THE IMPACT OF LAND COVER AND LAND USE ON THE HYDROLOGIC RESPONSE IN THE OLIFANTS

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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(Signature of candidate)

________________________day of ______________________ (year) ____________

To two godly women:

my mum for being an inspiration and a dependable spiritual ally, surely, "no man is poor who has a godly mother"[♣]*;*

my wife and extraordinarily good friend for being a rock solid anchor

and to the memory of my dear father

[♣] Abraham Lincoln

ABSTRACT

Water availability in Southern Africa is highly variable both in time and space, thereby exposing the region to high risks in water availability. This is further compounded by numerous human activities which have significant impact on water resources. The brunt of the risks associated with water scarcity is particularly heaviest on resource-constrained farmers who depend largely on rain-fed agriculture for subsistence. With continuously increasing demands on the water resources, the need for a better understanding of the hydrological systems becomes crucial as it forms the gateway for providing reliable information for managing water resources.

It is also increasingly becoming more important to address land and water linkages because land use decisions are water use decisions. Operational hydrology provides an insight into the effects of man-made changes, the foreseeable hydrological characteristics at a given site, and the long-term prediction of the future hydrological effects of human activities. This provides for a more holistic approach in managing land and water resources as well as the impact of land use on partitioning rainfall into streamflow.

This report discusses the application of the SWAT model to the B72E - F quaternary catchments in the Olifants Water Management Area to assess streamflow generation and the effects of human-environment interactions on the hydrology. Results show an expected correlation between land cover and the hydrologic response where an increase in land cover corresponds to a reduction in the streamflow. Range grass shows a higher reduction in the streamflow followed by forestry with arid land giving the highest increase in streamflow. Prediction in the similar neighbouring and ungauged B72A catchment gives a MAR of 68mm.

Additionally, a rigorous analysis of the concepts of a local hydrological model, HDAM, is done with respect to rainfall which is the main driver of the model. Modifications of some of the relationships used in the model are suggested with the potential of streamlining the model and making it more applicable in the region.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

The advent of civilisation brought with it the need to 'tame' the environment through various human activities which altered the environment in various forms. Most of these anthropogenic changes have a profound effect on the water cycle and ultimately, on the availability of water resources and their quality. Such effects become critical as water is crucial for human and environmental sustenance and development. In the light of this, a number of issues have becoming more pertinent in man's quest to improve his livelihood and environs. Such issues include environmental protection, sustainable development and the effect of climatic change. It has become important to understand the effect of land use changes, agricultural practises, afforestation and deforestation and related activities on water resources. This is taking place over and above the growing concerns of a global water crisis with about a third of the world's population living in water stressed environments (Hinrichsen *et al.*, 1998; CGIAR, 2006).

The prevalent global water crisis is prompting a lot of activity in integrated water resources management. It is becoming increasingly important to know the amount of fresh water resources that are available, both in space and time, and how these can be optimally and equitably allocated to the increasing population. As Southern African nations embrace water reforms, they are becoming more aware of the need to estimate the available water resources and how their quantity and quality are affected by any changes, spatially and temporally, in the natural environment.

South Africa has made tremendous progress in adopting integrated water resources management, including the underlying principles, and water is on the top agenda of the government (Schreiner and Naidoo, 1999). The Water Act of 1998 sets the policy framework on addressing water related issues. One mandate that has been enunciated by the Minister of Water Affairs and Forestry is to establish national monitoring and information systems (NWA, 1998). The purpose of the systems is to facilitate the continued and co-ordinated monitoring of various aspects of water resources by collecting relevant information and data, through established procedures and mechanisms. A crucial part of the data that has to be collected and processed is hydrological information, with the output at high enough resolution to be beneficially and easily put to use by the different water use sectors in the country.

With competition to meet the varying needs from the domestic, commercial, industrial and the agricultural sectors, including meeting the reserve requirements, it is clear that hydrological tools are necessary to help inform discussions about potential changes in water resources policies and investment plans.

1.1.1. The Challenge Program Project 17

The Consultative Group on International Agricultural Research (CGIAR), an international research organisation, is actively involved in research work on water and food meant to improve livelihoods. Together with a regional research body WaterNet, it is involved in a four year project known as the Challenge Program (CP) Project 17 which is on Integrated Water Resources Management for Improved Rural Livelihoods in the Limpopo basin. Three pilot catchments identified within the basin are the Mzingwane Catchment in Zimbabwe, the Olifants Catchment in South Africa and the Chokwe Catchment in Mozambique. Within each of the catchments smaller pilot areas were identified of which one was B72A, a quaternary catchment in the Olifants of South Africa. The overall goal of this project is to contribute to improved rural livelihoods of poor smallholder farmers through the development of an IWRM framework for increased productive use of green and blue water flows and risk management for drought and dry-spell mitigation at all scales in the Limpopo basin (Waternet and CGIAR, 2004).

A number of MSc and PhD work were sponsored to fulfil the above objective and that of capacity building. This research work is part of the sponsored projects and is meant to contribute towards the activities that deal with preliminary water resource evaluation to determine and model the process of blue water generation from rainfall. Additionally, water governance to increase water productivity and risk mitigation at catchment scale is an issue that needs to be addressed through understanding factors that have an impact on streamflow generation.

This research report therefore seeks to determine and model the process of blue water generation from rainfall through the use of hydrological models for selected quaternary catchments of the Olifants catchment in South Africa and assess the impact of land use and land cover activities on the hydrology.

1.1.2. The South African context

South Africa is emerging from a long history of colonial domination and racial segregation with at least 12 – 14 million South Africans in 1994 without any access to water and other natural resources such as land. The current government is redressing these wrongs and is committed to the eradication of poverty. In relation to access to water and water services, this approach is outlined in a number of crucial policy documents which include, the Constitution of the Republic of South Africa, (Act 108 of 1996), the Water Services Act (1997) (WSA), and the National Water Act (1998) (NWA) (Schreiner and Naidoo, 1999). Water management is seen by the government to have three main goals: meeting every person's health and functional requirements, raising agricultural output, and supporting economic development (RDP, 1994). Water resources of South Africa are therefore vital to the health and prosperity of its people, the sustenance of its natural heritage and to its economic development (DWAF, 2003).

Harnessing water resources to cater for these legitimate and crucial goals impinges tremendously on land use, land cover and ultimately on the water resources. A semi-steady state, at the very least, in terms of water resources, land cover and land use will continue to be elusive in view of the fact that both water and land reform are considered to still be at their infancy (e.g. Kirsten *et al.,* 2000). Livelihoods which still need to be improved will be another impetus for this dynamism as water is considered an instrument for social development (Schreiner and Naidoo, 1999) which is at the core of livelihood development. Water resources cannot, therefore, be assumed to be stationary in time where land cover changes are known or foreseen (Gallart and Llorens, 2004).

On the technical front, even before 1994 a lot of work has been done in quantifying the water resources of the nation and understanding hydrology. The late 1970's saw the start of a programme of process studies within small catchments in South Africa, largely funded by the Water Research Commission (Maareen, 1989). Before this most of the hydrological studies had focused on afforestation effects, whose results gave essential data that have been the basis for research into the application of hydrological models (Hughes, 2004a). Hughes (2004a) and Hughes *et al.* (2003) give a synopsis on hydrological work in past years and also cite examples of models that have been developed and extensively used in South Africa which include the Pitman model (also known as **W**ater **R**esources **S**ituation Assessment **M**odel, WRSM 2000) and the ACRU model. As of 1998, research in hydrology and water resources has mostly focused on supporting the National Water Act (NWA), with emphasis on equity of water distribution and environmental sustainability (Hughes, 2004a). As such, future research, if it is to be of relevance to the water sector in the country needs to support the National Water Act, and possibly improve its implementation and even the Act itself, where necessary. Contentious issues in the NWA (1998) include water allocation, streamflow reduction activities (SRF) and upstream-downstream interactions. In this light, plausible streamflow simulations become vital for the management of and allocation of scarce water resources. Allocation of water permits will become more and more a contentious issue as demand for water grows against a background of finite resources and as the country moves towards a more participatory system of water management (Royappen *et al.*, 2002).

The Department of Water Affairs and Forestry (DWAF) which is the custodian of the water resources in the country commissioned a number of studies meant to facilitate management of water resources in South Africa. The country has been divided into seven strategic planning areas or drainage regions, each of which has approximately uniform hydrometeorological characteristics (Basson, 1997). These drainage regions are further divided into a total of nineteen water management (WMA), one of which is Olifants Water Management Area. The Olifants river catchment is one of the principal sub-catchments of the Limpopo River Basin and lies within the Northern Region strategic planning area of the country.

The Olifants Catchment is further subdivided into five water management regions, which are further subdivided into seven secondary catchments as shown in the Figure 1.1 and Figure 1.2. Table 1.1 gives a brief description of the Olifants Catchment.

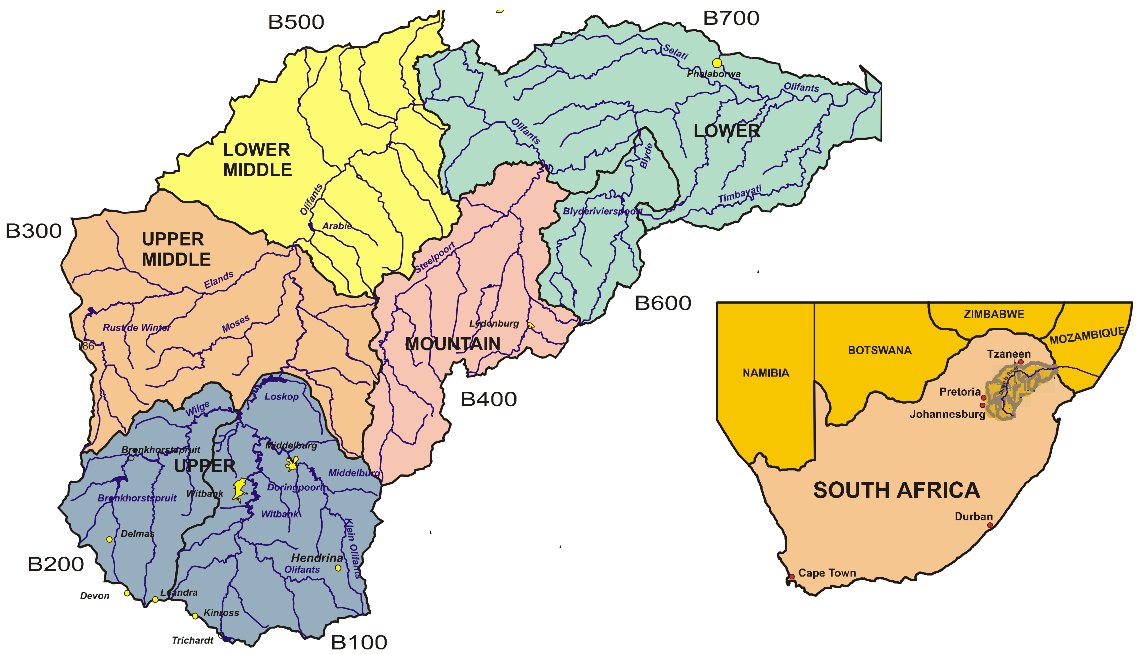


Figure 1.1: Location of the Olifants River Water Management Area and the boundaries of the five water management regions (IWMI, 2005).

Table 1.1: Description of the Olifants basin.

Catchment Area: 54,475 km^2
Location: between 2.5^o & 26.5^o South Latitude, between 28.5^o & 24.8^o East Longitude
Length of the Olifants River: 770 km
Mean Annual rainfall: 630mm
Altitude: 300 – 2300m

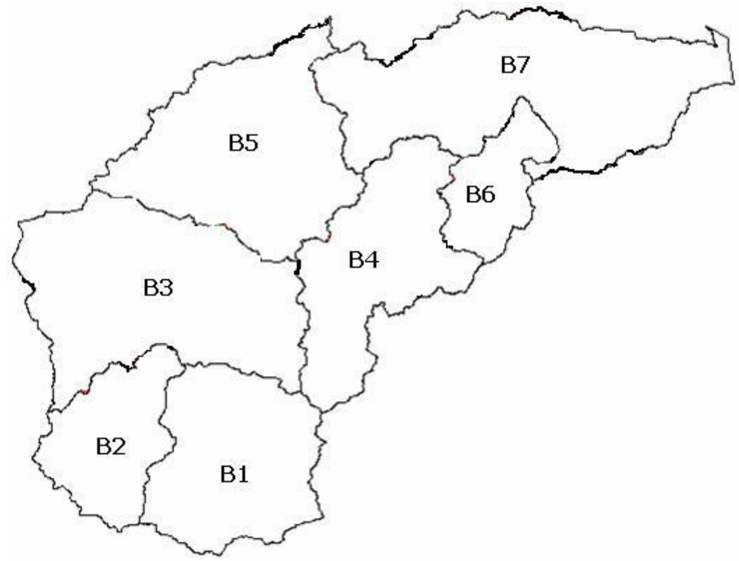


Figure 1.2: The Secondary Catchments of the Olifants

One particularly important baseline study of the entire water resources in South Africa was a Water Research Commission funded study known as the Surface **W**ater **R**esources of South Africa 19**90,** WR90 (Midgley *et al.*, 1994). The study involved the application of the Pitman model to assess the water resources in the country and generate natural time series. The study established 1946 quaternary catchments as the principal water management units, of which 117 are within the Olifants Catchment.

A second study, which was sequel to the WR90 study, developed a Water Situation Assessment Model (WSAM) to evaluate the status of water resources in the country (Schultz and Watson, 2002). A number of other related water resources studies have been undertaken by different organisations, most of which are funded by the Water Research Commission, and have given representative figures in terms of runoff generation of different catchments (e.g. Hughes, 1993; Hughes, 1994; Tarboton and Schulze, 1992; Kienzle *et al.*, 1997; Schultz and Pike, 2004). A particular recommendation from some of the studies is that models that provide spatial and time step output at a high resolution are needed to determine the available surface water resources (DWAF, 2004). The effect of human activities on the spatial and temporal availability of water and upstream-downstream interactions legislated in the Water Act (NWA, 1998) being of particular interest.

Other studies that have provided a wealth of knowledge to the hydrology of the country include the natural vegetation/veld types of the entire country by Acocks (1988) and a raster rainfall database of daily rainfall for Southern Africa by Lynch (2004).

1.2. LOCATION OF THE STUDY AREA

The study is conducted in the quaternary catchments B72E, F, G and H, which forms part of the Selati River Catchment of the B7 secondary catchment of the Olifants. Although the pilot quaternary catchment for the CP project is B72A, it is ungauged and therefore not amenable to be used for calibration of a hydrologic model. Similar quaternary catchments adjacent to B72A were therefore selected and their location is shown in Figure 1.3.

Part of the area falls under the former homelands which, due to the high population density, exerts enormous pressure on land and water resources. High spatial and temporal rainfall variability that is characterised by seasonal dry spells with an average mean annual precipitation (MAP) of 737mm (DWAF, 2006a) is also experienced in the area. With population growth it is inevitable that pressure and competition for water supplies will increase, prompting changes in water management and allocation.

1.2.1. Activities within the study area

The following activities have been identified within the quaternary catchments;

Agriculture: Under this sector commercial, emerging and non-commercial farmers exist. Water sources vary from one sub-sector to the other with use of both surface and groundwater, with ground water use being more extensive especially during the dry seasons.

Domestic: The greater population found in the former homelands rely on both surface and groundwater for domestic purposes, while the commercial sector mostly relies on groundwater.

Conservancy: There are a number of conservancies which are mostly located downstream of the catchment.

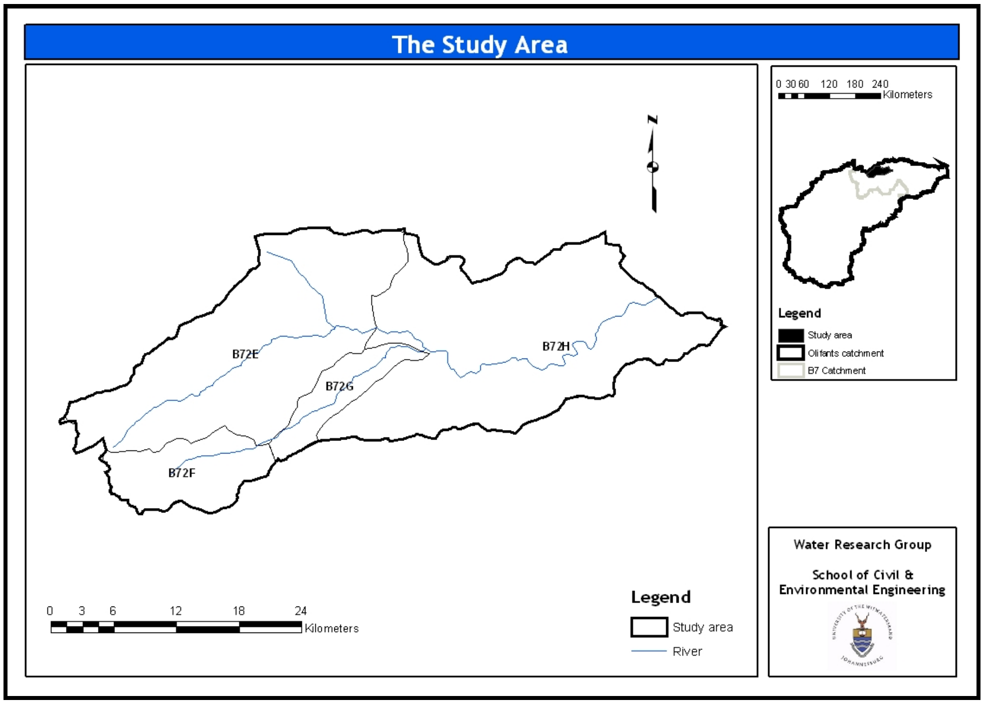


Figure 1.3: Location of the study area

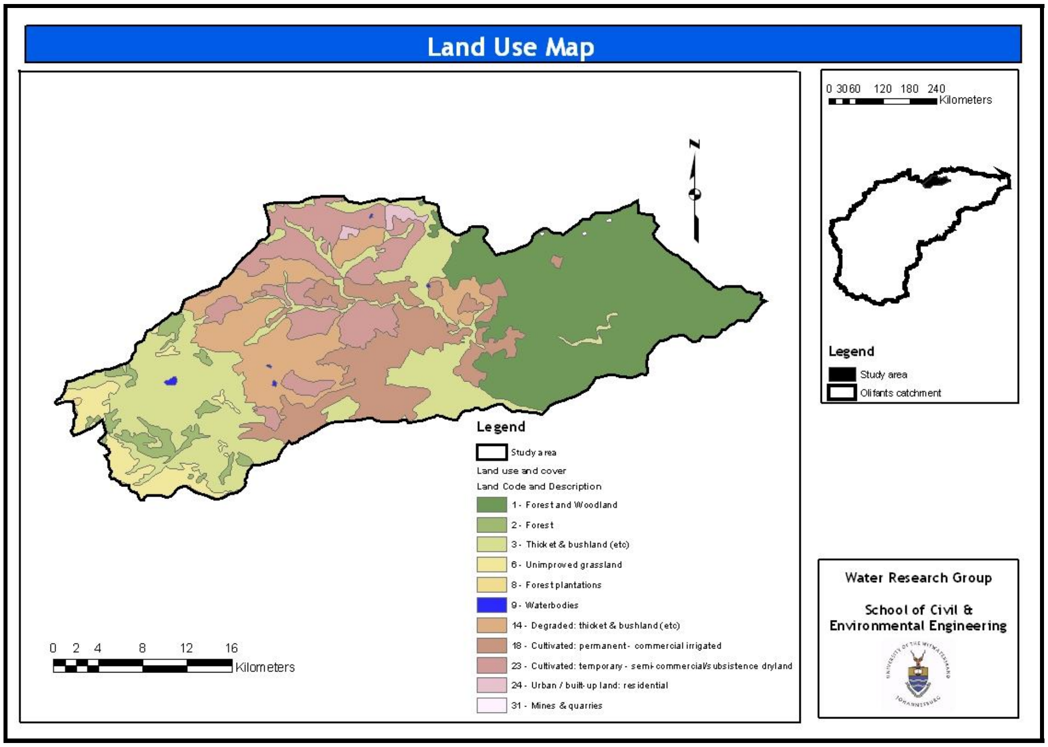


Figure 1.4: Land use in the study area

The land use/cover within the study area is shown in Figure 1.4 and is predominantly made up of forests and woodlands.

All the different land covers and corresponding uses have a legitimate claim to the water resources, thereby calling for co-ordinated water use and abstractions. This integration requires that upstream – downstream interactions be understood.

The soils map of the study area is shown in Figure 1.5 which, to some extent influences the land use and land cover in the area.

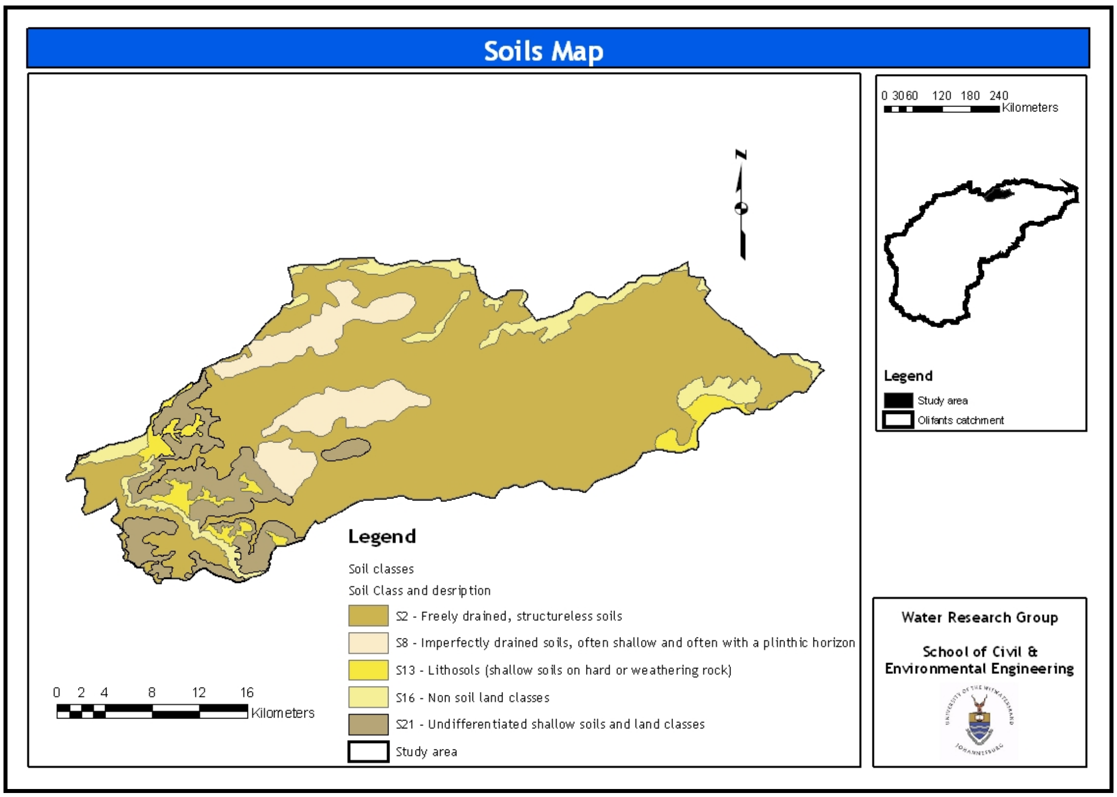


Figure 1.5: Soils in the study area

1.3. Objectives of the study

1.3.1. General objective

The fundamental goal of this project is to setup a tool in the form of a hydrological model that can be used to estimate runoff generation within the study catchment and thereby provide a basis for planners and decision makers to plan future land developments and assess their impacts on water resources.

1.3.2. Specific objectives

Through the application of a process-based model it is envisaged that the following can be accomplished;

- Assess and model runoff generation at a time scale relevant to all water users.
- Perform an impact assessment of the effect of anthropogenic activities, including land use, on the hydrology and the likely upstream-downstream interactions and effects.
- Establish water resources management and conservation needs in the sub-catchment.
- Compare the results of the model with the results of other studies.

1.4. Justification

Hydrologic response is an integrated indicator of watershed condition (Hernandez *et al.*, 2000) and therefore its determination is important in assessing the status quo and future states of watersheds. Setting up and application of a process based model allows for estimation of water resources and modelling of the blue water generation process from rainfall thereby giving some insight to the availability of surface water resources in the quaternary catchments. This aids planning authorities in water allocation activities and setting up water development strategies. It is imperative that a clear picture of available resources and the effects of planned developments be acquired at early stages of planning.

A governing principle of land management is that changes in land cover result in commensurate changes in watershed condition and hydrologic response (Hernandez *et al.*, 2000). To aid natural resources management, particularly land management, an assessment that provides information that will guide decision making is necessary. Such information should also include the effects of overland activities and upstream – downstream interactions, including streamflow reduction activities enunciated in the National Water Act. It is envisaged that this research will come up with such a tool that will allow for a preliminary determination of the feasibility of implementing land developments and their impacts on water resources. Such tools are crucial as significant changes in land cover may affect the overall health and function of a watershed.

Adoption of a daily time step in modelling ensures relevance to all users, especially water intensive activities such as irrigation. No daily time step model is known to have been applied in the study area. The use of a semi-distributed model which is physically based facilitates the prediction of runoff generation in nearby ungauged catchments with similar biophysical conditions.

CHAPTER 2: LITERATURE REVIEW

2.1. INTRODUCTION

Gleick (1993) describes a looming water crisis which is promoted by, among other things, a lack of knowledge and limited understanding of how human activities are changing the particulars and signatures of the water cycle and the water resources in general. Regional water scarcity in the future which will become a limiting factor for development in most sectors of life, including agricultural production. It is therefore advocated that socio-economic planning should be adapted to actual water constraints and ultimately policy tools capable of managing the shortage of common water resources between competing actors be developed.

This calls for a paradigm shift in terms of water management to deal with highlighted issues, since traditional management is ill-equipped to provide sustainable solutions. Prudent and successful water management depends on hydrological data and studies that will identify water-related problems and find the solutions, whether by structural or non-structural measures (Falkenmark and Chapman, 1989). With regards to hydrology, operational hydrology is most relevant as it provides answers on the effect of man-made changes, the foreseeable hydrological characteristics at a given site, and the long-term prediction of the future hydrological effects of human activities. It offers a more holistic approach relevant to land water management by looking at all stages that have an impact on partitioning rainfall, which is *the* water resource in any area, into stream flow.

In a region such as Southern Africa, where natural availability of water is highly variable temporally and spatially, and where both financial and human resources available to sustain long-term monitoring programmes are limited, practical hydrological estimation tools assume great importance (Hughes, 2004a).

The fundamental objective of modelling has been defined as a means of gaining an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner to increase human welfare and protect the environment (Schulze, 1998). Hydrological models are mathematical representations of processes involved in the transformation of climatic inputs such as precipitation, solar radiation and wind, through surface and subsurface transfers of water and energy into hydrological outputs, typically flow in rivers, soil moisture or water levels in aquifers (Hughes, 2004a). The objective of modelling is also part of the requirements of IWRM, and goes beyond meeting the traditional input requirements for engineers designing water related structures to addressing a range of diverse issues that include human impacts and other hydrologically related phenomena which needs integration.

With increasing demand on water resources throughout the world, improved decision-making, within the context of fluctuating weather patterns year to year, requires improved models (Beven, 2001). This does not necessarily mean coming up with new models but streamlining and innovatively applying existing models to support decision making. Additionally, during early years of model development there were definite constraints in terms of computing power which are no longer applicable. Information availability has become the principal constraint to model application (Hughes, 2004a).

Models come in different forms which are dependent mostly on the understanding of natural systems by the developer. An insight into the different types of models aid users in choosing a model that meets their requirements. The following section describes the different types of models.

2.2. TYPES OF HYDROLOGICAL MODELS

A basic classification of modelling strategy given by Beven (2001) differentiates between *lumped* and *distributed* models and *deterministic* and *stochastic* models.

2.2.1. Lumped and distributed models

Lumped models treat the catchment as a single unit, with state variables that represent averages over the catchment area while distributed models make predictions that are distributed in space, with variables representing local conditions by discretising the catchment into a large number of elements/grids and solving the equations for the state variables associated with every grid element. Deterministic models are in a sense lumped conceptual models at element scale as they use average variables at individual grids.

The characteristics of lumped models include the following (Kenan, 2001):

- The system dynamics are represented in an integrated form. It relates to a catchment or sub-catchment as a whole by considering its overall behaviour (Todini, 1988)
- assumes catchment homogeneity, i.e. spatial variation of hydrological response characteristics such as climate, soils, slopes and land cover changes within a catchment are ignored (Schulze, 1998)
- Values are regarded as being representative of the entire catchment, which implies the assumption of linearity of hydrological responses, thus violating one of the basic principles in hydrology of non-linearity (Schulze, 1998).

On the other hand, the characteristics of distributed models include the following (Angus, 1987):

- The variable and heterogeneous character of the catchment is conserved by discretising the catchment into a number of relatively homogenous hydrological response units.
- The integrated response of all the individual units contributes to the total catchment response.
- Each unit is assigned variables and parameters describing the climate, topography, soils and vegetation characteristics unique to that unit.
- It has the potential for more accurate simulation of hydrological responses than a lumped model, because it avoids linear relationships.

The main disadvantages of distributed models are (Schulze, 1998):

- They can be more complex than their lumped counterparts; however, more complex models do not necessarily perform better than simple models.
- Discretisation of a catchment into homogeneous units is theoretically difficult because the dominant physical processes and their interactions for differently sized units vary and information cannot necessarily be scaled up from a point to an area or from small homogeneous area to a larger homogeneous area.

Another major disadvantage is the fact that distributed models require huge amounts of input data, which may not be readily available in the required spatial resolution. Acquisition of the data is not only expensive but may require that the system that should be modelled be destroyed to get comprehensive spatial resolution. In overcoming the inadequate spatial resolution the same characteristics (e.g. soil and vegetation characteristics) and hence model parameters are assumed for larger areas than that covered by the data. This effectively means that for pragmatic purposes distributed models are lumped although over smaller areas.

Distributed physically-based models are therefore better placed to give a detailed and potentially more correct description of the hydrological processes in the catchment than the other model types.

Distributed models can also be classified as physically-based and conceptual. Physical-based models are discussed in Section 2.2.3.2 while conceptual model are discussed in Section 2.2.3.3.

2.2.2. Deterministic and stochastic models

Deterministic models permit only one outcome from a simulation with one set of inputs and parameter values while stochastic models allow some randomness in possible outcomes due to uncertainty in the input variables. The main thrust of stochastic models is that hydrological science cannot predict with exactness future occurrences, the sequential pattern of stream flow or other hydrologic phenomena which are needed to make well-founded water management decisions, which can not wait until the knowledge is available (Klemes, 1988).

A key point about stochastic models is that they assume stationarity in rainfall and flow. This means that they assume future rainfall/flow time series have the same statistical distribution as that of the past. For this to be likely, long data series are required to cover the whole range of possible conditions. Furthermore it cannot be correctly applied in catchments where land-use changes have altered the physical processes that affect runoff and also where it seems increasingly likely that changes in climate are changing rainfall patterns (McCartney, 2005).

A further classification of models can also be made in terms of structural classification. Three groups can be differentiated as given by Chiew *et al.* (1993)

2.2.3. Structural classification of models

2.2.3.1 Black box models

Empirical equations are used to relate inputs (rainfall) to outputs (e.g. runoff) with no understanding of the processes involved in the transformation so that only the input and output have physical meaning. Simple mathematical equations and time series analyses fall into this category.
This approach has pitfalls in that in some circumstances the input-output analysis leads to different conclusions about the operation of the system than an accepted theoretical analysis would suggest (Beven, 2000).

2.2.3.2 Process models

These models attempt to simulate the hydrological processes in a catchment by accounting for all processes through the use of many partial differential equations governing various physical processes and equations of continuity for surface and soil water flows. Deterministic and physically based models fall into this category. A good example of such models is the MIKE SHE model (Prutcha, 2004).

Process models require the use of many parameters, and data limitations and the difficultly in relating processes with theoretical equations (e.g. Darcy's law and the Richards' equations) that describe hydrological processes on small laboratory scales and extending them to spatial heterogeneous and time-varying systems in a catchment may not justify their use in runoff estimation. Even the most physically-based models cannot reflect the true complexity and heterogeneity of the processes occurring in the field (Hornberger *et al.*, 1985).

Physically-based models are usually very costly. Beven (2001) also argues that:

- It is very difficult to estimate effective model parameter values for those equations at the element scale using current measurement techniques; it would not be possible to measure all the parameter values required without destroying the focus of interest. As such, a model may be soundly based on 'real' hydrology, but its data requirements so stringent that they cannot be met with a reasonable degree of accuracy (Hughes and Sami, 1994)

- While they are over parameterised for the purposes of estimating discharges, they have not been properly tested in terms of simulating the internal state variable that is their principal advantage over catchment scale models.

Despite the criticism and problems outlined, a number of published studies suggest that the application of these physically based models has been successful (Abbott *et al.*, 1986). In principle these models can be applied to almost any kind of hydrological problem and their typical applications are (Refsgaard, 1996):

1) Prediction of the effects of catchment changes due to human interference in the hydrological cycle, such as changes in land use (including urbanisation), groundwater development and irrigation. Since parameters of the model tend to be more physically based, the change in parameter values corresponding to the catchment changes can be estimated directly.
2) Prediction of runoff from ungauged catchments and from catchments with relatively short records. The parameters of the distributed physically-based models may be assessed directly from intensive, short time field investigations.
3) Water quality and soil erosion modelling for which a more detailed and physically correct simulation of water flows is important.

2.2.3.3 Conceptual models

It seems inevitable that a compromise solution between the above categories is required, where, for practical application purposes, the component algorithms of a model will be used on a mixture of physically measurable and empirically estimated parameters (Hughes and Sami, 1994). This category is therefore some form of compromise as a partial understanding of processes exists. Conceptual models average inputs/outputs over an area and integrate several hydrological processes and their variability such that their "effective" parameters rather than physically meaningful are used.

The advantages of the conceptual models include the following (Schulze, 1998):

- They can be developed without much real understanding of the modelled phenomena and they use relatively simple input, they lump spatial/temporal heterogeneity and short-circuit (or simplify) complex causal chains (Klemes, 1982).
- They are catchment oriented, as against single component oriented (Bergstrom, 1991).
- They have limited data input demand.
- They use collected data with high cost effectiveness; are easy to use and are computationally fast. They are therefore highly applicable models that are often very useful engineering tools which give reasonable answers to practical problems.
- They can interface easily with GIS and databases.

The disadvantages of the conceptual models stem mainly from their non physically-based development in that processes are represented in a simplified/artificial way (Schulze, 1998), which include:

- The physical interpretation and derivation of input parameters is seldom possible or vague (Bergstrom, 1991).
- Cause/effect assumptions are sometimes false and the models may be too general in applicability or, alternatively, too site specific.
- Limited empirical association of crudely expressed characteristics is likely to produce output of varying quality and of limited value in prediction. This implies that there is no justification in applying the models beyond the bounds for which the input parameters were derived, and extrapolation involves the risk of simulating large errors. Furthermore, attempts to improve the models, without additional restructuring, may lead to over-fitting of parameters (Klemes, 1982).

Hughes (2004a) offers yet another classification of models based on complexity and also on the purpose of the model. Complexity classification is however, more or less similar to the "box" classification above except temporal complexity, which groups models in terms of time-steps used. Inevitably, clear associations between the different criteria are identified.

Models are a representation of the real system. Their usefulness as an aid in both management and understanding of physical processes cannot be overemphasised. This is despite limitations of both model structures and available data. For any selected model, of whatever type, the limitations mentioned above and also those of initial and boundary conditions usually necessitate some form of calibration (Beven, 2001).

All model calibrations and subsequent predictions will be subject to uncertainty as no model is a true reflection of processes, for example, involved in streamflow generation; it is impossible to accurately specify the required initial and boundary conditions; and the available observed data used for calibration is infrequently error-free (Beven, 2001). Additionally, no model can adequately capture the variability of weather patterns and other unforeseen natural phenomenon. The natural variability of hydrological systems in space and time, and the generally short periods of available observations, make it very difficult to study, understand and predict the effects of change, even when using the most physically based distributed models (Beven, 2001). As such, it is important that modellers and those using modelling result understand the risks involved in adopting model results for management decisions.

2.3. REVIEW OF SELECTED MODELS

A number of models were available to the project and these included the following;

2.3.1. SWAT - Soil and Water Assessment Tool

The model is a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time.

The model is physically based and therefore requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. SWAT is a continuous time model, i.e. a long-term yield model which is not designed to simulate detailed, single-event flood routing. For modelling purposes, a watershed may be partitioned into a number of sub watersheds or sub basins where different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact on hydrology (Neitsch *et al*., 2002)

2.3.2. ACRU

ACRU is an agro-hydrological modelling system which has physical-conceptual process representation founded on daily multi-layered soil water budgeting procedures. The model can be operated as a lumped or distributed catchment simulator of streamflow components, with options for reservoir yield, sediment yield, irrigation demand/supply, crop yield and climate change analyses, with a strong focus on land use impacts on hydrological responses. The model contains a dynamic input option to account for changes, either abrupt or gradual, in the catchment over time. ACRU is not a parameter fitting or optimising model. Variables (rather than optimised parameters values) are, as a rule, estimated from physically based characteristics of the catchment. The model has been developed to use data that is usually available locally.

The *ACRU* model has its *hydrological* origins in a distributed catchment evapotranspiration based study in the early 1970s in the Department of Agricultural Engineering, (now School of Bioresources Engineering and Environmental Hydrology) at the University of KwaZulu-Natal, South Africa. Since then the model has developed with funding provided primarily from the Water Research Commission (WRC), to its present status (Schulze and Smithers, 2003)

2.3.3. VTI – Variable Time Interval Model

The model was developed by the Institute for Water Research at Rhodes University, South Africa. The model represents a pragmatic compromise between highly detailed physically based and completely empirical approaches by using a semi-distributed approach, but incorporating some effects at scales of less than the sub-area level. The model is designed to be applicable to a range of situations by incorporating surface-groundwater interactions to allow recharge and baseflow to be simulated as well as channel transmission loss component. As the name suggests, the model also focuses on also giving attention to the temporal resolution by using a variable interval approach. The simulation time step varies – shorter time steps are used when there is a lot of rainfall and storm flows are generated – longer time steps when there is no rain and just recession flow to be modelled.

Parameter information requirements for this model are high but empirical estimates from physical data are known to be available (Hughes and Sami, 1994).

2.3.4. MIKE SHE

MIKE SHE is a powerful, physically based, distributed-parameter, fully integrated code for three-dimensional simulation of hydrologic systems that simulates hydrological and water quality processes on a basin scale. MIKE SHE is able to simulate both surface and ground water with precision equal to that of models focused separately on either surface water or ground water. The MIKE SHE modelling system simulates most major hydrological processes of water movement, including canopy and land surface interception after precipitation, snowmelt, evapotranspiration, overland flow, channel flow, unsaturated subsurface flow, and saturated ground water flow. It has been successfully applied at multiple scales, using spatially distributed, continuous climate data to simulate a broad range of integrated hydrologic, hydraulic, and transport problems in humid as well as semi-arid and arid areas.

MIKE SHE 2003 was developed by DHI Water and Environment with an earlier version, SHE, developed in cooperation with the British Institute of Hydrology and SOGREAH Consultants. It is generally applicable for most hydrologic, water resources, and contaminant transport applications.

Because of its physical nature, parameter information requirements for this model are very high (Yan and Zhang, 2004 and Prutcha, 2004)

2.3.5. HDAM – Hydrological Drought Analysis Model

The hydrological drought analysis model (HDAM) developed by Nyabeze (2003a; 2005) applies a rainfall-runoff sub-model based on the RAFLER model of Stephenson and Paling (1992).

The model is semi-distributed and is interfaced with a Geographical Information System (GIS) to integrate definition and calculation of parameter values for spatial features (Nyabeze, 2003a). It requires the input of monthly rainfall data, observed streamflow data, catchment parameter values derived from GIS data and other pertinent empirical constants. The output includes a streamflow histogram on a monthly time step. Although the input and output is at a monthly time step, the basic driver of the model are storm events which are calculated from the estimated number of rain days in a month.

2.3.6. PITMAN Model and the WR90 Study

The Pitman model is a coarse time scale model that utilises two inputs, monthly precipitation in terms of mean annual percentage and monthly potential evapotranspiration (Pitman, 1973) to simulate monthly runoff. The model is widely applicable and well tested for South African conditions, requires few and well documented input data and is able to simulate long time series (DWAF, 2006c). One version of the model known as the WRSM90 was used in the *Surface Water Resources of South Africa* (WR90) study (Midgley *et al.*, 1994) to generate quaternary streamflow data.

The *Surface Water Resources of South Africa* publications have provided a valuable source of baseline regional hydrological and water resource information. The data were generated using consistent approaches and cover the whole of South Africa, Lesotho and Swaziland based on a spatial subdivision into 1 946 so-called quaternary catchments, varying in size from 50 to 18 000 km2 (with a median size of 445 km^2). The database includes 70-year time series (based on a standard period of 1920 to 1989) of naturalized monthly streamflow volume and monthly rainfall depth for each quaternary catchment, as well as naturalised flow data for all the Department of Water Affairs and Forestry (DWAF) streamflow gauging stations that had more than about 5 years of data prior to 1989 (Hughes, 2004b).

2.4. LAND USE AND LAND COVER

The land surface is the focus of most human activities as it is where we live, grow our food and harvest our fresh water. Many details have to be considered at the land surface, with processes often occurring in non-linear relationships. However, any attempt at understanding all these details can only be realised through the simplified algorithms which we use to represent, for example, the land cover and land use components in agrohydrological models (Schulze, 2003).

It is getting increasingly essential to address land and water linkages because land use decisions are water use decisions, and because rural areas must be sustained for poverty reduction and food security (Falkenmark and Rockstrom, 2005). In the quest of meeting society's needs, the natural landscape is manipulated for purposes of livelihood in both physical terms (e.g. land conversion) and chemical terms (e.g. pollutant production) with some impact on the water resources (Schulze, 2003). Water-impacting land-use has an impact on rainwater partitioning through soil and vegetation (Falkenmark *et al.*, 1999) hence the importance of assessing its effects on the hydrologic response.

Land-use dynamics are a major determinant of land-cover changes. Land use involves considerations of human behaviour, with particularly crucial roles played by decision makers, institutions, initial conditions of land cover, and the inter-level integration of processes at one level with those at other levels of aggregation (Nunes and Augé, 1998). Schulze (2000; 2003) defines land use and land cover as follows:

2.4.1. Land cover

Land cover refers to the biophysical state of the earth's surface and upper subsurface in terms of broad categories such as cropland, natural or man-made forest, grassland, settlements, water bodies or mines. These broad land cover categories can be changed by natural forces such as long-term climate changes or climatic persistence (for example, consecutive years of drought), or by naturally occurring episodic events such as fire, volcanic activity or flooding (Hu *et al.*, 2005; Beven, 2001). However, land cover is largely altered to land use by human actions through land cover conversion or modification, primarily for purposes of agricultural production and settlement. Land cover change effect on stream discharge has a unique signature from the topography and soil distribution in the watershed (Hu *et al.*, 2005).

2.4.2. Land use

This refers to the utilisation, human inputs and management levels, driven by changing production and consumption dynamics, and is subject to social, political and economic factors. Land use and its management may have significant hydrological response impact by both enhancing or retarding infiltration, and effectively increasing or reducing stream flow generation and its temporal distribution. The relationship between land use and land cover is shown in Figure 2.1.

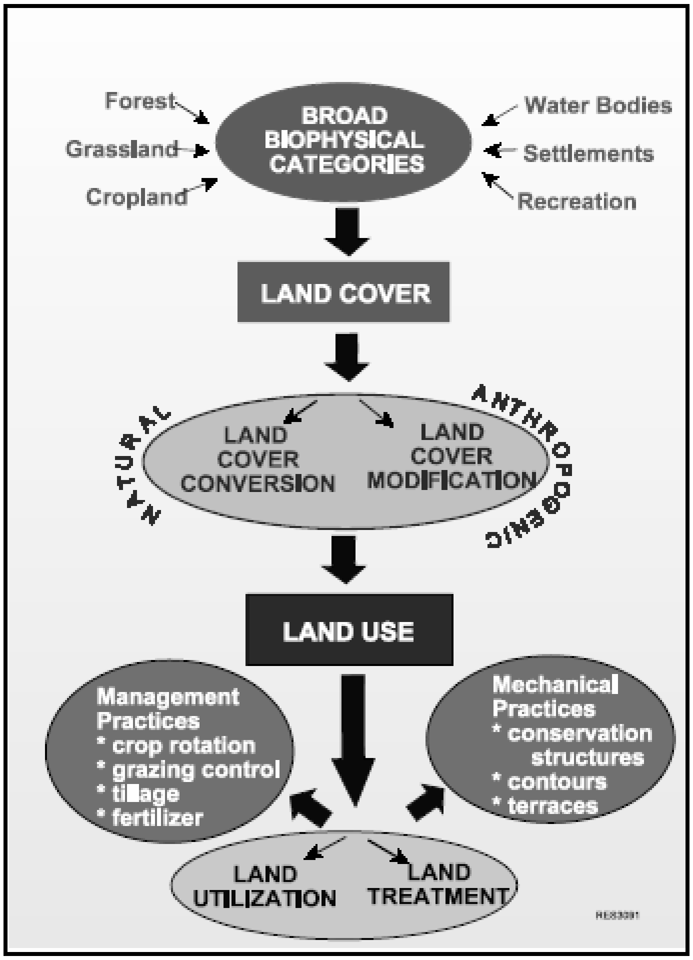


Figure 2.1: The relationship between land cover and land use (Schulze, 2000)

Different land uses are normally associated with certain mechanisms of water utilisation and runoff generation as given by Schulze (2003);

- Commercial plantation afforestation reduces stormflow and groundwater recharge and ultimately alters the generation of streamflow. This is however not always the case; it may depend on the drainage that is introduced which may also change over time as trees age.

- Human settlements give rise to higher stormflows, peak discharges and change the times at which the peaks occur.
- Irrigation reduces streamflows where direct abstractions are implemented. However, further downstream the effect is attenuated.
- Agricultural practices such as ploughing may reduce stormflow by enhancing the soil's water holding capacity.
- Grazing enhances stormflow where it is poorly managed while well managed grazing reduces stormflow.
- Riparian vegetation such as alien plants reduce streamflow depending on the physiological characteristics of alien growth.

The general impacts of land use on the hydrological response include the following;

- Hydrological responses are highly sensitive to, and dependent on, land use and its change (Kienzle *et al.*, 1997; Schulze, 2000).
- Abrupt land use changes at local scale may be hydrologically far more significant than gradual land cover at regional to global scale (Scott and Schulze, 1992; Schulze, 2000).
- The detail of spatial information may be vital in assessing hydrological responses of critical land uses (Schulze, 2000)
- The impact of land use often depends on its intensity (e.g. intensity of urbanisation on streamflow), (Schulze, 2003).
- Land use change has both negative and positive feedbacks on the hydrological response as depicted in Figure 2.2 (Schulze, 2003).
- Land use management often has more significant hydrological effects than land cover change (Schulze, 2003).

Water resources cannot be assumed as stationary in time where land cover changes are known or foreseen (Gallart and Llorens, 2004) and this is because rainfall-runoff relationships are primarily driven by the interaction of climate, land cover and soil (Harnandez, 2000). Stable land use/cover status is generally elusive, especially for developing nations that are in the process of establishing some form of quasi-equilibrium in most sectors. Given the foregoing, an understanding of the influence of land cover and land use on hydrology is therefore postulated.

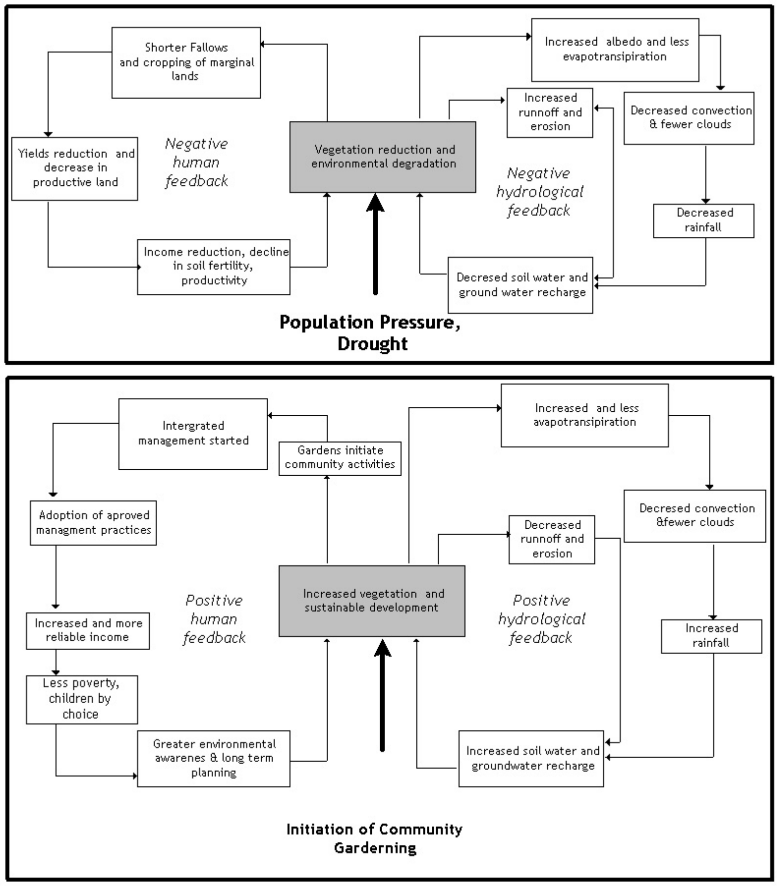


Figure 2.2: Negative (top) and positive (bottom) feedback to hydrology (Schulze, 2003)

CHAPTER 3: METHODOLOGY

3.1. PREAMBLE

This chapter details the various steps taken in the implementation of the research work. Modelling results largely depend on the quality of the input data; as such a lot of time was spent in ensuring the integrity of the input data such as rainfall, climatic and soils data. The 80% rule of spending as much as 80% of the entire time processing and understanding the input data is applied in this project.

3.2. MODEL SELECTION

It was required to use two models to simulate streamflow generation, one of which was to be a locally developed model while the other was to be an internationally acclaimed model that has been validated by numerous studies, bearing the project's objectives in mind. The emphasis on a locally developed model was to enable the use of tools developed in previous related studies and hence promoting locally developed tools which are bound to be more geographically relevant.

The Soil Water Assessment Tool (SWAT) was chosen as one of the models as it had been extensively used in related studies that had similar objectives of finding the impact of land use changes, among other things. User support was available within the CP Project, the developers and user groups. Most of the input data needed to run the model was available, although in an unprocessed format.

The locally developed rainfall-runoff model of HDAM was also chosen as the second model, with the choice being based on its strength of applicability in data-scarce semi-arid Southern African region. The readily available technical support within the CP Project was another key factor in favour for its adoption. It is however noted that certain modifications are required for the model to be suited to the project requirements, and that the driving processes have to be verified and validated using available data as the model has not been extensively used. The validation process is expected to provide a basis for conceptual modifications to the model to make it better suited for data scarce regions.

Data used in the research project is described in the following sub headings, including the processing steps taken to make it suit the selected models requirements.

3.3. Data inventory

Rainfall

There are a total of 22 rainfall stations within, or in close proximity to the study area. Of these, only 19 have daily rainfall data for varying time periods. The recorded rainfall data were obtained from a rainfall database by Lynch (2003), which have been patched from as early as 1900 to 2000. The level of patching ranges from a minimum of 23% to a maximum of 96%. These high levels of patching warranted a further look at the original dataset, which is summarised in Table 3.1 and graphically in Figure 3.1 providing a visual assessment of discontinuities in the time series. The gaps give an explanation to the high patching levels of the data.

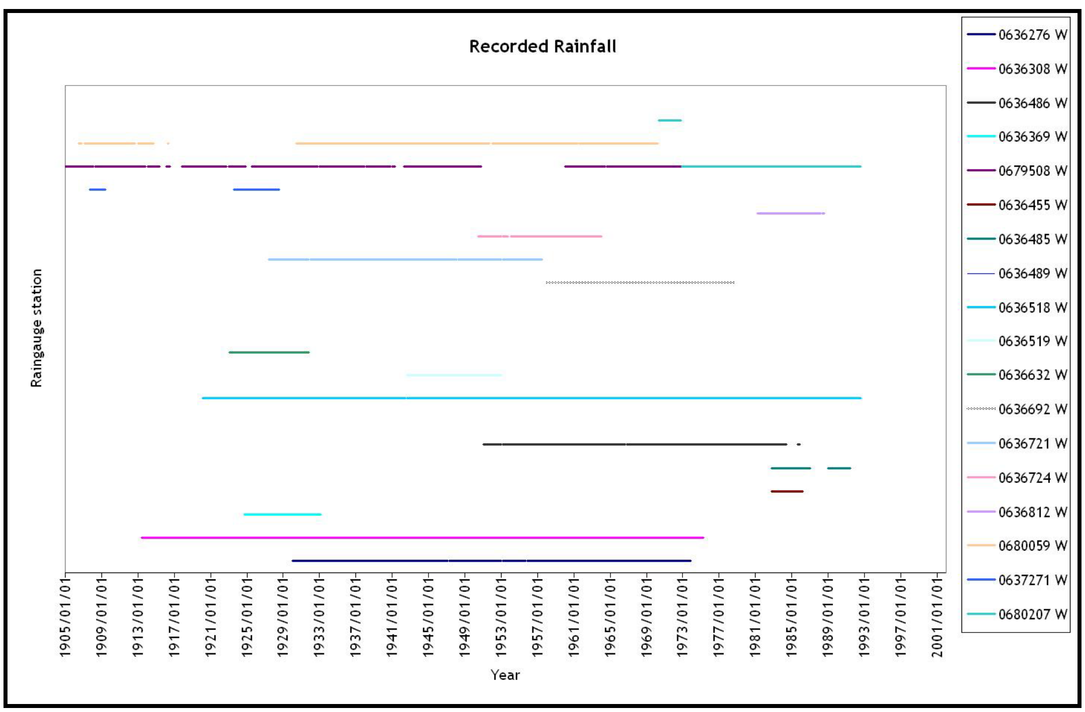


Figure 3.1: Discontinuities in daily rainfall

Table 3.1: Summary of rainfall stations

Station ID	*Start year*	*End year*	*Approx. Period*	*Missing data**
0636276 W	1930/01/01	1973/11/02	44 years	2 %
0636308 W	1913/06/01	1975/03/22	62 years	1 %
0636369 W	1924/10/01	1933/02/28	8 years	3 %
0636455 W	1982/10/01	1986/03/15	3 years	0 %
0636485 W	1982/10/01	1991/05/31	9 years	23 %
0636486 W	1951/02/01	1985/11/30	35 years	6%
0636489 W	1993/07/01	2000/07/31	7 years	2 %
0636518 W	1920/03/01	1993/09/30	73 years	2 %
0636519 W	1942/08/01	1953/12/31	11 years	11 %
0636632 W	1923/02/01	1931/10/31	8 years	3 %
0636662 W	1978/09/01	1980/12/31	2 years	0 %
0636665 AW	1920/12/01	1926/06/30	5 years	3 %
0636692 W	1958/01/01	1978/07/31	28 years	1 %
0636721 W	1927/06/01	1957/06/30	30 years	4 %
0636724 W	1950/07/01	1964/01/31	14 years	5 %
0636812 W	1981/04/01	1989/05/31	9 years	12 %
0637271 W	1907/09/01	1928/07/31	21 years	68%
0680059 W	1906/07/01	1970/03/31	64 years	29 %
0680207 W	1970/05/01	2000/07/31	30 years	1 %

* This is the percentage of missing data within the respective gauge's time period.

All stations with less than ten years of data were disregarded leaving a total of 11 stations within the study area. The location of these stations is shown in Figure 3.2.

Considering the fact that an exact measurement of rainfall is impossible to obtain owing to random and systematic errors in measurement (Schultz, 1985), the extent of patching and the inherent randomness of daily runoff may discourage the use of daily rainfall in favour of rainfall of coarser timescales. However, daily runoff and streamflow estimates are necessary, especially for operational purposes, hence what is more important is how useful is the data as opposed to how error-free it is (Furthering *et al.*, 2000). The level of confidence in using rainfall data increases as one moves from daily to annual measurements as such issues as what really constitutes a daily rainfall reading become less important but this does not eliminate the need for daily and even sub-daily measurements and simulations.

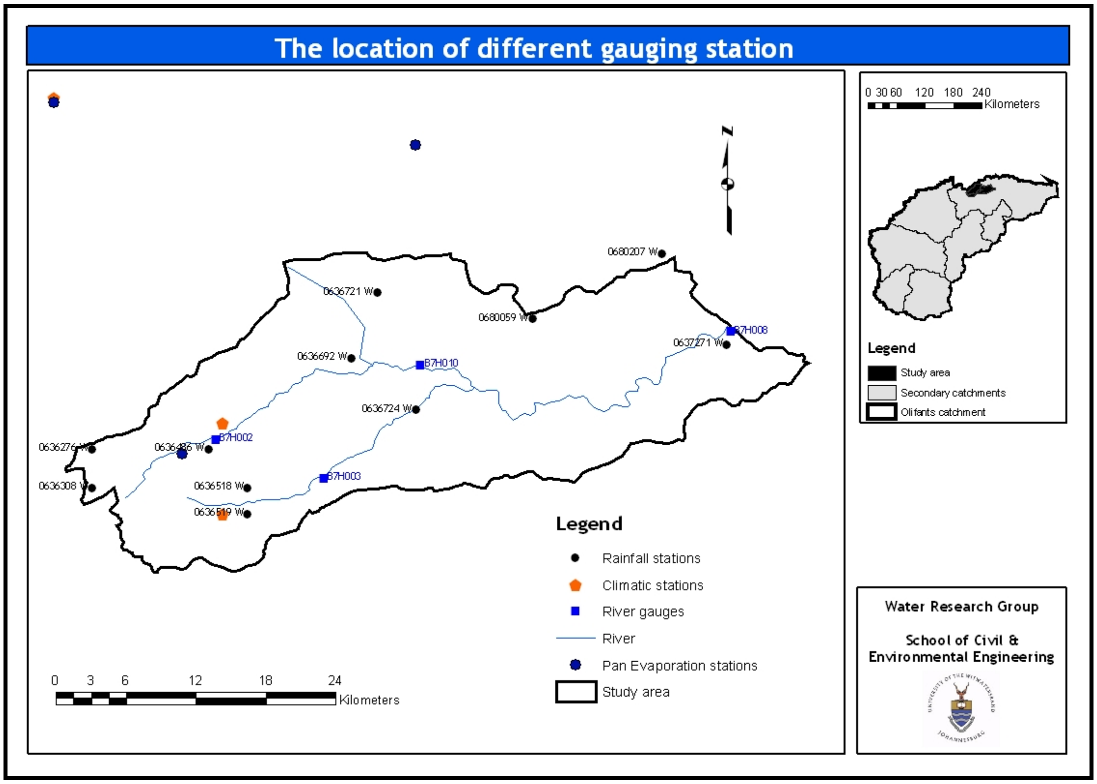


Figure 3.2: The location of gauging stations

Streamflow

There are a total of six gauging stations within the catchment with daily discharge data obtained from DWAF's hydrology website (DWAF, 2006a). The data from the gauge stations are summarised in Table 3.2.

Gauges B7H014 and B7H003 are located on the same latitude and longitude and are probably one and the same gauge that was transferred in 1972 -1973 period. The composite gauge was renamed as B7H003C and has 52 years of data and 21% of missing data. Similarly, gauges B7H002 and B7H023 are also in the same spot and the composite gauge was renamed as B7H002C with 52 years of data and 21% of missing data. The locations of the gauges used for the project are also shown in Figure 3.2.

Table 3.2: Summary of streamflow gauging stations

Station ID	*Start year*	*End year*	*Approx Period*	*Missing data**
B7H002	1960/10/01	2001/04/01	41 years	30 %
B7H023	1948/11/01	1960/06/01	12 years	15 %
B7H014	1973/10/01	2001/04/03	28 years	5 %
B7H003	1948/10/01	1972/04/22	24 years	34 %
B7H010	1960/10/01	2001/04/03	41 years	11 %
B7H008	1966/12/13	1995/09/30	29 years	22 %

* This is the percentage of missing data within the respective gauge's time period.

Pan Evaporation data

Pan evaporation data was also obtained from DWAF (2006). Only one evaporation station (Tours - B7E006) exists within the study area. There are, however, a number of other stations around the area and because of the less variable nature of evaporation data and a strong correlation between stations, data from two other stations was used to infill and extend the evaporation record within the catchment area. The infilling and extension of the datasets is described in Section 3.3. The data from the evaporation stations are summarised in Table 3.3.

Table 3.3: Summary of pan evaporation stations used

Station ID	*Start year*	*End year*	*Approx Period*	*Missing data**
B7E006	1992/10/01	2001/12/01	13 years	17 %
B8E001	1960/10/01	2005/09/01	45 years	0 %
B8H003	1969/12/01	2005/03/01	35 years	3 %

* This is the percentage of missing data within the respective gauge's time period.

Climatic Station data

This is historic daily data on wind speed, humidity, temperature, and sunshine hours required as input to the SWAT model. The data was obtained from the South African Weather Services (SAWS). Within the study area there are a total of four stations, two of which have data for between one to a maximum of four years. The two stations with less than four years of data were not considered in the analysis. The remaining two stations have between six to ten years of data with some discontinuities. Two other stations, Tzaneen and Levubu, are outside the study area and have thirteen and about thirty-eight years of data respectively. The stations are summarised in the table below. Tours, Lekgalameetse and Tzaneen are shown in Figure 3.2 but Levubu is further north outside the view of Figure 3.2.

Table 3.4: Summary of climatic stations used

Station ID	*Name*	*Altitude*	*Approx period*
0636485 9	Tours	716 m	1982 - 1991
0636489 6	Lekgalameetse	800 m	1993 – 2000
0679260 4	Tzaneen	716 m	1979 – 1991
0723485A0	Levubu	706 m	1965 - 2000

GIS data

Different shape files were obtained from the WR90 study, DWAF, Agricultural Research Council, ARC and the CSIR. The data includes the catchment delineated shapes files of South Africa (from primary to quaternary), gauging stations, land use data, topographic data and soils data. These files were modified to suit model requirements. This involved removing duplicate stations, adding of attribute data such as soils profile information from hard copy printouts, and merging different shape files from different sources.

3.4. DATA PROCESSING

The selected two models are on different time steps and this warranted that the data be processed individually on a monthly time step and on a daily time step. This considerably increased the work load as the data came in different formats which necessitated designing of different spreadsheets to handle and manipulate the data. The major processing tools that were used were MS Excel customised with macros, an evaluation version of TextPad, a powerful text editor for Windows, and ArcView GIS for all GIS data. The GIS data requirements for both models are also different; as such different sets of input data were prepared.

For the sake of brevity, the following descriptions refer to the collective data processing for both models.

There was minimal processing done on the patched rainfall data as it came in a ready and usable form with all gaps patched from the rainfall database. However, for observed data spreadsheets were used to determine the gaps indicated in Figure 3.1. Additional processing was also done in order to verify the rainfall processes of the HDAM, which are mentioned in Chapter 4. However, preliminary analysis of the rainfall data, the general randomness of daily rainfall from year to year for each rainfall station is apparent. A typical graph showing such randomness is presented in the Figure 3.3.

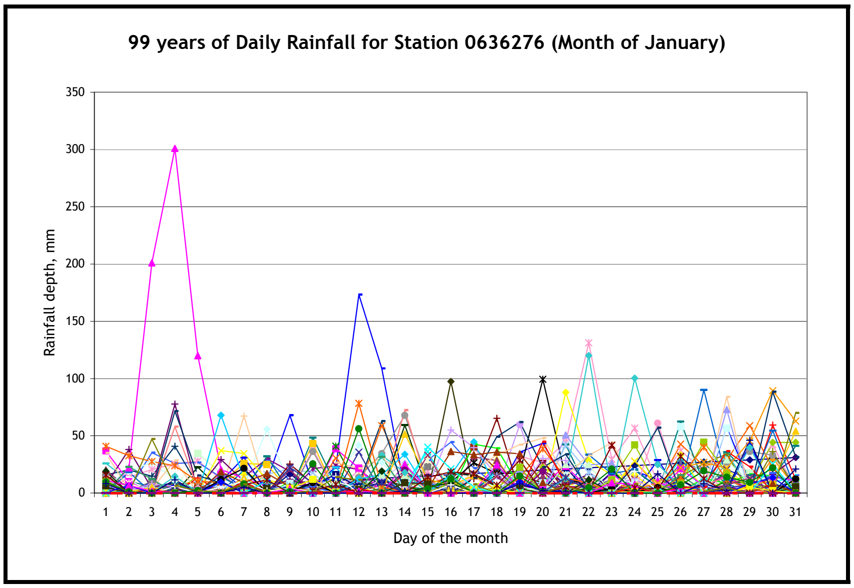


Figure 3.3: 99 years of daily rainfall for the month of January – Station 0636276

The major function of the streamflow data is to compare and calibrate simulated runoff, hence its integrity is important. There are numerous gaps in the streamflow time series which are a limitation as proper comparison by means of mass curve analysis, among others, can not be used to get meaningful results. The gaps in time series of the gauge at the watershed outlet were filled by adding up the flow in gauges preceding and subtracting average flow recorded in the preceding gauges when zero flow was recorded at the watershed outlet. For the other gauges, calibration is done using the longest uninterrupted time series.

In the case of the pan evaporation dataset, the yearly average was used to fill in all the gaps and a correlation between the different stations was done to extend the periods of the stations with shorter time periods. This was done by finding the relationship between the three different stations and adopting a relationship with the highest correlation factor. A typical graph is shown in Figure 3.4 where stations B8E003 and B8E006 are compared to station B8E001. A graph showing the general variation of the measuring stations justifying this approach is shown in Figure A.1 of Appendix A.

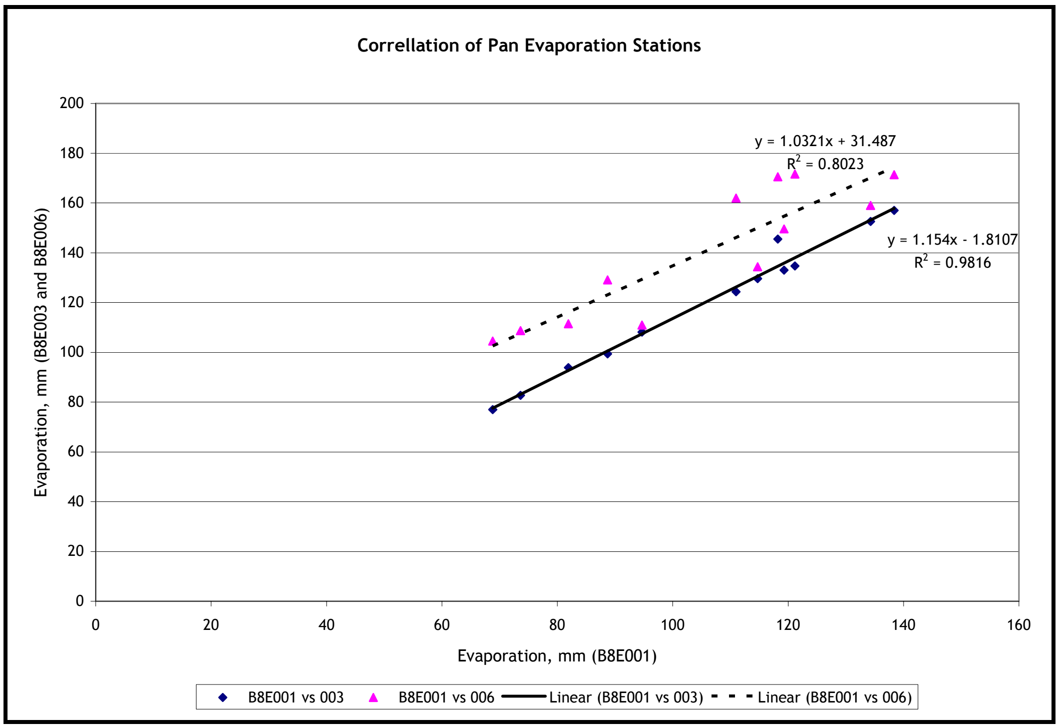


Figure 3.4: Correlation of pan evaporation stations

For the climatic stations data the main thrust was to extend and patch missing data for the Tours and Lekgalameetse stations which fall within the study area. A correlation of each of the stations with Levubu and Tzaneen was done to find any form of relationship, which was thereafter used to extend and patch the datasets. A typical correlation graph is shown in Figure 3.5, while the rest of graphs obtained from the correlation exercises are attached in Appendix A.

In some cases there were no historic values for either Lekgalameetse or Tours, or the correlation with the other two stations was very poor. For such cases, either of the two stations was taken to be representative for both and in extreme cases Tzaneen data was assumed to be representative as it is the nearest to the stations in question and has the same altitude as the Tours station.

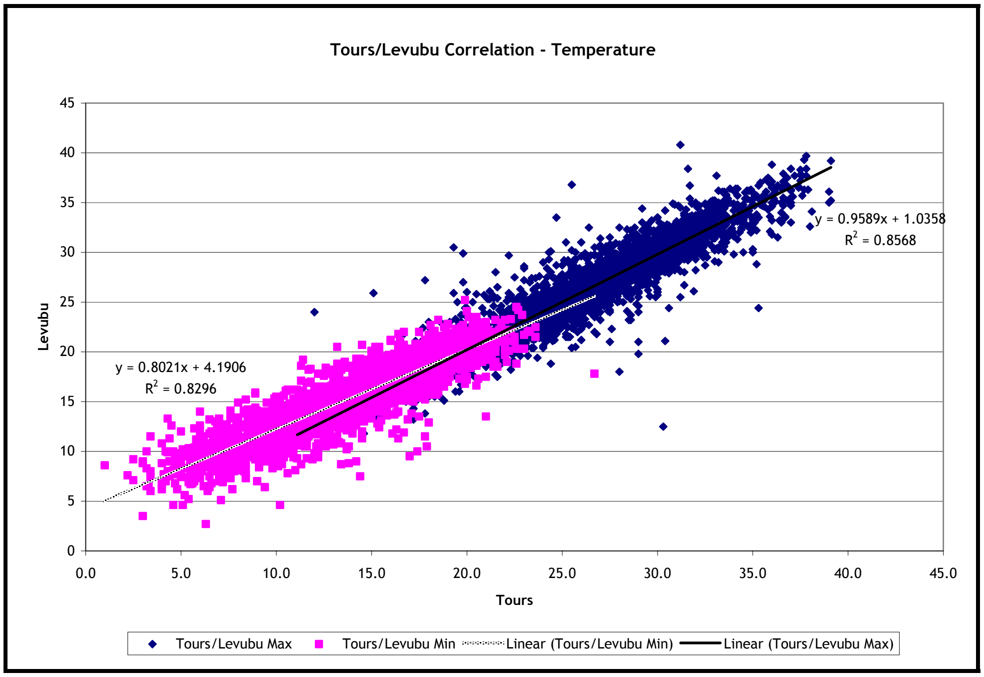


Figure 3.5:Typical correlation between climatic stations

Calculation of Short-wave Radiation (R_s)

In cases where shortwave radiation measurements are not available, as was the case, daily sunshine hours can be used to calculate solar radiation. Daily sunshine values were therefore obtained from the SAWS and solar radiation was calculated by using its relation to the radiation received at the top of the atmosphere (extraterrestrial radiation) (R_a) and the fraction of actual to maximum possible sunshine hours. This formulation was first developed by Ångström (1924) and it corrects the extraterrestrial radiation value for ratio of actual (n) and maximum possible (N) sunshine hours;

$$R_s = \left[a + b\frac{n}{D} \right] R_a \qquad (MJm^{-2}day^{-1}) \qquad \textbf{3.1}$$

Where;

a, *b*: Regression constants for estimation of shortwave radiation from sunshine duration. These vary seasonally, regionally and to a certain extent depend on the time scale (i.e. daily, weekly or monthly). The general values for Southern Africa are 0.24 and 0.53 respectively (Schulze, 1995)

n : the actual sunshine duration (hours)

D : the maximum possible sunshine duration (hours), which varies with latitude and time of year. This value is derived from Table A.2 in Appendix A.

R_A : extra-terrestrial solar radiation, i.e. solar radiation received on a horizontal plane at the top of the atmosphere. This value is derived from Table A.1 in Appendix A.

Table 3.5 summarises the interpolated values for D and R_A obtained from the Tables A.1 and A.2 in Appendix A. The latitude for the study area is 24 degrees south of the equator.

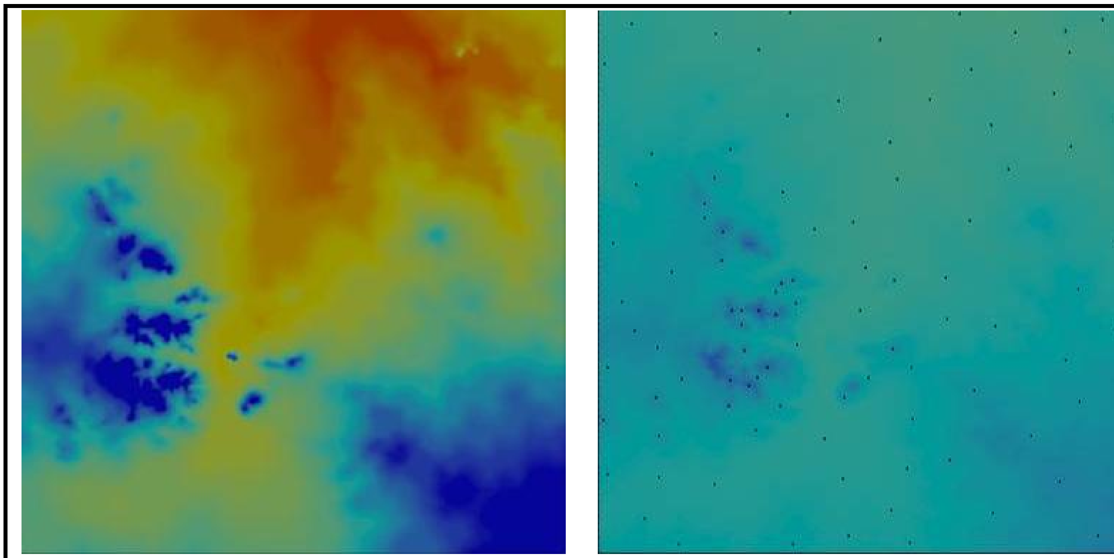
Table 3.5: Interpolated Values for D and R_A

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
D, hrs	13.26	12.84	12.30	11.68	11.14	10.84	10.94	11.46	12.00	12.62	13.14	13.38
R_A, MJ/m^2	41.58	40.83	29.97	23.44	17.10	15.18	16.09	20.88	28.59	34.86	41.58	42.82

The above values, together with the daily sunshine hours time series, were used in calculating the daily solar radiation using equation 3.1 from 1966 to 2000.

3.5. Digital Elevation Model Creation

In order to delineate the watershed into several ‘hydrologically’ connected sub-watersheds, a digital elevation model is required. Available to the project is a 90m DEM from the Shuttle Radar Topography Mission (SRTM), however, this resolution was deemed not adequate. This can be seen by comparing the SRTM DEM with one created using 20m topographic data shown in Figure 3.6 which clearly reflects a loss in key topological features in the 90m DEM despite the addition of spot heights.



From Topographic Data (20m) From SRTM (90m) + Spot Heights

Source: IWMI – South Africa (2006)

Figure 3.6: Topographic vs SRTM DEM

To reduce this loss of resolution, topographic data (relief lines and points) was obtained from the DLA (2006) and DWAF (2006b). The data was processed using ArcView 3.3 with the Spatial Analyst and 3D Analyst extensions.

The input layers to the DEM creation process were the line maps (contours) and point maps (spot heights) which ensured the elimination of unnecessary sinks. A Triangulated Irregular Network (TIN) was created from the features with the height attributes being selected as the height source for the study area. The TIN was thereafter converted to raster format with a cell size of 0.0001. Figure 3.7 shows the created DEM for the study area.

The same approach was attempted in creating a DEM for the entire Olifants basin. Creation of the TIN was time consuming and the TIN could not be converted to a grid because of the relatively fine resolution and the processing power required. As such, for the HDAM component of the project, slopes were derived from the generated TIN while the existing delineation from the WR90 was adopted with the sub-quaternary delineation done manually following key topographical and land use features.

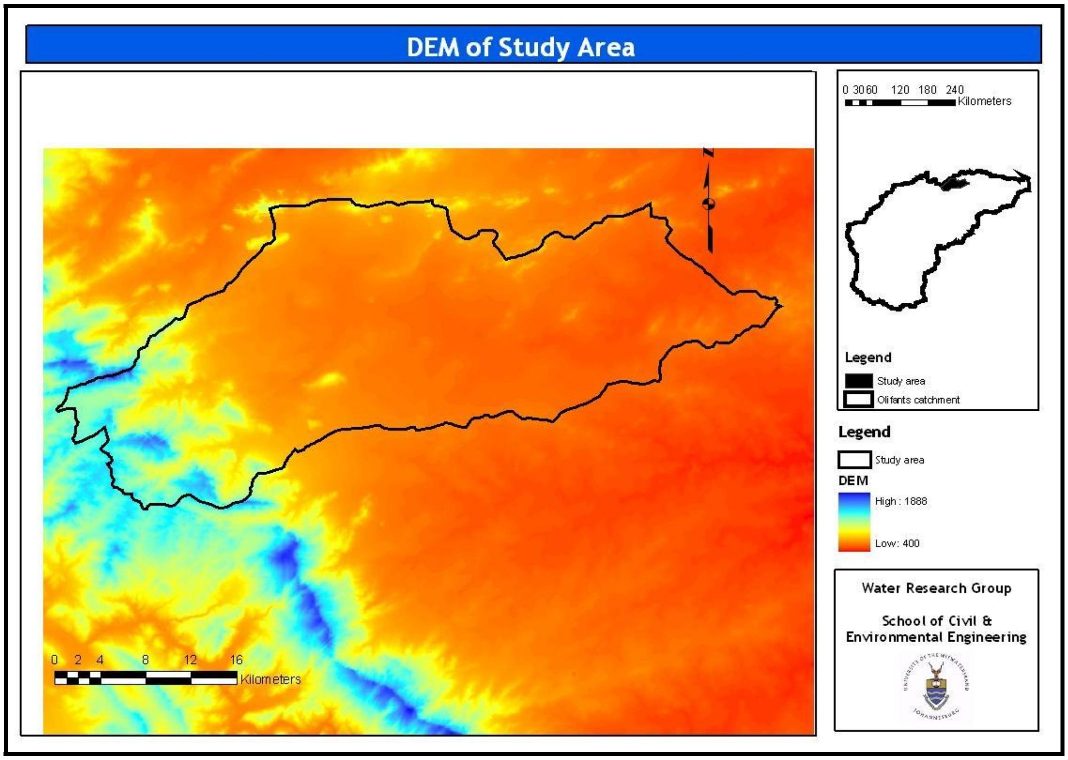


Figure 3.7: DEM for the study area

The setting up and application of the respective models is described in the following chapters.

CHAPTER 4: HYDROLOGICAL MODELLING WITH THE HDAM

4.1. PREAMBLE

HDAM is the acronym for the Hydrological Drought Analysis Model developed by Nyabeze (2003a; 2005). The model applies a rainfall-runoff sub-model based on the RAFLER model of Stephenson and Paling (1992).

In order to understand the rainfall-runoff component of the model and evaluate its applicability, a review is herein presented of its features in relation to its main driver which is rainfall.

4.2. CONCEPTS OF THE HDAM

The model is applied in a semi-distributed mode around the concept that runoff is generated from rain which falls in blocks of time. The number of days receiving rain each month is estimated from the following equation;

$$N_m = N_y \frac{P_m(I)}{\overline{P}_y(I)} \qquad \textbf{4.1}$$

Where

N_m: rain days per month (raindays/mth)

N_y: average raindays per year (raindays/yr)

P_m: rain received during month (mm/mth) in module (I)

$\overline{P}_y$: mean annual precipitation (mm/year) in module (I)

The relationship between N_m and P_m is therefore a linear one in the form of

$$N_m = kP_m \qquad \textbf{4.2}$$

where k is some constant depending on average rain days per year and the mean annual precipitation.

The rain is assumed to occur in wet-dry clusters and the calculated rain days in a month are counted from the beginning of the month and in the event that these are greater than the days in a calendar month the remainder is carried forward to the subsequent month. As such all the rainy days are clustered together at the beginning of each month with the remainder of the month being considered as dry. The hours of rain in a month are thereafter calculated using equation 4.3 below;

$$N_H = \frac{N_y}{f_{DH}} \left(\frac{12 P_m(I)}{\overline{P}_y(I)} \right)^a \qquad \textbf{4.3}$$

Where;

N_H: rain hours per month (hrs/mth)

f_{DH} : rain days to hours factor found by optimisation

P_m: rain received during month (mm/mth) in module (I) read from input file.

$\overline{P}_y$: mean annual precipitation (mm/year) in module (I)

a : factor for adjusting for rainfall peaks. This factor captures the power relationship between N_H and P_m but not that between Nm and Pm.

Rain is assumed to fall in storms during each of the rainy days and the sum of the periods of all storms per month should typically add up to N_H. Runoff estimation is based on intensity and the duration of each particular storm is estimated from;

$$D_s = \frac{N_H}{N_s} \left(\frac{L \times N_m}{N_y} \right) \qquad \textbf{4.4}$$

Where

D_s: average hours of rain per storm

L: length of the rainy season (no. of months)

N_s: number of storms per month (empirical value)

D_S is the modelling time-step for the HDAM. The f_{DH} aggregates the influence of micro climate on rainfall events and in the HDAM it takes a unique value for each quaternary catchment. It is assumed that under steady state conditions, for any rainfall received during any month, the catchment generates the maximum runoff if the correct f_{DH} value is applied.

Intensity of the rainfall is simply estimated from the relationship

$$i = \frac{P_m}{N_H} \qquad \textbf{4.5}$$

The model has been used to obtain a time series of runoff at a monthly time step for the Mzingwane catchment in Zimbabwe with simulated time series closely matching observed values in Nyabeze (2005).

4.3. VERIFICATION OF THE CONCEPTS OF HDAM

The model had previously been used in data scarce regions with acceptable results (e.g. Nyabeze, 2003a; 2005) but this has not been done extensively by different users, hence the need to verify whether the concepts noted in the previous sub section are actually reflected by observed daily rainfall data.

Data analysis was done for patched records of the 18 of the 19 rainfall stations in the B72E – H quaternary catchments. 99 years of rainfall data was obtained from Lynch (2004).

As a starting point the variation of daily rainfall within each particular month of the year for the 99 years was analysed and no noticeable trends were observed as shown in Figure 3.3.

The variation in Figure 3.3 is further reinforced by a probabilistic analysis of the likelihood of having a rainfall event in a particular day of the month presented in Figure 4.1. It can be seen that for most days of the year there is a non-zero probability that a rainfall event will occur. The variation between seasons can also be noted where after day 150 variations increase substantially as the dry season approaches, and become more pronounced after day 200. It should be noted that day 1 in Figure 4.1 corresponds to October 1 of a particular year.

Although rainfall does fall in clusters, these clusters can be anywhere within a particular month. A plot of the cumulative raindays per year was then done to observe any particular trends and possibly the occurrence of rain clusters. This is shown in Figure 4.2 for one of the stations, Station 0636276.

Figure 4.2 shows that for the 99 years of analysis, rain days were distributed within an envelope corresponding to the wettest and driest years. Within this envelope, there is a wide variation in the distribution of rain days for each year. A simplification of each year's curve yields two linear curves which reflect two distinct wet and dry seasons. Furthermore, such a linear relationship is indicative of rain falling every day which cannot be the case in reality. Essentially, although rain storms could occur in clusters there is no defined pattern to adduce any relationship of the form assumed in HDAM.

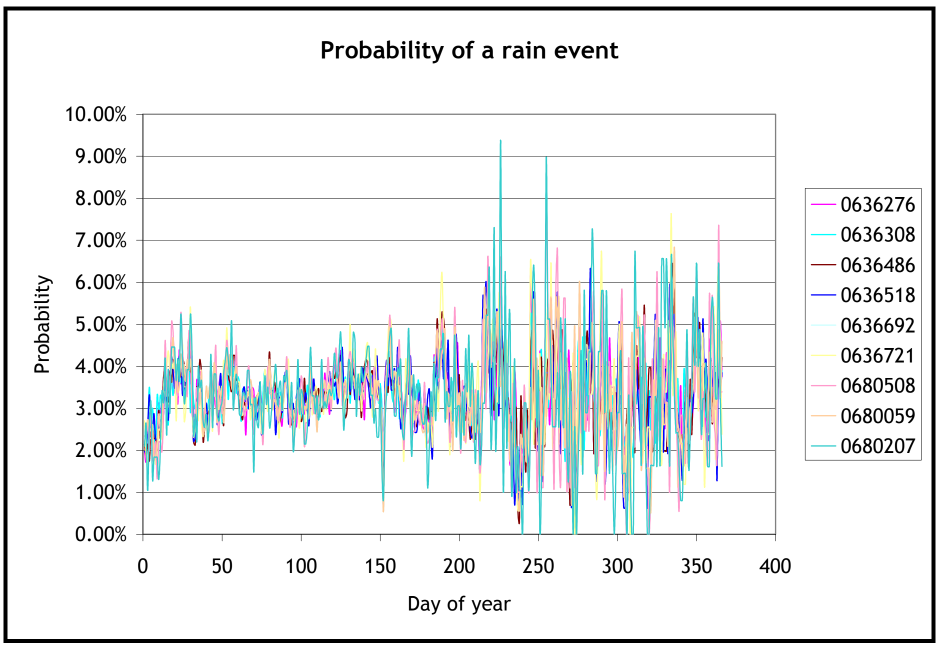


Figure 4.1: Probability of a rainfall event

The relationship of rain days and the monthly precipitation was thereafter investigated by plotting the number of rain days corresponding to specific monthly precipitation. A typical plot of the data is shown in Figure 4.3. For all the stations analysed, it was found that the form of relationship between N_m and P_m is not of the linear form as depicted by equations 4.1 and 4.2 but of the form

$$N_m = b \times P_m^c \quad \textbf{4.6}$$

Where

b : a constant varying from 0.74 to 1.2 for the different stations

c : an exponent approximately equal to 0.5 for all the stations.

The factors b and c are claimed to be factored in equation 4.3 but this would not necessarily be correct as the average is also factored. The nonlinear relationship expressed in equation 4.3 between the monthly rain hours, N_H, and the monthly precipitation, P_m, where a is not unity does not fully reflect and capture the correct relationship between N_H and P_m. Rather than attempting to arbitrarily vary a in equation 4.3, it is better to directly calculate b and c in equation 4.6.

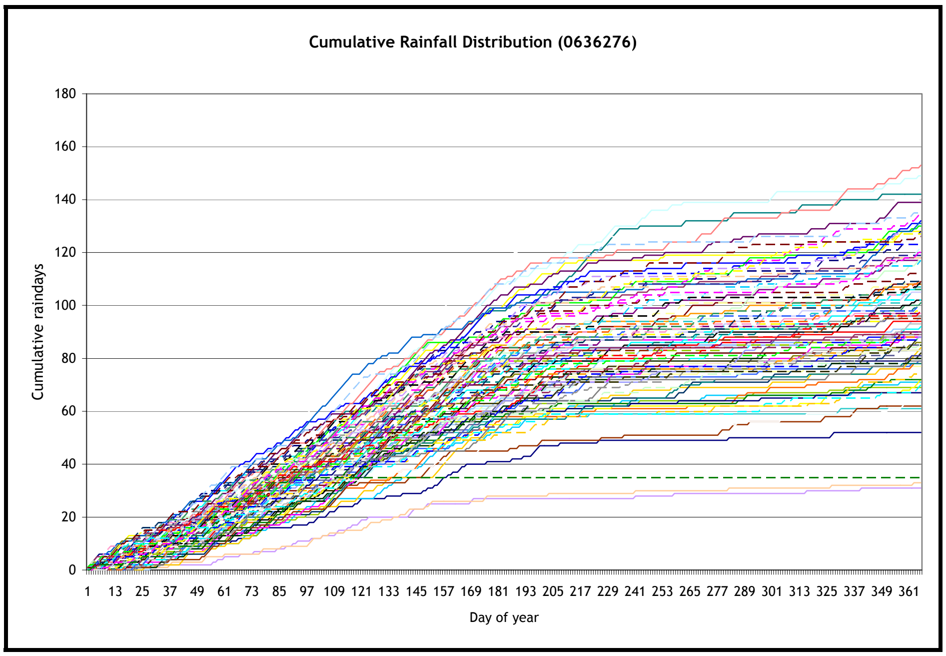


Figure 4.2: Cumulative rain days distribution

The above is therefore a departure from the current concept in the HDAM. The correlation coefficient of the analysed data shown in Figure 4.3 ranges between 0.60 and 0.74 and gives credence to the application of equation 4.6.

The variation of rain hours in a month was not validated as there was insufficient data to allow for such analysis.

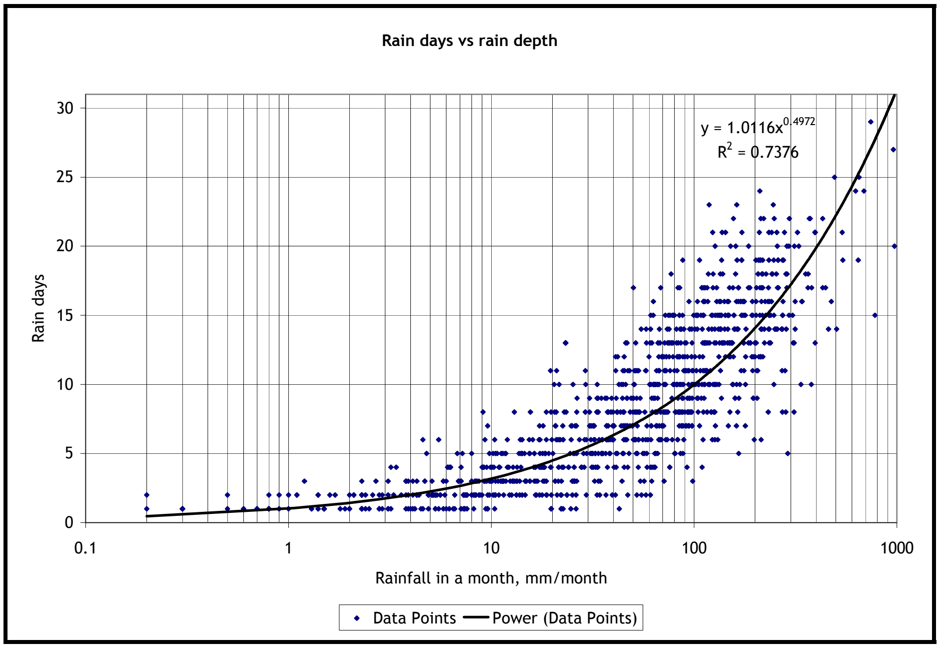


Figure 4.3: Relationship of rain days to monthly rainfall

Equation 4.4 assumes a constant storm duration value, D_S, for all the N_S storms while the intensity for each storm is given by equation 4.5. There is however no perceived value in the computation of D_S, which takes a constant value for all rainfall events as the intensity, is also constant for the entire month. These assumptions, which are inaccurate, are useful only in instances where such data are unavailable.

The f_{DH} factor in equation 4.3 is the only factor (a non-physical parameter) that is calibrated in the model and is meant to correct for the effects of micro-climate on rain events. This has a shortcoming in that there are other non-climatic factors that have influence on rainfall partitioning and may also need calibrating such as physical data (e.g. soils) which are generalised for large areas using point data representation. As such, a strong correlation between simulated and observed values may not necessarily imply a correct representation of the watershed being modelled. Calibration using the f_{DH} factor should therefore be done keeping in mind that there are other parameters that may need to be refined.

In this report, only results of one station (Station 0636276) have been presented to facilitate the presentation. Results for the other stations in the study area are shown in Appendix B.

4.4. APPLICABILITY OF THE HDAM TO THE RESEARCH WORK.

The fundamental objective of this research project is to setup and apply a tool in the form of a hydrological model that is able to, among other things:

- Assess and model runoff generation at a daily time step.
- Perform an impact assessment of the effect of anthropogenic activities, including land use, on the hydrology and the likely upstream-downstream interactions and effects.

HDAM can be used to do achieve the above objectives except that it is on a monthly time step and it does not use daily precipitation in runoff generation. There is no provision within the model for disaggregating monthly rainfall data into daily precipitation. In addition, the model lumps all the rainfall events to the beginning of the month with no regard for the spacing of the wet-dry rainfall clusters, which may be appropriate for a monthly time step but certainly not for a daily one.

Daily rainfall and streamflow data is readily available for South Africa and is usable despite the high levels of patching for a number of rainfall stations. The same cannot be said of the entire Southern Africa region. Therefore, for HDAM to meet user requirements in the region, it has to be modified to perform at least one of the following options:

- Use the available daily data to generate daily runoff.
- Disaggregate monthly rainfall to daily rainfall in a scientifically plausible manner that is able to capture the statistics of daily rainfall and ultimately daily runoff.

The available options are explored further in the following sub-sections.

4.4.1. Option 1: Use daily data

This option takes advantage of the availability of the existing data. It however disregards the rain days concept of the HDAM but maintains the concept that runoff is intensity driven. Because daily data is used, there is a high likelihood of a close match between simulated and observed runoff data, assuming that runoff generation is modelled properly.

In order to find the nature of the intensity of daily rainfall the preferred method was to use available data as opposed to empirical relationships. Hourly rainfall data for Grenshoek Tzaneen (Altitude 893, 6 years of data) and Van Reenen (Altitude 1680m, about 9 years of data) stations were analysed to find the correlation between daily rainfall and intensity. This is shown in Figure 4.4 and Figure 4.5, which indicate relationships between intensity and daily precipitation.

Figure 4.4 shows a series of straight lines with each line corresponding to a particular rainfall duration. This is illustrated in Figure 4.6 while the percentage occurrence of each rainfall duration is depicted in Figure 4.7.

The intensity was found by averaging the total daily precipitation over the total number of hours over which the rain amount fell. Although variations in intensities occur over the duration of storms, this simplification of average intensity over the duration of the storm is a valid generalisation in view of limited available information. This approach is better than averaging intensity over a month.

A more plausible approach in establishing the relationship between rainfall depth, P_d, and intensity, i, could be obtained by using storm durations of, say, 75% probability of occurrence.

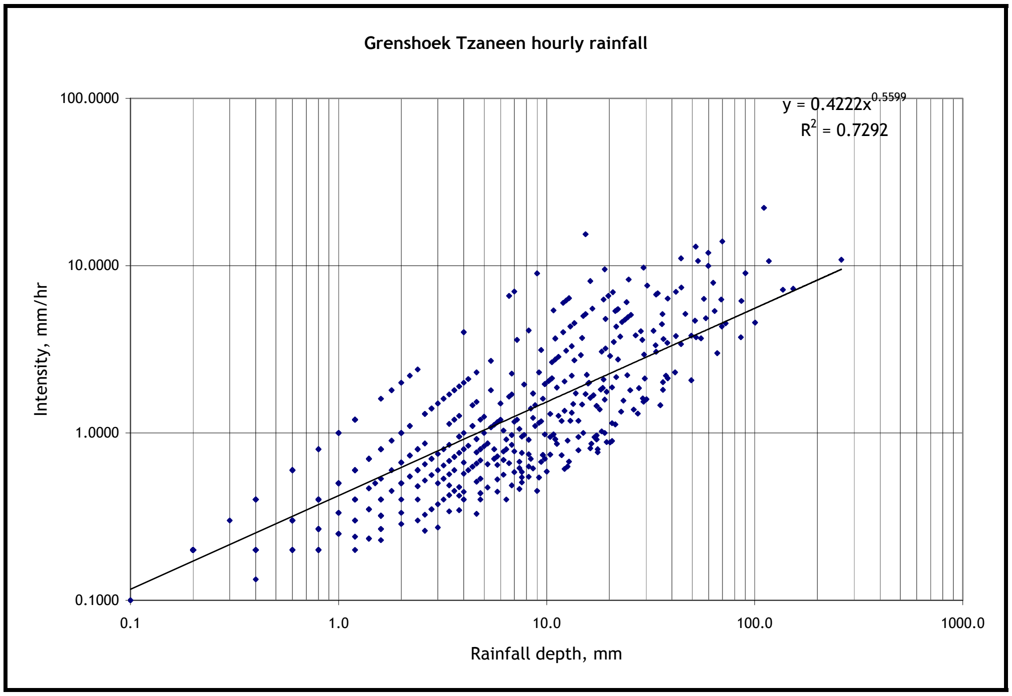


Figure 4.4: Intensity – precipitation relationship for Tzaneen

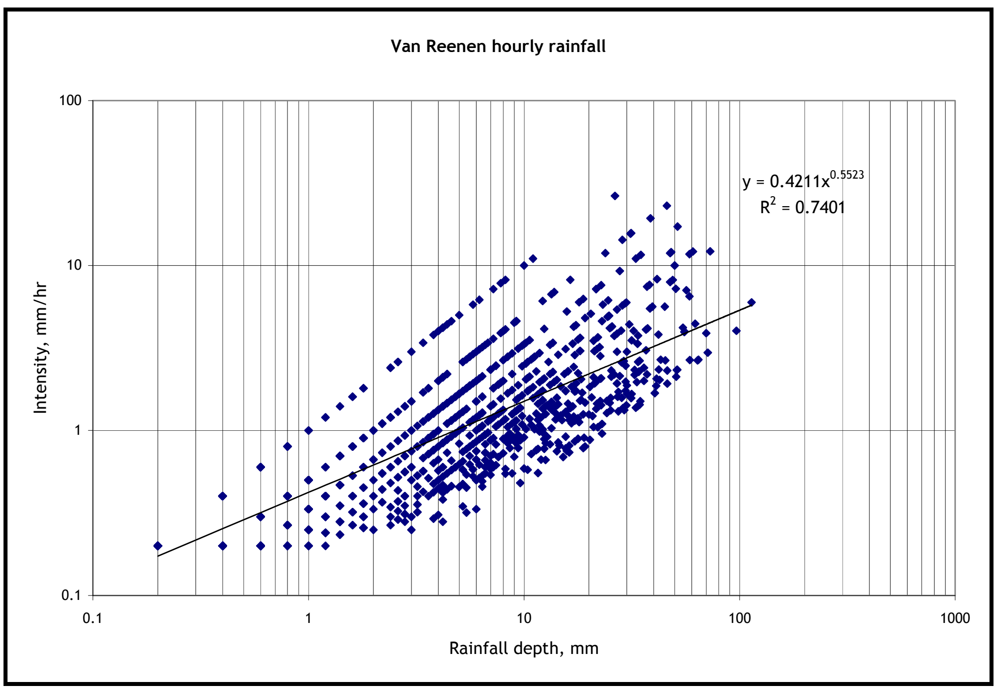


Figure 4.5: Intensity – precipitation relationship for Van Reenen

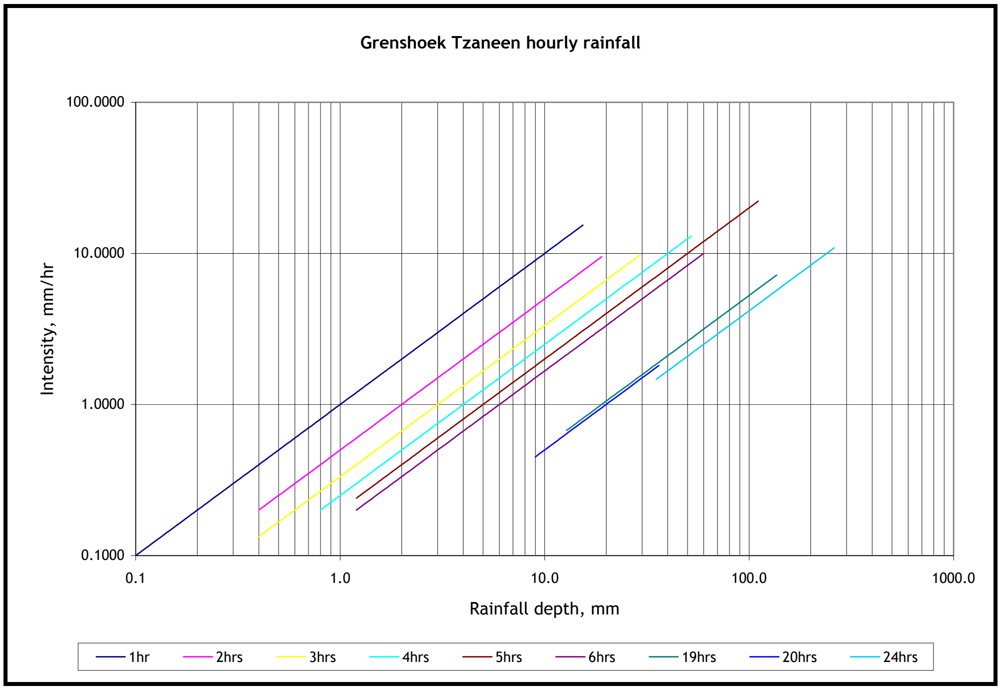


Figure 4.6: Intensity – precipitation relationship for different durations of rainfall

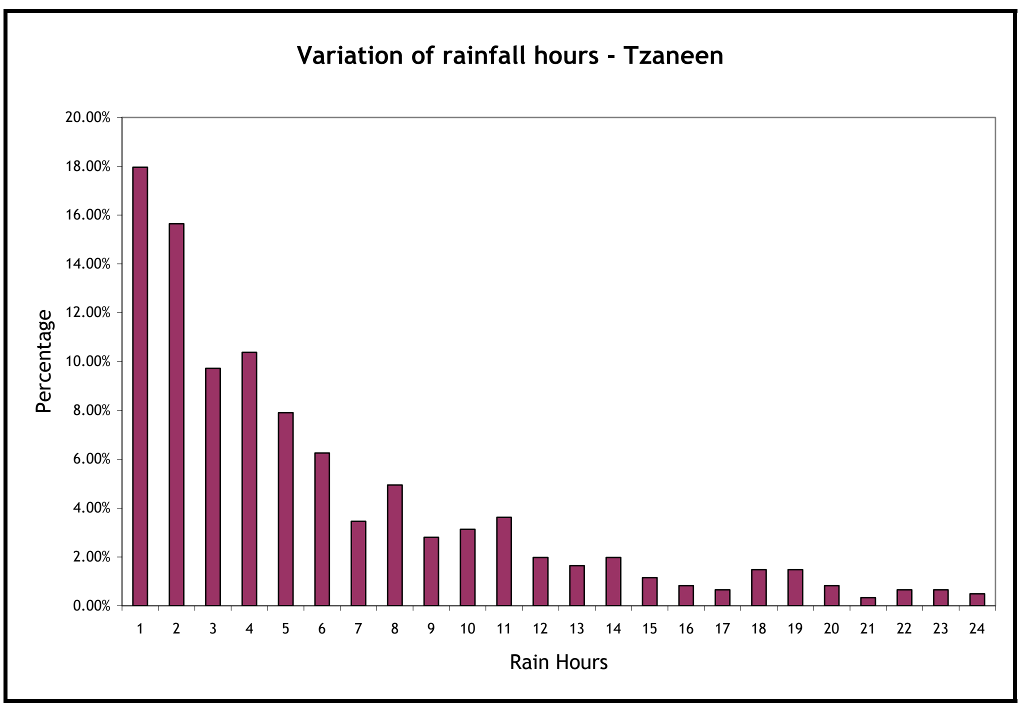


Figure 4.7: Percentage variation of rainfall durations per event

This relationship of the form

$$i = eP_d^f \qquad \textbf{4.7}$$

Where e and f are factors to be calibrated by an optimisation algorithm. This relationship (equation 4.7) of intensity and precipitation is based on observed data and provides a better representation of local conditions.

Effectively, the required daily rainfall input into the model is converted to intensities using equation 4.7. The appropriate factors in these equations are optimised to get the best representation of the observed streamflow. It is however noted that the length of the hourly rainfall records may not be sufficiently long and that the use of only a few stations in close proximity may not allow for conclusive generalisations. Additional analysis using representative station throughout the country is recommended.

4.4.2. Option 2: Disaggregate monthly rainfall to daily rainfall

This option maintains the conceptual processes of the HDAM while adding a new dimension of disaggregating monthly rainfall.

Maintaining the rain days concept calls for modifications according to equation 4.6 to capture the power relationship based on observed data as opposed to the current linear relationship. Although the rainfall records used are patched it remains representative of local conditions as the patching procedure preserves the statistic and location specific properties of the rainfall. The input to the model shall be monthly rainfall from which rain days in a particular month is calculated and thereafter used in the subsequent computations.

The key issue in this particular option is disaggregating monthly rainfall to daily rainfall in terms of both volumes and time to capture the variation of daily rainfall used to generate daily runoff.

Distribution of rain days could be done by using data from Figure 4.2 coded in binary data i.e. 1 0 1 1 1 0 0 01, with 1 indicating a rainfall event greater or equal to some threshold value of 1mm and 0 a non event. Because Figure 4.2 is based on 99 years of data, there is a high level of confidence that in any particular year rain days will fall within the prescribed envelope. Upon calculating N_m from equation 4.6, a curve corresponding to the number of rain days in the particular month (which will be a cumulative total from October 1) is then identified and raindays are distributed as defined by that particular curve.

However, disaggregating rainfall volumes could be an uncertain issue as Figure 3.3 clearly depicts. There is no plausible relationship that can be obtained from the data except maybe by some stochastic analysis. The use of stochastic or some other probabilistic methods is invaluable in forecasting analysis or where the required daily data is not available. Adoption of such an approach requires the use of weather generators such as the WXGEN weather generator included in SWAT. This particular generator has been successfully modified and used by Muthuwatta (2004) to preserve the higher series quantities. It must be noted that the main objective of weather generators is to obtain lower scale time series based on properties of higher scale time series for the purposes of forecasting or providing unavailable information. The entire CP Project stands to benefit as there is limited data in certain parts of the Limpopo basin, if homogeneity of the rainfall patterns is assumed.

Another approach would be to use an average intensity for the month for all the rain events as is done in the current model setup. The temporal variation in runoff, and subsequently streamflow, is not properly captured by this approach, thereby not allowing for a comparison between simulated and observed values. This is considerably more valuable in data scarce areas, which is the strength of the HDAM.

Option 2 suggests a higher reliability and usability of monthly rainfall data in comparison to daily data as daily rainfall data, where available, is ignored. Although daily rainfall measurement is fraught with numerous inconsistencies, synthetic daily rainfall data obtained by disaggregating monthly data will rarely be as good as observed daily data with errors. It is argued that the better approach will be to minimise these errors rather than disregard the data.

4.4.3. Option 3: Combination of Option 1 and 2

This option realises the value of both option 1 and 2 and the fact that some users may have the data while others may not. The usefulness of HDAM could be enhanced if the users have the choice of either Option 1 where daily data is available or Option 2 when data is limited.

Extensive modifications of HDAM would have been required in the light of the foregoing discussion to make it applicable to the current work. However, time constraints and lack of adequate support from the developer necessitated the shelving of the model in favour of SWAT. Although it would have been desirable to compare the results of the two models, it is believed that the physically based nature of the SWAT model gives high confidence to its results without any comparison with another model.

It is however recommended that the discussion that has been done in this chapter be used as a basis of improving the HDAM in future to make it versatile in accepting either daily or monthly rainfall and be able to disaggregate monthly rainfall in a plausible manner.

CHAPTER 5: HYDROLOGICAL MODELLING WITH SWAT

5.1. SOIL AND WATER ASSESSMENT TOOL (SWAT)

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) is a continuous time, spatially semi-distributed watershed model with a GIS interface that outlines the sub-basins and stream networks from a Digital Elevation Model (DEM) and calculates daily water balances from meteorological, soil and land-use data (Conan *et al.,* 2003). The model was developed to simulate the impact of management decisions on water, sediment and agricultural chemical yields in river basins in relation to soil, land use and management practices (Bouraoui *et al.*, 2005)

The model represents the large-scale spatial variability of soil, land use and management practices by discretising the catchment into a number of sub-units using a two-step approach. The initial step is topographic discretisation which is done by dividing the catchment into sub-catchments based on a defined threshold area. Thereafter, each sub-catchment is further divided into several homogeneous hydrological response units (HRUs) representing unique combinations of soil and land use. The responses of each HRU in terms of water, sediment, nutrient, and pesticides transformations and losses are determined individually, and then aggregated at the sub-basin level and routed to the associated reach and to the catchment outlet through the channel network. The water budget for each sub-basin is based on the following equation.

$$SW_t = SW_0 + \sum_{t=1}^{t}(R_i - Q_i - ET_i - W_i - QR_i) \qquad \textbf{5.1}$$

Where

SW_t : final soil water content,

SW_0 : initial soil water on day i,

R_i, Q_i, ET_i, W_i, and QR_i : are precipitation, surface runoff, evapotranspiration, seepage flow and return flow on day i, respectively.

Figure 5.1 shows the hydrological component of the SWAT model which illustrates how runoff is calculated for each sub-basin (Muthuwatta, 2004).

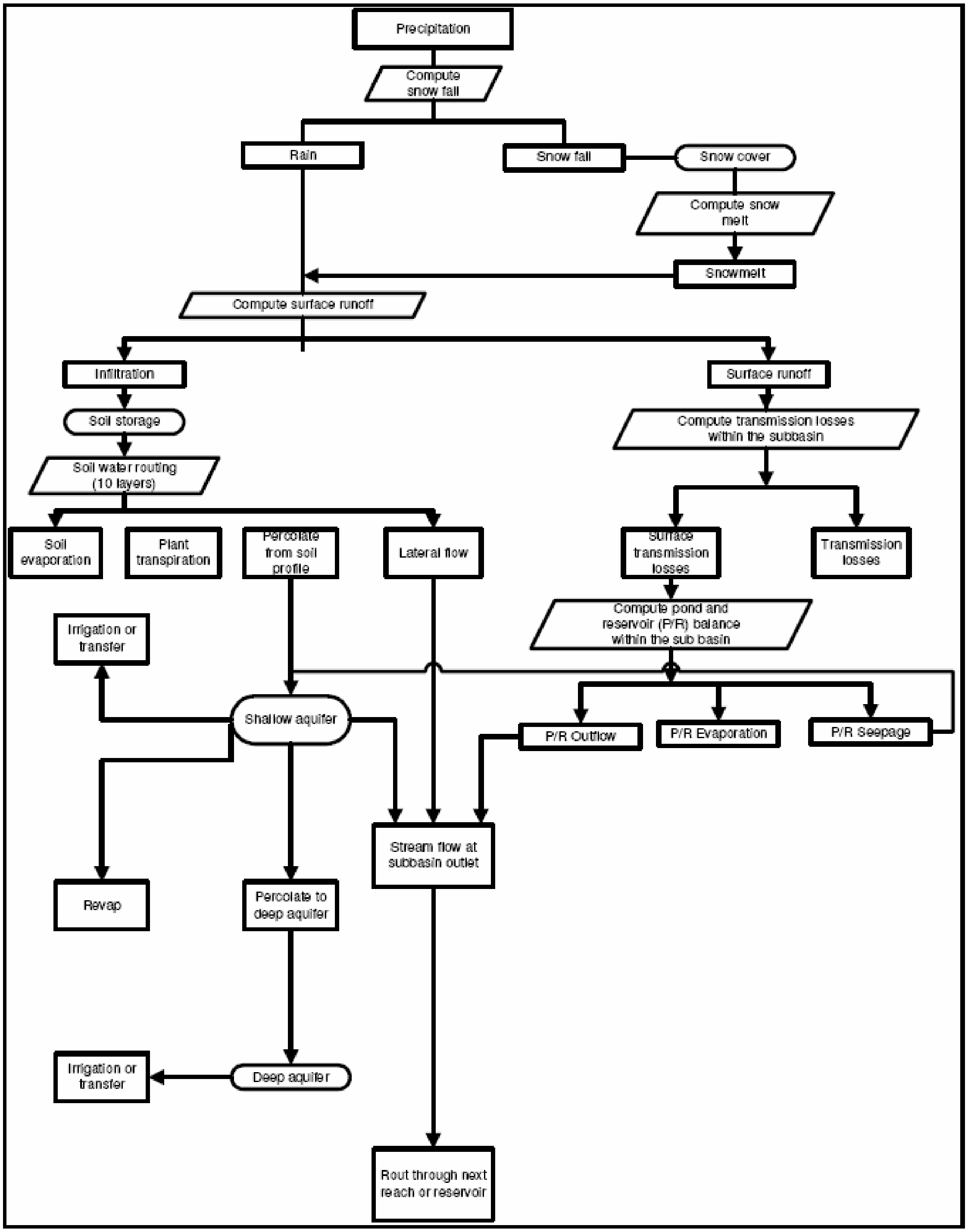


Figure 5.1: Overview of the SWAT hydrologic component (Muthuwatta, 2005)

5.2. MODEL SETUP

The model is setup following the procedures laid down in Di Luzio *et al.* (2002) which details the use of the ArcView interface for SWAT 2000 known as AVSWAT. The following subsections summarises the key processes followed in the setting up of the model.

5.2.1. Sub-basin delineation

Automatic watershed delineation tool in SWAT discretises the watershed into sub-basins and generates the stream network based on topography, flow directions and flow accumulations. During the delineation process, the program fills all the sinks in the DEM in order to create a flow vector. In this way, the elevation of the sinks increases until overflow occurs. The flow accumulation grid is created by counting the number of flowing cells into each unit in the grid. High values of flow accumulation are associated with the cells, which are potentially part of the stream network (Muthuwatta, 2004).

The automatically generated sub-basin outlets were modified to suit the project requirements and that meant manually adding outlet positions at the gauging station points in order to use the observed discharge for the calibration. The model automatically estimates the channel length, average slope of the channel and other sub-basin characteristics. This process demands extensive time in manual techniques and the output parameters are stored in SWAT input files.

A report generated by SWAT detailing the statistical summary and distribution of discrete land surface elevations in the watershed and sub- watersheds is attached in Appendix C and the delineated sub-basins are shown in Figure 5.2.

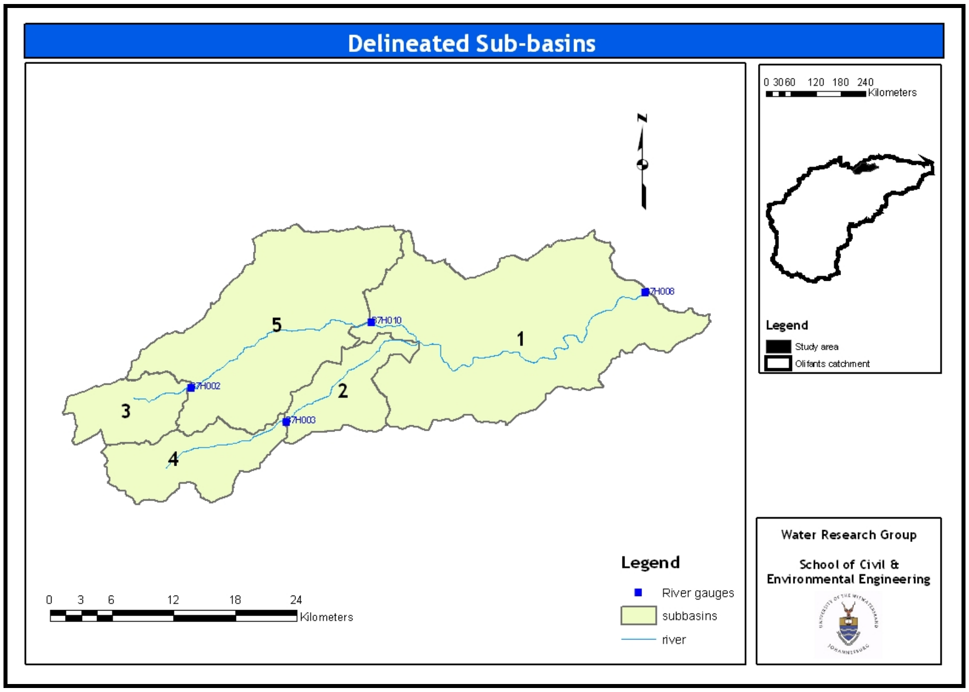


Figure 5.2: Delineated sub-basin

5.2.2. Land use and Soil Definition and overlay

Land use and soil data are required to determine the area and hydrologic parameters of each land/soil category to be simulated. These land/soil categories form the basis of the hydrological response units (HRUs) and terrain parameters are identical for all HRUs within a given sub-basin, except for the channel length parameter used to compute the time of concentration, which varies depending on the size of the HRU.

The land cover shape file used was that from CSIR (2003). The different land cover classes are classified according to the available SWAT land cover classification for most of the classes with the residential class being modified to suit local conditions by using an estimated impervious area of 0.3%. These are shown in Figure 5.3.

The land use map in Figure 5.3 shows the naming convention used in SWAT and the physical names of these are as follows;

AGRC: Agricultural Land - Close grown

AGRR: Agricultural Land – Row crops

FRSE: Forest – evergreen;

FRST: Forest - mixed

RNGB: Range – brush

RNGE: Range - grasses

SWRN: Range – arid (South-western US)	UIDU: Industrial
URHD: Residential (High density)	WATR: Water

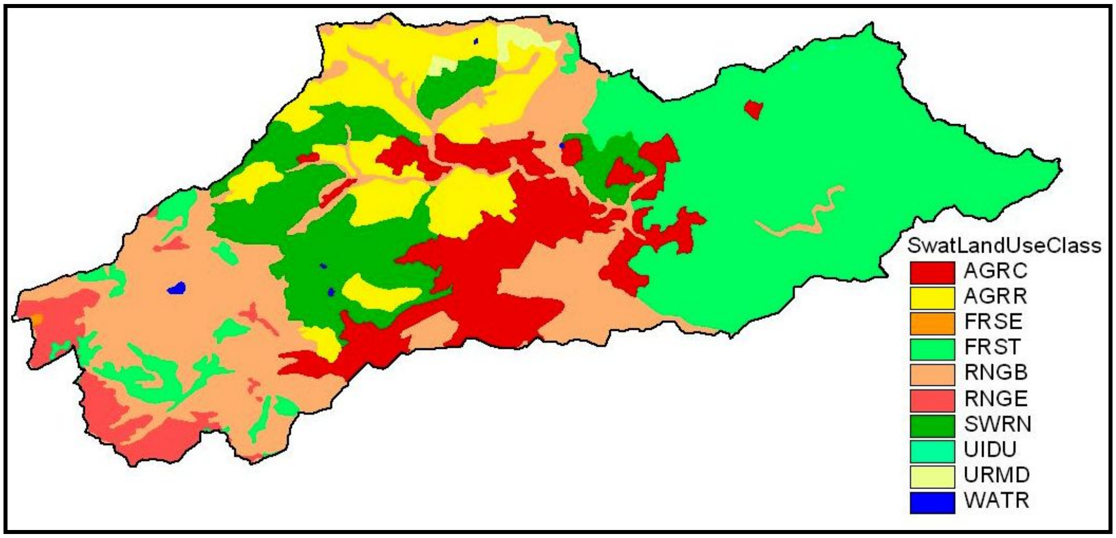


Figure 5.3: SWAT Land use classification

The different soil classes were defined in the user's soil database using data from the Agricultural Research Institute: Institute of Soil, Water and Climate (ARC) and the ACRU model datasets which has generic information for South Africa. The different soil classes (referred to as land types by the ARC) are shown in Figure 5.4.

The soil definition was done using hard copies of soil profile data for the dominant soil series in the land type. The information from the profiles was individually added to the soils database in SWAT from which the model incorporates parameter values defined spatially by the soils shape files. A number of other land types were available in the watershed but had the same dominant soil series that allowed for the merging of such land types.

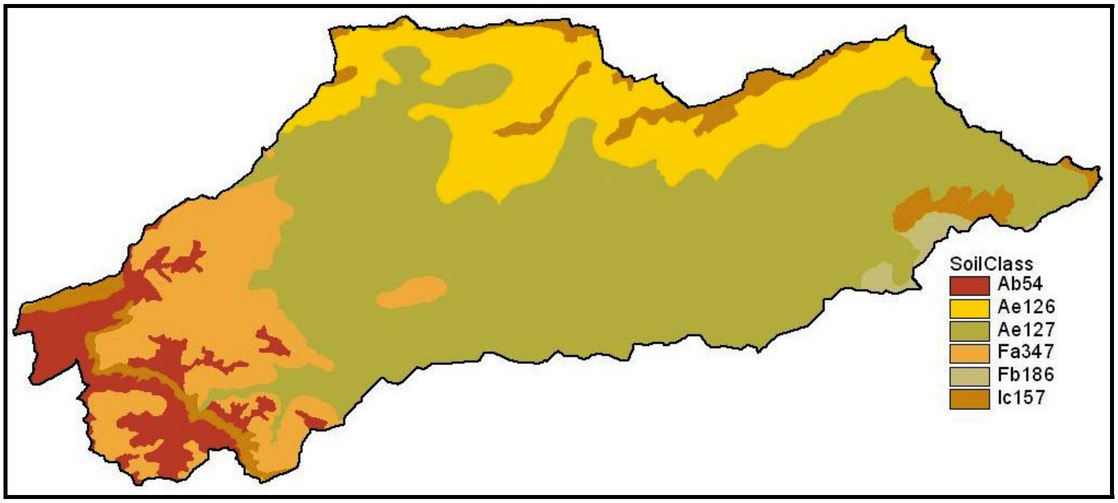


Figure 5.4: SWAT Soils classification

The following were the adopted soil series and profile numbers for the land types;
Ab54: Hutton Hu16 (Profile P949)
Ae126: Hutton doveton Hu27 (Profile P1482)
Ae127: Hutton shorrocks Hu36 (Profile P954)
Fa347: Hutton musinga Hu26 (Profile P950)
Fb186: Hutton shorrocks Hu36 (Profile P987)
Lc157: Rock

The available water moisture is obtained from the ACRU soils dataset for South Africa for the respective land types, while bulk density, saturated hydraulic conductivity, SCS grouping, erosion hazards and soil albedo values were obtained from tables in Schulze (1995) which are reproduced in Appendix C.

The use and soil class distribution report for watershed and each of the sub-basins is attached in Appendix C.

5.2.3. Hydrological Response units

Sub-basins can further be subdivided into hydrological response units (HRU), each of which represents a particular combination of soil and land-cover within the sub-basin. While the sub-basins are delineated and located spatially, the further subdivision into HRUs is performed in a statistical way by considering a certain percentage of the sub-basin area, without any specific location in the sub-basin (van Griensven *et al.,* 2006). The HRUs were defined by using the virtual approach which creates at least one HRUs for each sub-basin based on the given threshold values on percentage areas of land use and soil within the sub-basin. This study used 5% as the threshold value for both the land use and soils. This means that if the percentage of the soil type or the land cover type is less than 5% of the sub-basin area, it is considered negligible and is therefore not included in the ensuing analysis. The HRU distribution report for each sub-basin is also attached in Appendix C.

The following chapter gives a summary of the results obtained from the SWAT model and the different scenarios considered.

CHAPTER 6: <u>RESULTS AND DISCUSSION</u>

6.1. PREAMBLE

The SWAT model was set up as detailed in Chapter 5 and was applied using the parameter sets discussed in the same chapter. Default values of a number of other parameters such as the Manning's roughness and channel properties were adopted using generic descriptors of the rivers in the study area.

6.2. RESULTS

An initial run was done for the period 1966 - 1983 and a comparison of the simulated streamflow at the outlet of the study area is shown in Figure 6.1 below.

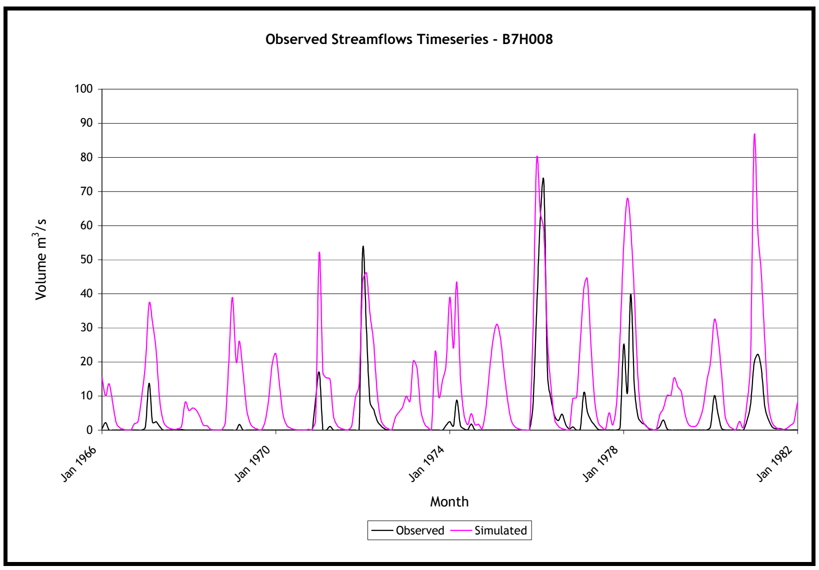


Figure 6.1: Observed and simulated flow before calibration

The above figure shows that there is basically no base flow in the study area. River flows are seasonal with little to no flows for most of the year. The trend of the simulated values closely follows the observed time series although the flows are over estimated for most of the time indicating the need to calibrate the model parameters. The different sub-basins follow a somewhat similar trend except for sub-basin 4 which shows no correlation between simulated and observed results. This inconsistency can only be attributed to incorrectly recorded streamflow records as the simulation parameters which worked for sub-basin 3 are similar to this particular sub-basin.

Manual calibration is a complicated process in distributed models such as SWAT as over-parameterisation is a well known problem (Box and Jenkins, 1976; Beven, 1989). The important issue before calibration is to reduce the number of parameters that require fitting with input-output data by identifying parameters that have a significant influence on model simulations. This is done by performing a sensitivity analysis for the study watershed. It should however be noted that sensitivity analysis results for hydrological models are not transferable between basins (van Griensven *et al.,* 2006).

6.2.1. Sensitivity Analysis

The latest version of SWAT, SWAT 2003, incorporates sensitivity analysis tools applied in the study. However, this meant re-setting up the study area in AVSWAT-X (as opposed to AVSWAT 2000) as the different model versions are not compatible.

The sensitivity analysis is based on the LH-OAT (*Latin Hypercube – One-factor-At-a-Time*) method (van Griensven *et al.,* 2006). The LH-OAT method performs LH sampling followed by OAT sampling. It starts with taking N Latin Hypercube sample points for N intervals, and then varying each LH sample point P times by changing each of the P parameters one at a time. Distributed parameters are varied according to a relative change (± 50%) that maintains their spatial relationship (van Griensven *et al.,* 2006).

The analysis is done using predefined sets of input parameters that depend on what is being simulated as the model can simulate for flow, or flow in combination with sediments only or with water quality. In this case, only river flows were considered. The output of the sensitivity analysis is ranked based on observed flows and also independently of the observed flow values but from a mass balance of the model outputs.

The sensitivity analysis was done per sub-basin to ensure that the spatial variation within the watershed is captured. And because the results of the sensitivity analysis depend on the time period of the simulations, a 15 year simulation period was used.

The lowest rankings per sub-basin of the parameters considered are shown in Table 6.1, with the last column showing the global minimum rank of each parameter. The global rankings can be categorized as follows (van Griensven *et al.*, 2006);

Rank 1 - Very important
Ranks 2 – 7 - Important
Ranks 8 – 27 - Slightly important
Rank 28 - Not important

It should be noted that rankings for sub-basin 2 could be misleading as they are not based on observed data.

The description of the very important parameters (according to the above categorisation) is given below while definitions of all the parameters are given in Table D.1 of Appendix D;

CN2: Initial SCS runoff curve number for moisture condition. The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions. Typical curve numbers for moisture conditions are listed in the tables for various land covers and soil types done by the SCS Engineering Division (1986).

ALPHA_BF: Baseflow alpha factor (days). The baseflow recession constant is a direct index of groundwater flow response to changes in recharge. Values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response. Although the baseflow recession constant may be calculated, the best estimates are obtained by analyzing measured streamflow during periods of no recharge in the watershed.

ESCO: Soil evaporation compensation factor. This coefficient has been incorporated to allow the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks. As the value for ESCO is reduced, the model is able to extract more of the evaporative demand from lower levels.

SOL_AWC: Available water capacity of the soil layer (mm H2O/mm soil). The plant available water, also referred to as the available water capacity, is calculated by subtracting the fraction of water present at permanent wilting point from that present at field capacity, $AWC = FC - WP$ where AWC is the plant available water content, *FC* is the water content at field capacity, and *WP* is the water content at permanent wilting point.

CH_K2: Effective hydraulic conductivity in main channel alluvium (mm/hr).

Table 6.1: Sensitivity Analysis results

Parameter	Lowest Rank Per Sub-basin					Global Rank
	1	**2**	**3**	**4**	**5**	
ALPHA_BF	4	7	1	1	4	1
CN2	1	12	3	4	1	1
ESCO	3	28	2	1	2	1
SOL_AWC	4	5	1	2	4	1
CH_K2	3	1	2	2	3	1
GWQMN	2	11	28	28	3	2
SURLAG	2	15	3	3	2	2
SOL_Z	5	2	4	3	5	2
CANMX	7	16	5	5	7	3
RCHRG_DP	6	3	28	28	6	3
SLOPE	10	4	6	6	9	4
SOL_K	8	20	7	7	8	6
GW_REVAP	11	14	28	28	8	6
BIOMIX	14	6	10	9	13	6
CH_N	10	10	9	9	10	8
SLSUBBSN	11	8	28	28	11	8
EPCO	12	18	12	13	17	9
REVAPMN	13	28	28	28	12	9
SOL_ALB	20	9	13	13	21	9
SMTMP	22	17	14	28	22	12
GW_DELAY	18	28	28	28	16	12
TIMP	28	28	16	28	23	13
SMFMX	22	13	17	28	28	13
BLAI	21	28	28	28	19	14
SFTMP	28	19	28	28	28	16
SMFMN	28	28	28	28	28	28
TLAPS	28	28	28	28	28	28

The respective sensitivity indices give an insight on the parameters that are key to the streamflow generation process in the watershed. The scattered appearance of the higher ranked parameters shows that ranking is location specific and therefore modelling on smaller spatial scales is more representative. As one moves from the upstream end of the watershed (sub-basins 3 and 4) the hydrology becomes more sensitive to the runoff curve number (CN2) which is strongly influenced by land cover and the soil's permeability. The increasing impact of CN2 can be attributed to a decreasing percentage of rocks as one moves away from the mountains and the increasing forest cover in the same direction. Baseflow recession has a greater impact in the upstream parts of the watershed where there is more rainfall and less permeability (due to higher rock content). The effective hydraulic conductivity in the main channel is more significant in the upstream area where there is a mountain range. Higher values imply that there is more infiltration than the actual as the channel is probably underlain by rock.

After analysis of each sub-basin and having obtained the ranking of parameters with some significant effect on the model results, auto-calibration was done on the basis of the respective sensitivity results of each sub-basin.

6.2.2. Auto Calibration

The auto-calibration tool included in AVSWAT-X is based on an efficient and statistically based method known as ParaSol (van Griensven and Meixner, 2004). It is built on the global optimisation technique of the Shuffled Complex Evolution algorithm (SCE-UA) (Duan et al., 1992). ParaSol is able to perform multi objective optimisation and parameter uncertainty estimation in an efficient way (Sin *et al.*, 2005). It has been applied with success on a river water quality model-using SWAT (van Griensven and Meixner, 2004). ParaSol applies the *Sum of the squares of the residuals (SSQ)* and the *Sum of the squares of the difference of the measured and simulated values after ranking (SSQR)* given by equations 6.1 and 6.2, respectively, as its objective functions.

$$SSQ = \sum_{n=1,N} [TF(x_{n,measured} - TF(x_{n,simulated})]^2 \qquad \textbf{6.1}$$

$$SSQR = \sum_{n=1,N} [x_{rank\_r,measured} - x_{rank\_r,simulated})]^2 \quad \textbf{6.2}$$

Where n is the number of pairs measured ($x_{measured}$) and simulated ($x_{simulated}$) variables, TF is a predefined transformation function and r is the rank. The SSQ method was adopted in this case as it captures the time occurrence of a given value of the variable.

Multi-objective optimisation is done using a Global Optimisation Criterion (GOC) which uses several SSQs (or SSQRs) (van Griensven and Meixner, 2004);

$$GOC = \sum_{m=1}^{M} \frac{SSQ_m \times N_m}{SSQ_{m,\min}} \quad \textbf{6.3}$$

The auto calibration exercise was done in groups of three from upstream to downstream; sub-basins 3 and 4 then sub-basin 5 and 2 and lastly sub-basin 1. Best parameter results of each group were incorporated before calibrating the next group. Sub-basin 2 is not gauged and as such was not auto calibrated, however, the results of sub-basin 5 were used as the sub-basins share similar biophysical properties. Similarly, an auto calibration run for sub-basin 4 was not done because of the low confidence expressed about the recorded streamflow values for the sub-basin. Best parameter values from sub-basin 3 were therefore adopted for use in sub-basin 4.

The results of the best parameters from the optimisation runs are shown in Table 6.2. It was however not possible to auto calibrate for the soil depth as the model has a bug that is activated whenever auto calibration for SOL_Z is selected.

The parameter values of Table 6.2 were incorporated into the model for simulation. The results of the simulations are compared to the observed flow time series in Figures 6.2 to 6.4 while their correlation for the different gauging stations is shown in Figure 6.7. It would have been ideal to make comparison using a cumulative mass curve but the numerous gaps in the observed streamflow time series could not allow for this as no meaningful results would be obtained.

Table 6.2: Best parameter values

Parameter	Sub-basins 3 & 4*	Sub-basins 2 & 5*	Sub-basin 1*
ALPHA_BF	0.01	0.00	0.00
CANMX	9.87	9.50	9.58
CH_K2	55.20	146.81	143.27
CH_N	0.14	-	_
CN2	46.82	83.67	80.00
ESCO	0.01	0.27	0.09
GWQMN	-	1441.40	1441.40
RCHRG_DP	-	0.79	0.94
SOL_AWC	0.50	0.41	0.40
SOL_K	0.00	2.19	27.14
SURLAG	9.80	4.57	9.56

* A dash value indicates a parameter that was not included in the auto calibration

Figure 6.2 shows a general overestimation of the observed stream flow by an average of 16Mm^3/a. Since the auto calibration exercise is based on the principle of varying the distributed parameters by a relative change that maintains their spatial relationship, the difference can be attributed to river abstractions whose values are not known. The WARMS database, which has all registered users in quaternary catchments, does not have river abstraction for the period of simulation. In any case, the use of WARMS database data can be misleading as these are not the actual abstractions (but the maximum authorised volumes) and the given figures are known not to be so representative (e.g. DWAF, 2006d). It is assumed that the gauging station records used to obtain the best parameter values for the sub-basin are representative thereby giving credence to the calibrated simulation results.

Figure 6.3 and Figure 6.4 show a better correlation of the streamflow with correlation factors of 0.56 and 0.51 respectively. Figures 6.5 to 6.7 show the correlation between observed and simulated streamflows for each of the stations used. The inconsistencies in some of the differences between the simulated and the observed streamflow could be an indication of the unreliability of the observed streamflow values. DWAF does not check, verify or patch the numerous streamflow records around the country and it is doubtful that the rating curves for some of the gauges found in small stream, as of this study, are updated.

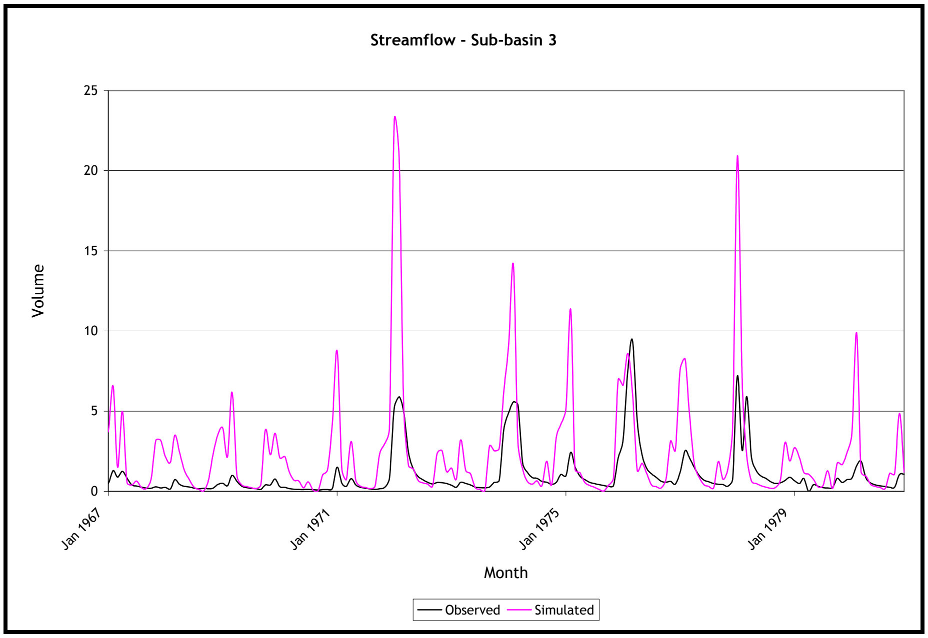


Figure 6.2: Observed and simulated streamflow for Sub-basin 3 after calibration

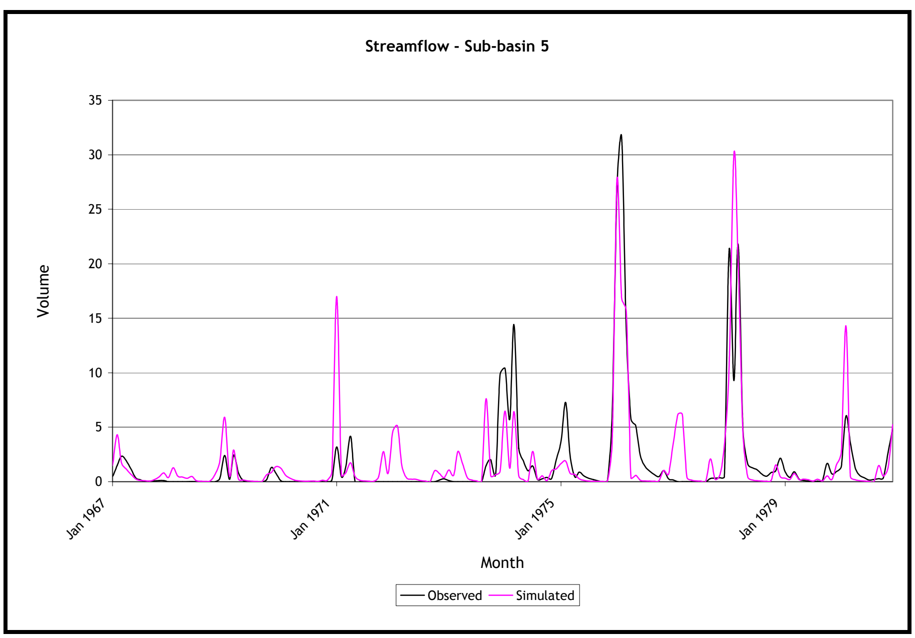


Figure 6.3: Observed and simulated streamflow for Sub-basin 5 after calibration

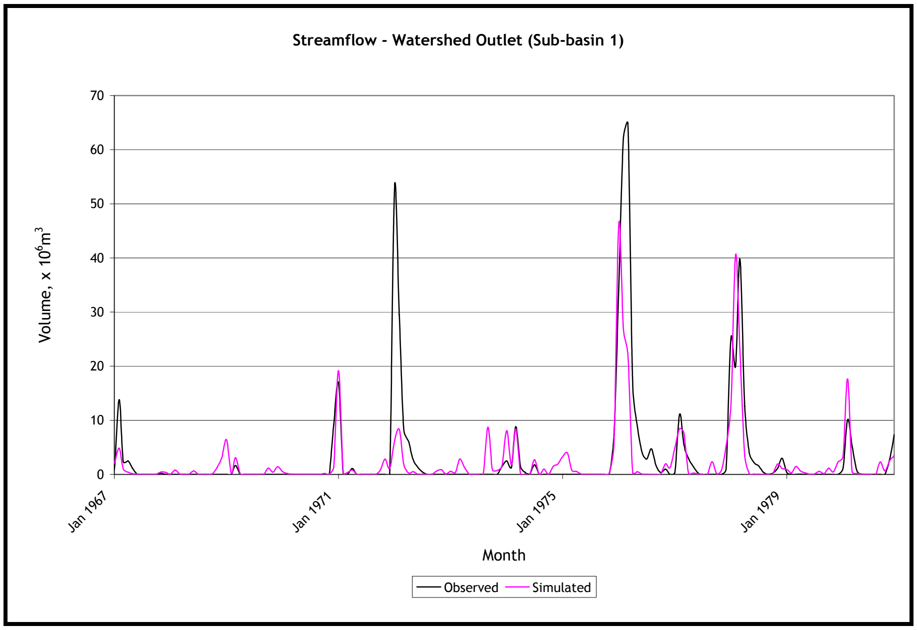


Figure 6.4: Observed and simulated streamflow for the watershed after calibration

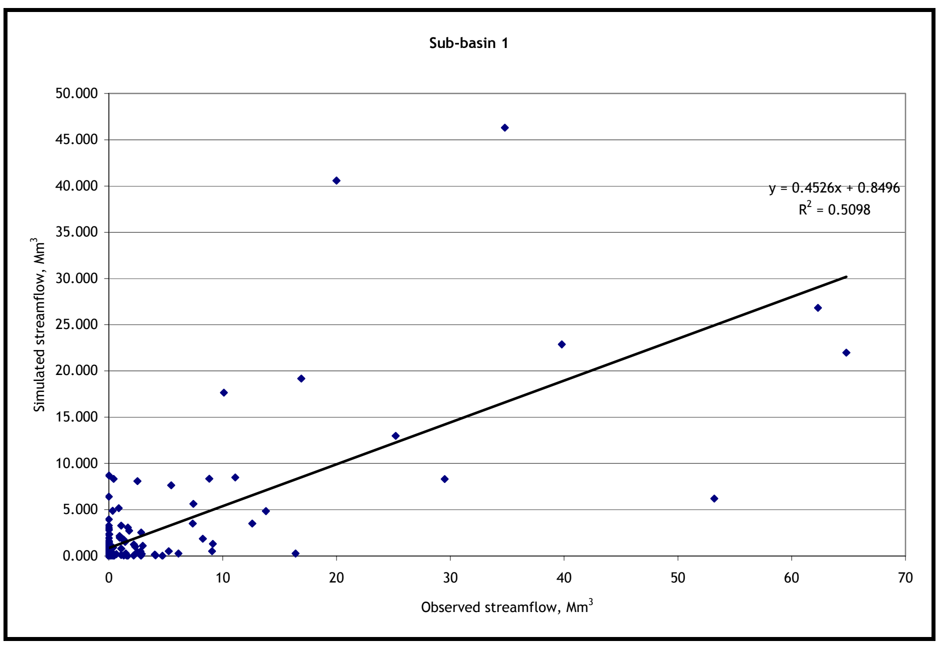


Figure 6.5: Correlation of simulated and observed streamflows - Sub-basin 1

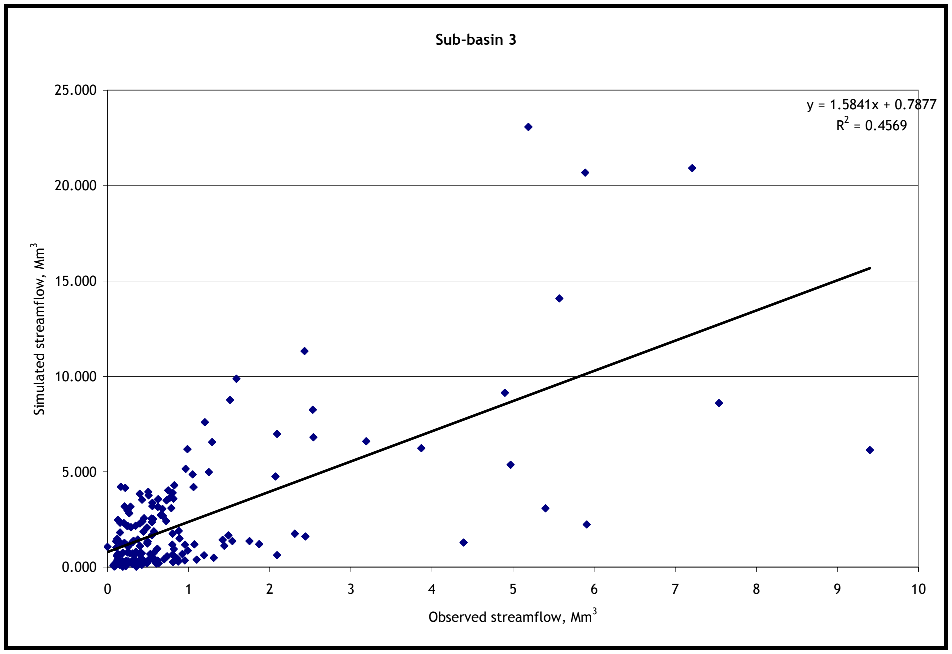


Figure 6.6: Correlation of simulated and observed streamflows – Sub-basin 3

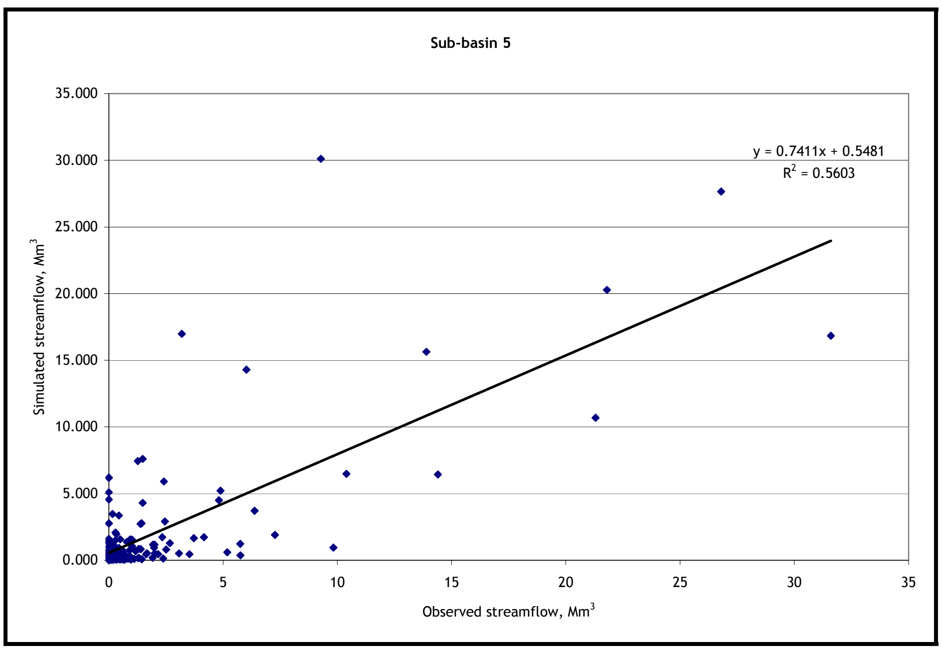


Figure 6.7: Correlation of simulated and observed streamflows – Sub-basin 5

Higher precipitation volumes are recorded in the upstream parts of the watershed which are effectively more important as the source of most of the water. Preserving the integrity of these upstream areas in a pristine state ensures that downstream users are not adversely affected as upstream streamflow reduction activities will inevitably trickle downstream.

No hydrological studies are known to have been undertaken in the study area except for the nationwide WR90 study (Midley *et al.,* 1994). The WR90 study however dealt with baseline land covers and generated streamflows for the pristine catchment conditions. The use of observed data provides for the needed check and validation of the model results. The common period for all stations in the auto calibration was from 1976 – 1983 and as such the other periods outside this window can be taken as the validation periods. It was not possible to simulate for other periods as the 1966 – 1983 period was the only period in which the required input data was available with minimal discontinuities.

6.2.3. Impact of land cover change

The use of auto calibration in SWAT tends to transform it from a physically based model to a conceptual one because averaged inputs over an area are used as “effective” rather than the “actual” physical parameters. This has shortcomings in that the effects of parameters such as land cover cannot be adequately analysed using the averaged parameters which extend beyond the spatial boundaries of the different land use categories. The analysis was therefore done using the initial parameters values (before auto calibration) to be able to capture the spatial variability of the land cover. As such, the analysis is more qualitative than quantitative.

Land use has been taken to be adequately represented by the land cover conditions as land cover bears the strong signature of land use. Land cover changes are represented by the CN2 parameter in the SWAT model and different land cover scenarios can be modelled by varying only the CN2 factor. As a result, the adopted approach in this part of analysis was to retain all other parameters values while varying the CN2 parameter to change the land cover of the watershed.

A total of eight different runs were done for the different land covers in the study catchment. The percentage of each land classification in the current land cover for the watershed is shown in Table 6.3.

Table 6.3: Percentage of different land classification in current land cover

Class	Percentage
Forest mixed	30%
Forest evergreen	3%
Range – brush	25%
Range – grass	4%
Agriculture	25%
Arid	12%
Residential	1%

After the "current" land cover run, the land cover was subsequently changed to be 100% of the different land cover classifications in the above table. The effect of the different covers is shown in Figure 6.8.

The results show an expected trend; increasing vegetation cover results in decreased runoff and subsequent reduced streamflows, and vice versa. Grass accounts for the maximum decrease in runoff followed by forestation while arid land has the expected largest increase in runoff.

The substantial increase of streamflow when the land cover is changed to agriculture is surprising but this could be because elimination of forests and range (brush) which are responsible for inhibiting runoff frees more water to the watershed that is recorded as streamflow. The arid range did not give rise to the expected level of runoff increase although it shows the highest increase in runoff. This could be attributed to the use of a lower CN2 factor to allow for more runoff generation. The residential class also records an increase in the streamflow as expected. A semi-rural setup with about 50% of the area being pervious, as is estimated to be currently the case, was used and it is envisaged that with the advent of urbanisation the increase in the impact will be substantial.

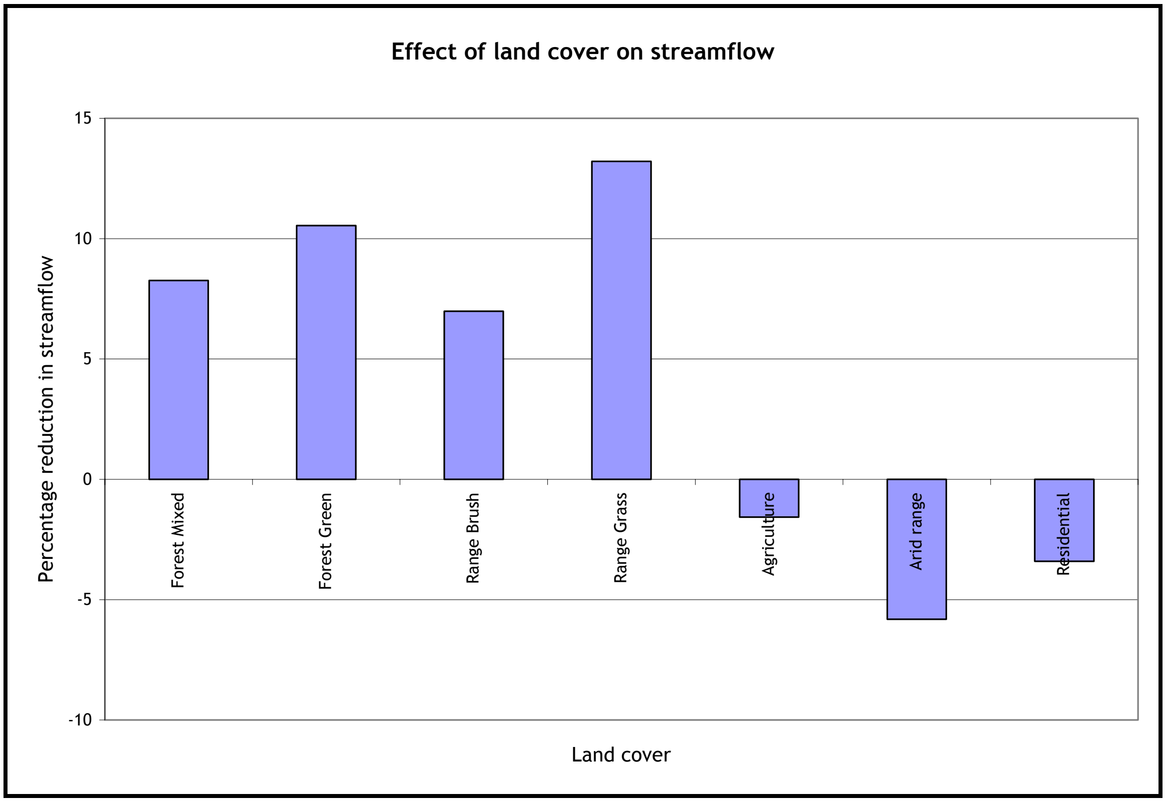


Figure 6.8: Effect of land cover on streamflow

Forestation and grass have the largest impact on the streamflow and this conforms to the results of other studies (e.g. Gush *et al.*, 2002). The greater decrease of the grass as compared to both the indigenous and exotic forests is rather surprising. This may imply that for areas that have the natural cover as the savannah grass forestation is not a streamflow reducing activity. This is however not true. Streamflow reduction from commercial afforestation has been a major research area in South Africa for quite sometime because of its great impact on runoff. Exotic forests show an expected larger streamflow reduction than indigenous forests.

Although Figure 6.8 is not strictly a quantitative representation, it can be observed that the streamflow reduction is as much as 50mm for exotic forests. This is a substantial figure especially over extensive areas. Such trends should strongly inform land planning activities within the area and other similar areas and will become more pertinent as in-stream and/or ecological flow requirements are mandated for all catchments of South Africa. This same approach should also be applied in the adoption of any water resources management strategies in the area as streamflow reduction activities will impact on the yield of the water resources.

The SWAT model is therefore able to adequately characterise the relative effects of different land cover conditions. However, for the model to be used for qualitatively evaluating the effects of land cover change on watershed response, it is necessary to adjust the CN parameter to improve model efficiency (Hernandez *et al.*, 2000). This requires better representation of the watershed and the use of the correct parameters of all major parameters that impact on streamflow generation.

6.2.4. Prediction in the ungauged B72A quaternary catchment

The B72A quaternary catchment is located to the south of the study area and has similar biophysical properties as shown in Figure 6.9 and Figure 6.10.

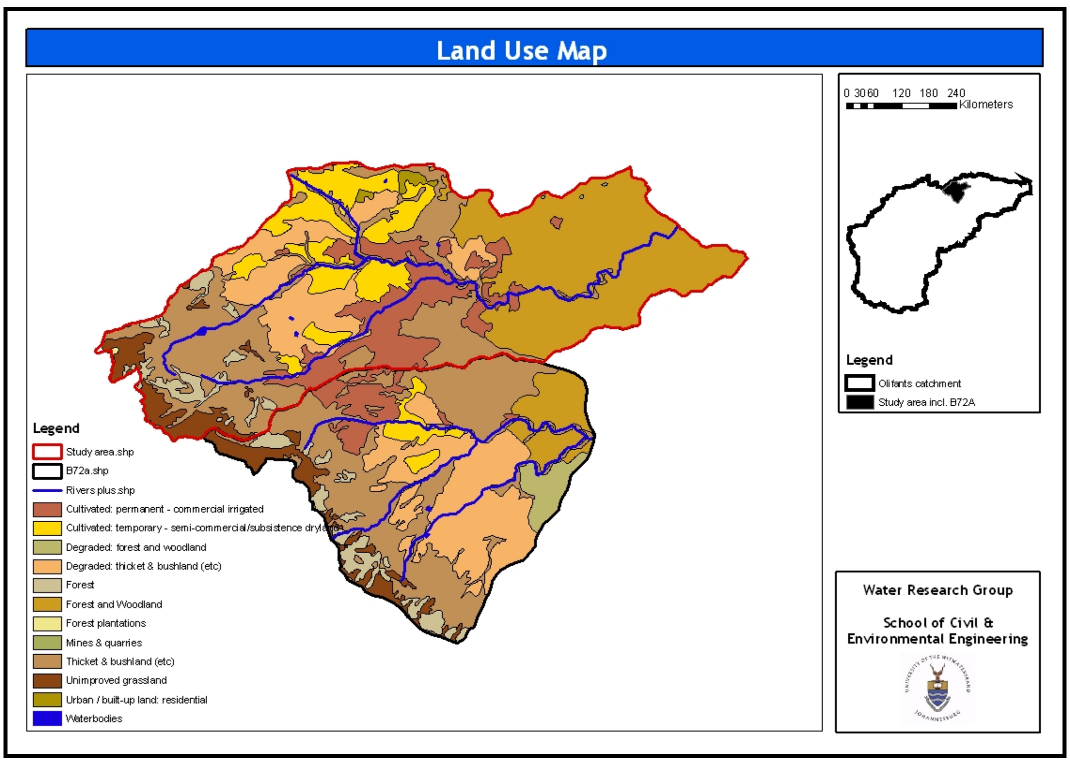


Figure 6.9: Comparison of land cover

Figure 6.9 shows the land cover map of the two areas and the similarity is clearly evident. Although the area of the different land covers is different, the similarities do allow for general comparisons and deductions to be made, given the lack of streamflow gauges in the B72A. The topography is also identical as both catchments start with a mountainous range in the west to low lying plains to the east.

Figure 6.10 also shows the similarity in the soils of the two areas. Even in cases of different soils classification, the soils properties were not that different thereby allowing for the correlation between the two areas.

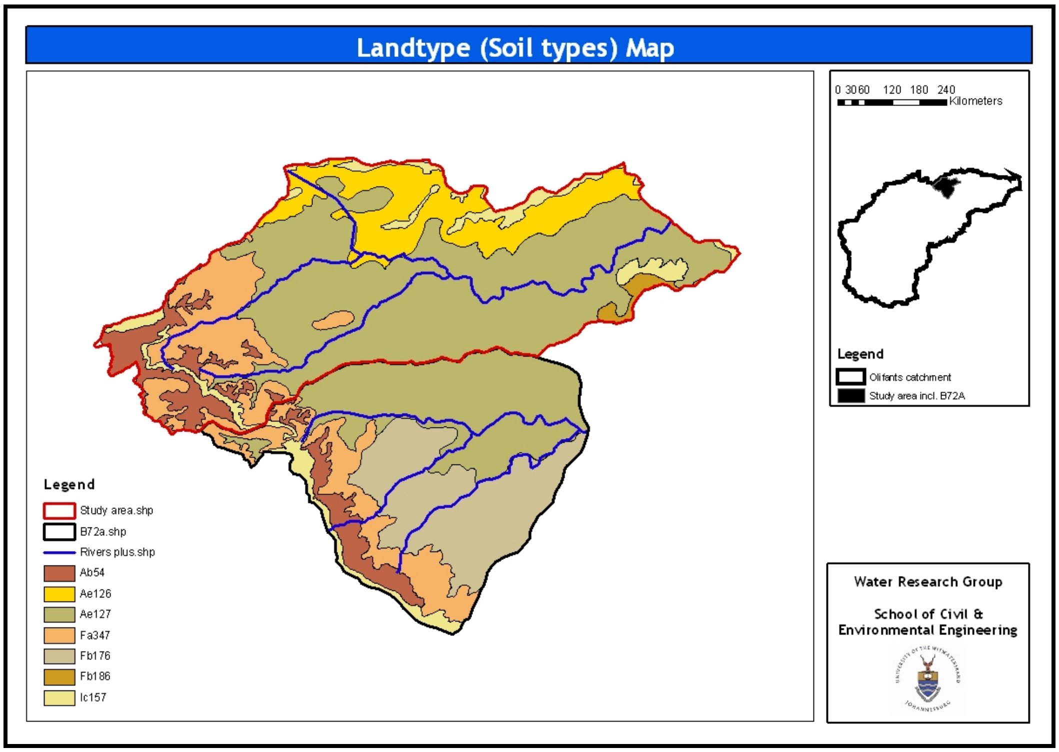


Figure 6.10: Comparison of soils

The catchment was set up following the procedure detailed in Chapter 5. The area has a total of three rain gauges (shown in Figure 6.11) but does not have any climatic stations within it. Climatic stations used for the study catchment were therefore adapted for the B72A catchment. The lack of climatic stations in the area increases the error margin especially considering that the climatic stations in the study area were patched and extended using climatic stations further north of the study area.

The resulting sub-basins from the delineation process are shown in Figure 6.11 which also shows that some of the mid-stream sub-basins start from the beginning of the watershed. This poses a challenge in the adoption of best parameter values that were obtained in the previous sub-sections as the watershed cannot be simply divided into three areas as was done for the study watershed. Another challenge is that sensitivity analysis results used to obtain the best parameters are not necessarily transferable between different watersheds as was demonstrated by the differences in the sub-basins of the study area.

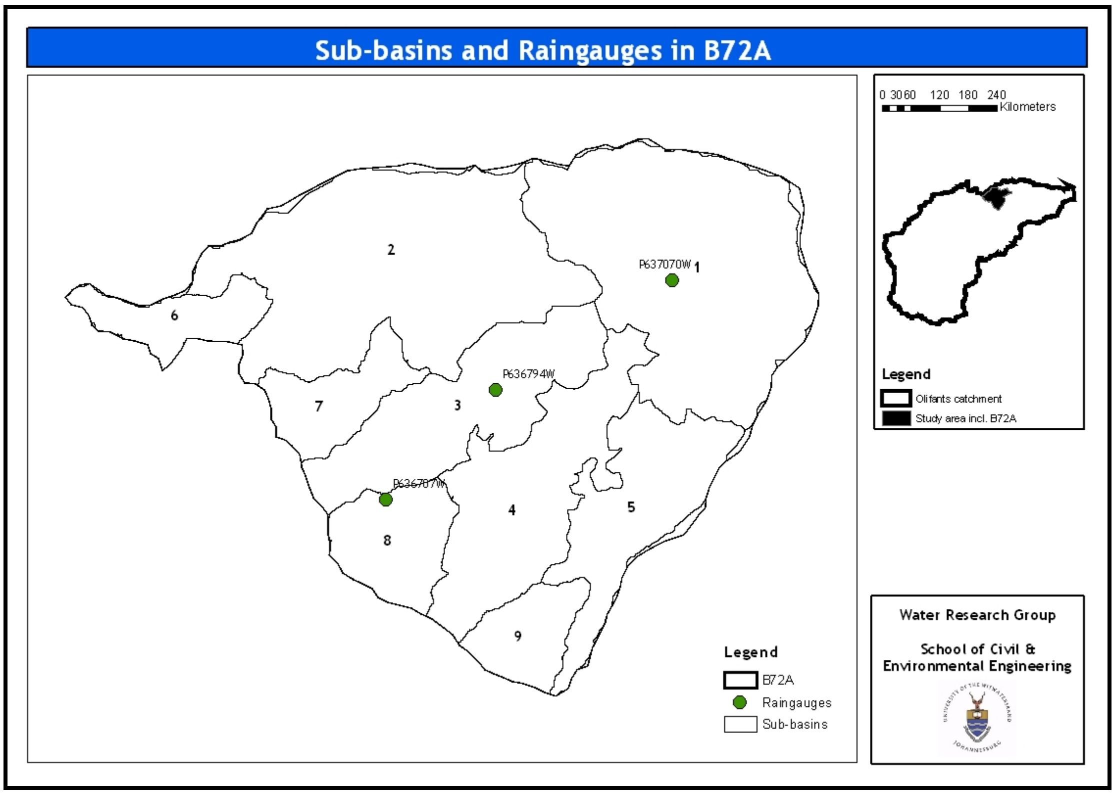


Figure 6.11: Sub-basins of the B72A catchment

However, the best parameter results derived from the study area remain the best alternative to characterising the flow in the ungauged B72A quaternary catchment. These parameters were applied for the same period 1966 – 1983 as was used for the study area and the resulting streamflow results are depicted in Figure 6.12.

The average streamflow in the quaternary catchment is 8.25Mm^3/a (approximately 60mm/a). The estimated MAR from the Water Situation Assessment Model (WSAM) database for virgin conditions is about 79mm/a (Schulze and Watson, 2002). The simulated flow is about 20% less than the virgin conditions streamflow and this difference can be readily attributed to various human activities such as afforestation which exist in the area.

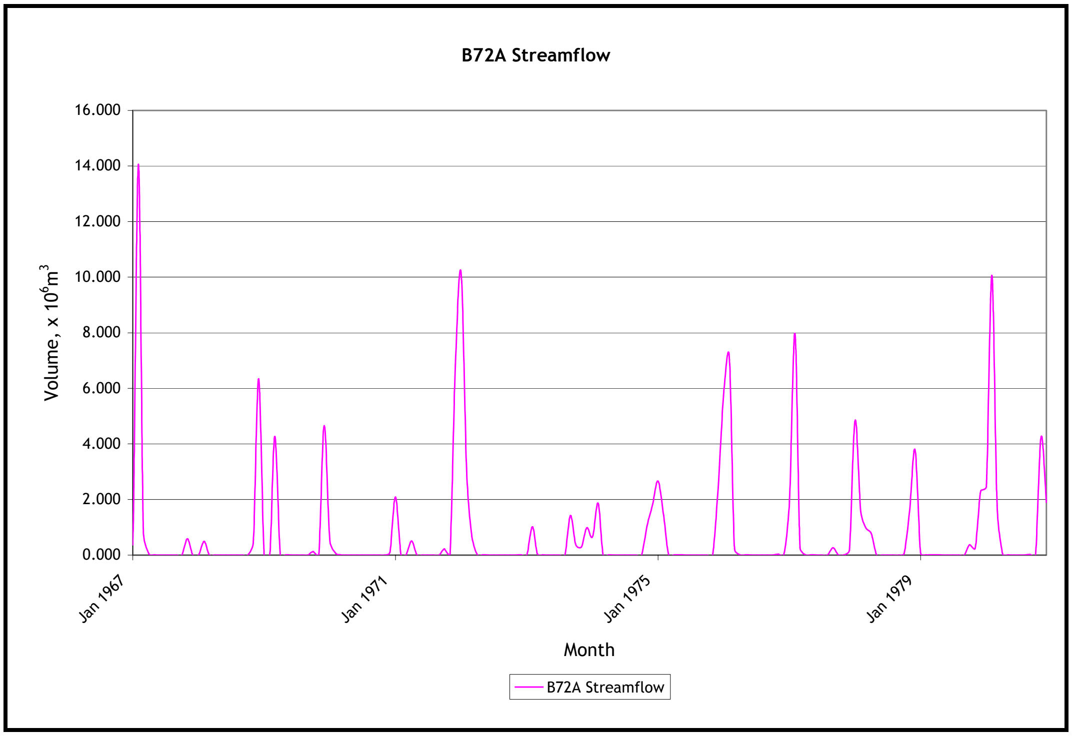


Figure 6.12: Simulated streamflow for the B72A catchment

As is the case with the study area, streamflow occurs during the rainy season between October and April while the remainder of the period is dry. There is also limited to no baseflow contribution to the streamflow in the area.

The estimation of flows in the B72A could have been better estimated if climatic stations were present in the area. Estimation in ungauged catchments can only be meaningful if spatial variations in the land cover, the soils and the climate are adequately captured. However, the foregoing is deemed an adequate estimation considering the proximity of the two areas and the generally similar climatic conditions.

6.3. Discussion

The impacts of land use on streamflow can be deduced from field measurements but conceptual – physical hydrological simulation models that are validated with observed hydrological data provide another means of assessing these impacts (Lumsden *et al.*, 2003). The use of models is not only cheaper but allows for versatility in assessing different effects that impact on the streamflow. Results from the SWAT model show that the model also falls within this category of models as it reproduced plausible streamflows for the study watershed. It is however noted that the integrity of the input data has a strong bearing on the results. The available data sets were derived from point data averaged over larger areas and could therefore not have correctly represented the conditions on the ground. For example, one identified important factor to the streamflow generation process is the CN factor which is a function of the soil's permeability, land use and antecedent soil water conditions. The challenge is how to estimate these parameters in the model so that their spatial distributions are correctly represented as the required spatial data is not widely available. However, the match between observed and simulated streamflows even before calibration is a good indication that the catchment is well represented to some good extent. Calibration is however a necessary requirement needed to improve the model efficiency by correcting for all the parameters until they are adequately represented. The complexity of the model makes it more efficient to adopt an optimisation procedure, as implemented in this study, than a manual calibration procedure. However, there are no records of abstractions from the river that could be used to validate the best parameters adopted for the sub-basin. Sami (2005) shows that groundwater abstractions have high impact on surface water resources of sub-basins 3 and 4 (quaternary catchments B72E and F). Without these records, discrepancies between simulated flows and observed flows are bound to exist.

Recorded streamflows are not properly maintained by DWAF and are therefore another potential source of error. This needs to be addressed to ensure proper water resources management which is backed up by relevant information management systems. In addition, monitoring systems that accurately record water resources information such as groundwater levels, flows and abstractions, streamflows need to be implemented to give a good description of the water resources in the area. Science, under which modelling falls, requires observation, and without the observations we will cease to progress in understanding our environment, and therefore in managing it appropriately (Silberstein, 2006).

Although prediction in ungauged catchments is to develop and apply models that work in catchments with minimal data, the modus operandi is to maximise data collection (Silberstein, 2006). This is the only way that such predictions can be meaningful as assumptions and inferences are limited to an unavoidable minimum.

Groundwater has at times suffered from being taken as a secondary resource in water resources analysis. Analysis of the WARMS database with respect to water use in municipalities adjacent to the study area shows that groundwater use constitutes over 60% of total water use. As noted from Sami (2005), there are strong interactions between groundwater and surface water in the area and Ntseme (2005) also reports that there is some perceived groundwater – surface water interactions in the B72A which is similar to the study watershed. These findings underscore the importance of understanding these interactions and seeing how best the conjunctive use of groundwater and surface water can be best optimised and integrated. This also gives a holistic view of the available water resources by accounting for all parts of the water balance.

The results from the different land cover simulations show the capability of the model in characterising the relative effects of different land cover conditions. The relative responses of land cover changes in the catchment were significantly in line with expectations. A quantitative analysis requires an adjustment of parameters, particularly the CN parameters, per land cover type to improve model efficiency. Additionally, baseline land covers such as the Acocks Veld Types (Acocks, 1988) can be used to simulate pristine catchment conditions and to specifically assess streamflow reduction activities. However, for management purposes the qualitative analysis gives general indicative impacts of land developments on streamflows. It is also noted that land management practices may be more influential on hydrological responses than land cover *per se* (Lumsden *et al.*, 2003). Of particular concern are land management practises related to agriculture as these are widely varied both spatially and temporal in addition to the diverse crop types. Different results can therefore be obtained depending on a particular crop and management practice adopted. Although land management practices are such an important factor they are however less well represented and verified than land covers. Analysis and adoption of land cover effects (both qualitative and quantitatively) should therefore bear these dynamics in mind.

The land use in a catchment partitions rainfall between water vapour flows to the atmosphere as evapo-transpiration (green water), and flows into rivers and groundwater (blue water). Total evaporation losses form a larger component of the water balance, especially in the Southern Africa region where evaporation exceeds the rainfall. It could therefore be more pragmatic if efforts are concentrated on this larger component of the water balance in not only managing it but also assessing its impact on the streamflow (Lumsden *et al.*, 2003). Research action in the maximising of green water for agricultural production is already ongoing (e.g. Taigbenu *et al.*, 2005; CGIAR, 2002) and could be extended to assessing the impact of green water on streamflow.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

The fundamental goal of this project was to setup a hydrological model to estimate runoff generation within the study catchment and provide a basis for planners and decision makers to plan future land developments and assess their impacts on water resources. This objective was achieved through the setting up and calibration of the SWAT model to adequately reproduce the recorded streamflow. This also achieved the specific objective of assessing and modelling runoff generation at a daily time scale which is the most relevant to all water users in the area and also for operational purposes.

The lack of river abstraction data introduced another dimension of uncertainty although in general the inadequacy of detailed input data was not much of a constraint as was expected considering the plausible results that were obtained. This however does not relegate the need for intensive data collection of basic and traditional forms of data which is lagging behind despite the vast improvements in technology and modelling power.

In the process of setting up SWAT, a number of useful datasets and files of potential great use to other studies in the area were created. These include a digital elevation model derived from 20m contours and spot heights, soils database of soil profile data in the area from hardcopies of the same and shape files which were created by adding soils profile data to the existing landtype files. This is particularly important for other related projects in the Challenge Program.

Sensitivity analysis helped in identifying the important parameters that were used in the calibration exercise. These important parameters included CN2, ALPHA_BF, ESCO, SOL_AWC and CH_K2 as defined in the preceding chapter. The results of the sensitivity analysis shows that modelling on smaller spatial scales is more representative as different areas of the watershed respond differently to different parameter changes, which are in turn dependent on the physical characteristics of the sub-basins. This therefore highlights the importance of using distributed models that captures this spatial variability. Use of model results from lumped models and even conceptual models can be misleading if the catchment has widely varying spatial properties.

The application of the auto calibration tool in SWAT was quite helpful. The concept of trying different parameter values within a specified range with a view of maintaining their spatial relationship yielded properly optimised parameters as evidenced by a reasonable match between observed and simulated streamflows. The set of the optimised parameters along with the other parameters that were used can therefore be accepted as the representative set of parameters for the system. These best parameter values were applied in the B72A quaternary catchment which has similar biophysical properties, thereby enabling prediction in the ungauged catchment.

The watershed showed an expected response to land cover change scenarios; increasing land cover reduces the streamflow that is recorded at the catchment outlet, and vice – versa. Unexpected results were also realised as grass seemed to reduce the streamflow by the largest margin while bare land showed a lower than expected increase in streamflow. This could have been due to the use of incorrect CN parameters.

The verification of the HDAM concepts provides a wealth of information with regards to relationships that involved the main driver of the runoff generation process, rainfall. A number of adjustments to the model have been suggested in Chapter 4.

7.1.1. Limitations

The major limitation to hydrological modelling is data availability and the integrity of the available data. In this case, numerous challenges were faced with the available datasets that were not patched and whose integrity was doubtful such as climatic and streamflow data. Deficiencies in data that constitute a greater fraction of the water balance within a catchment give rise to uncertainties of a similar magnitude. The lack of detailed spatial data on the soils was also another handicap faced. The SWAT model could not auto calibrate for soil depth because of a bug in the model despite the fact that the parameter was also found to be of importance to the streamflow generation process. It is also known that the values used for the soil depth are only point specific and may not be representative. The proposed best parameter values should be used with this factor in mind.

The land cover impact assessment performed is strictly speaking a qualitative analysis and should only be taken as such.

Groundwater is seen to be an important factor in the watershed as mentioned previously. However, no effort was made to properly model the groundwater components and possibly capture the interactions. Moreover, the groundwater component in SWAT is only one-dimensional and does not address flow between sub-basins (Muthuwatta, 2004).

Prediction in the ungauged B72A catchment was done using a simple approach of catchment similarities. It is however appreciated that this rule of thumb method may not adequately capture the complexities involved in prediction of flows in ungauged catchments.

Establishing of water resources management and conservation needs in the catchment was not done upon the realisation of the depth required in fulfilling this objective. The proposed approach with respect to streamflow reduction activities is however very relevant to water resources management and the conservation of the environment.

7.2. RECOMMENDATIONS

A summary of recommendations emanating from this study is presented below:

- The results obtained from the SWAT simulations indicate the capability of the model to adequately represent a South African watershed and reproduce meaningful streamflows. The model is also capable of adequately characterising the relative effects of different land cover conditions. Despite the perceived data intensiveness of the model, it has been possible to apply it to an area with limited data. It is therefore recommended that the model be adopted for use in the region. The model also has components for pesticides, nutrients and agricultural management which, although not applied in this study, are very useful. A fully calibrated model with all these components in use is an invaluable management tool.

- The lack of maintenance of some of the datasets from the DWAF is a serious cause of concern. Observation data of good integrity is a crucial requirement of all modelling exercise. As such DWAF should not only endeavour to provide the data but ensure that it is appropriately maintained, verified and patched.
- Groundwater has been identified as an important resource within the catchment and that there are possible groundwater – surface water interactions. It is proposed that this linkage be investigated further.
- Another important issue that was identified is that land management practises may be more influential in impacting streamflow than land cover. It is therefore proposed that investigation be made with regards to land management practises and their influence on runoff.
- The high percentage of total evaporation losses in the water balance warrants that this component is given a closer look to determine how it can be managed and how it is impacted by changes in total evaporation. This can be done through the adoption of certain land covers which will affect the streamflow.

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APPENDICES

TABLE OF CONTENTS

A. APPENDIX A

A.1. TABLES USED IN CALCULATING SOLAR RADIATION

Table A.1: Angot's values of short-wave radiation flux R_A at the outer limit of the atmosphere in g cal/cm^2/day* as a function of the month of the year and the latitude.

Lat (deg)	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
N 90	0	0	55	518	903	1077	944	605	136	0	0	0
80	0	3	143	518	875	1060	930	600	219	17	0	0
60	86	234	424	687	866	983	892	714	494	258	113	55
40	358	538	663	847	930	1001	941	843	719	528	397	318
20	631	795	821	914	912	947	912	887	856	740	666	599
Equator	844	963	878	876	803	803	792	820	891	866	873	829
20	970	1020	832	737	608	580	588	680	820	892	986	978
40	998	963	686	515	358	308	333	453	648	817	994	1033
60	947	802	459	240	95	50	77	187	403	648	920	1013
80	981	649	181	9	0	0	0	0	113	459	917	1094
S 90	995	656	92	0	0	0	0	0	30	447	932	1110

* 1 g cal/m^2 = 41.9 kJ/m^2

Source: Wilson E.M., (1990), *Engineering Hydrology, 4th Edition*. The MacMillan Press

Table A.2: Mean daily maximum hours of sunshine for different months and latitudes.

Latitude (. South)	*July*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.5	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.	12.1	12.1	12.1

Source: Wilson E.M., (1990), *Engineering Hydrology, 4th Edition*. The MacMillan Press

A.2. CORRELATION RESULTS FOR CLIMATIC STATIONS

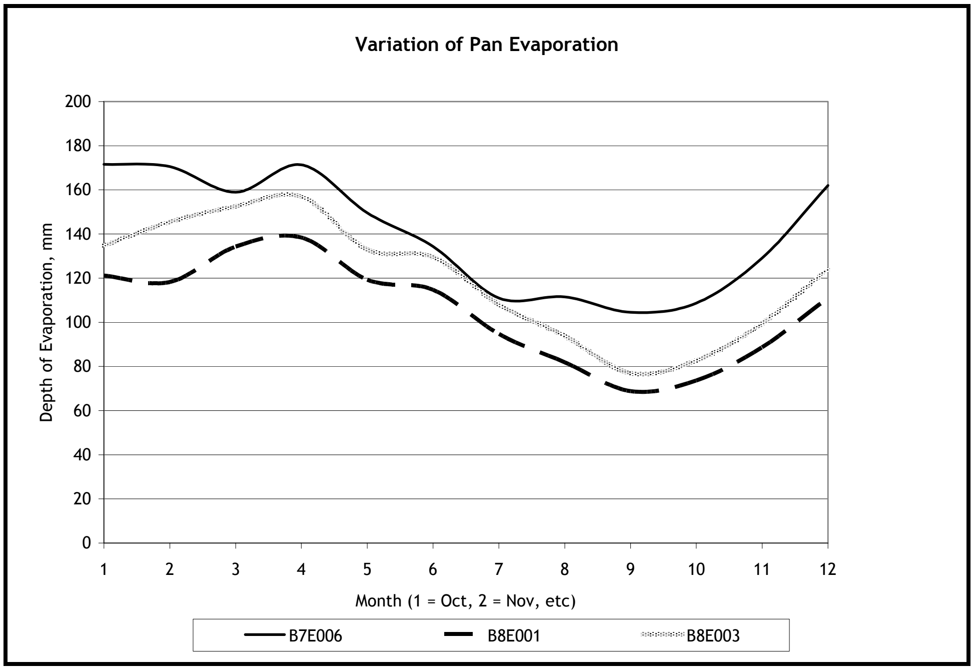

Figure A.1: Variation of Pan Evaporation data

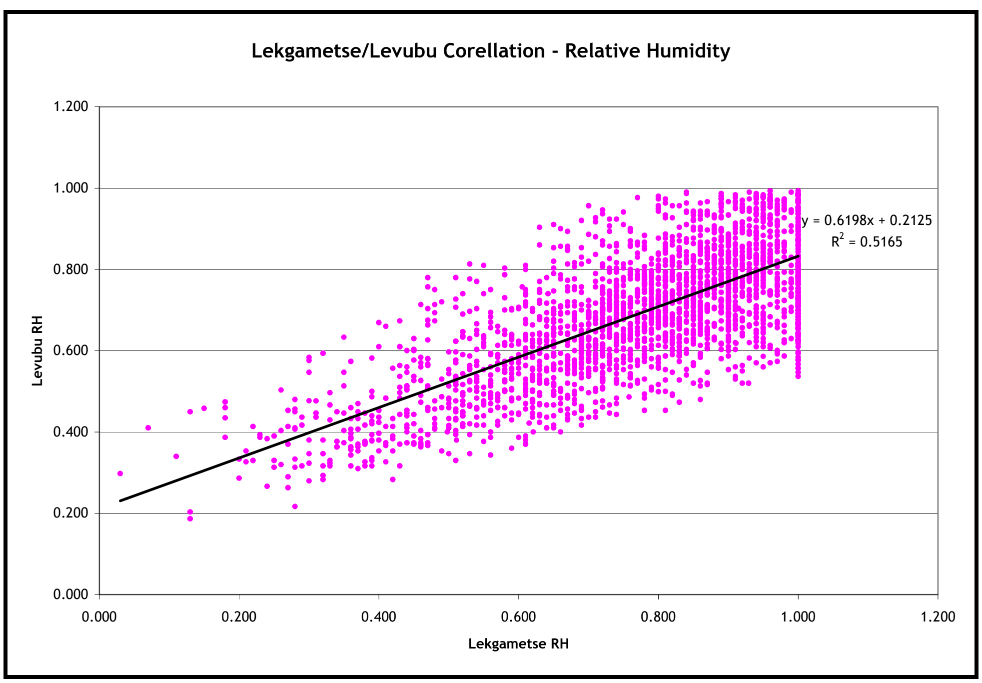

Figure A.2: Relative humidity – Lekga/Luvubu

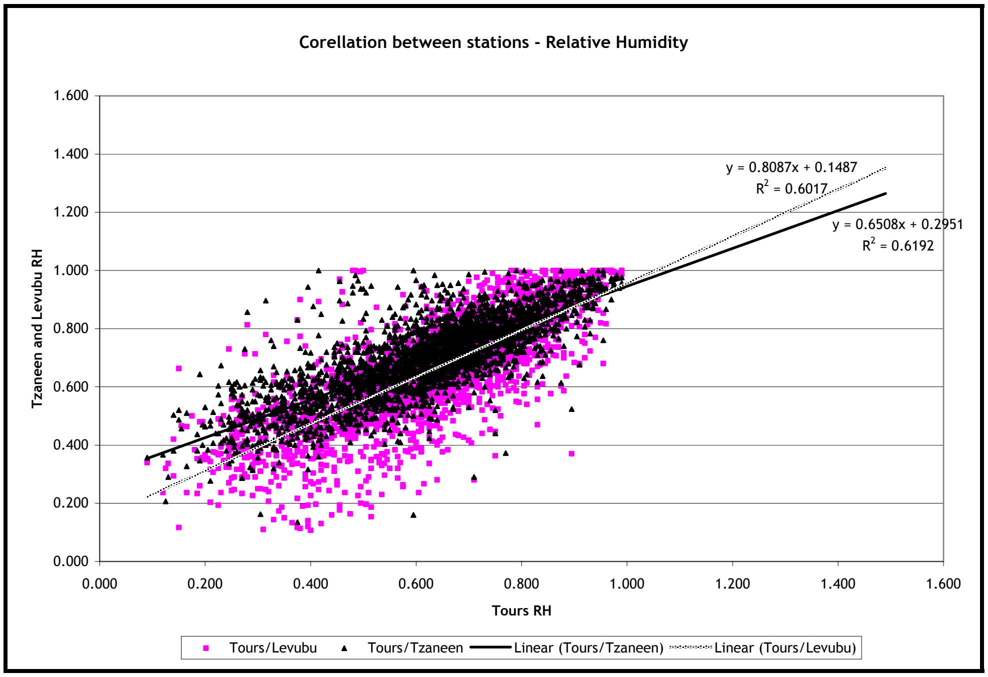

Figure A.3: Relative humidity – Tours/Levubu & Tzaneen

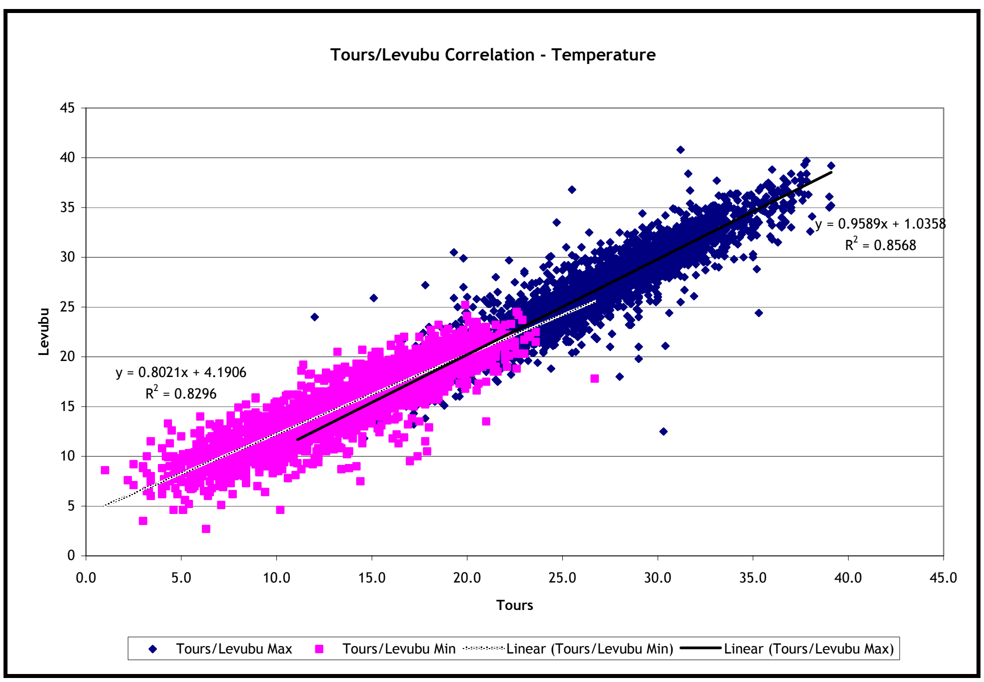

Figure A.4: Temperature – Tours/Levubu

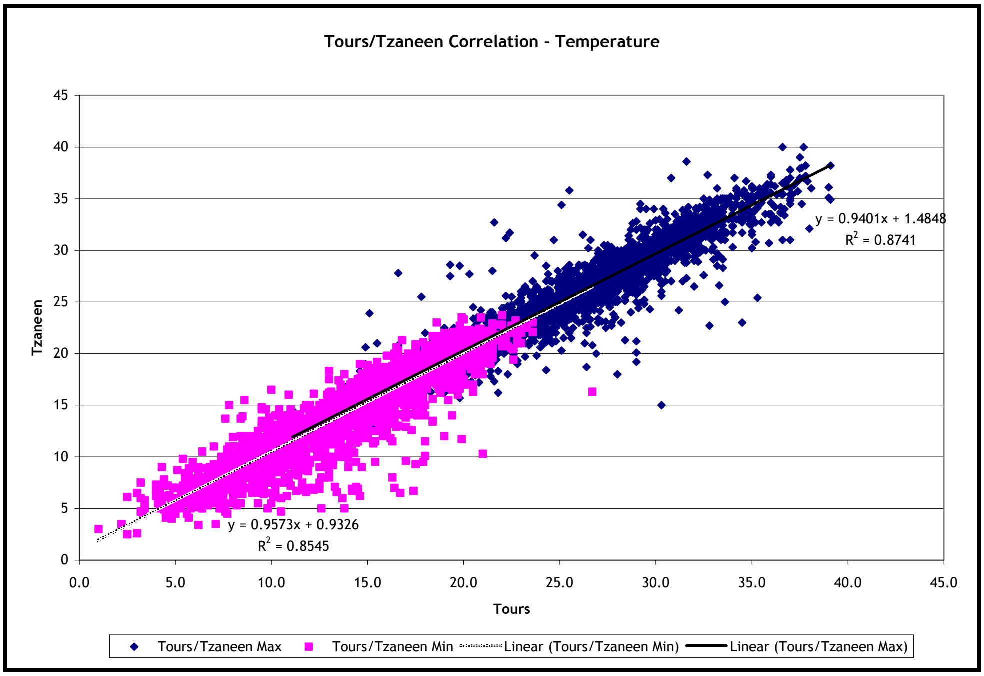

Figure A.5: Temperature - Tours/Tzaneen

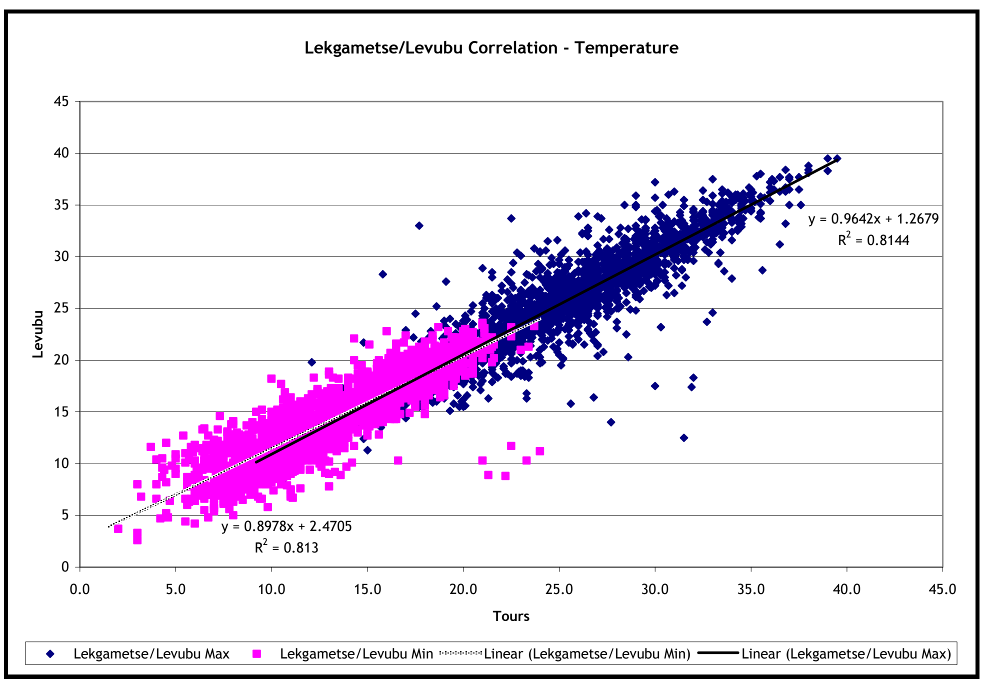

Figure A.6: Temperature - Lekga/Levubu

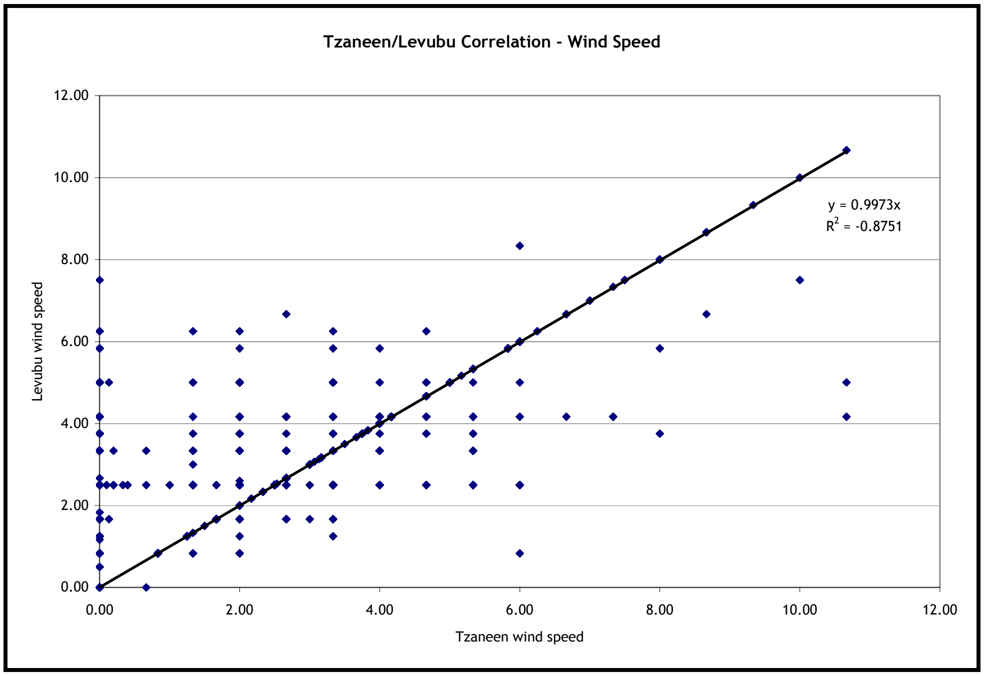

Figure A.7: Wind speed – Tzaneen/Levubu

B. APPENDIX B

B.1. RAINFALL DATA ANALSYSIS CURVES FROM THE VERIFICATION EXERCISE

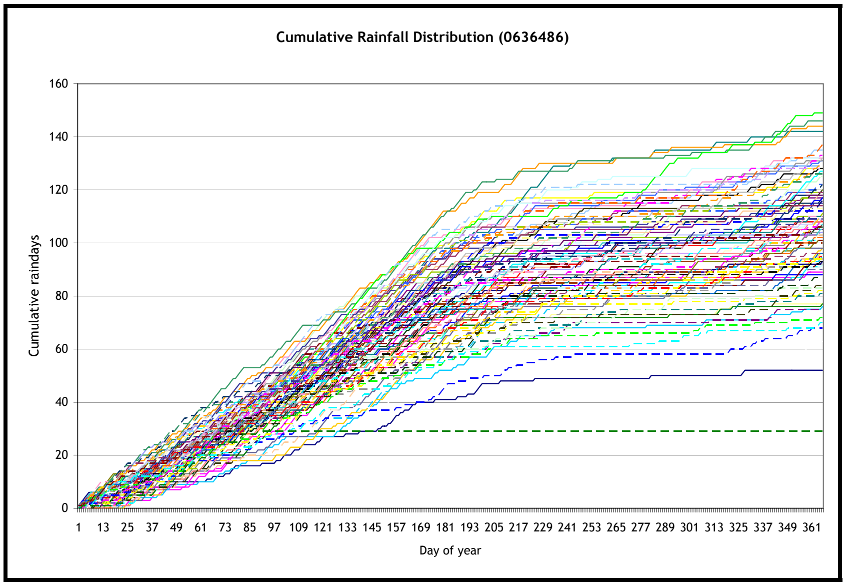

Figure B.1: Cumulative rainfall days - Station 0636486

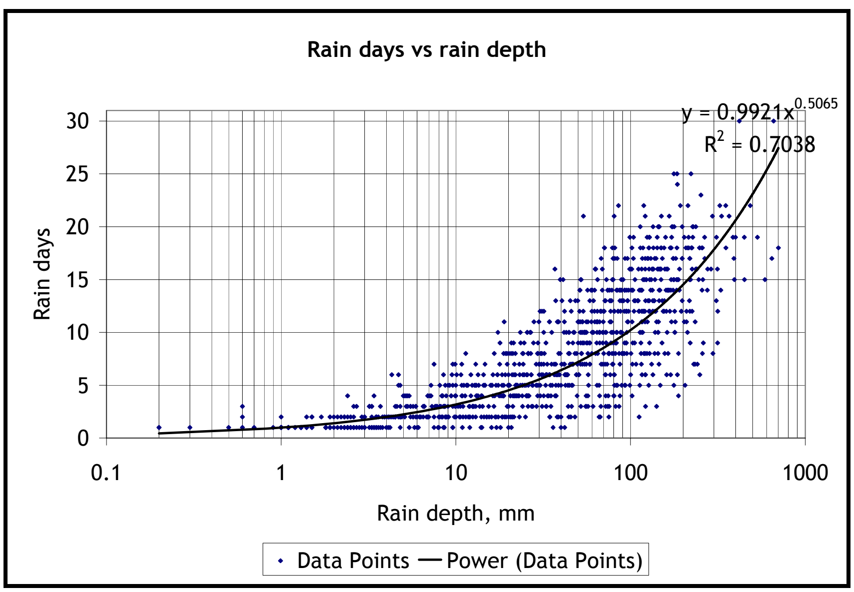

Figure B.2: Rain days and depth relationship- Station 0636486

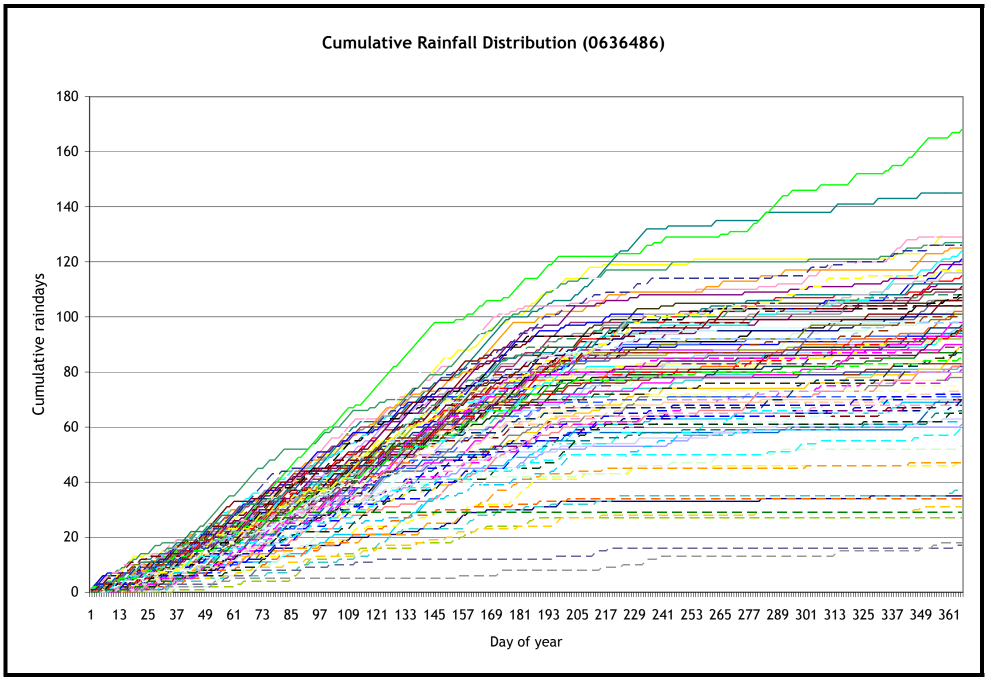

Figure B.3: Cumulative rainfall days - Station 0636486

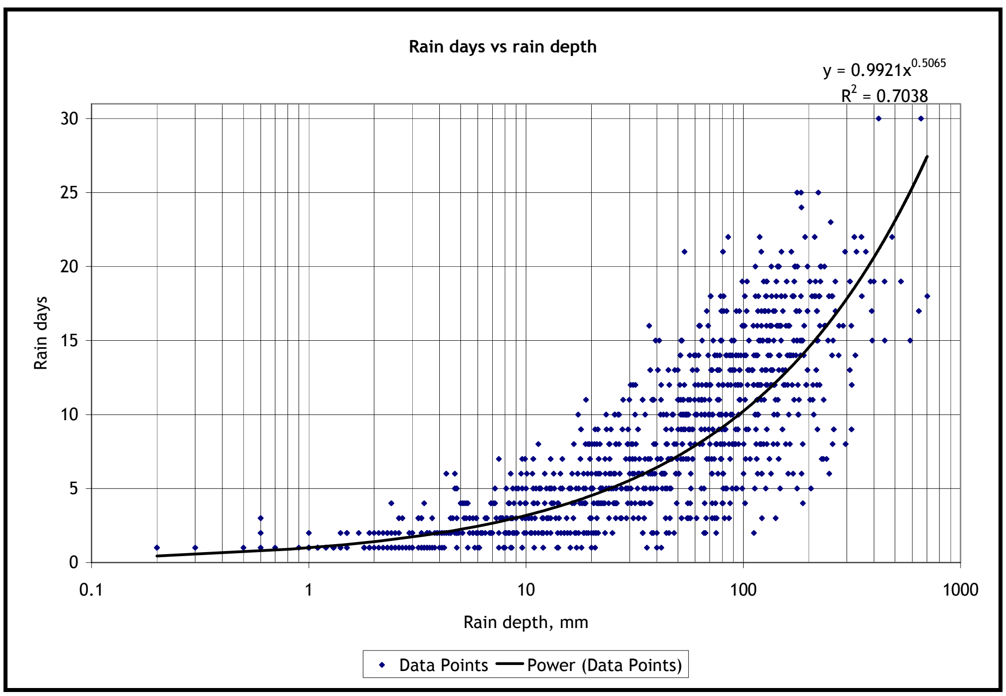

Figure B.4: Rain days and depth relationship- Station 0636486

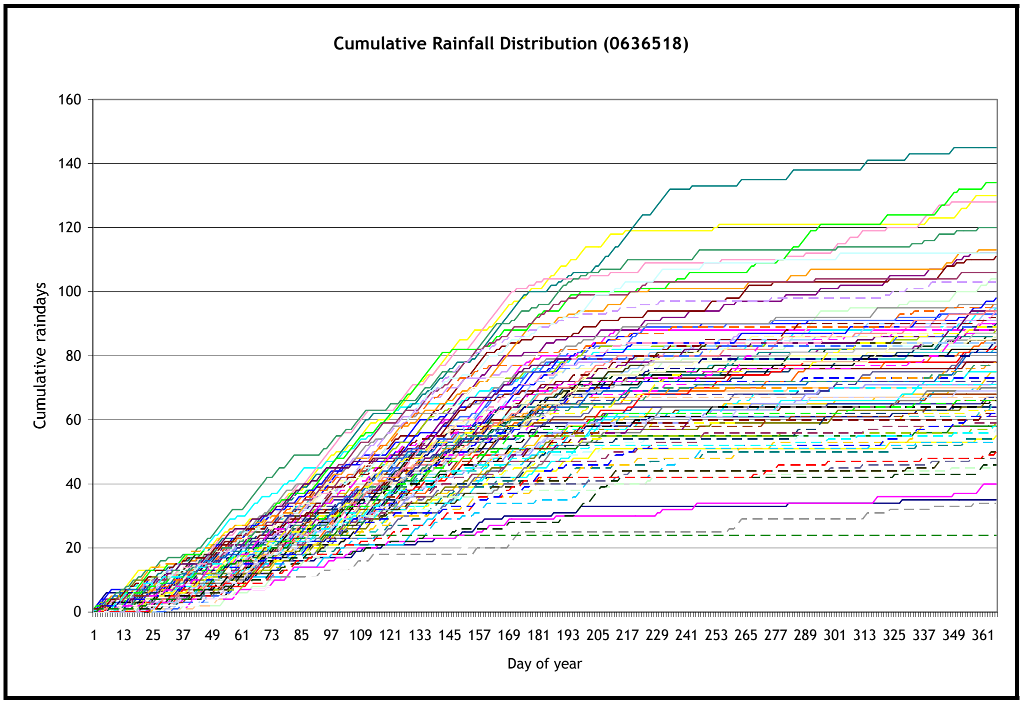

Figure B.5: Cumulative rainfall days – Station 0636518

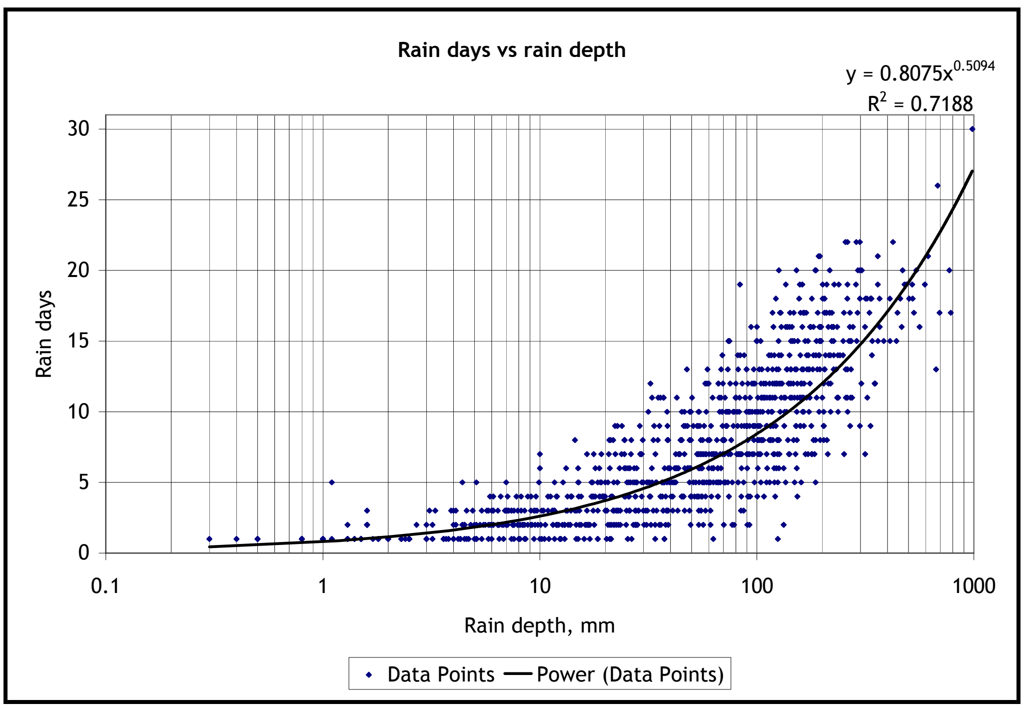

Figure B.6: Rain days and depth relationship- Station 0636518

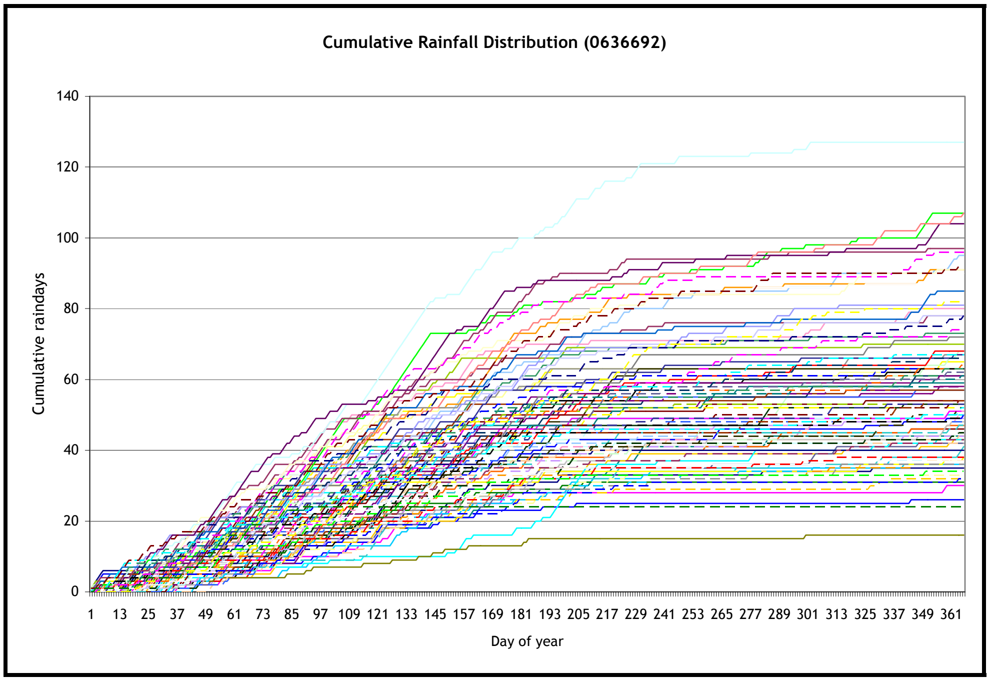

Figure B.7: Cumulative rainfall days – Station 0636692

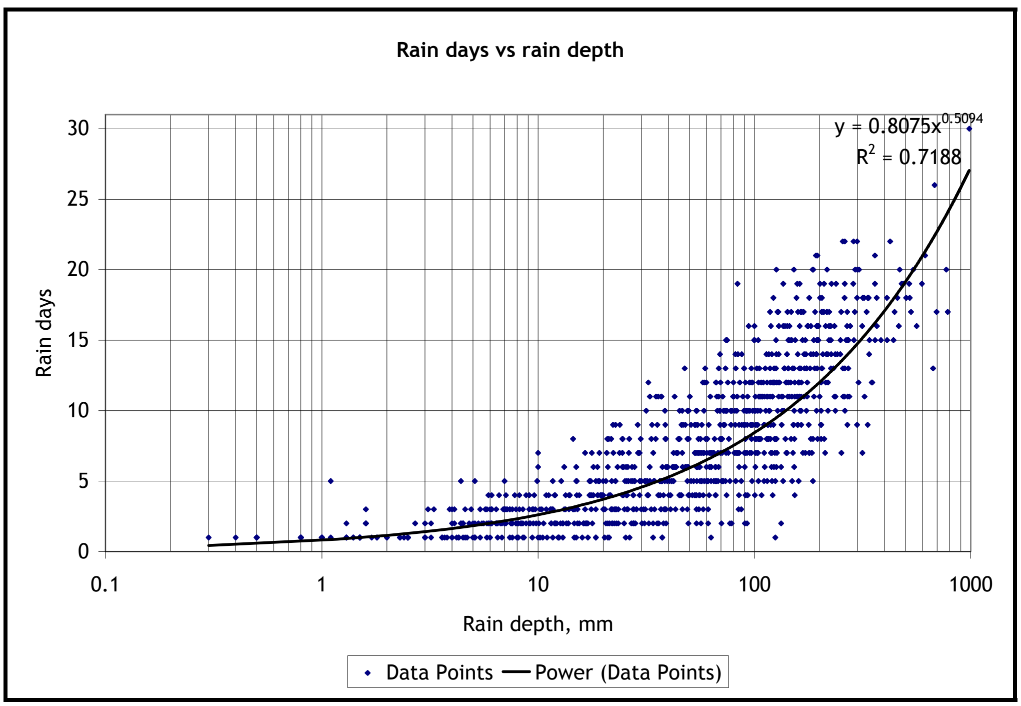

Figure B.8: Days and depth relationship – Station 0636692

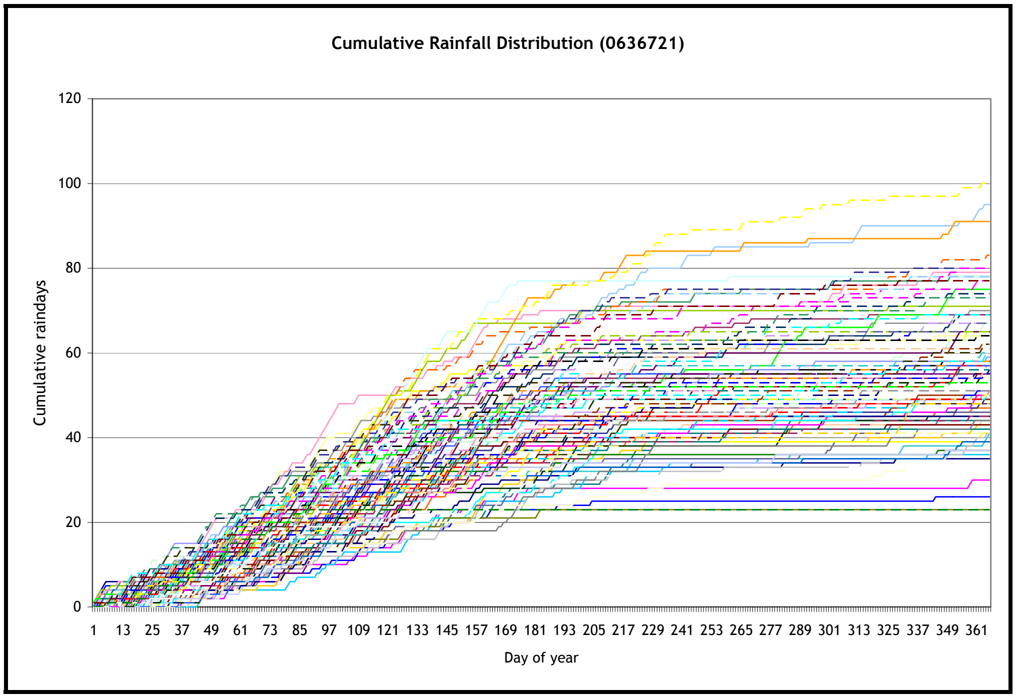

Figure B.9: Cumulative rainfall days – Station 0636721

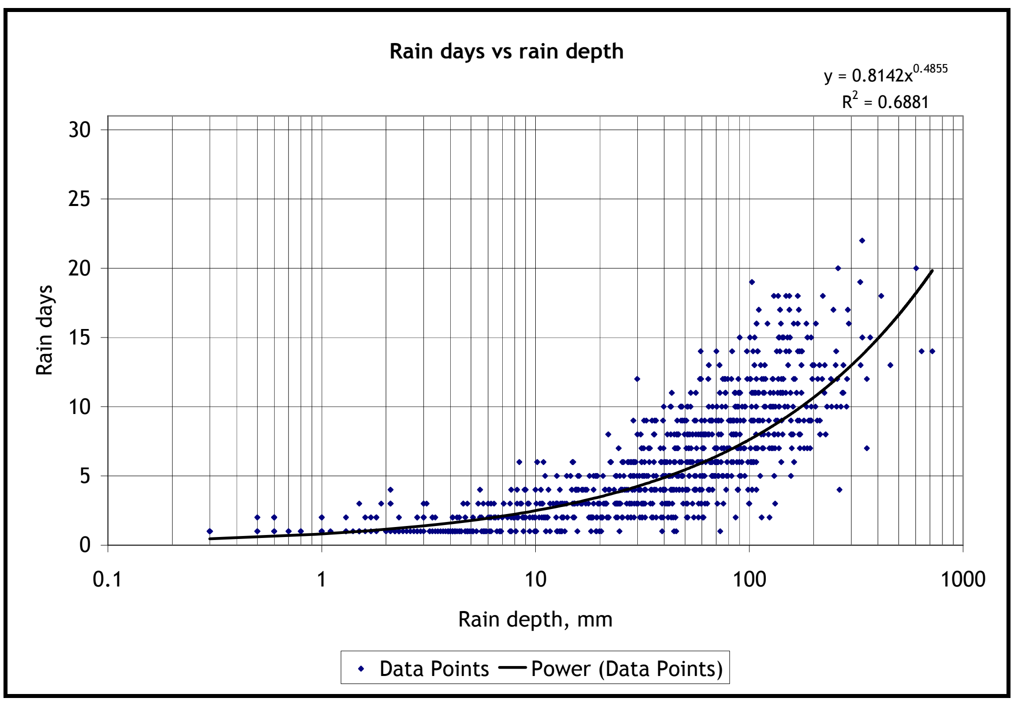

Figure B.10: Days and depth relationship – Station 0636721

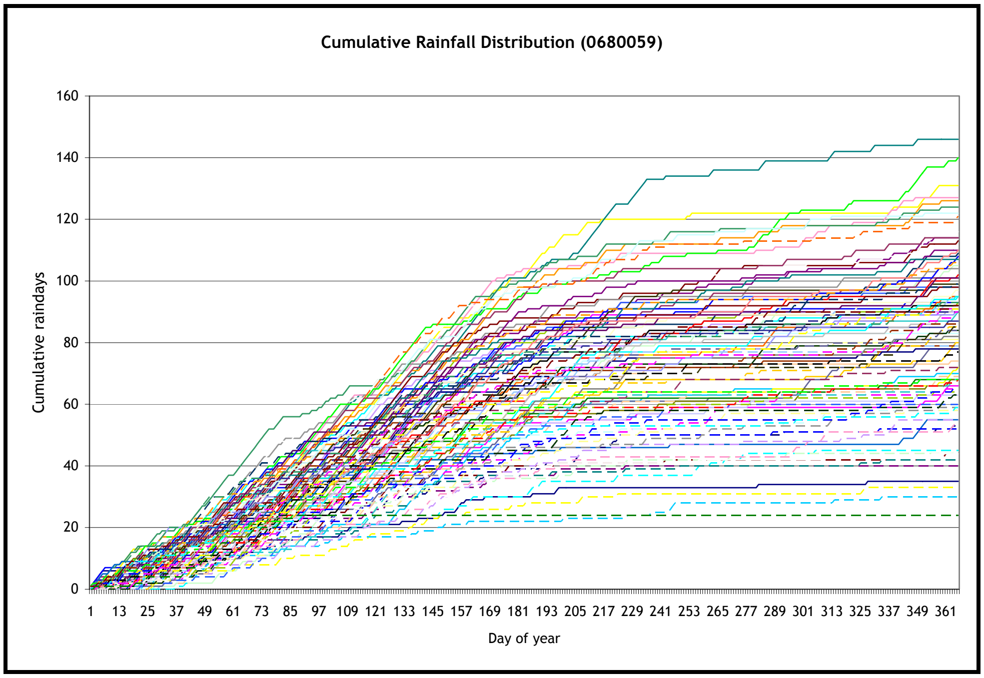

Figure B.11: Cumulative rainfall days – Station 0680059

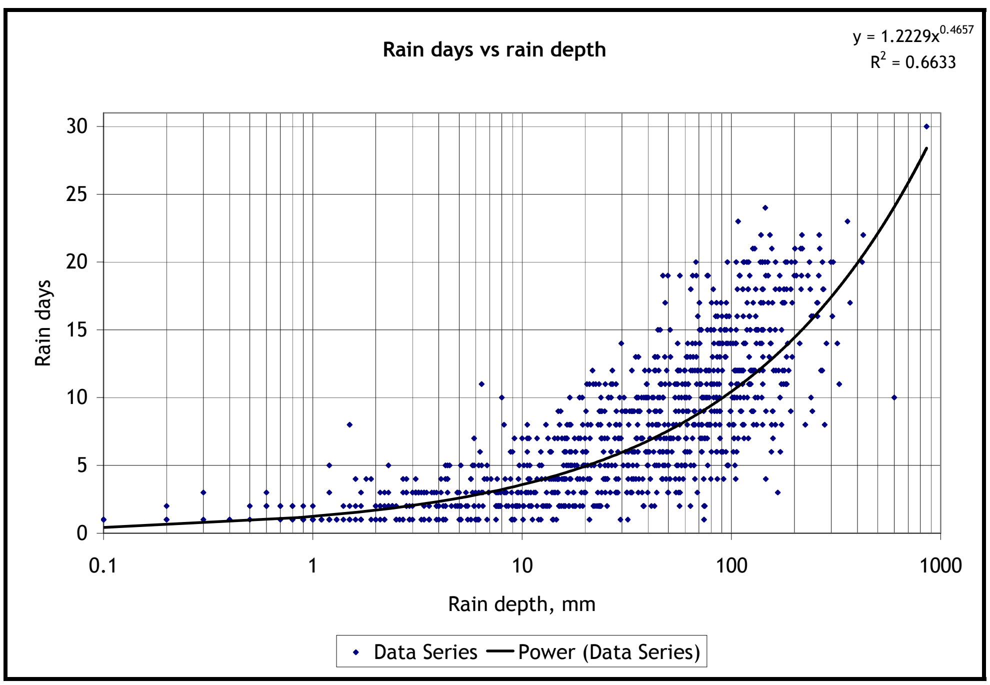

Figure B.12: Days and depth relationship – Station 0680059

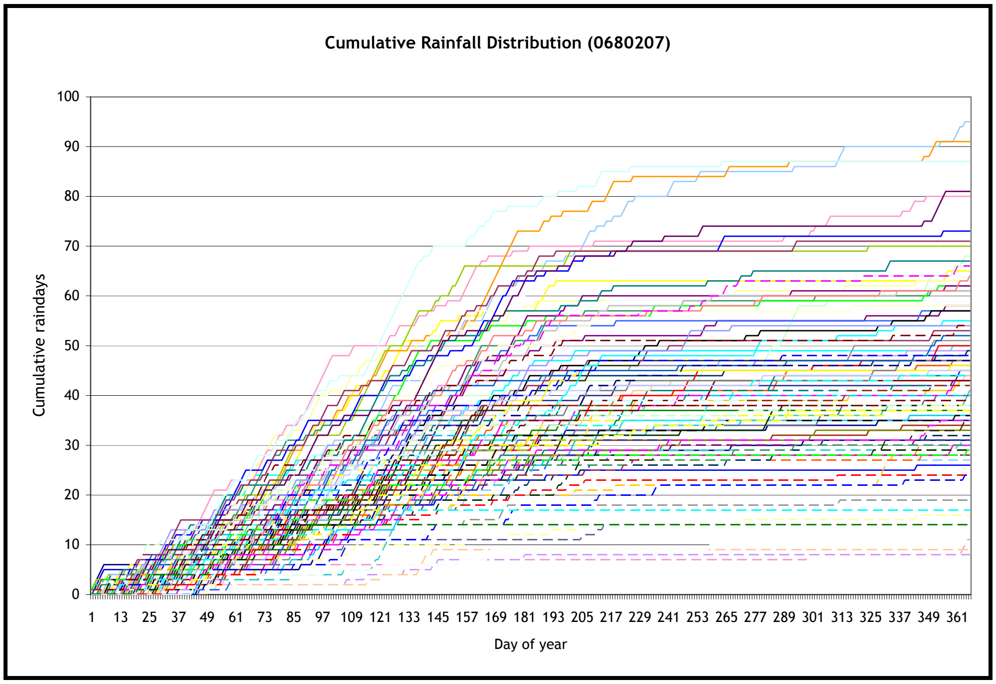

Figure B.13: Cumulative rainfall days - Station 0680207

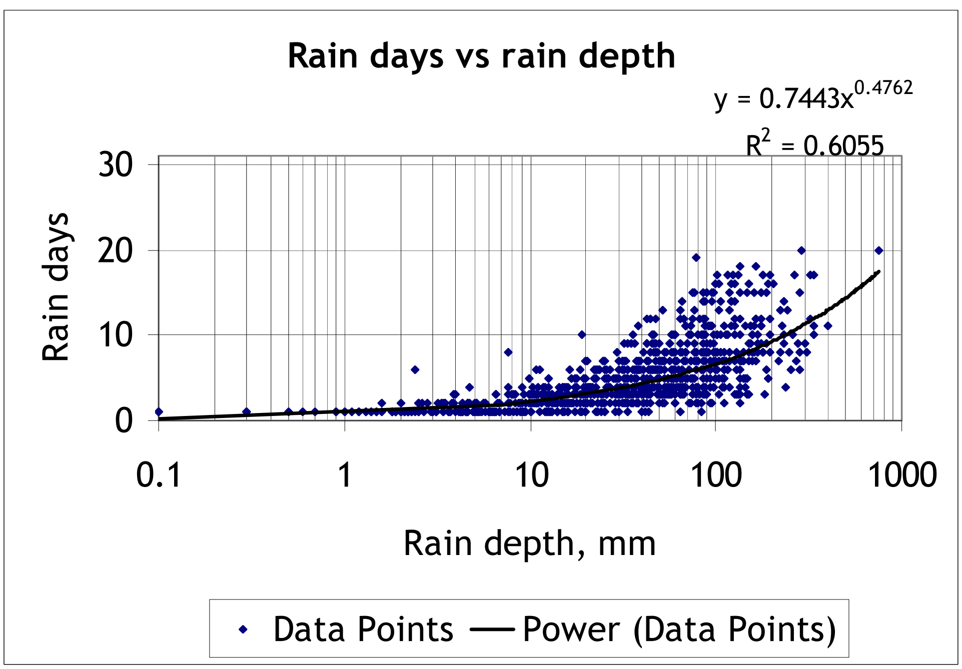

Figure B.14: Days and depth relationship - Station 0680207

C. APPENDIX C

C.1. WATERSHED SOILS INFORMATION

Soil albedo = 0.07 (Default value for ACRU)

Table C.1: Hydrological properties of soils in southern Africa by soil form and series (Binomial Classification). After Smithers and Schulze, (2004).

Soil Form	*Code*	*Soil Series*	*SCS Grouping*	*Typical Texture Class*	*Erosion Hazard Rating*
HUTTON	Hu 16	Hutton	A	SaClLm	Low
	Hu 26	Msinga	A	SaClLm	Low
	Hu 27	Doveton	A/B	SaCl	V.Low
	Hu 36	Shorrocks	A/B	SaClLm	Mod
	Hu 37	Makatini	B	SaCl	Low
	Hu 38	Marikana	B	Cl	Low
MISPAH	Ms 10	Mispah	C	SaClLm	Mod

Legend:

A – low runoff potential

B – moderately low runoff potential

C – moderately high runoff potential

Sa – sand

Cl – clay

Lm – loam

Table C.2: Soil erodibility factors (*Knom*) for various erodibility classes. After Smithers and Schulze, (2004).

Soil Erodibility Class	K_{nom}
Very High	> 0.70
High	0.50 - 0.70
Moderate	0.25 - 0.50
Low	0.13 - 0.25
Very Low	< 0.13

Table C.3: Typical values of soil hydrological input parameters for different textural classes (after Schulze, 1990)

Soil Texture Number	*Soil Texture Class*	*Horizon*	*Typical percentages of*				*Bulk density*, Mgm^{-3}*	*Effective porosity, m^3m^{-3}*	*Saturated Hydraulic conductivity, mmh^{-1}*
			Clay	Silt	Sand	Organic Carbon			
1	Clay	Topsoil Subsoil	50	37	13	0.38	1.21 1.37	0.536 0.470	0.6
2	Loam	Topsoil Subsoil	18	25	57	0.52	1.18 1.42	0.512 0.464	13
3	Sand	Topsoil Subsoil	3	4	93	0.71	1.25 1.50	0.452 0.430	210
4	Loamy sand	Topsoil Subsoil	7	7	86	0.61	1.24 1.51	0.457 0.432	61
5	Sandy loam	Topsoil Subsoil	10	15	75	0.71	1.19 1.46	0.505 0.448	26
6	Silty loam	Topsoil Subsoil	18	55	27	0.58	1.07 1.34	0.527 0.495	6.8
7	Sandy clay loam	Topsoil Subsoil	27	8	65	0.19	1.30 1.58	0.486 0.393	4.3
8	Clay loam	Topsoil Subsoil	32	22	46	0.10	1.17 1.41	0.497 0.451	2.3
9	Silty clay loam	Topsoil Subsoil	33	46	51	0.13	1.23 1.40	0.509 0.469	1.5
10	Sandy clay	Topsoil Subsoil	40	5	55	0.38	1.30 1.53	0.430 0.423	1.2
11	Silty clay	Topsoil Subsoil	50	37	13	0.38	1.22 1.38	0.531 0.476	0.9

Notes:

1. Values of bulk density are an average of tilled and untilled topsoil.
2. Comparative percentages and propotions of the clay, silt, sand and organic carbon (which were obtained from the soil profiles) were used to determine the bulk density and hydraulic conductivity.
3. The topsoil properties were assumed to be valid for all first layers of the soil profiles although it is known that the depth of topsoil could be less that the depth of the first layer. Subsoil properties were used for all other layers of the profile.

C.2. Reports generated from SWAT.

C.2.1. Landuse/soil distribution.

```
Detailed   LANDUSE/SOIL    distribution         SWAT   model   class
Sun Aug 06 17:49:55 2006


Area [ha]        Area [acres]

Watershed
88652.0282         219063.5943


Area [ha]        Area [acres] %Wat.Area

LANDUSE
                                 Range-Brush        -->        RNGB
23841.5611          58913.6895     26.89
                               Range-Grasses        -->        RNGE
3779.9430           9340.4282      4.26
                Southwestern    US    (Arid)    Range    -->    SWRN
10206.8698          25221.6857     11.51
                                Forest-Mixed        -->        FRST
26351.4136          65115.6605     29.72
               Agricultural      Land-Close-grown      -->      AGRC
14176.1512          35029.9785     15.99
                 Agricultural     Land-Row     Crops     -->     AGRR
10296.0895          25442.1519     11.61

SOIL
                                                Fa347
10149.1631          25079.0894     11.45
```

Fb186

1197.7915 2959.8027 1.35

Ab54

5016.3730 12395.7084 5.66

lc157

4919.0242 12155.1547 5.55

Ae126

14908.8163 36840.4304 16.82

Ae127

52460.8602 129633.4085 59.18

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 1

38329.3288 94713.6879 43.24

LANDUSE:

Range-Brush --> RNGB

5988.9576 14799.0137 6.76 15.63

Southwestern US (Arid) Range --> SWRN

1197.7915 2959.8027 1.35 3.13

Forest-Mixed --> FRST

26351.4136 65115.6605 29.72 68.75

Agricultural Land-Close-grown --> AGRC

4791.1661 11839.2110 5.40 12.50

SOIL:

lc157

2395.5831 5919.6055 2.70 6.25

Ae126

7186.7492 17758.8165 8.11 18.75

Ae127

27549.2051 68075.4632 31.08 71.88

Fb186

1197.7915 2959.8027 1.35 3.13

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 2

6924.0078 17109.5695 7.81

LANDUSE:

Range-Brush --> RNGB

1384.8016 3421.9139 1.56 20.00

Agricultural Land-Close-grown --> AGRC

5539.2062 13687.6556 6.25 80.00

SOIL:

Ae127

6924.0078 17109.5695 7.81 100.00

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 3
6182.1498 15276.4013 6.97

LANDUSE:
Range-Brush --> RNGB
4945.7198 12221.1210 5.58 80.00
Range-Grasses --> RNGE
1236.4300 3055.2803 1.39 20.00

SOIL:
Fa347
2472.8599 6110.5605 2.79 40.00
lc157
1236.4300 3055.2803 1.39 20.00
Ab54
2472.8599 6110.5605 2.79 40.00

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 4
8902.2957 21998.0178 10.04

LANDUSE:
Range-Brush --> RNGB
5087.0261 12570.2959 5.74 57.14
Range-Grasses --> RNGE
2543.5131 6285.1479 2.87 28.57
Agricultural Land-Close-grown --> AGRC
1271.7565 3142.5740 1.43 14.29

SOIL:
Fa347
3815.2696 9427.7219 4.30 42.86
Ae127
2543.5131 6285.1479 2.87 28.57
Ab54
2543.5131 6285.1479 2.87 28.57

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 5
28314.2461 69965.9178 31.94

LANDUSE:
Range-Brush --> RNGB
6435.0559 15901.3450 7.26 22.73

Southwestern US (Arid) Range --> SWRN
9009.0783 22261.8829 10.16 31.82
Agricultural Land-Close-grown --> AGRC
2574.0224 6360.5380 2.90 9.09
Agricultural Land-Row Crops --> AGRR
10296.0895 25442.1519 11.61 36.36

SOIL:
Fa347
3861.0336 9540.8070 4.36 13.64
lc157
1287.0112 3180.2690 1.45 4.55
Ae126
7722.0671 19081.6140 8.71 27.27
Ae127
15444.1342 38163.2279 17.42 54.55

C.2.2. HRUs Landuse/soil distribution.

SWAT model simulation Sun Aug 06 17:50:17 2006
MDL

MULTIPLE HRUs LandUse/Soil OPTION THRESHOLDS : 5 / 5 [%]
Number of HRUs: 29
Number of Subbasins: 5

Area [ha] Area [acres] %Wat.Area

WATERSHED:
88652.0282 219063.5943

LANDUSE:
Range-Brush-->RNGB
24034.7533 59391.0770 27.11
Range-Grasses-->RNGE
3779.9430 9340.4282 4.26
Southwestern US (Arid) Range-->SWRN
9009.0783 22261.8829 10.16
Forest-Mixed-->FRST
27201.4591 67216.1656 30.68
Agricultural Land-Close-grown-->AGRC
14330.7050 35411.8886 16.17
Agricultural Land-Row Crops-->AGRR
10296.0895 25442.1519 11.61

SOIL:

Fa347

10149.1631 25079.0894 11.45

Ab54

5016.3730 12395.7084 5.66

lc157

5114.0563 12637.0888 5.77

Ae126

15376.1574 37995.2536 17.34

Ae127

52996.2785 130956.4540 59.78

Area [ha] Area [acres] %Wat.Area %Sub.Area

SUBBASIN # 1

38329.3288 94713.6879 43.24

LANDUSE:

Range-Brush-->RNGB

6182.1498 15276.4013 6.97 16.13

Forest-Mixed-->FRST

27201.4591 67216.1656 30.68 70.97

Agricultural Land-Close-grown-->AGRC

4945.7198 12221.1210 5.58 12.90

SOIL:

lc157

2590.6152 6401.5396 2.92 6.76

Ae126

7654.0902 18913.6397 8.63 19.97

Ae127

28084.6234 69398.5087 31.68 73.27

HRUs:

1 Range-Brush-->RNGB/Ae126

1236.4300 3055.2803 1.39 3.23 1

2 Range-Brush-->RNGB/Ae127

4945.7198 12221.1210 5.58 12.90 2

3 Forest-Mixed-->FRST/Ae126

5181.2303 12803.0792 5.84 13.52 3

4 Forest-Mixed-->FRST/Ae127

19429.6137 48011.5469 21.92 50.69 4

5 Forest-Mixed-->FRST/lc157

2590.6152 6401.5396 2.92 6.76 5

6 Agricultural Land-Close-grown-->AGRC/Ae126

1236.4300 3055.2803 1.39 3.23 6

7 Agricultural Land-Close-grown-->AGRC/Ae127

3709.2899 9165.8408 4.18 9.68 7

```
Area [ha]   Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                          2
6924.0078     17109.5695      7.81

LANDUSE:
                                             Range-Brush-->RNGB
1384.8016      3421.9139      1.56     20.00
                           Agricultural    Land-Close-grown-->AGRC
5539.2062     13687.6556      6.25     80.00

SOIL:
                                                          Ae127
6924.0078     17109.5695      7.81    100.00

HRUs:
8                                         Range-Brush-->RNGB/Ae127
1384.8016      3421.9139      1.56     20.00    1
9                       Agricultural Land-Close-grown-->AGRC/Ae127
5539.2062     13687.6556      6.25     80.00    2


Area [ha]   Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                          3
6182.1498     15276.4013      6.97

LANDUSE:
                                             Range-Brush-->RNGB
4945.7198     12221.1210      5.58     80.00
                                           Range-Grasses-->RNGE
1236.4300      3055.2803      1.39     20.00

SOIL:
                                                          Fa347
2472.8599      6110.5605      2.79     40.00
                                                          lc157
1236.4300      3055.2803      1.39     20.00
                                                           Ab54
2472.8599      6110.5605      2.79     40.00

HRUs:
10                                         Range-Brush-->RNGB/Ab54
1236.4300      3055.2803      1.39     20.00    1
11                                        Range-Brush-->RNGB/Fa347
2472.8599      6110.5605      2.79     40.00    2
12                                        Range-Brush-->RNGB/lc157
1236.4300      3055.2803      1.39     20.00    3
13                                       Range-Grasses-->RNGE/Ab54
1236.4300      3055.2803      1.39     20.00    4
```

```
Area [ha]   Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                       4
8902.2957     21998.0178     10.04

LANDUSE:
                                             Range-Brush-->RNGB
5087.0261     12570.2959      5.74     57.14
                                           Range-Grasses-->RNGE
2543.5131      6285.1479      2.87     28.57
                           Agricultural    Land-Close-grown-->AGRC
1271.7565      3142.5740      1.43     14.29

SOIL:
                                                          Fa347
3815.2696      9427.7219      4.30     42.86
                                                          Ae127
2543.5131      6285.1479      2.87     28.57
                                                           Ab54
2543.5131      6285.1479      2.87     28.57

HRUs:
14                                         Range-Brush-->RNGB/Ab54
1271.7565      3142.5740      1.43     14.29    1
15                                        Range-Brush-->RNGB/Ae127
1271.7565      3142.5740      1.43     14.29    2
16                                        Range-Brush-->RNGB/Fa347
2543.5131      6285.1479      2.87     28.57    3
17                                       Range-Grasses-->RNGE/Ab54
1271.7565      3142.5740      1.43     14.29    4
18                                      Range-Grasses-->RNGE/Fa347
1271.7565      3142.5740      1.43     14.29    5
19                      Agricultural Land-Close-grown-->AGRC/Ae127
1271.7565      3142.5740      1.43     14.29    6


Area [ha]   Area [acres] %Wat.Area %Sub.Area

SUBBASIN #                                                       5
28314.2461     69965.9178     31.94

LANDUSE:
                                             Range-Brush-->RNGB
6435.0559     15901.3450      7.26     22.73
                            Southwestern  US  (Arid)  Range-->SWRN
9009.0783     22261.8829     10.16     31.82
                           Agricultural    Land-Close-grown-->AGRC
2574.0224      6360.5380      2.90      9.09
                             Agricultural   Land-Row   Crops-->AGRR
10296.0895     25442.1519     11.61     36.36
```

```
SOIL:
                                                                  Fa347
3861.0336      9540.8070      4.36     13.64
                                                                  lc157
1287.0112      3180.2690      1.45      4.55
                                                                  Ae126
7722.0671     19081.6140      8.71     27.27
                                                                  Ae127
15444.1342     38163.2279     17.42     54.55

HRUs:
20                                          Range-Brush-->RNGB/Ae126
1287.0112      3180.2690      1.45      4.55    1
21                                          Range-Brush-->RNGB/Ae127
1287.0112      3180.2690      1.45      4.55    2
22                                          Range-Brush-->RNGB/Fa347
2574.0224      6360.5380      2.90      9.09    3
23                                          Range-Brush-->RNGB/lc157
1287.0112      3180.2690      1.45      4.55    4
24                        Southwestern US (Arid) Range-->SWRN/Ae127
7722.0671     19081.6140      8.71     27.27    5
25                        Southwestern US (Arid) Range-->SWRN/Fa347
1287.0112      3180.2690      1.45      4.55    6
26                       Agricultural Land-Close-grown-->AGRC/Ae126
1287.0112      3180.2690      1.45      4.55    7
27                       Agricultural Land-Close-grown-->AGRC/Ae127
1287.0112      3180.2690      1.45      4.55    8
28                         Agricultural Land-Row Crops-->AGRR/Ae126
5148.0447     12721.0760      5.81     18.18    9
29                         Agricultural Land-Row Crops-->AGRR/Ae127
5148.0447     12721.0760      5.81     18.18   10
```

D. APPENDIX D

D.1.1. Parameter Definition

Table D.1

Parameter	*Definition*
ALPHA_BF	Baseflow alpha factor (days)
BIOMIX	Biological mixing efficiency
BLAI	Leaf area index for crop
CANMX	Maximum canopy index
CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/hr)
CH_N	Manning coefficient for channel
CN2	SCS runoff curve number for moisture condition II
EPCO	Plant evaporation compensation factor
ESCO	Soil evaporation compensation factor
GW_DELAY	Groundwater delay (days)
GW_REVAP	Groundwater ‘revap’ coefficient.
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)
RCHRG_DP	Groundwater recharge to deep aquifer (fraction)
REVAPMN	Threshold depth of water in the shallow aquifer for ‘revap’ to occur (mm).
SFTMP	Snowfall temperature (^oC)
SLOPE	Average slope steepness (m/m)
SLSUBBSN	Average slope length (m).
SMFMN	Minimum melt rate for snow during the year (mm/^oC/day)
SMFMX	Maximum melt rate for snow during the year (mm/^oC/day)
SMTMP	Snow melt base temperature
SOL_ALB	Soil albedo
SOL_AWC	Available water capacity of the soil layer (mm/mm soil)
SOL_K	Soil conductivity (mm/h)
SOL_Z	Soil depth
SURLAG	Surface runoff lag coefficient
TIMP	Snow pack temperature lag factor
TLAPS	Temperature laps rate (8C/km)