# 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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# 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.

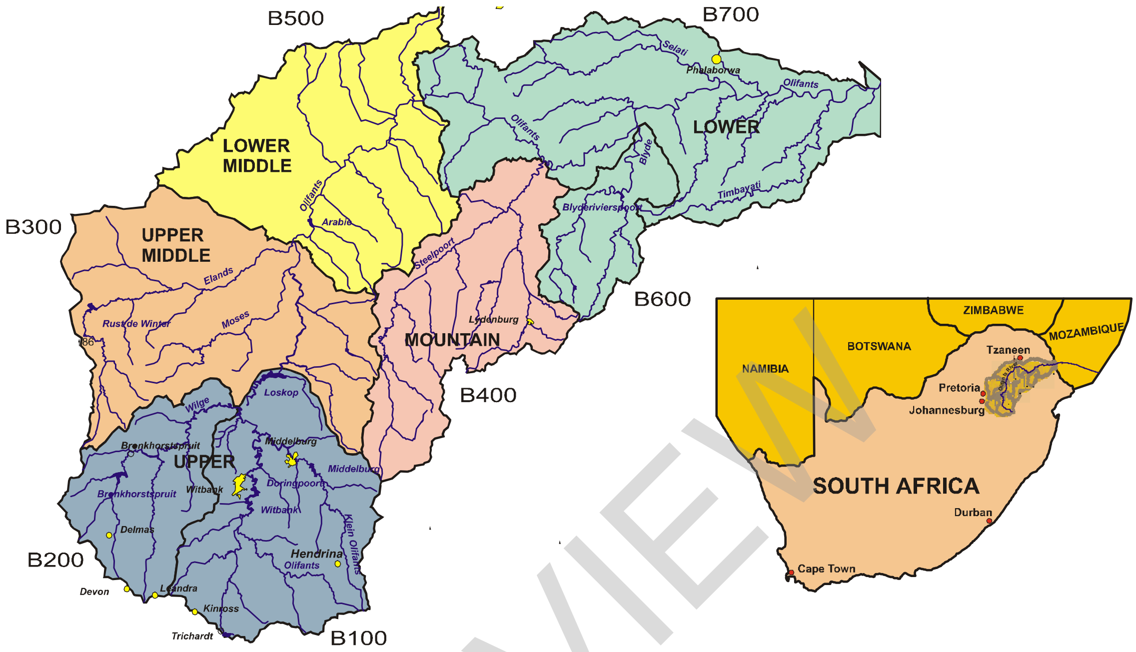

Figure 1.1: Location of the Olifants River Water Management Area and the boundaries of the five water management regions (IWMI, 2005).

**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 |

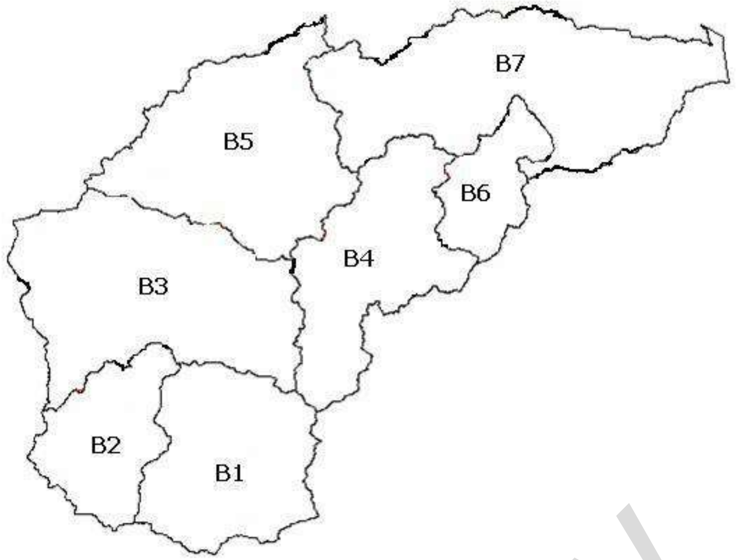

**Figure 1.2: The Secondary Catchments of the Olifants**

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.

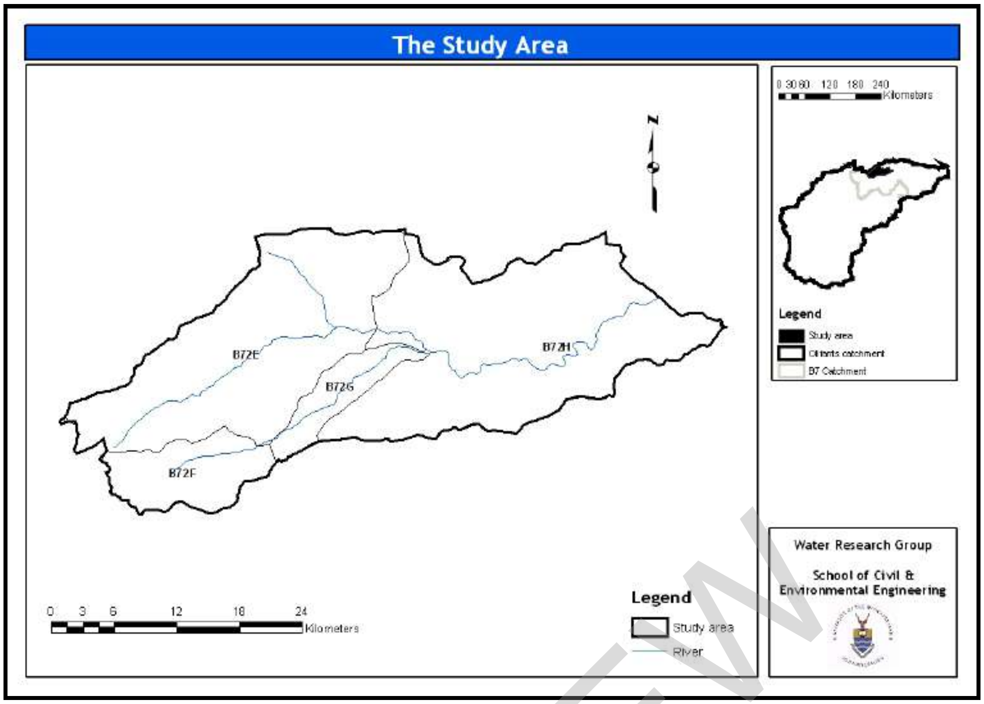

Figure 1.3: Location of the study area

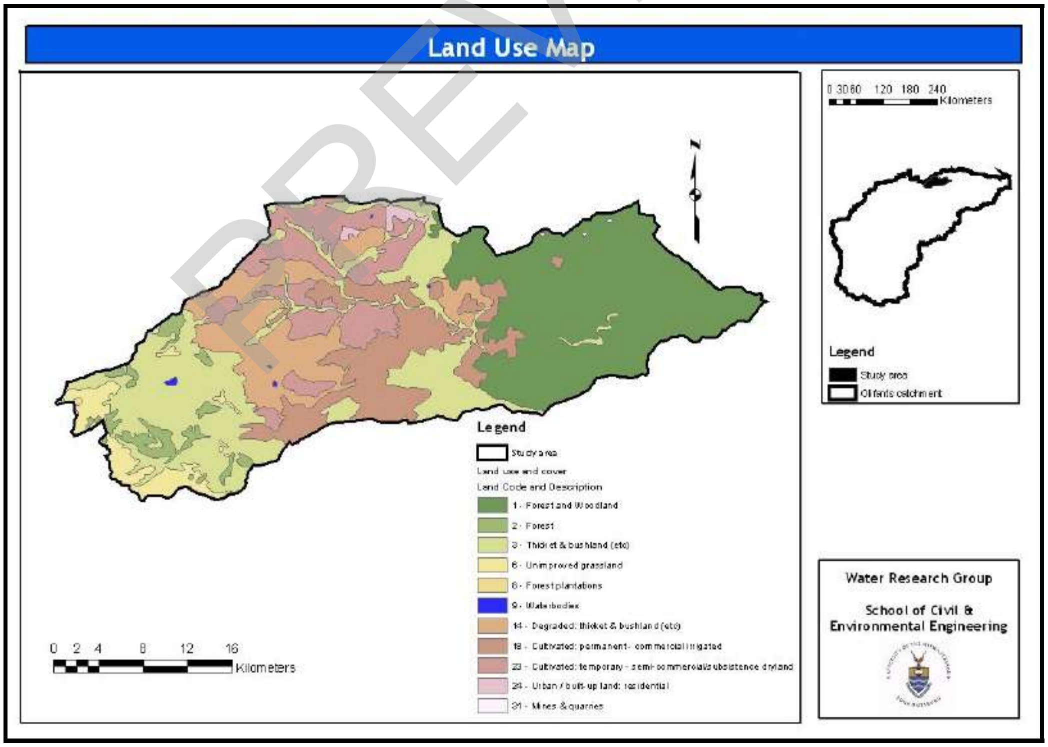

Figure 1.4: Land use in the study area

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.

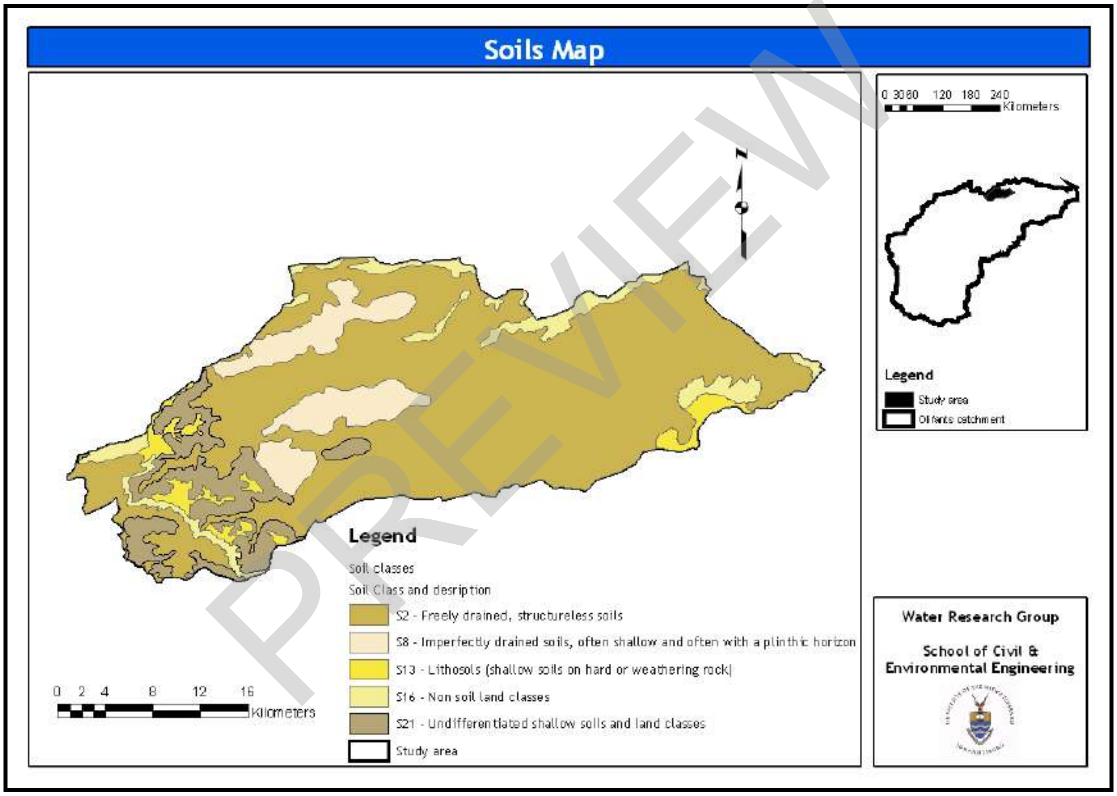

Figure 1.5: Soils in the study area

## 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.