotNet), Microsoft .Net Framework 1.1. To read the help files, Adobe Acrobat Reader Version 7 or higher is needed.

3.5.2. Installation of the software

To install ArcSWAT, the .zip file is extracted, and then the ArcSWAT install program is activated by double-clicking on the "setup.exe" icon. The ArcSWAT documentation and help files are installed in the ArcSWAT\ArcSWATHelp\ folder in the install directory (C:\Program Files\SWAT\ArcSWAT).

The first step after setting up the software is to check that all the required data is available in the correct format. Several documents provided by the SWAT producers are available to detail these requirements (Neitsch et al 2002; 2004; 2005; Srinivasan 2005). Some of these documents hail back to earlier versions of the programme; for example, they may refer to the AVSWATX extension designed to use in conjunction with ArcView 3.2 and SWAT2000. Although many parts of this documentation are valid, the user is cautioned not to confuse the different versions of SWAT. SWAT2005 is the most recently published version of SWAT. It may require a measure of interpretation where the old technology meets the new if an older manual is consulted. Several versions of these documents are available, and the user needs to ensure that they have the most recent documentation if using ArcSWAT to avoid confusion. Srinivasan (2005) provides a step by step set-up procedure for the model, using default datasets and US data.

Figure 3.13 below provides a brief overview and road map for setting up an ArcSWAT project to run. The green boxes indicate data inputs for the model, for example, soil, land use and slope classes. These are fed into the grey blocks which represent SWAT tools or processes. These processes provide outputs (in the orange boxes) at various stages of running the model. The topographic report for instance is the result of a topographic analysis run by the ArcSWAT interface using the DEM. It provides topographic information on each sub basin delineated by the model. The purple boxes indicate iterative processes where variables can be adjusted to change outputs and results from the model until a satisfactory final report is produced.

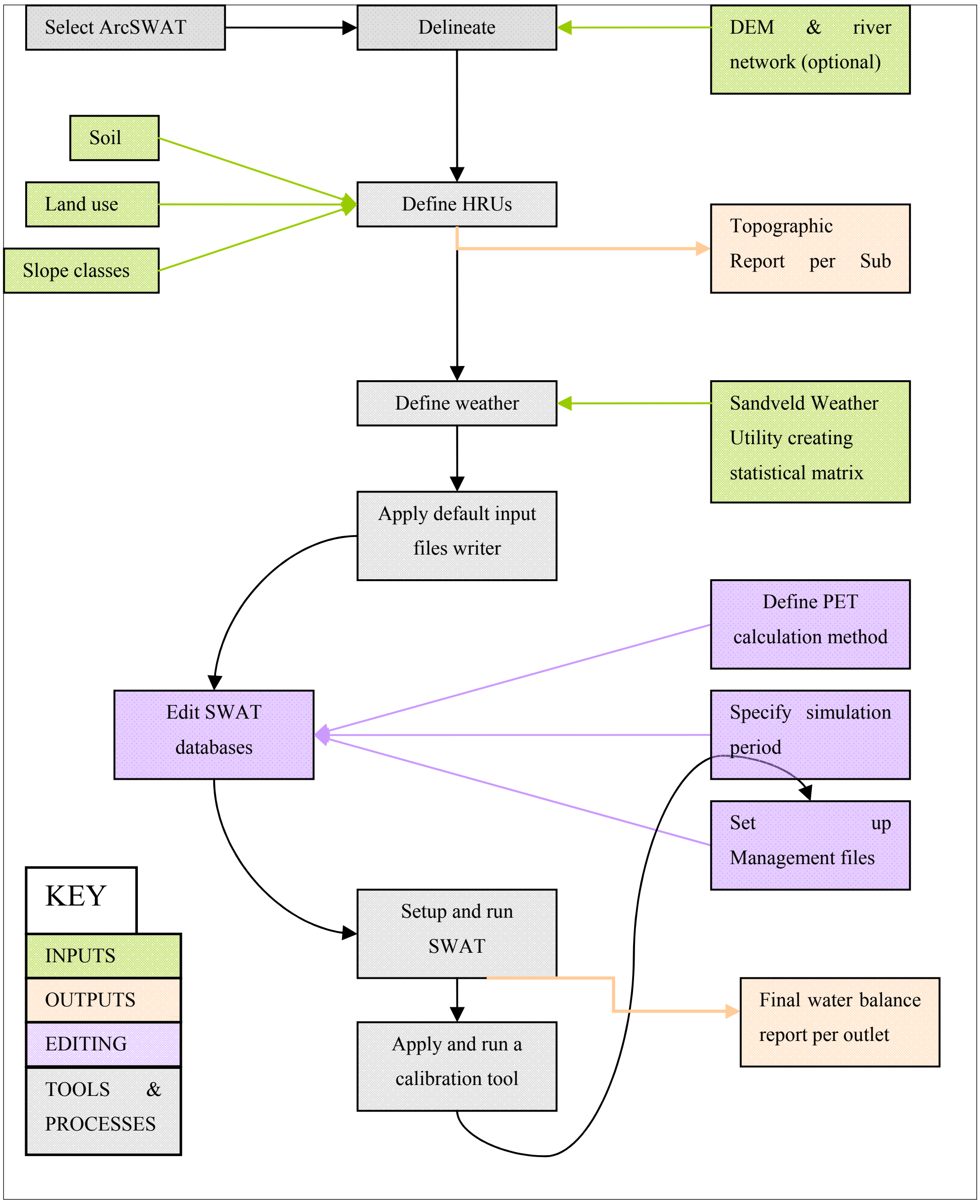
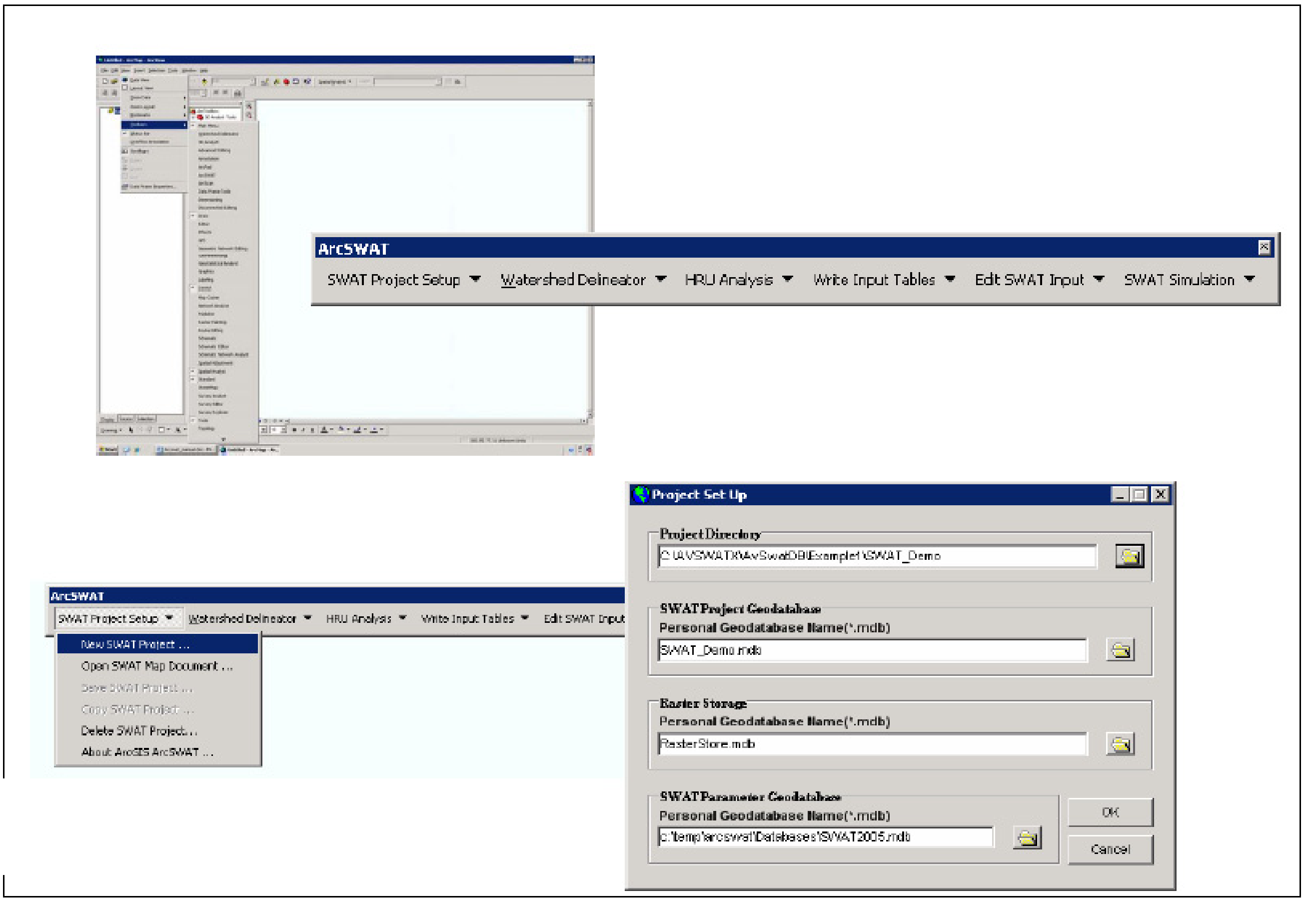


Figure 3.13 Workflow diagram to setup and run ArcSWAT

3.5.3. Setting up the model

GIS data was first collected, the DEM, soils data and land cover, each of these processed as described earlier in sections 3.2.2, 3.2.3 and 3.2.4. The SWAT menu bar (Figure 3.14) appears in the graphic user interface (GUI) of ArcGIS, and the user starts on the left hand side at the first menu option, which allows basic project and data management functions. This is where the project name and directory are opened, set up and saved.



Project Directory
C:\AVSWATX\AvSwatDB\Example1\SWAT_Demo

SWAT Project Geodatabase
Personal Geodatabase Name(*.mdb)
SWAT_Demo.mdb

Raster Storage
Personal Geodatabase Name(*.mdb)
RasterStore.mdb

SWAT Parameter Geodatabase
Personal Geodatabase Name(*.mdb)
c:\temp\arcswat\Databases\SWAT2005.mdb

Source: Srinivasan (2005)

Figure 3.14 Main toolbar and project set up menu

ArcSWAT sets up a default folder structure within the project folder created by the user. The next menu option from the left is the Watershed Delineation sub menu (Figure 3.15). In this section, the DEM is uploaded, clipped to a mask if necessary and processed by the Spatial Analyst component of the GIS as directed by ArcSWAT. Sinks are filled; flow direction and flow path (channels) are identified. If accurate river networks are available, they are added once the DEM has been processed. The software then creates a channel network with flow direction, outlets and a longest path dataset in vector format. The processed and newly created datasets are stored in the current project directory in the typical ArcGIS geodatabase architecture, with a generic ArcSWAT configuration. The sequence of steps is to first create a stream network and then to delineate the catchment (Figure 3.15). The size of sub basins can be manipulated for sub catchment determination, by manually editing inlet and outlet points.

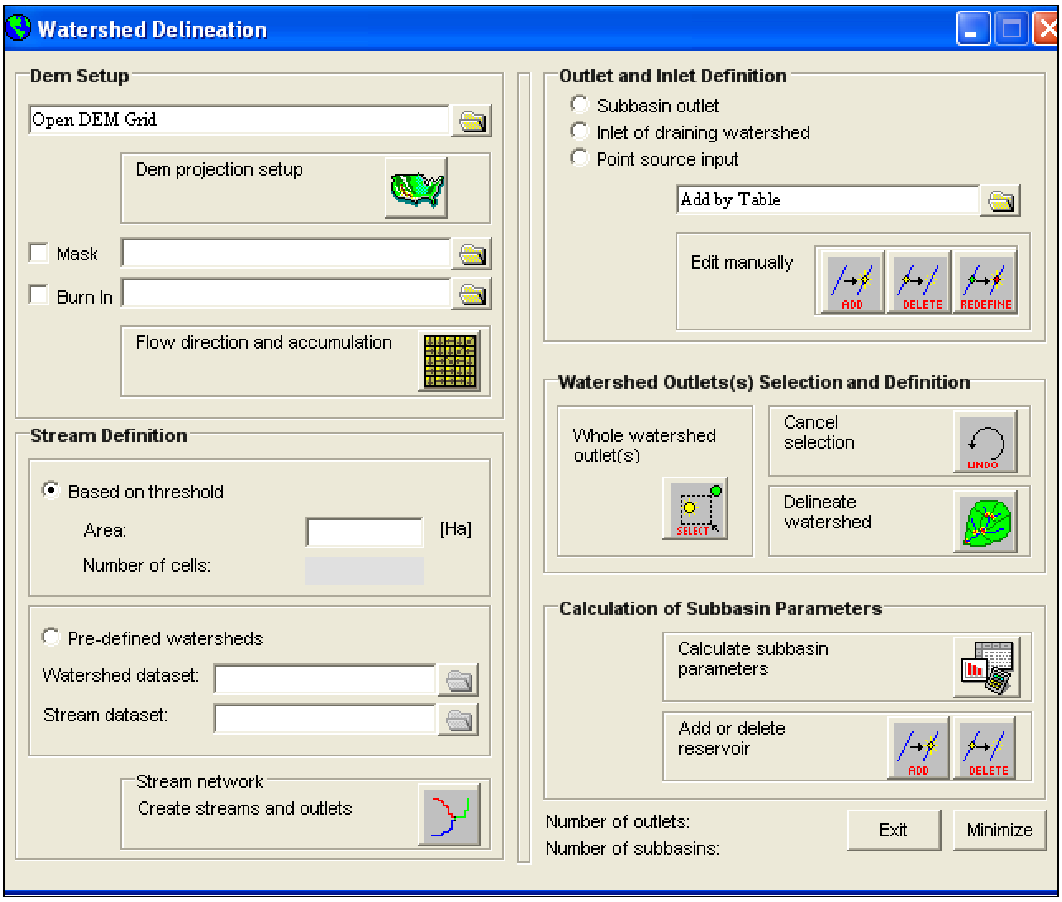
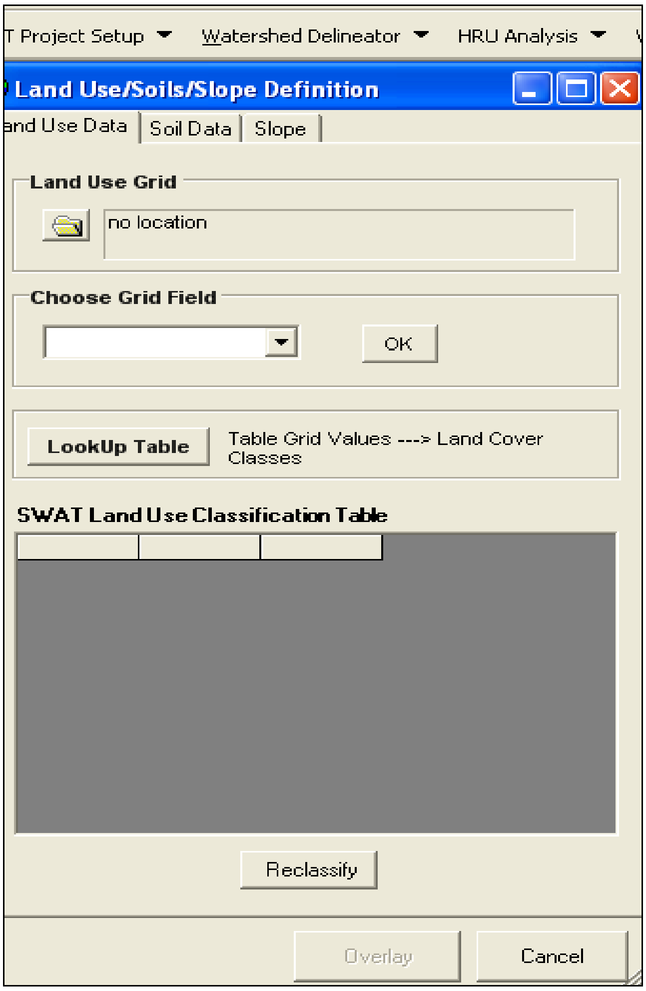


Figure 3.15 The Watershed delineation sub menu

This menu is important in setting up the actual hydrology for the area. Placement of outlet and inlet points determines how the software delineates the subbasins and reaches. The final outlet point must be selected before the delineation process begins. The final option in the menu is for inputting reservoirs providing one of the useful ways to reflect water storage within the model. For the purposes of this study, water abstraction and impoundment was not taken into account. The interface accesses ArcGIS and Spatial Analyst to create the basin (or watershed), and set up flow direction between pixels, so that drainage lines can be established. Sub basins are created between inlet/outlet points that the user places strategically. In this way the number of sub basins is determined and can be refined to emulate actual functioning of drainage areas in a watershed. This is where a good knowledge of the local hydrology is essential for interpretation into the model, considering its strengths and weaknesses.

Once the watershed component is set up, the user moves onto the next sub menu in which the land use and soil data layers are added to the watershed framework. It is in the overlay menu in Figure 3.16 that the input layers that determine Hydrological Response Units (HRU) are defined.

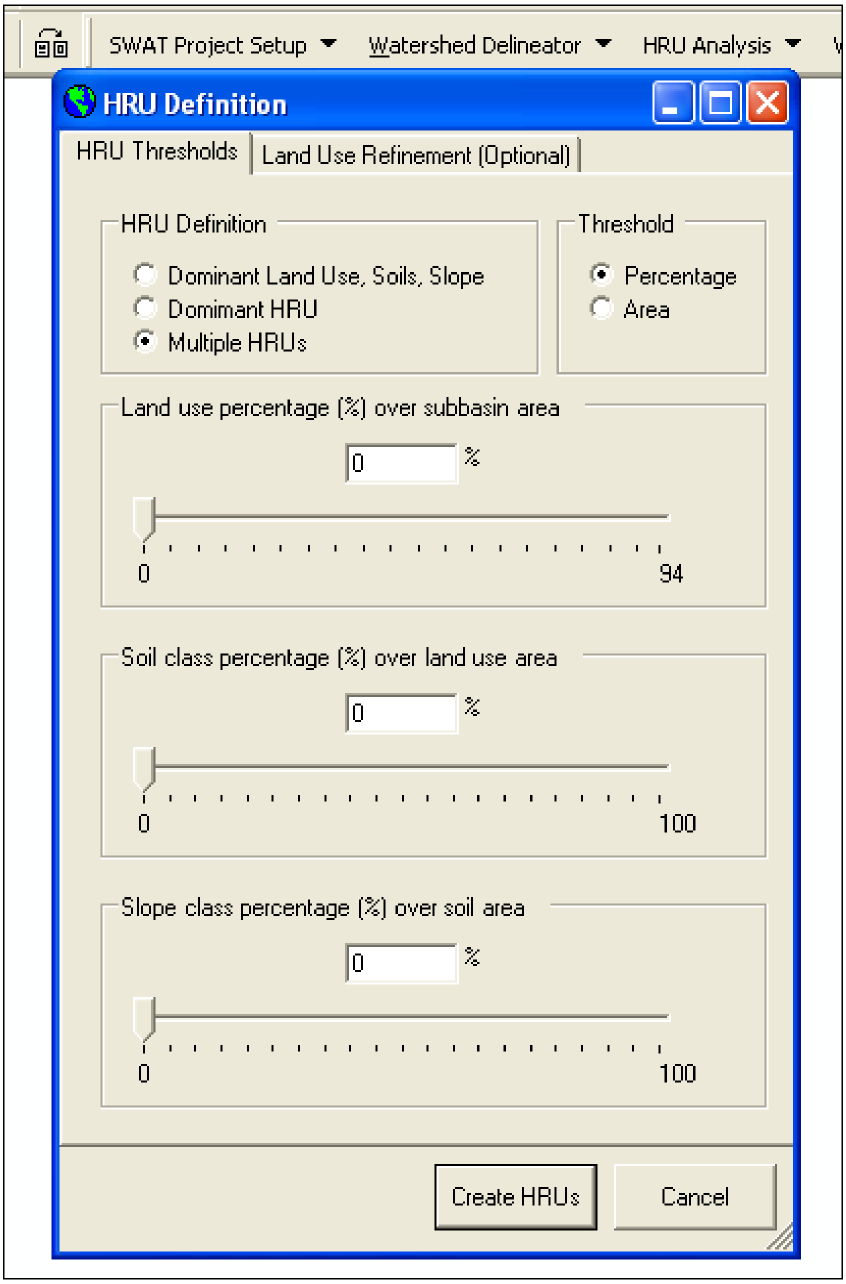


no location

Table Grid Values ---> Land Cover Classes

Figure 3.16 Menu for overlay analysis

SWAT uses grid data sets although shapefiles are an input option for land use and soil data; these are converted to raster for the overlay process. Results from the delineation process provide slope inputs. The user may choose whether to use the average slope over the whole catchment or to divide slope into specified elevation bands. In this run of the model, single slope (i.e. the average slope) was used. Slope, land use and soil data are overlaid to identify unique areas that form homogenous hydrological response units, i.e. an HRU. If data from elsewhere other than the United States is used, as in this case, the input data requires a special look-up file for the reclassification of the input files before the overlay function is performed. Once all of these factors have been defined, the overlay button at the bottom of the form becomes active and the first part of HRU definition is initiated. Figure 3.17 is a screenshot of the next step in the process where the thresholds defining HRU's can be manipulated.



HRU Definition
○ Dominant Land Use, Soils, Slope
○ Dominant HRU
● Multiple HRUs

Threshold
● Percentage
○ Area

Land use percentage (%) over subbasin area: 0 %

Soil class percentage (%) over land use area: 0 %

Slope class percentage (%) over soil area: 0 %

Figure 3.17 Menu for threshold setting – HRUs

The overlay function is a computationally intense, where spatial variability and resolution of the input data sets determine the length of time required for processing the spatial data. It is important to produce an output with HRUs that reasonably emulate the real world problem without creating, unnecessary detail. For this study the percentage area thresholds of 10 percent each for slope, land use and soil properties were set. None of the land use refinement options were used. This is one area where the skill and knowledge of an experienced hydrologist might play an important role in determining the success of the project. Correct preparation of GIS data and pragmatic weighing of resolution versus processing time are essential. Several iterations of this process may be necessary until an acceptable result is achieved.

The following sub menu (Figure 3.18) fronts a large body of algorithms and complex mathematical modelling. This menu converts pre-processed input files to SWAT-format files.

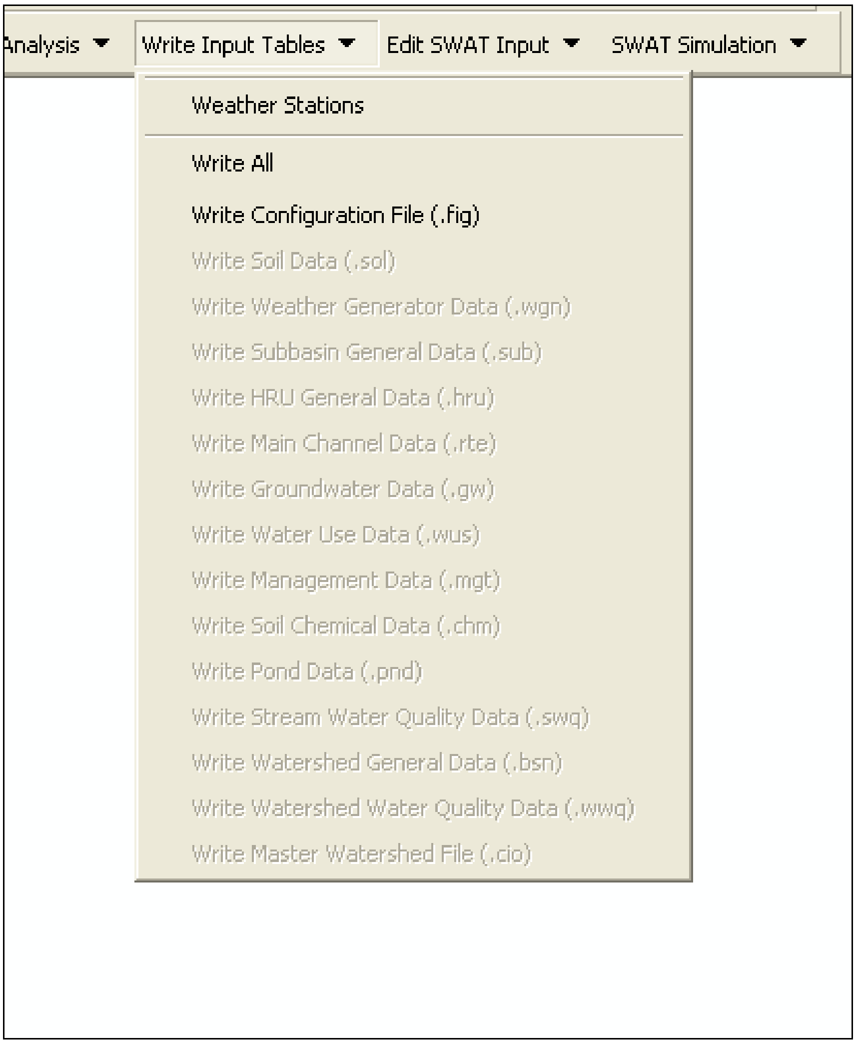
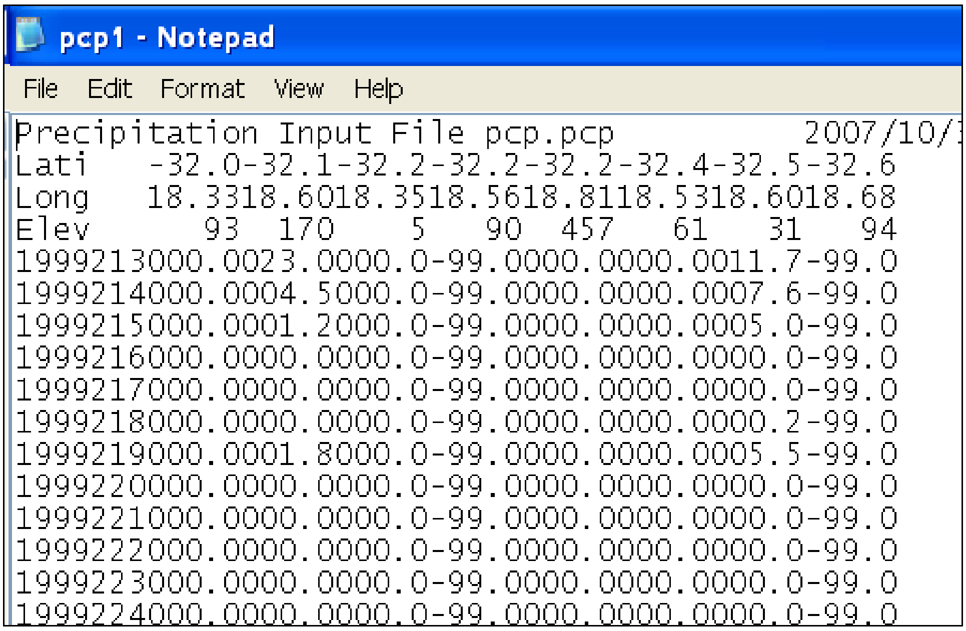


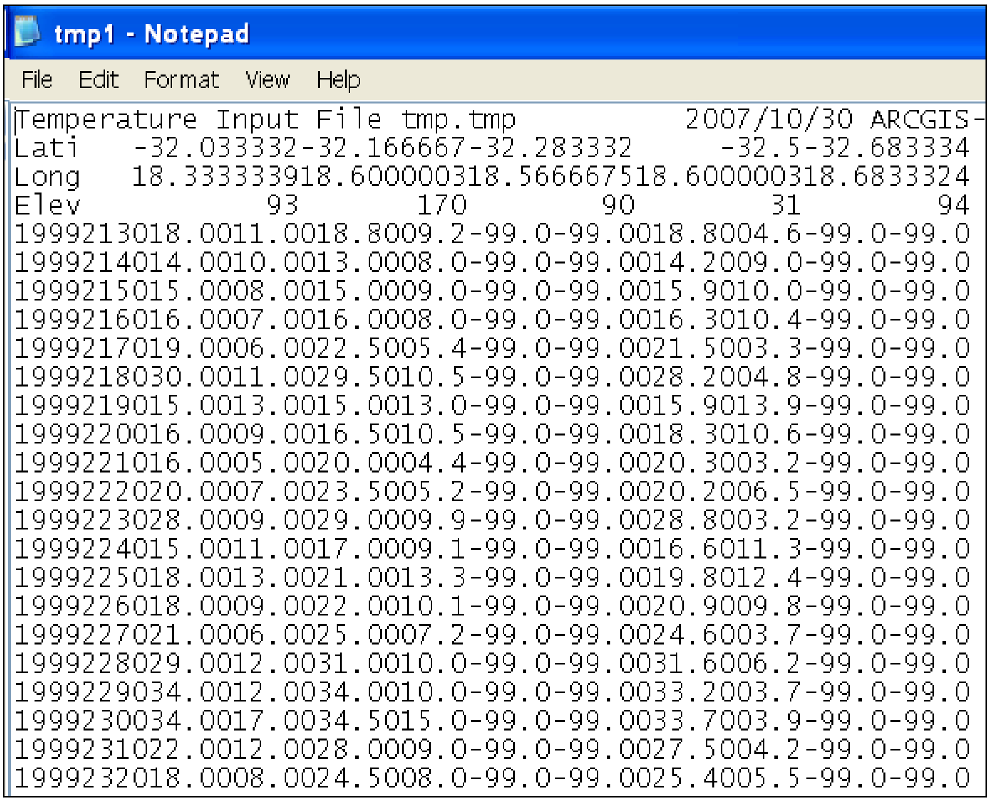
Figure 3.18 Write inputs menu

The input text files need to be in the file format with the exact naming convention specified in Neitsch et al (2004). The model will look for specific tables in routines linked to various process algorithms. Figure 3.19 and Figure 3.20 show the text file formatting for daily precipitation and temperature data respectively. These input files are imported into and saved in the ArcSWAT geodatabase.



```
Precipitation Input File pcp.pcp        2007/10/
Lati   -32.0-32.1-32.2-32.2-32.2-32.4-32.5-32.6
Long   18.3318.6018.3518.5618.8118.5318.6018.68
Elev      93  170    5   90  457   61   31   94
1999213000.0023.0000.0-99.0000.0000.0011.7-99.0
1999214000.0004.5000.0-99.0000.0000.0007.6-99.0
1999215000.0001.2000.0-99.0000.0000.0005.0-99.0
1999216000.0000.0000.0-99.0000.0000.0000.0-99.0
1999217000.0000.0000.0-99.0000.0000.0000.0-99.0
1999218000.0000.0000.0-99.0000.0000.0000.2-99.0
1999219000.0001.8000.0-99.0000.0000.0005.5-99.0
1999220000.0000.0000.0-99.0000.0000.0000.0-99.0
1999221000.0000.0000.0-99.0000.0000.0000.0-99.0
1999222000.0000.0000.0-99.0000.0000.0000.0-99.0
1999223000.0000.0000.0-99.0000.0000.0000.0-99.0
1999224000.0000.0000.0-99.0000.0000.0000.0-99.0
```

Figure 3.19 Screenshot to illustrate format of precipitation input text file



```
Temperature Input File tmp.tmp          2007/10/30 ARCGIS-
Lati   -32.033332-32.166667-32.283332     -32.5-32.683334
Long   18.333333918.600000318.566667518.600000318.6833324
Elev           93       170        90        31        94
1999213018.0011.0018.8009.2-99.0-99.0018.8004.6-99.0-99.0
1999214014.0010.0013.0008.0-99.0-99.0014.2009.0-99.0-99.0
1999215015.0008.0015.0009.0-99.0-99.0015.9010.0-99.0-99.0
1999216016.0007.0016.0008.0-99.0-99.0016.3010.4-99.0-99.0
1999217019.0006.0022.5005.4-99.0-99.0021.5003.3-99.0-99.0
1999218030.0011.0029.5010.5-99.0-99.0028.2004.8-99.0-99.0
1999219015.0013.0015.0013.0-99.0-99.0015.9013.9-99.0-99.0
1999220016.0009.0016.5010.5-99.0-99.0018.3010.6-99.0-99.0
1999221016.0005.0020.0004.4-99.0-99.0020.3003.2-99.0-99.0
1999222020.0007.0023.5005.2-99.0-99.0020.2006.5-99.0-99.0
1999223028.0009.0029.0009.9-99.0-99.0028.8003.2-99.0-99.0
1999224015.0011.0017.0009.1-99.0-99.0016.6011.3-99.0-99.0
1999225018.0013.0021.0013.3-99.0-99.0019.8012.4-99.0-99.0
1999226018.0009.0022.0010.1-99.0-99.0020.9009.8-99.0-99.0
1999227021.0006.0025.0007.2-99.0-99.0024.6003.7-99.0-99.0
1999228029.0012.0031.0010.0-99.0-99.0031.6006.2-99.0-99.0
1999229034.0012.0034.0010.0-99.0-99.0033.2003.7-99.0-99.0
1999230034.0017.0034.5015.0-99.0-99.0033.7003.9-99.0-99.0
1999231022.0012.0028.0009.0-99.0-99.0027.5004.2-99.0-99.0
1999232018.0008.0024.5008.0-99.0-99.0025.4005.5-99.0-99.0
```

Figure 3.20 Screenshot to illustrate format of temperature input text file

The final result is a range of text output files which are written to the project directory. The write input tables menu first deals with climate station location points, and links the spatial data to daily measured (text files) and statistical data (in the project database, in the **USERWGN** table). Next the user has the option to 'write all' files, which should read all input files in the specified directory and create all the remaining necessary data files required by the SWAT programme. This option was not possible in any of the iterations tried in this study. The model did not respond, and the computer automatically shut down. The process was taken up repeatedly at the beginning of this menu. No error message was produced to help identify problematic inputs. The alternative method where each input file is written individually (one after the other becomes available on the drop down menu once the previous one is completed) was more useful in identifying problematic datasets. A trial-and-error approach was necessary to complete the menu where each input was rejected by the model until it was absolutely correct.

Once this menu is completed, the model is almost set for running a simulation. At this point, the user has the option to edit input parameters in the "edit SWAT input" menu. Some parameters are easily adjusted, while other records where the data includes a multitude of numeric input can be time-consuming and provide opportunity for more input errors. The menu can be accessed at any point hereafter again, to reset parameters for 'tuning' the model or to run several scenarios. Each time the edit menu is used and values are adjusted, the model must be re-run. Should some of the initial input files be edited e.g. land use and soil, then the user has to return to the watershed delineation menu and re-run all the processes from that point forward.

In the hands of the experienced hydrological modeller, this becomes an analytical and management powerhouse. It is important for the user to understand which routines would best suit the data available and the results sought. So knowledge of the equations used, their strengths and weaknesses in terms of the output they generate is invaluable. For instance SWAT offers the choice of two options for surface estimation; the SCS curve number method (SCS 1972; Rallison & Miller 1981) as well as the Green and Ampt infiltration method (Green & Ampt 1911). The user needs to specify which of these equations will be used, and know the inputs required for each in order to apply it appropriately. In South Africa the SCS curve number method is commonly used and has been adapted for our conditions (Schulze 1995).

The final sub menu on the SWAT menu bar is the SWAT simulation tab. The 'run simulation' command runs the model, creating final output reports. Reports are discussed in more detail in Chapter 4.

The remaining options on the menu bar are: sensitivity analysis, auto calibration and uncertainty analysis; rerun calibrated model and sensitivity/calibration reports are covered in Section 3.7.

3.6. CHALLENGES

The SWAT hydrological model uses the ArcSWAT interface for ArcView 9.1 and 9.2. The software presents many challenges to the user as its design can be problematic. The greatest challenge is preparing input data into a format that the model will accept. Information on how to correctly format the data are embedded in copious, sometimes conflicting documentation. The user is required to employ a trial-and-error approach until the model accepts the input data. This problem is exacerbated by the software's lack of insightful error reporting. Certain functions in the software do not work; the software may become unresponsive during processing and simulation requiring a complete computer shutdown.

To set up the model intensive data gathering and insight into the origin and appropriate application of the data are required. The data are collected from diverse study fields and experts, and include topographical, soil, climate, and land use data, each requiring a competent level of understanding.

Special effort is required to prepare input data where temporal gaps exist within datasets or where no data is available for a particular variable. For example precipitation where measured daily values are not available must be statistically produced.

Data gathering and integration from diverse fields of expertise and mastering of the software implementation of the model are the most challenging aspects of setting up ArcSWAT.

Due to many initial problems with ArcSWAT, a trial run using the DOS interface in SWAT2005 was attempted. To keep matters simple a first run was done simulating all climate variables (precipitation, temperature etc.) as opposed to using all available measured rainfall and temperature data option. The Sandberg precipitation data was duplicated for each sub basin and used for the simulation. The run was successful and flow results were acquired from the .rch text file to which SWAT2005 writes the flow data for each reach. The results did not agree with the flow data at all, and using the DOS interface defeated the object of testing ArcSWAT as a GIS related product. This effort was abandoned for further attempts with ArcSWAT.

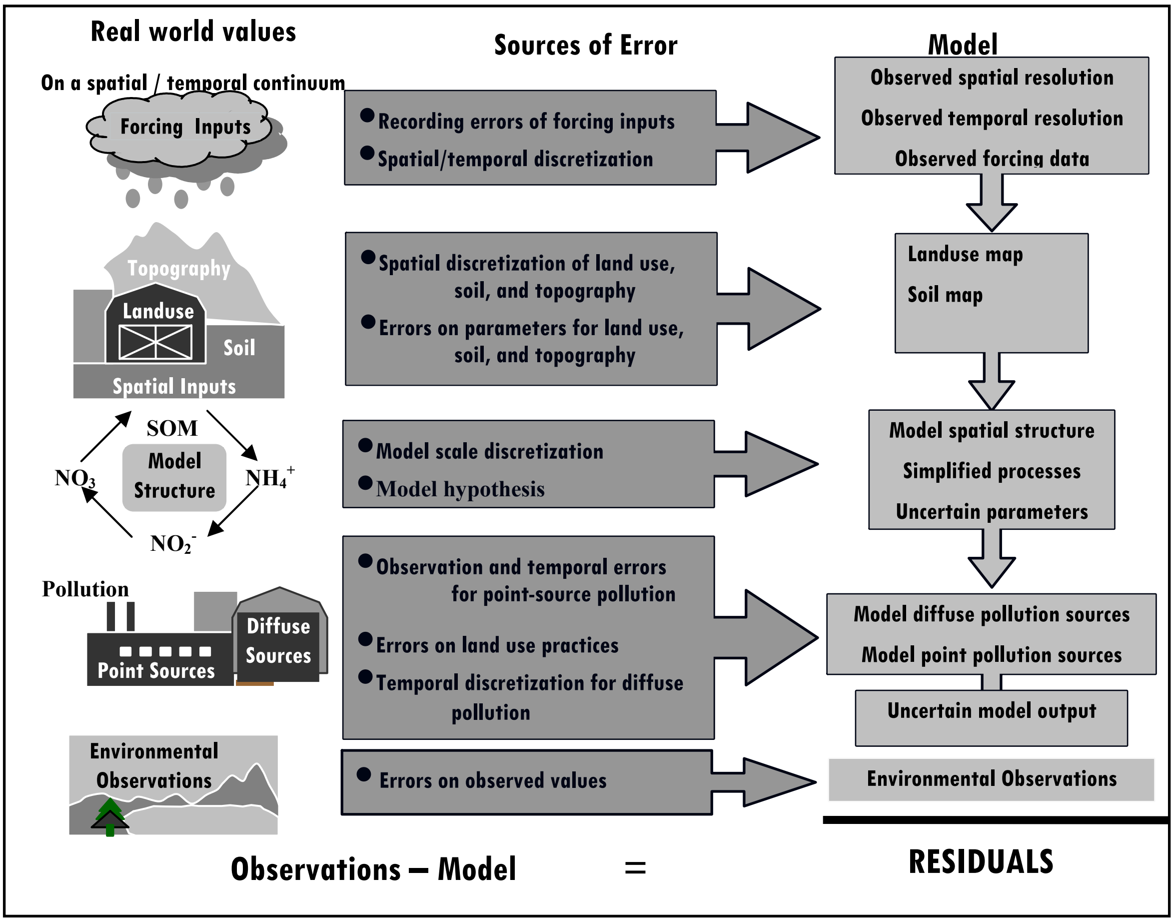
3.7. SENSITIVITY, UNCERTAINTY ANALYSIS AND MODEL CALIBRATION

The subject of model calibration and sensitivity and uncertainty analysis is a vast and complex specialisation which lies beyond the focus of this study. It makes use of statistics to provide a relative comparison between models or between a model and measured data or reality.

Sensitivity analysis is used to estimate the rate of change in model outputs in relation to changes in model inputs. It helps determine which parameters are important for accurate results. It facilitates understanding the behaviour of the system being modelled, as well as evaluating the applicability of the model (Srinivasan & Van Griensven 2007). There are several statistical tools to perform this function.

Uncertainty pervades any modelling endeavour, as it presumes to replicate, in simplified format, a real and complex process or event. In hydrological modelling the foremost source of uncertainty is the precipitation data, which also forms the heart of the model. Uncertainty is difficult to quantify or assess and is often neglected in modelling studies. Uncertainties exist in input data, outputs, the structure of the model, and in the model parameters themselves. Uncertainty analysis aims to quantify the uncertainty in model outputs relative to the uncertainty in model inputs. Most studies in uncertainty analysis deal with parameter uncertainty, there are no known studies of all sources of uncertainty (Srinivasan & Van Griensven 2007). Beck (1987) maintains that models used for decision support around policy and land management decisions lose credibility if they do not include uncertainty analyses.

The Latin Hypercube and Monte Carlo sampling techniques allow for both sensitivity and uncertainty analysis. The diagram below (Figure 3.21) illustrates some sources of error which contribute to the uncertainties in the hydrological modelling environment. Various types of errors occur as the interpretation of the real world problem is fed into a model. Errors can occur at the input phase through forcing data to fit a certain parameter. Spatial accuracy may be affected in the GIS capture process, or in the categorisation of attribute values. Errors of scale are possible where inappropriate application of data at the wrong scale occurs. Errors of logic in setting up the model hypothesis are possible. Errors of omission due to lack of attention to detail or even perhaps due to lack of actual data may occur. Almost any aspect of decision making could be made in error and have a detrimental effect on the model results.



Source: Srinivasan & Van Griensven 2007

Figure 3.21 Scheme of sources of errors in distributed water quality modelling

SWAT2005 uses the LHS-OAT method for sensitivity analysis. It is a combination of Latin Hypercube Sampling (LHS) and One-At-a-Time (OAT) methods. This combines several benefits from each individual system. Srinivasan & Van Griensven (2007) list them as:

- the entire parameter space is taken into consideration,
- sensitivity can be clearly attributed to one model parameter,
- it is computationally efficient,
- the assumptions or linearity in the multiple regressions are avoided,
- parameter correlation can be included in the analysis.

For auto-calibration and uncertainty analysis, ParaSol (Parameter Solutions method) is built into the ArcSWAT menu. It facilitates optimisation in performance uncertainty analysis in a single method, assessing model parameter uncertainty. Optimisation is performed using the shuffled complex evolution algorithm for up to 16 parameters, which is widely used in hydrology and watershed model calibration. Eckardt & Arnold (2001) provide more detail on the calibration tools and hydrologic and water quality parameters tested with SWAT.

The SUNGLASSES (**S**ources of **UN**certainty **GL**obal **A**ssessment using **S**plit-**S**ampl**ES**) method, on top of ParaSol, can assess predictive uncertainty other than parameter uncertainty. Historically models have been evaluated using data that was not incorporated in running the model. It is referred to as the split sample method, where typically one half of the data is used to calibrate the model, and the other half to evaluate the calibration set.

In the SWAT model, the following order of events holds for the uncertainty analysis, auto-calibration and sensitivity analysis continuum:
First the sensitivity analysis is done, followed by auto-calibration using ParaSol. Then the best parameter set is rerun, after which the good parameter set is also rerun. Auto-calibration using SUNGLASSES brings an end to the calibration routines. Reports are produced by the interface for each step and iteration using these analysis tools. SWAT also makes provision for manual calibration of model parameters.

3.8. SWAT2005

The SWAT2005 programme in FORTRAN can be accessed directly through the DOS window. This was recommended by the software support desk (Sammons 2007, pers com) at one point after ArcSWAT repeatedly crashed in initial attempts to set up the model. Once all the necessary input files are created and stored in the same file directory, the SWAT2005 executable file can be run from this environment. This was tried in one of the prior simulations leading up to these results. The modeller needs to have sufficient knowledge of DOS command language and the processes that SWAT runs. It is not recommended for general use.

3.8.1. Setup and data

In the TxtInOut folder contains text input files for each HRU, where the file name contains the number allocated to a particular HRU and the file extension indicates what data is contained in the file. For example, 0000020000.wgn is the weather generator data for sub basin 2 which simulates the weather data necessary for some of the complex algorithms. While pcp2.pcp is the input of measured daily precipitation data per rain gauge within sub basin 2. The fig.fig files is the set up file for the drainage sequence from one sub basin to the next. The file.cio is the general input output file where important parameters are set; for instance whether the precipitation data is measured or should be simulated for the required run. Instructions for relevant instruction codes as well as the necessary formats can be found in the SWAT Input Out documentation (Neitsch et al 2004). The output.rch file contains flow values simulated for each reach. This data is used for comparison with the measured flow gauge data.

3.8.2. SWAT processes

Zhou and Fulcher (1997) and Bian et al (1996) describe the wealth of model processes built into SWAT. They include calculations of water balance (i.e. surface runoff, return flow, percolation, evapotranspiration, and transmission losses), crop growth, nutrient cycling, and pesticide movement. Model outputs include sub basin and watershed values for surface flow, groundwater and lateral flow, crop yields, as well as sediment, nutrient and pesticide yields.

Measured streamflow and sediment concentrations can be statistically compared with model predictions. Anthropogenic influences like management inputs such as crop rotations, tillage operations, planting and harvest dates, irrigation, fertilizer use, and pesticide application rates are also included. SWAT’s in-stream quality assessment module is based on the QUAL2E model (Abbaspour et al 2007; Brown & Barnwell 1987).

CHAPTER 4: RESULTS

4.1. ARCSWAT REPORTS

The following SWAT reports were obtained through the ArcSWAT interface. They were created by the interface and stored in the project folder, and the default text report folder (Project#\Watershed\text). They are designed to provide the hydrological modeller with all the aspects of information required for setting up the model effectively.

4.1.1. Topographic report

The simple elevation report below (Table 4.1) creates a line of data for each elevation value found within the watershed, and then lists them again separately for each sub basin. It provides figures for the area below (cumulative) the represented elevation value, as well as the percentage area of the watershed or sub basin covered by that particular value.

Table 4.1 An extract from a topographic report produced by ArcSWAT

<table>
<tr><td colspan="3">Elevation report for the watershed 0001/01/01 08:30:29 AM 2007/08/25 12:00:00 AM

Statistics:
All elevations reported in meters
Min. Elevation: 0
Max. Elevation: 1445
Mean. Elevation: 216.773654852076
Std. Deviation: 158.424088614638</td></tr>
<tr><td>Elevation</td><td>% Area Below Elevation</td><td>% Area Watershed</td></tr>
<tr><td>0</td><td>.02</td><td>.02</td></tr>
<tr><td>1</td><td>.04</td><td>.02</td></tr>
</table>

In the final run of ArcSWAT 7 sub basins were defined (Figure 4.1), based on the number of outlets defined by the user in the delineation input menu. Each subbasin boundary marks the end of a reach, the end point of which is the accumulation point for all flow data from upstream which is then fed into the downstream sub basin and reach. Once flow lines are established, the model uses other physical layers to determine HRUs.

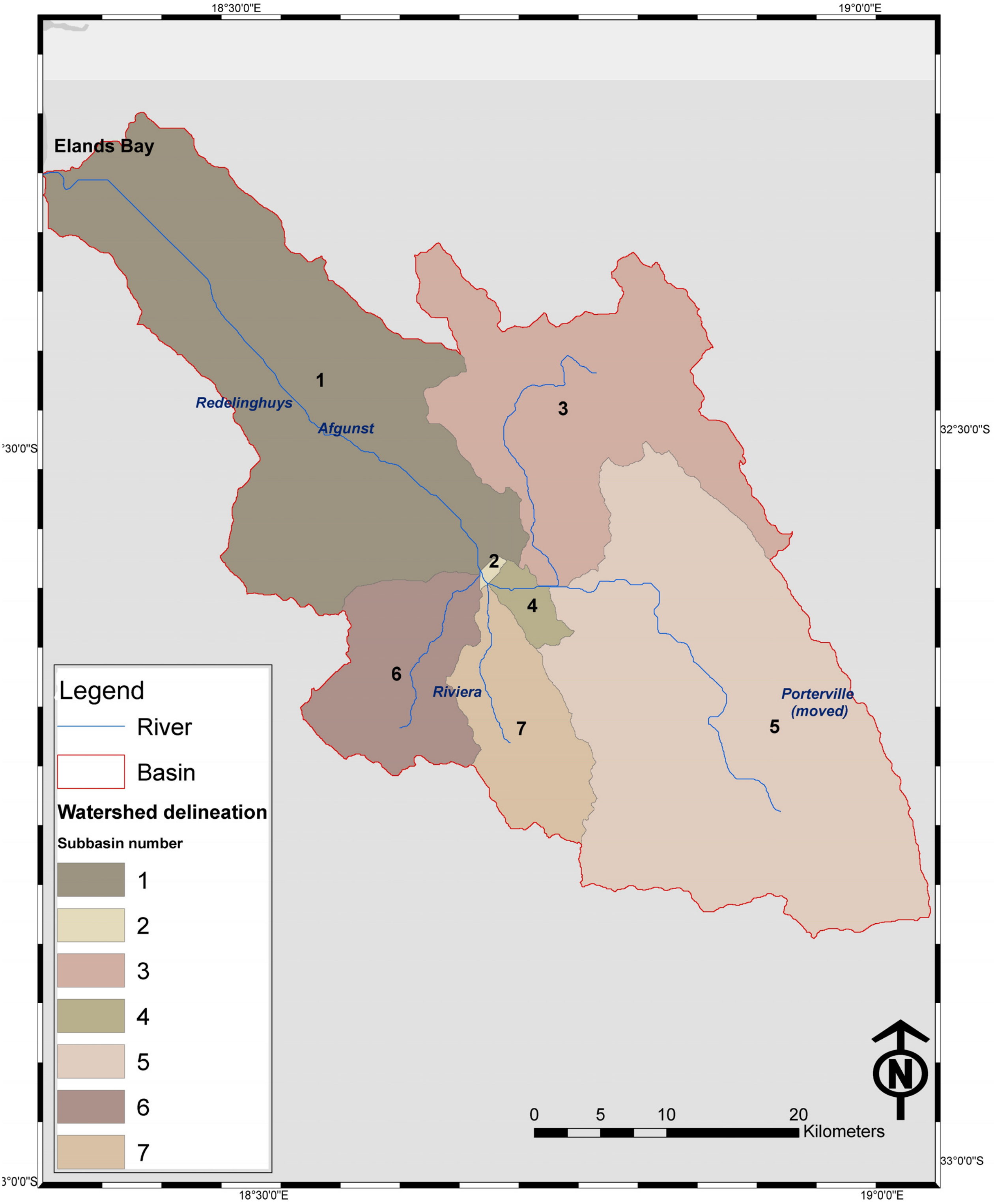


Figure 4.1 Sub basin delineation resulting from ArcSWAT

Unique hydrological response units were defined in the GIS based process described in Section 3.5.3. The final run of the software produced 16 HRU's represented in Figure 4.2. This was a reasonable number of processing units for computational efficiency. The model lumped all hydrological inputs per HRU and used representational areas for each HRU value within a subbasin.

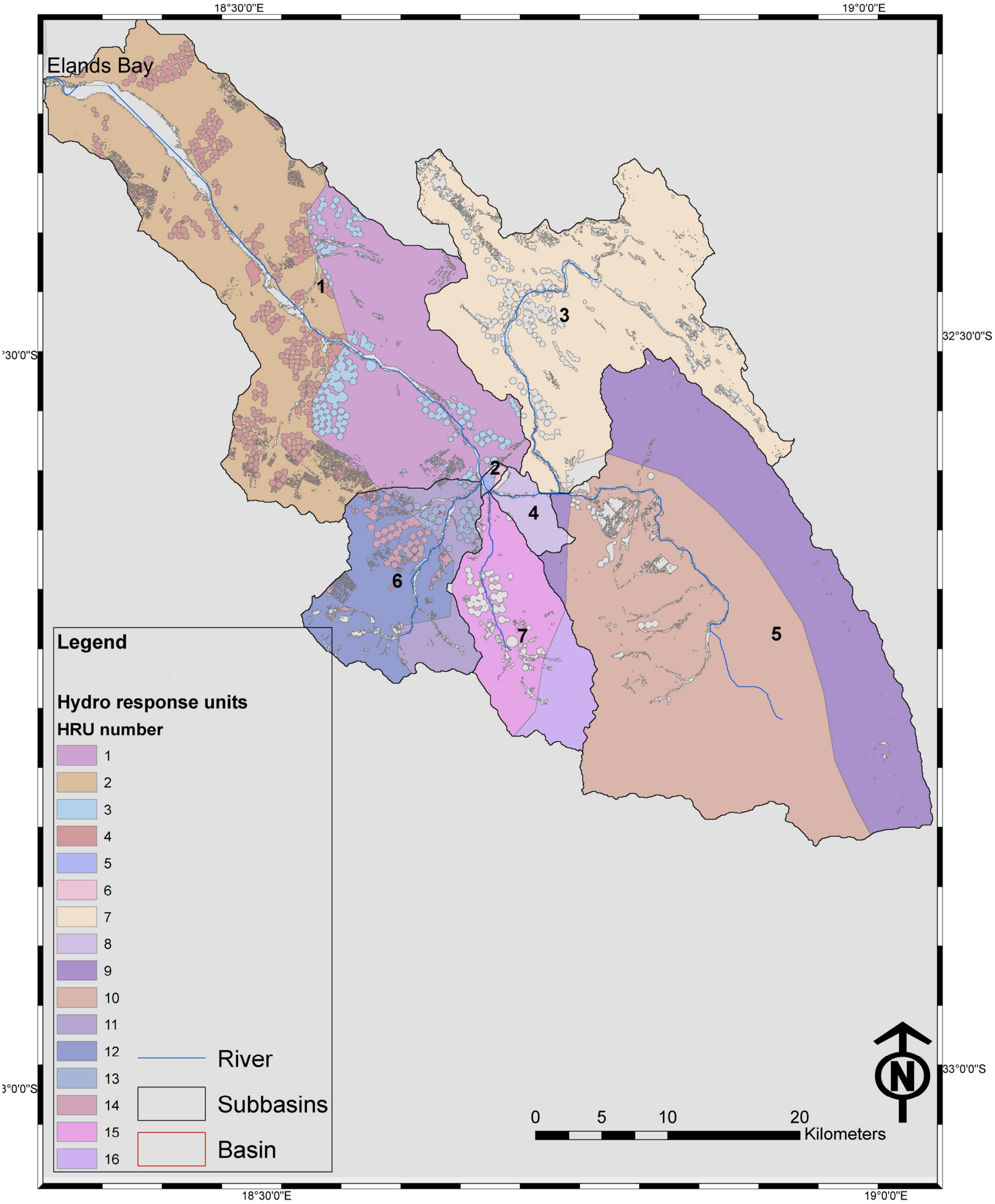


Figure 4.2 HRU results from SWAT

4.1.2. Delineation reports

ArcSWAT created two land use-soil-slope reports in the project#\Watershed\text folder. The first was the LandUseSoilsReport.txt seen in Table 4.2, which is a general description of the watershed in terms of the three factors it uses for the analysis. It describes the land use, soil type and slope cover for each sub basin.

Table 4.2 Subbasin distribution of land uses-soil-slope

Description	Area [ha]	%Watershed Area	%Sub basin.Area
SUBBASIN # 1	22327.6800	7.02	
LANDUSE:			
Range-Brush --> RNGB	16695.1931	5.25	74.77
Potato --> POTA	5632.4869	1.77	25.23
SOILS:			
Lc62-2bc-720	4312.2046	1.36	19.31
Qa7-1a-862	18015.4754	5.67	80.69
SLOPE:			
0-20	22327.6800	7.02	100.00

Table 4.3 is a further refinement of the delineation process and indicates which proportion of area each HRU covers within a particular subbasin and of the entire watershed

Table 4.3 Landuse-soil-slope groupings in each HRU

HRU	Grouping	Hectares	% of Subbasin	% of Watershed
1	Range-Brush --> RNGB/Lc62-2bc-720/ 0-9999	19230	10.31	32.78
2	Range-Brush --> RNGB/Qa7-1a-862/ 0-9999	30150	16.7	51.4
3	Potato --> POTA/Lc62-2bc-720/ 0-9999	2967	1.6	5.06
4	Potato --> POTA/Qa7-1a-862/ 0-9999	6315	3.39	10.77

The HRULandUseSoilsReport.txt file is the final HRU report produced in the phyiso-graphic processing. An extract from the SWAT results is shown in Table 4.3 below. It contains detail about its unique physical characteristics: landuse, soil type and slope classes to the level of each HRU within the sub basin.

Table 4.4 Final HRU distribution report from ArcSWAT for the whole watershed

Area Description	**Class definition**	**Hectares**
Watershed		186509
LANDUSE		
SOILS	Lc62-2bc-720	95935
	Qa7-1a-862	45947
	Qa8-1ab-863	44627
SLOPE:	0-9999 (only one class)	186509
SUB BASIN 1		58662
	Range-Brush --> RNGB	49380
	Potato --> POTA	9282
SOILS	Lc62-2bc-720	22197
	Qa7-1a-862	36465
SLOPE:	0-9999 (only one class)	58662
LANDUSE:	Range-Brush --> RNGB	49380
	Potato --> POTA	9282
HRUs		
1	Range-Brush --> RNGB/Lc62-2bc-720/0-9999	19230
2	Range-Brush --> RNGB/Qa7-1a-862/0-9999	30150
3	Potato --> POTA/Lc62-2bc-720/0-9999	2967
4	Potato --> POTA/Qa7-1a-862/0-9999	6315

Table 4.5 below demonstrates typical configuration input and output information (CIO) for the sub basins. It starts with the date and the version of the SWAT software in use. Essential details on number of years, start and end of simulation as well as the Julian calendar day. SWAT uses the Julian day for time calculations. It indicates the precipitation codes for stations, where for measured data the value is 1, and where the data has been simulated by SWAT's weather generator, it is 2.

The CIO file also indicates that a daily rainfall time step was selected, with a skewed rainfall distribution. Had the exponential rainfall distribution option been selected, the value of the exponent would be 1.300, set as a default value.

Table 4.5 The FILE.CIO text file format

```
Master Watershed File: file.cio
Project Description:
General Input/Output section (file.cio):
2008/08/29 12:00:00 AMARCGIS-SWAT interface AV

General Information/Watershed Configuration:
fig.fig
           23    | NBYR : Number of years simulated
         1985    | IYR : Beginning year of simulation
          182    | IDAF : Beginning julian day of simulation
          212    | IDAL : Ending julian day of simulation
Climate:
            0    | IGEN : Random number seed cycle code
            1    | PCPSIM : precipitation simulation code: 1=measured, 2=simulated
            0    | IDT : Rainfall data time step
            0    | IDIST : rainfall distribution code: 0 skewed, 1 exponential
        1.300    | REXP : Exponent for IDIST=1
```

4.2. ARCSWAT RESULTS

A final successful run with acceptable surface flow results was achieved through the ArcSWAT interface. Simulated flow curves closely followed the measured flow at the Verlorenvlei gauge. The gauge is situated in the middle of the river where wetland dominates the shores. The photographs below in Figure 4.3 show the gauge and its position from various aspects in the Verlorenvlei.

Flow results for subbasin 5 were extracted from the output.rch files which contain the simulated flow for each reach as cumulative flow at the outlet of the reach.

Figure 4.4 shows the position of the flow gauge in relation to the rest of the catchment and the outlet monitoring point of sub basin 5.

Figure 4.3 Views of the Verlorenvlei gauge

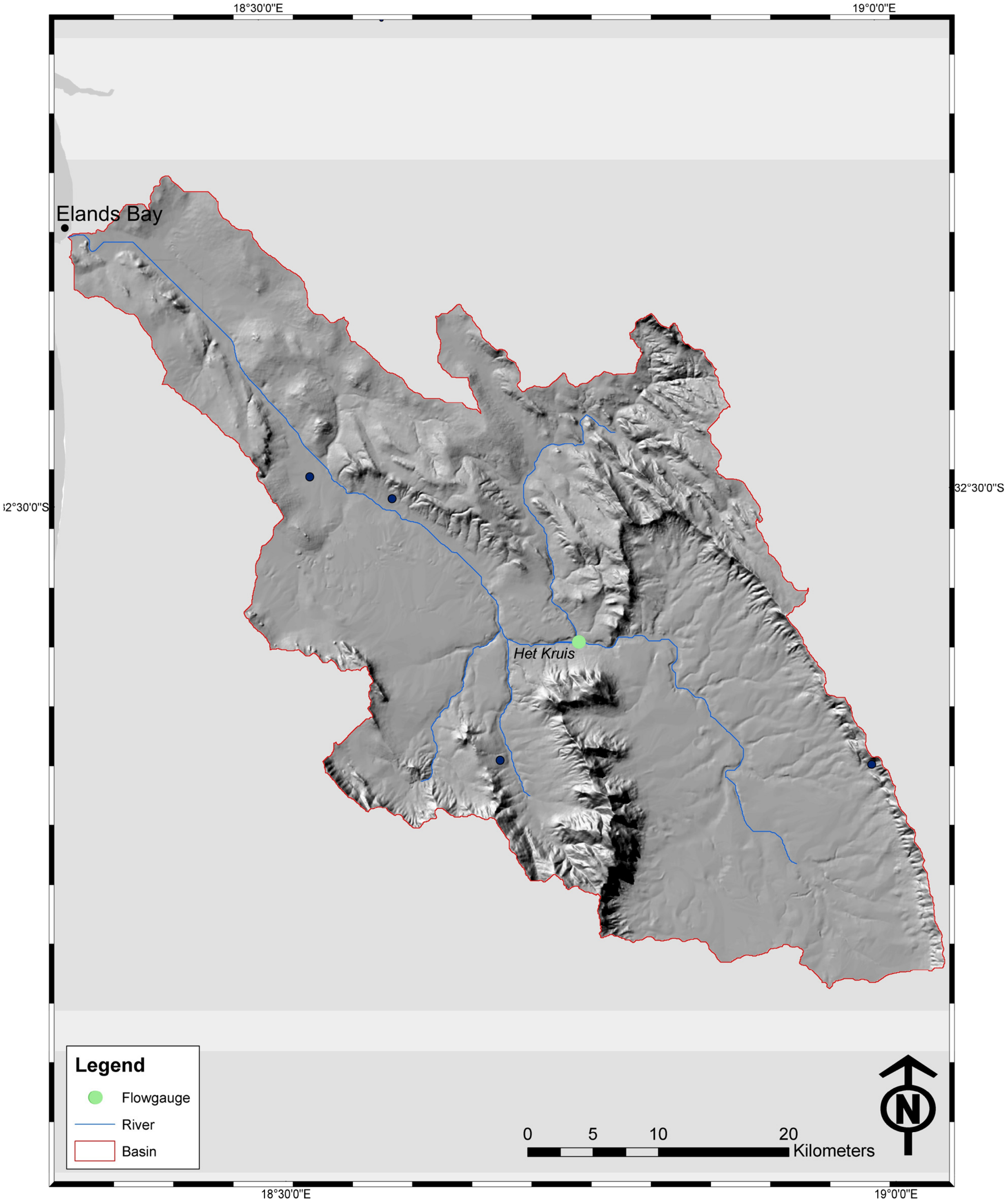


Figure 4.4 The position of the Verlorenvlei flow gauge within sub basin 5

4.3. FLOW RESULTS

The following graphs (Figure 4.5 and Figure 4.6) show precipitation records for the same time period as the comparative graph of flow results and measured flow.

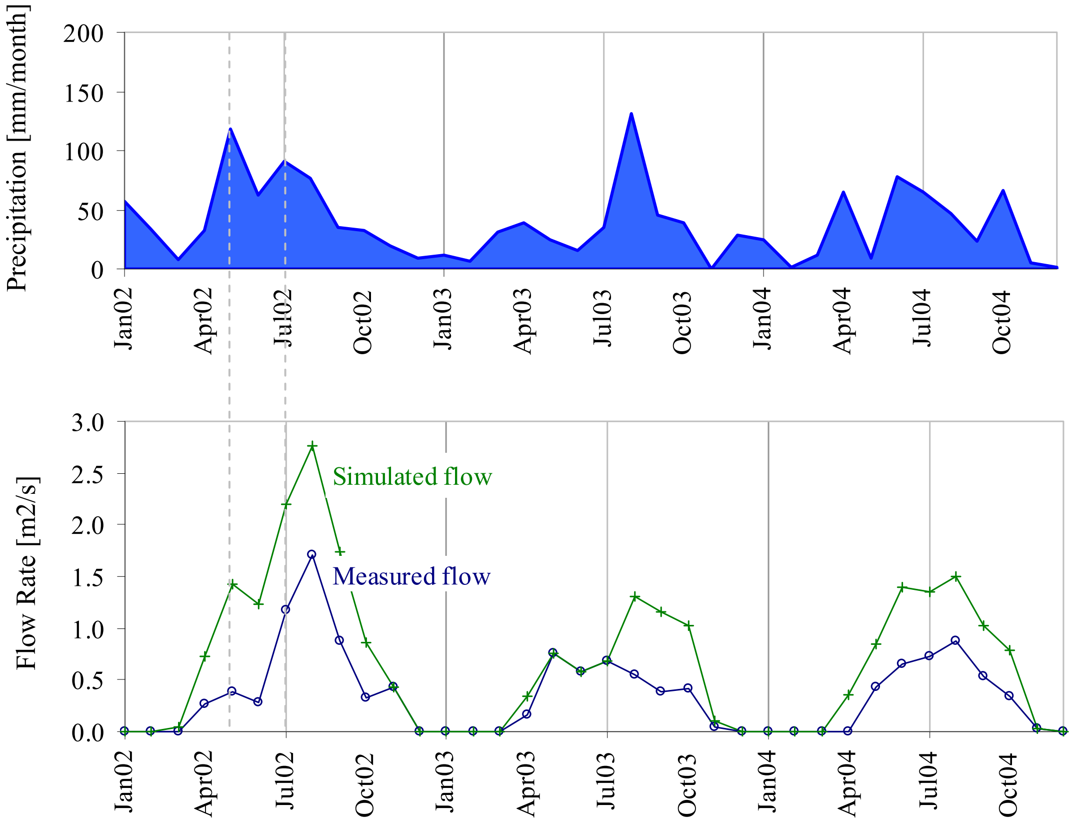


Figure 4.5 A comparison of rainfall, simulated and measured flow for sub basin 5 from January 2002 to October 2004

The simulated data result is based on the output.rch average monthly values for flow at the outlet to subbasin 5. The measured flow data was converted from daily flow to monthly average flow and data ranges from the final years of the simulation are depicted (January 2002 to October 2006). The volume of data makes it impractical to display the data for all 23 years.

Several interesting observations can be made from Figure 4.5 and Figure 4.6. Firstly, the precipitation data follows a more detailed and irregular pattern than that of the simulated and measured flow in the river, as one would expect from rainfall which is the initial hydrological input. Measured and simulated flows represent the hydrological process further down the chain of events where cumulative effects have caused water to flow in larger masses with slower response curves.

Secondly the rainfall peak for May2002 (along the left dotted grey line on Figure 4.5) is almost simultaneous with the flow measurements for the same time, however for June 2002 (along the right dotted grey line on Figure 4.5) the lag effect of accumulated rainfall is clearly depicted by the delayed steep rise in both measured and simulated flow. Simulated and measured flows follow very similar curves, although the simulated curve is consistently higher than the measured curve. This could be due to the fact that the model was not set up to take into account impoundments and water abstraction from the river.

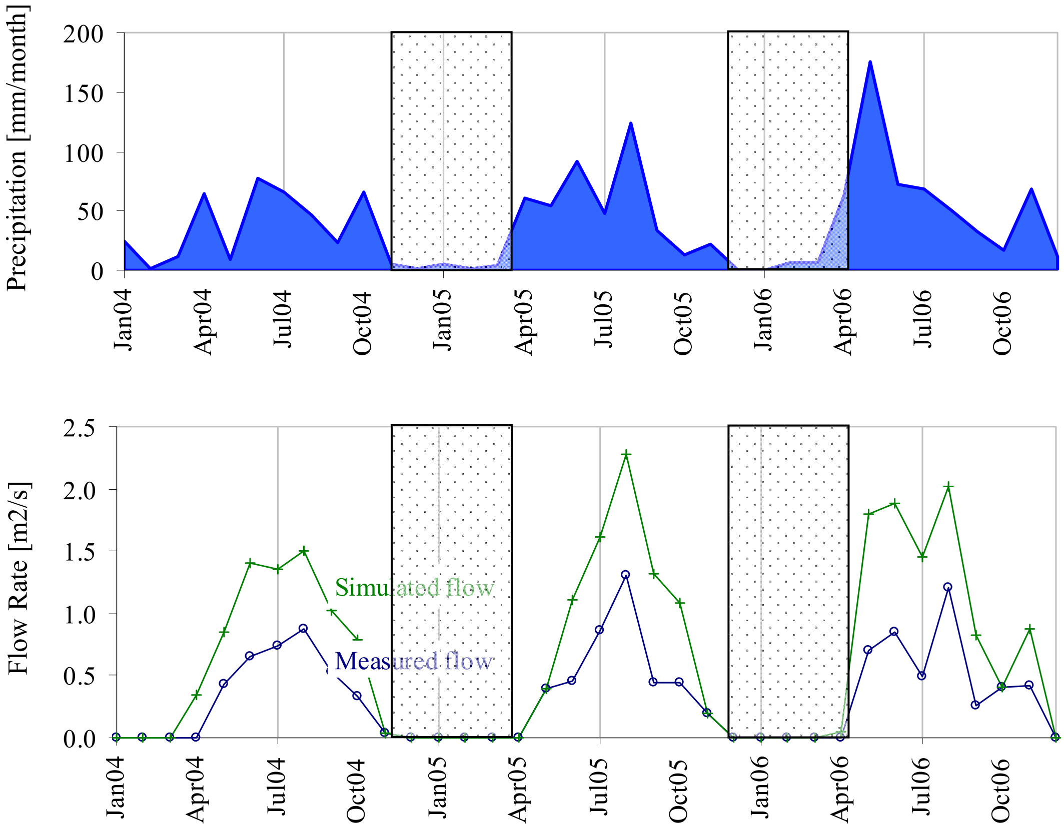


Figure 4.6 A comparison of rainfall, simulated and measured flow for sub basin 5 from January 2004 to October 2006

A third interesting phenomenon occurs between November 2004 and April 2005 as well as between December 2005 and April 2006 (see the dotted rectangles in Figure 4.6), similar periods of very low rainfall in the dry summer months. Both the simulated and the measured flow results concur on zero flow for those periods. What this could indicate is that the model is successfully simulating infiltration and storage losses.

CHAPTER 5: DISCUSSION

SWAT, with its various interfaces, has much to recommend it as a watershed scale model focusing on agricultural land use. As all models are simplified representations of the real world we are trying to study, it is understandable that there will be shortcomings in this approach. The shortcomings identified by each modeller will depend on what they are trying to achieve. In this study the aim is to derive accurate channel flow results from the model. Accuracy is determined by how well the model results compare to the measured flow-gauge data. This will indicate how much confidence can be placed in the model's ability to represent the study area's hydrology. We need to question whether the correct emphasis has been placed on climate and soil variables in the model, and whether the input data are valid and accurate.

In this study area, as with most of Southern Africa, available, measured flow-gauge data is limited by the small number of available gauges. The gauges using rating table methods may not be accurate, or collection methods limit the ability to accurately represent maximum flows, e.g. during floods, which are key event in most riparian systems, and particularly in arid stochastic environments like the Sandveld. Missing data resulting from days where gauges are out of action add to inaccuracy.

5.1. THE LIMITATIONS OF THE SWAT MODEL

Some of the problems identified with the SWAT model were indicated by Uhlenbrook (2006b) in his lectures to students at the Institute for Hydrological Education in Delft, the Netherlands. He indicated that HRU's do not represent local features adequately in terms of pervious and impervious substrates (for example, flow will be affected by varying density or porosity of substrate). This is true for both surface and groundwater. SWAT does not account for these differences in flow from one to the other. Flow varies significantly dependent on the antecedent substrates in so far as they provide buffers for nutrient retention. The subbasin remains the smallest hydrological response unit that is spatially explicit, as HRU output data is lumped and weighted into a sub basin result.

As a result of SWAT's semi-distributed model structure, it is difficult to represent the space-time variability of hydro-climatic input data. This is compounded by no 'real' fully distributed routing of flows, with limited feedback (into the system) and hardly any 'neighbour-effects'. The modeler is hard-pressed to decide how to deal with return flows or local groundwater-surface water

interactions, as SWAT deals with them very simplistically through indirect devices. Only one continuous groundwater body is simulated, which is not representative of reality.
Uhlenbrook (2006b) points out more shortcomings in the model as it does not deal with sub-grid variability or with changing stream networks during events (e.g. storms or droughts), which are especially relevant in arid catchments as we find in the Sandveld. SWAT ignores the influence of geology and the importance of other physiographic parameters like topography for orographic rainfall and temperature effects is only accounted for in the elevation band option. Abbaspour et al. (2007) found this recently added option able to adjust for orographic effects to a small degree, and found useful in correcting flow dynamics overall.

The SCS curve number method is used for runoff, but peak runoff is calculated using a modification of the Rational Formula (Chow et al. 1988). Concentration time is calculated using Manning's formula for overland as well as channel flow. In his lecture notes Uhlenbrook (2006b) further argues that the SCS method, for rainfall-runoff calculations, is not process based enough for accurate hydrological results that reflect the real world. Using the SCS method for water quality simulations would be inadequate, as hydrochemistry is particularly reliant on correct simulation of runoff generated and different runoff components differ in their hydro-chemical composition. Uhlenbrook (2006b) suggests that the Green & Ampt method as an alternative to the SCS method calculates infiltration in a more processed based manner, although it requires sub-daily precipitation input data, which is more difficult to acquire and computationally intensive.

Saleh (2007) recommends that SWAT is more useful for comparative scenarios than for absolute results. One reason for this is that when using the SCS method, the curve number remains constant for all simulations, along with the retention factor (*F*). Saleh found that the most useful results from SWAT were for annual estimations, but for monthly and daily analyses the results are increasingly less secure.

Other weaknesses identified by Saleh (2007) are the lack of a concentrated animal feeding component and related manure application routines in SWAT. It is problematic to represent multiple cropping (e.g. inter-row crops) in the model. The simulation of filter strips uses an empirical approach, not a process based one. Riparian strips, buffer zones and other conservation practices are not adequately incorporated into SWAT.

Calibration is challenging due to uncertainties in the form of process simplification, processes not accounted for in the model, and processes occurring in the watershed unbeknown to the modeler. The largest uncertainty remains in rainfall and temperature data, further compounded by regionalization in SWAT at sub basin level, which could be particularly detrimental in mountainous areas.

5.2. THE LIMITATIONS OF THE AVAILABLE DATA SETS

GIS data for the Sandveld is of a relatively high quality and satisfactory for use in the SWAT model. Gökmen (2007) found that collecting of soil data was a time consuming part of his study as the soil parameters that SWAT requires are not readily available outside of the United States. The same problem exists in the Sandveld, and the FAO soils dataset (FAO, 1995) which covers the whole world was used. It is not accurate or of an appropriate resolution for a watershed scale study as previously discussed in Chapter 3.

The most time-consuming data problems in this study resulted from gaps and inaccuracies in the weather data. The lack of certain data sets that SWAT requires, like wind speed, were converted from recorded data for total wind run. In the same way, daylight hours were used to estimate solar radiation using the empirical equation by Glover & McCulloch (1957). Weather data was created in the correct format for SWAT using the Sandveld weather utility created by Beuster (2007) specifically for the purpose of populating the SWAT weather generator module.

In this case study, the USDA crop data base default values for potato cultivation were chosen due to lack of expert knowledge, interpretation, formatting and input into the model. There will be inherent flaws with this choice, as the USDA crop differs from the Sandveld considerably, in that where SWAT considers it only as a cold season crop, it is planted in the Sandveld at almost any time of the year. The only time where potatoes will not be found in the soil in the Sandveld is in the hottest months, January and February, when the soil temperature will cause potatoes to rot (Brink 2007, pers com).

5.3. DOES ARCSWAT FULFILL WATSON'S CRITERIA?

Watson & Burnett (1995) explain that mathematical models seldom meet the complexity of real hydrologic systems and they must therefore be judged in terms of obtaining a good result with some inaccuracy. In terms of the criteria to be considered for model selection according to Watson & Burnett (1995), SWAT can be evaluated as follows:

5.3.1. Is the model appropriate for the study area and the problem being investigated?

- Watson & Burnett (1995) recommend that the model used should be well understood by the modeller so that it can be determined whether the model will meet the specific requirements of the study and produce accurate results. In this study, the model is complex and the modeller has acquired a good understanding of the main processes, which besides the groundwater section, are well suited to looking at land use issues in the Sandveld.
- In terms of addressing the specific hydrological conditions in the Sandveld the first consideration is that most surface water is groundwater driven (Conrad 2005). The SWAT model treats groundwater as one large aquifer (Uhlenbrook 2006b), and is not an appropriate vehicle in terms of groundwater modelling. It does not take into account non-homogenous aquifers with anisotropic conditions (Uhlenbrook 2006a).

  SWAT has, however, been very successfully used in a modular way in conjunction with the groundwater model MODFLOW (Kim et al. 2007, Sophocleous & Perkins 2000).Combining SWAT with MODFLOW results could improve overall results dramatically given that groundwater is the primary water source supporting human activities in the Sandveld.
- SWAT does not account for changing boundary conditions (for example expanding and contracting wetland areas from dry to wet season, or how flow changes as the soil profile dries out both vertically and horizontally), but does to some extent include time variable precipitation and infiltration rates in terms of the semi-distributed structure of the model. It includes appropriate lag components for time of concentration in surface water and groundwater.
- In deciding how suitable a model is in terms of the problem being studied, SWAT may not be the best model from every aspect, but it does focus on agricultural practices and land use, both major driving forces in the Sandveld.

5.3.2. What are the input data requirements?

- Preparing data for a model normally requires some manipulation into the correct format for the specific model. SWAT has very strict requirements which if not adhered to may provide a myriad of difficulties for the user. The input requirements are very thoroughly documented in Neitsch et al. (2004). The largest portion of preparation time was spent on preparing the input data, which should never be under estimated.
- The best available input data were used, but there is still a paucity of good hydrological data in this area. The flow gauge on Verlorenvlei is the only known flow data source for the entire catchment. Climatological data is spatially well represented, but the quality of this data has been called into question (Beuster 2007, pers com). Interpolation and other statistical techniques have

been essential to fill measured data gaps, reducing the accuracy of the inputs and, eventually, the outputs.

5.3.3. What are the computer requirements, and ease of use and user support?

- The hardware and software requirements for SWAT are quite stringent, but not impossible to meet. It might be beyond the budget of a small water users' association, but is reasonable for a provincial agency where GIS is already employed, as this software demands a substantial capital outlay (R40 819.41 as at January 2008). The best possible hardware makes the job a lot easier in terms of minimising time and frustration spent on preparing data and running iterations of the model.
- Iterations seem to be well handled by the SWAT programme, once it is up and running. Using ArcSWAT, the user has two main areas where parameters or inputs are changed, firstly in the way the hydrology base is set up with GIS layers representing physical features. If this is altered in any way, the model has to be run from the beginning again. The second main option is for changing non-spatial data like chemical inputs or land management practices which affect scenarios; this can be done with relative ease in the "edit databases" menu. The model is then only rerun through the last parts of the menu, writing input files and simulation.
- ArcSWAT has a clear menu structure, which is plain to follow and the software is easy to install.
- It is debatable whether the SWAT model is well constructed or not. For those who are able to read the FORTRAN code and follow the processes in this way, it may be easier to decipher what the programme is doing at each step in the menu. Those modellers wanting to make use of the model that do not have the programming background or hydrological expertise, the model may be difficult to follow. Errors may occur in the running of scripts, where the user cannot identify the problem, and may spend many hours using 'trial and error' methods solving it. This makes the effort and support required a substantial issue for the SWAT modeller.
- Watson & Burnett (1995) agree that graphical pre- and post-processing ability are extremely beneficial to hydrological modelling. In the case of ArcSWAT, the ESRI ArcGIS software provides a well-known solid graphical pre-processing tool. The Spatial Analyst extension and ArcHydro capabilities are wonderful technology to interpret terrain and drainage lines for hydrology. Users who are not familiar with the GIS may find this a steep learning curve, however, as it requires some specialist knowledge of the software and GIS theory.
- The GIS takes care of mesh generation to the necessary level of detail, and SWAT condenses the results per reporting unit. This allows for some margin of elasticity in presenting the results.

5.3.4. Are the output requirements met?

- To assess how SWAT interprets the output data, the modeller needs to know which algorithms are being used in each step of the various processes. Each one has its strengths, weaknesses and more appropriate area of application. None of them will represent reality perfectly. The hydrology of the study area must be well understood by the modeller, or modelling team, so that areas that are inadequately interpreted can be identified and alternative approaches identified, if there are others available in the model. One of the great strengths of SWAT is that it has been used successfully in conjunction with other models that have specialist functions for the areas that SWAT does not cover as comprehensively.
- SWAT does not have a post-processing graphical interface. The outputs are all in the form of text files, hailing from the FORTRAN programming era of its inception. The results are presented per HRU, or for final water availability and water quality, per sub basin and reach. VizSWAT is a relatively new visualisation module for SWAT results, but it must be purchased separately.
- SWAT units of measure are standardised and documented in the Neitsch (2004) input output theory document. It does not allow for flexibility in use of units of measure other than its own standard. The user must provide for this separately, by changing input units to meet SWAT's requirements, and creating extra facilities for output units other than those provided in the programme, should this be necessary.
- SWAT has an extensive archive of documentation for the user. Neitsch et al. (2002; 2004; 2005), and Srinivasan (2005) have created detailed documentation for each version of SWAT. This study used the version SWAT2005 with the ArcSWAT interface.
- The accuracy of the results is questionable due to the lack of hydrological and perhaps other subject expertise support for input variables (e.g. agricultural, nutrient and pesticide practices). For this study default values which may not be appropriate to the study area were used.

5.3.5. An alternative assessment of SWAT

Uhlenbrook (2006b) offers the following succinct critique on SWAT:

- Fully distributed routing of flows is not possible in SWAT because of the semi-distributed model structure.
- Feedback is limited as few 'neighbour-effects' are taken into account.
- It is unclear how SWAT deals with return flows and localised groundwater-surface water interactions.

- Variability is taken into account only to the resolution of each grid unit, in this case an HRU, so sub-grid variability is ignored.
- SWAT does not allow for changes in stream network during events, as would be typical of an arid catchment such as this one.
- He also maintains that the effect of physio-graphic parameters (topography, geology etc.) is ignored.
- SWAT has great manuals and documentation available which is not often the case for comparable models.
- He suggests that good technical support exists via the internet user forum and via email directly from the suppliers.
- Although the model is physically based, it is full of assumptions and many parameters that are often not or hardly measurable. This forces the modeller to make very strong assumptions about the system under investigation!
- Relatively simple, empirical approaches are used to describe complex hydrological processes. For example, the Green & Ampt (1911) approach for infiltration simulation is somewhat more process based than SCS approach, but both are still far away from reality.
- He concludes that SWAT is a great tool for applied hydrology and research.

5.4. APPROPRIATE PAST APPLICATIONS OF SWAT

There is a very small user base for SWAT in South Africa at this time. The Council for Scientific and Industrial Research (CSIR) has successfully applied AVSWATX in KwaZula Natal. The articles by Govender and Everson (2005), and Savage (2006), focus on the forestry industry, as opposed to agriculture.The Agricultural Research Council (ARC) in Pretoria has also used AVSWATX for hydrological modelling with some success (Germishuyse 2008, pers com). Maharaj (2006, pers com) and Beuster (2007, pers com) set up a hydrological project for Ninham Shand using ArcSWAT in 2006.

Julich et al. (2007) in their article discuss the use of SWAT and SWAT-G in modelling for catchments where most of the water moves in either lateral sub surface storm flow in anisotropic conditions, or infiltrates to groundwater. They suggest that SWAT performance for baseflow periods requires further research and development. Calibration should be done on a small parameter set where land use does not influence the results; however, SWAT is heavily dependent on landuse data. This is followed by the running of land use scenarios to evaluate the impact of changes in land use on water and nutrient balance.

Van Orshoven et al. (2007) found that SWAT2000 did not perform well for scenario modelling in a study on changing farming practice in Belgium. They mention several shortcomings in the model for the parameterisation of farming practices. Biomass development was inadequate to measure crop residue production. Management parameters did not allow for crop succession from where there was a shift from annual to perennial or permanent crops form one year to another. They found the tillage algorithm only takes note of the mixing of residue and nutrients in the soil, where they required more effects from the input of tillage data. The soil organic carbon module was found to contain questionable default values and a separate, more complete, module for this function is suggested.

In a sediment yield study done in Greece using SWAT, Panagopoulos et al. (2007) found that land use change scenarios based on application of crop-rotations and best management practices on agricultural land could be efficient erosion mitigation measures. Although sediment is not the direct focus of the Sandveld study, the creative use of best management practices for scenario testing in SWAT may prove to be of use in future planning for the Sandveld.

5.5. CONCLUSIONS

As a semi-distributed catchment scale model, SWAT allows for spatio-temporal variability of climatic representation up to sub basin level. It provides a dynamic, non-linear overlay of processes at a workable resolution. It is an impressive tool for distributed modelling. Although good results were achieved in the running of the model on the Verlorenvlei catchment, it may however limit accurate representation (of flow results and hydrochemistry) due to the lumping concept. Other important issues are that it uses simple empirical equations to explore complex hydrological processes and lacks a graphical interface for displaying and querying output.

Several boundary interactions are questionably simplistic in their treatment in SWAT. The movement of water from overland to channel flow, as well as the interaction of surface runoff and groundwater, are examples of this.

The model is physically based, but remains full of assumptions and some of the parameters required are often not measurable, or hardly so. They make very strong assumptions of the system under investigation because of the lack of options to describe variability.

Precipitation for Porterville rainfall station, measured flow data for the Verlorenvlei gauge and the simulated dataset compare well in the temporal axis, the trends show similar peaks and valleys. The simulated data is almost always higher than the measured data. Several factors could be influencing this.

Some of the factors influencing the results could be that his run of the model does not take abstraction or storage into account in the water balance. Also, the *Mannings N* value of 0.014 as set by the default of ArcSWAT is a much smoother surface than what local hydrological modellers would use. These two factors could account for the model estimating higher runoff than was measured.

Elements of uncertainty pervade hydrological modelling and this case is no exception. There is a measure of uncertainty in the flow gauge measurements, as the apparatus can only measure flow up to the height of the rating table. Flows exceeding this level cannot be accurately accounted for. Missing data records in the measured flow, precipitation and temperature data could cause inaccuracies in the monthly averages and other statistically inferred data. The inappropriate FAO soils data, does not closely reflect the soil properties of substrates found in the catchment adding to the overall uncertainty relating to input data. Furthermore, Abbaspour et al. (2007) identify the following examples of uncertainties in modelling with SWAT, the effects of wetlands and reservoirs on hydrology and chemical transport, large constructions (roads, dams, bridges etc) in terms of sediment affecting water quality. These are important factors which have not yet been taken into account for the Sandveld where flow diversions and loss of wetland function have increased over time.

The SWAT documentation is a vast cornucopia of knowledge built up over the time that the software has been developed. Good support exists for user groups in Europe and America, but South Africa still has a small user base and is not well supported due to lack of direct contact with regular users and support groups. It has been one of the largest obstacles to overcome in this study.

ArcSWAT remains a powerful hydrological modelling tool. However the conditions in the Sandveld and the particular problems needing focused study, will require that SWAT be used in conjunction with other software, for instance, to assess groundwater and surface water interaction in greater detail.

5.6. RECOMMENDATIONS

Supposing that a larger user and support base for SWAT is developed in South Africa, it would be viable to investigate the possibility of an integrated modelling suite, with SWAT at its kernel. Gassman (2007) and Saleh (2007) report on the successful integration of SWAT into a suite of targeted software for integrated environmental modelling. The Comprehensive Economic and Environmental Optimisation Tool (CEEOT) makes use of SWAT for watershed scale hydrological modelling; APEX, a field scale crop yield model for crops and livestock improving the accuracy of agricultural outputs, and a farm level economic model, FEM. Together they contribute to a fuller sustainability data matrix. If this suite of software could incorporate MODFLOW as the groundwater analysis component, the Sandveld would have a tool that would address all its sustainability concerns to a high degree of accuracy and detail. We should take note of Schuol & Abbaspour (2007) who recommend that more attention be given to 'green water' i.e. soil water, evapotranspiration processes and crop dynamics, which are of importance for ecological services and rainfed agriculture.

The current DWAF initiative of establishing catchment management agencies (CMAs) throughout the country to provide a framework for Integrated Water Resource Management (IWRM) seems like a good framework on which to test this inclusive approach. It will require a group of experts and inter agency collaboration and could provide a wide range of information useful for managing the whole catchment sustainably. It would be pointless to go to all the trouble of creating a scientific base of information if the landowners and local stakeholders were not consulted in the process. Before any collaborative studies are initiated, a public participation process should be facilitated. In this way the people directly affected by, and working with, these issues on a daily basis will have the chance to highlight what they consider important and to prioritise the outcomes of the study. In this manner, scientific collaboration could assist the cohesive management of a CMA on the principles of IWRM.

5.7. FUTURE SCENARIO APPLICATION POSSIBILITIES

The success of this initial study may lead to more studies where the model can be used extensively including water quality inputs and outputs. This would require multi-disciplinary expert input from the following specialist fields: agronomy, GIS, ecology, hydro-geology, and hydrology. The most suitable model or combination of models would be used to run several scenarios. The following scenarios could be kept in mind in terms of suitability of the software to provide relevant results for eventual application in sustainable natural resource management:

5.7.1. Water savings investigating alternative irrigation practices

The Department of Agriculture: Western Cape (DAWC) has collected three years of irrigation monitoring data in support of increased efficiency of water usage involving potato crops using centre pivot irrigation. This data might be suitable to test water efficiency scenarios relating to seed and table potato crops.

5.7.2. Alternative crop scenarios

Currently table potatoes are produced in two to three growing seasons in the Sandveld. GIS and the hydrological model could be used to compare the current production scenario with a scenario where only one of the production periods is modelled within a given year, for instance only the winter cycle. The possibility also exists of comparing the effects of seed potato plantings on hydrology and water quality versus table potato production. Seed potatoes have a much longer fallow period than table potatoes, but may have more intense nutrient and pesticide requirements. Seasonal cover crops would be interesting to factor into these scenarios.

5.7.3. Reclaiming land for rehabilitation

Scenarios for rehabilitation of a percentage of the land currently under production or fallow could provide a tool to measure the relative value of ecological services. The effect of rehabilitation on water savings, water quality and soil-water related benefits could be investigated in such scenarios.

5.7.4. Reduction of soil salination and water pollution

Best practice guidelines could be consulted for optimum application of pesticides and herbicides on non-diseased crops. The impact of fertilisers on water quality and the effect of pesticides and herbicides on soil chemistry could be interrogated through the model.

5.7.5. Suitable areas for land reform projects

The model could assist in deciding on appropriate land and water resource pockets for the specific needs of previously disadvantaged farmers as per the initiatives of the national and provincial departments of agriculture.

Above are some of the opportunities afforded by the SWAT hydrological model and the flow results already achieved by this study. It would make sense to follow up on the work already done by investigating scenarios that landowners and relevant management agencies would find useful.

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