HYDROLOGICAL FLOW MODELLING USING GEOGRAPHIC INFORMATION SYSTEMS (GIS): THE CASE STUDY OF PHUTHIATSANE CATCHMENT, LESOTHO

BY

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ABSTRACT

Despite of Lesotho having abundant water, it is still faced with freshwater challenges as the current water supply cannot meet the needs of the population. In addition, water has become the main driver of development in Lesotho as it is one of the few natural resources of economic importance hence construction of water storage dams has been identified as a development strategy. Modelling of water flow is one of the techniques used in describing the movement of water and determining flow accumulation within the catchment. Rainfall-runoff modelling in Lesotho has been based on traditional methods which only focus on the discharge at the outlet neglecting the distribution of runoff over the catchment. GIS enables modelling of spatial variability hence this study is aimed at determining flow distribution and accumulation within Phuthiatsane Catchment and estimating runoff potential in a GIS environment. In order to achieve this, ArcHydro extension of ArcGIS was used in the determination of flow distribution and subsequent catchment delineation while ArcCN-Runoff tool was used to determine the potential runoff based on land cover, soil type and amount of rainfall. The delineated catchment covers an area of 468 km^2 and has an average runoff of 30.943 MCM. Suitable dam sites, volume and the areas that would be submerged were then identified using other ArcGIS tools. It was concluded that GIS can produce accurate hydrological modelling results for Phuthiatsane Catchment. Simulation of dam sites and storage capacities has also proven to be efficient in GIS environment and a 70m high dam with a storage capacity of 327.92 MCM was considered to be the most suitable. It is recommended that further research should include ground truth surveys for the validation of results. Further research should also incorporate stakeholder concerns in deciding on the location and size of a dam.

PREFACE

The work reported in this dissertation was carried out in the School of Environmental Sciences at the University of KwaZulu-Natal, Westville under the supervision of Prof. Fethi B. Ahmed.

These studies represent original work by the author and have not been submitted in any form for a degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Signed: .... Date: ....

Lipalesa Khalema (Candidate)

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Prof. Fethi Ahmed (Supervisor)

DECLARATION – PLAGIARISM

I, Lipalesa Esther Khalema declare that

1. The research reported in this dissertation, except where otherwise indicated, is my original research.

2. This dissertation has not been submitted for any degree or examination at any other university.

3. This dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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    a. Their words have been re-written but general information attributed to them has been referenced

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5. This dissertation does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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DEDICATION

This dissertation is dedicated to my parents Seng Khalema and ‘Makarabo Khalema

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LIST OF ABBREVIATIONS

AMSL	Above Mean Sea Level
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CEC	Consulting Engineering Center
DEM	Digital Elevation Model
dll	dynamic link library
DTM	Digital Terrain Model
ERSDAC	Earth Remote Sensing Data Analysis Centre
ESRI	Environmental Systems Research Institute
FVM	Finite Volume Method
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GIS	Geographic Information Systems
HRU	Hydrological Response Unit
HSG	Hydrological Soil Group
ICOLD	International Commission on Large Dams
IFR	Instream Flow Requirements
ITCZ	Inter-tropical Convergence Zone
LHWP	Lesotho Highlands Water Project
LSPP	Land Surveys and Physical Planning
MCM	Million Cubic Metres
NASA	National Aeronautics and Space Administration
NEXRAD	Next Generation Weather Radar

NMDS	National Manpower Development Secretariat
NRCS	Natural Resource Conservation Service
SCS	Soil Conservation Service
TIN	Triangulated Irregular Network
WGS	World Geodetic System

CHAPTER ONE: INTRODUCTION

1.1 Background

The existence of every creature including human beings is dependant on water. Water is one of the crucial factors maintaining the ecosystems and sustenance of human lives (Maidment, 2002). In addition, most development activities are dependant on water and it has become an important economic natural resource. The availability of fresh water is therefore one of the major concerns of the world today (Maidment, 2002).

Water has become the main driver of development in Lesotho as it is one of the few natural resources of economic importance. Due to the volume of runoff being generated, construction of storage dams has been identified as a development strategy for Lesotho (Tilt *et al*., 2009). Water-based income accounts for approximately 14% of Lesotho's Gross Domestic Product (GDP) through the Lesotho Highlands Water Project (LHWP) which is aimed at transferring water from Lesotho Highlands into Vaal River, in South Africa for the benefit of the two countries (Tromp, 2006). The recent economic growth can be accredited to water-based projects (Tromp, 2006). Lesotho also takes advantage of water by generating hydroelectric power from Muela dam in order to meet some of the basic electricity needs of the country (Tromp, 2006; Tilt *et al*., 2009). Muela hydropower station is one of the initiatives of LHWP.

Despite of Lesotho having abundant surface water resources which exceed both the current and future needs of the population (Eales *et al*., 2005), it is still faced with water provision challenges as the current water supply cannot meet the current and future needs of the population. The majority of homes in the country do not have access to running water. This is caused by a number of factors including lack of capital resources for efficient engineering methods for harnessing this water and delivering it to the people (Eales *et al*., 2005). A significant amount of runoff is often rapid and occurs in remote rugged terrain of Lesotho (Eales *et al*., 2005). The other factor is that there is insufficient planning data on settlements and urban development (CEC *et al*., 2003). With the increasing demand on water, the challenge of water supply is worsening. The water demand study that was undertaken in 2003 projected that the main influence on water demand is the predicted industrial expansion especially the wet industries such as textile industries (CEC *et al*., 2003). Wet industries are industries that use more than 2000 m^3 per day (Government of Lesotho Ministry of Natural Resources, 2003) .The other factor increasing the water demand is migration of people from rural areas to the capital Maseru and the surrounding towns. Domestic demand is associated with the rate of increased service coverage and the service levels required within the urban areas (CEC *et al*., 2003). The population of Maseru is expanding outwardly rather than densification hence the need to increase water supply in neighbouring towns (CEC *et al*., 2003).

It has therefore become important to understand the hydrological processes and dynamics affecting water availability and identify efficient ways of estimating the amount of runoff for the purposes of dam construction and catchment monitoring. Modelling of water flow is one of the techniques used in describing the movement of water within the basin and determining flow accumulation at the outlet of the catchment (Olsson and Pilesjo, 2002). Determination of flow distribution and accumulation provides information that can be used to support informative decision making to solve the current water challenges in developing countries.

There are however challenges facing the application of hydrological modelling in Lesotho. These include the uncertainty in data accuracy and spatial detail for modelling the potential dam sites (Hughes, 2004). There are also calibration problems due to scale differences between available data and model parameters. In addition, there is insufficient funding and expertise for modelling (Hughes, 2004). A number of dams have been constructed and several locations identified for more dams based on the discharge of the rivers in these areas. Lack of data for some streams in mountainous, inaccessible areas and data gaps in gauged areas have posed more challenges for hydrological modelling in Lesotho (Hughes, 2004). The incorporation of GIS into hydrological modelling holds promise for modelling the hydrology of the study area, Phuthiatsane catchment in Lesotho. Phuthiatsane River has its highest flow in the lowlands of Lesotho hence it has been chosen to host a dam that will provide water for Maseru and the surrounding lowland areas (CEC *et al*., 2003).

1.2 Hydrological Flow Modelling

Hydrological modelling can be used to identify suitable areas for dam construction so as to solve the current and future water challenges. The field of hydrological modelling is very broad ranging from quantification of flow to pollution monitoring (Maidment, 2002). Traditional hydrological modelling was aimed at the simulation of discharge from a catchment and neglecting the distribution of water within a catchment (Olsson and Pilesjo, 2002). Due to the advent of GIS, the focus has shifted to spatially distributed models instead of lumped models (Olsson and Pilesjo, 2002).

Distributed models describe flow processes at every point within the catchment (Olsson and Pilesjo, 2002). The terms watershed, catchment, basin and drainage area are usually used interchangeably to refer to an area draining to a point on a river system, stream segment or a water body (Maidment, 2002).The nature of distributed modelling allows simulation and estimation of spatial characteristics and deviations within the catchment (Olsson and Pilesjo, 2002). This model does not only calculate the discharge at one outlet but temporally and spatially distributed multiple yields (Olsson and Pilesjo, 2002). Spatially distributed models can resolve three main problems, namely: dividing precipitation into evaporation and contribution into the river basin; separating water input into runoff and infiltration; and the movement of subsurface water and surface runoff within the catchment (Olsson and Pilesjo, 2002). This study is however focused on the separation of rainfall input into runoff and infiltration through quantification of runoff. The study also focuses on the movement of surface flow within the catchment.

GIS-based hydrological modelling introduces a spatial component into hydrology making it easier to simulate spatially distributed hydrological processes. According to Smith *et al.,* (2004), the introduction of GIS and the improved computer capabilities have dealt with the historical obstacles that faced distributed models in the past.

One of the major strides in GIS-based hydrological modelling is the development of ArcHydro which is a geographical data model that describes hydrological systems. ArcHydro is capable of storing hydrological data in a common understandable structure hence the combination with GIS software capabilities enhances integration of applications and models (Strassberg *et al*., 2006).

A data model is a set of concepts put in a form of a data structure and it describes the models using tables and relationships within a database (Strassberg *et al*., 2006). These models utilise GIS technology in the description of the physical world and conceptualisation of hydrological systems such as river channels, catchment and groundwater systems (Strassberg *et al*., 2006). Common understanding and characterisation provided by ArcHydro can be used as a common structure for various models, analysis tools and decision support systems (Strassberg *et al*., 2006). ArcHydro is therefore useful for the achievement of some of the objectives of this research. ArcCN-Runoff tool is also very important for this research as it is an ArcGIS-based tool for the calculation of potential runoff volume and depth.

1.3 Motivation

Most of the hydrological modelling which has been carried out in Lesotho has focused on determination of discharge from a catchment ignoring the distribution of runoff over the entire catchment. The Pitman model is the most commonly used model in Lesotho and it was used in the feasibility study of the dam to be constructed in the Phuthiatsane catchment. This model was developed for Pulane sub-catchment and then applied to Metolong sub-catchment (see Figure3.1) with adjustment of some parameters including rainfall. Pulane sub-catchment is upstream of Metolong sub-catchment in which the dam site proposed by CEC *et al*., (2003) is located. The stream flow at the dam site was determined by factoring the flow series for the Masianokeng station (see Figure 3.1), located in Masianokeng sub-catchment which is downstream of Metolong (CEC *et al*., 2003).

The use of Pitman model can be accurate as the Pitman model has been approved for Southern Africa (Hughes, 2004). However, CEC *et al*., (2003) did not incorporate the spatial distribution of runoff in rainfall-runoff modelling of Phuthiatsane catchment. Proper catchment management requires proper knowledge of hydrological processes occurring at every point within the watershed. GIS is useful in distributed models as it is able to generate spatially distributed results (Jain and Singh, 2005). Factors such as land use[1] affect runoff hence it is important to have information on the variables and processes at every point within the catchment (Jain and Singh, 2005). Knowledge on the distribution of flow is important in water resource management as changes in the amount of runoff can be related to changes in certain variables affecting generation of runoff such as rainfall, soil properties and land cover (Melesse *et al*., 2003)

GIS has been applied in hydrological analysis such as calculation of catchment areas for Lesotho major water projects such as Instream Flow Assessment for Metolong Dam by SMEC (2007). Nevertheless, the capabilities of GIS in hydrological modelling have not been fully utilised in the previous hydrological studies in Lesotho since GIS was comparatively costly in the past (Hughes, 2004). Topography is the major factor controlling flow paths of both surface runoff and subsurface flow and manual methods of analysing catchment topography can be time consuming but the availability of digital terrain data in GIS format has made simulation of flow paths easier and automatic (Breddia, 2000). In addition, determination of spatially distributed runoff and identification of suitable dam sites have been

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[1] Land use and land cover are used interchangeably in this study

made manageable in a GIS environment (Jain *et al*., 2004; Santasmita and Paul, 2006). Due to the above reasons, it is believed that this study will be crucial in determining flow distribution and modelling the potential dam sites in the study area through the application of GIS.

1.4 Aim and Objectives

The aim of this study is to determine flow distribution and accumulation, estimate potential runoff within Phuthiatsane Catchment in Lesotho, and determine the suitable dam sites

The specific objectives are as follows:

- To determine flow distribution through stream definition
- To delineate Phuthiatsane catchment
- To determine potential runoff
- To identify the most suitable dam sites

1.5 Dissertation Outline

Chapter one describes the importance of water as one of the major development strategies of Lesotho and the challenges facing water supply in the country. It also introduces hydrological modelling and provides the motivation and the aim and objectives of the study. Chapter two provides a review of literature on hydrological modelling and the integration of GIS in modelling of surface water distribution, runoff and potential dam sites. Chapter three describes the study area, datasets and methods used in this study while chapter four presents the findings and the discussion of these findings. Chapter five then describes the conclusions and the recommendations made based on the findings of the study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter provides a review of literature on hydrological modelling, integration of GIS with hydrological models and the description of runoff modelling. The chapter also gives a review on the application of GIS in the determination of suitable dam sites and the storage capacity. An overview of similar case studies is then provided followed by a summary of major aspects of this chapter.

2.2 Hydrological Modelling

A model can be defined as a simplification or representation of reality and it can also predict and simulate future conditions (Olsson and Pilesjo, 2002). The major purpose of developing models is to aid the decision making process through the information outputs provided by these models. Information outputs such as spatially based indicators form part of the most useful tools in decision making, assessments and monitoring (Aspinall *et al*., 2000). Catchment models are aimed at integrating knowledge of hydrologic systems in order to mimic natural hydrologic processes (Melesse *et al*., 2003).

Catchment models deal with catchment area ranging from a gully system to a small stream system (Pullar and Springer, 2000). A model has to deal with various components of the water cycle such as rainfall, overland flow, runoff and flow routing in streams. Water quality measurements such as nutrients transported by hydrological processes like runoff are also made on top of hydrological measurements of those processes (Pullar and Springer, 2000). Decision makers have to consider catchment models in resource management since a catchment is a natural management area. Model outputs usually give an estimate for the entire catchment as well as processes at different parts of the catchment (Pullar and Springer, 2000).

2.2.1 History

Modelling components of the water cycle can be traced back to at least the Ancient Greeks but the mathematical hydrological modelling started when M. Darcy (1856) published his findings that water flows down a pressure gradient at a certain rate based on the hydraulic conductivity of a medium through which it is flowing (Silberstein, 2006). A milestone in the description of runoff generation was reached by Horton (1933) who made mathematical representations of infiltration, groundwater flow, overland flow generation and stream routing feasible (Silberstein, 2006). The addition of Kinematic surface flow greatly improved mathematical description of runoff making modelling of water pathways possible by the 1970s. Many advances in hydrological modelling have been made since then and any component of catchment processes can be added (Silberstein, 2006).

2.2.2 Types of Hydrological models

There are various ways of categorising models based on the modelling approach, distribution of spatial data, precision of events over time and the relationship between the inputs and outputs (Pullar and Springer, 2000).

2.2.2.1 Approaches to modelling

Hydrological modelling approaches can be categorised into either deterministic or stochastic models. A deterministic model, which is the most common in hydrologic modelling (AghaKouchak, 2009), produces one output for a specific input whereas an output of a stochastic model may vary with randomly varied input and at different time steps (Olsson and Pilesjo, 2002; Silberstein, 2006; AghaKouchak, 2009). Stochastic models therefore allow one to determine uncertainty of the results based on the uncertainty of input data (AghaKouchak, 2009).

2.2.2.2 Distribution of Spatial data

Deterministic models can further be divided into empirical lumped, empirical distributed, and physically-distributed models (Olsson and Pilesjo, 2002). Pullar and Springer (2000), state that lumped or distributed models differ in the treatment of spatial data by the model. Lumped models calculate the output of an area based on the average inputs of an area and a catchment polygon is normally used as the smallest spatial element (Pullar and Springer, 2000; Olsson and Pilesjo, 2002; Silberstein, 2006). These models are often used in rainfall-runoff modelling and averages can either be empirical or physically obtained (Olsson and Pilesjo, 2002). The problem with lumped models is that they average the outcomes for a large area hence important environmental problems in specific areas may be overlooked (Pullar and Springer, 2000). However dialects like physical lumped model and lumped models with some distributed parameters still exist (Olsson and Pilesjo, 2002).

On the other hand, distributed models describe hydrological processes at every point within the catchment but most of them have been modified to use pixels or sub-catchments as the smallest spatial units in order to reduce the memory and time required for modelling (Pullar and Spinger, 2000; Olsson and Pilesjo, 2002). Calculations are then accumulated to make estimations for each sub-catchment and the entire catchment. These models are compatible with GIS and remotely sensed data (Olsson and Pilesjo, 2002). Water discharge can be calculated for each cell and the resulting flow distribution mapped for the entire catchment (Olsson and Pilesjo, 2002). The distributed nature of these models allows simulation of spatial and temporal variation, changes and characteristics within a watershed therefore providing various outputs based on those variations (Olsson and Pilesjo, 2002). Distributed models are advantageous in that they can better account for local variability in natural conditions hence they are appropriate for land management as it requires more understanding of land processes within a catchment (Pullar and Springer, 2000). These models are however problematic in that they are not easy to implement and huge volumes of data are required to represent the variability in the landscape (Pullar and Springer, 2000).

2.2.2.3 Precision of events over time

Hydrological models can also be divided according to the time frame over which the model runs. Pullar and Springer (2000) express that single event models are based on a single rainstorm event and last for the duration of that rainstorm until the runoff drains from the catchment. Continuous time step models are used to calculate results for longer periods like a year (Pullar and Springer, 2000). The application of these models is based on the type of dataset since the single time step may not be accurate for long term modelling and the continuous time step may not be accurate for modelling of single storms (Pullar and Springer, 2000).

2.2.2.4 Conceptual, Empirical or Physical

All models whether lumped or distributed are described as conceptual, empirical, or physical (Silberstein, 2006). This type of classification is based on how the model produces an output from input data. Conceptual or “stocks and flows” models describe hydrologic processes with simple mathematical equations and they are advantageous in that they are easy to solve from a mathematical viewpoint (AghaKouchak, 2009). Nevertheless, the application of conceptual models is tricky in ungauged catchments and requires considerable calibration and optimisation even in gauged catchments (AghaKouchak, 2009).

Empirical or statistical models are dependant on data and are often built up using statistical tools such as regression analysis and neural networks hence they produce rationally good results (Olsson and Pilesjo, 2002; AghaKouchak, 2009). These are normally straightforward since the relationship between input and output is represented as transfer functions (Silberstein, 2006). However, the models are normally not applicable to other areas other than the study area and a change in land use or climate renders them invalid (AghaKouchak, 2009). In addition, it is not easy to directly derive understanding of physical processes from such models. The model developed by the United States Soil Conservation Service (SCS) is a good example of an empirical model for predicting runoff (AghaKouchak, 2009).

On the other hand, physical hydrological models represent physical processes with parameters that can be measured independently, and readily assigned to the appropriate model parameters (Silberstein, 2006). Physical models perform very well in solving small scale problems and require few calibration parameters (AghaKouchak, 2009). The models are however problematic in that they require substantial input data and complex mathematical solving procedures (Coskun and Musaoglu, 2004; Tsheko, 2006; AghaKouchak, 2009).

2.3 Hydrological cycle

Understanding of the hydrological cycle is critical for proper simulation of hydrological processes hence this section explains different components of the hydrological cycle. Water is constantly circulating on and in the ground and atmosphere in different physical states and this circulation is referred to as the hydrological cycle (Olsson and Pilesjo, 2002; Melesse and Graham, 2004). Olsson and Pilesjo, (2002) emphasises that knowledge of hydrological processes is useful in the development and assessment of hydrologic models. These processes include evaporation, precipitation, transpiration, interception, overland flow, subsurface flow infiltration, and percolation (Liu and Zheng, 2004; Kosgei *et al*., 2008).

Water particles on the surface of water bodies and land are evaporated by the solar energy or stored heat (Olsson and Pilesjo, 2002). Evaporation is the change of the state of water from liquid to water vapour and the rate of evaporation depends on the moisture gradient between the surface and the surrounding air (Olsson and Pilesjo, 2002). Loss of water through vegetation is referred to as transpiration and it differs from evaporation in that it is controlled by vegetation. Moist air is held in the atmosphere until it reaches a dew point temperature which is the temperature at which a water droplet is formed and precipitation occurs. Precipitation can be in a form of snow or rain depending on the temperature (Olsson and Pilesjo, 2002).

A portion of precipitation is intercepted by vegetation while some reaches the ground and surface water bodies (Olsson and Pilesjo, 2002). Water which reaches the ground will either infiltrate or flow into streams as overland flow but a larger portion infiltrates into the soil. Overland flow is a result of precipitation intensity exceeding infiltration capacity (Tsheko, 2006). It can also result when saturated soil gives rise to overland flow without precipitation falling on it (Olsson and Pilesjo, 2002). Infiltration takes place till the soil is saturated and cannot hold anymore water. Infiltrated water moves downwards or laterally as subsurface flow and some may be taken up by plants where it may be to be lost back to the atmosphere through the process of transpiration. Subsurface flow may end up in streams while vertically moving water may end up as ground water (Olsson and Pilesjo, 2002). Vertical flow through unsaturated soil is referred to as percolation (Olsson and Pilesjo, 2002; Wahren *et al*., 2009). Both groundwater and surface flow contribute to stream flow which transports the water back to the ocean and completes the hydrological cycle (Olsson and Pilesjo, 2002; Tsheko, 2006). These processes are illustrated in a Figure 2.1.

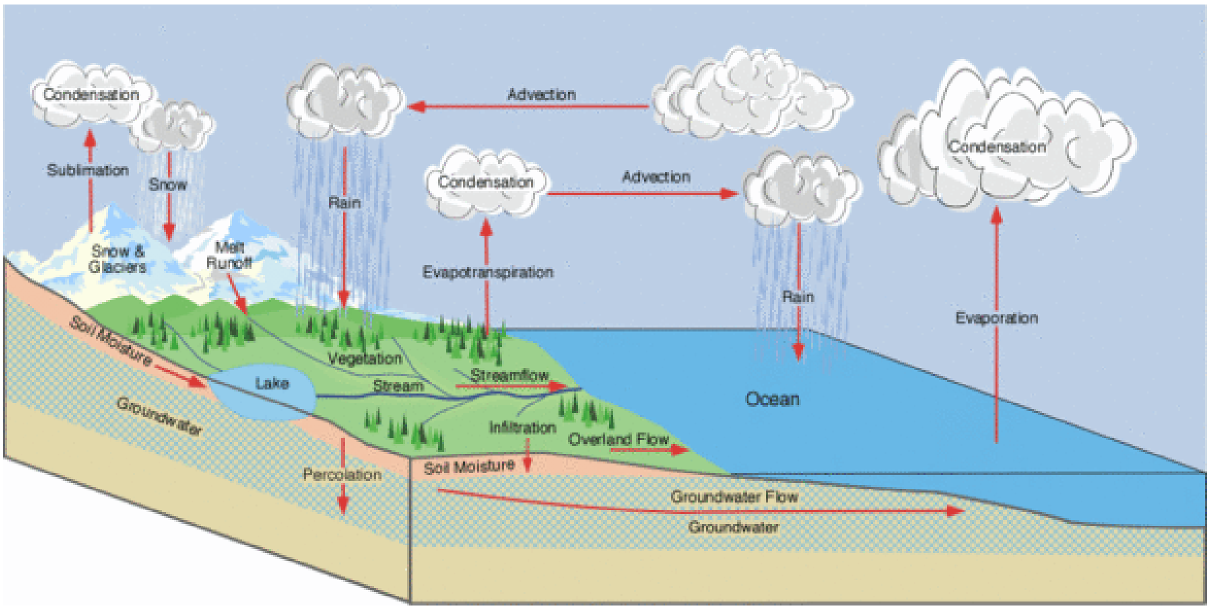

Figure 2.1: A Summary of the Hydrological Cycle (Hubbart *et al*., 2010)

2.4 Geographic Information Systems (GIS)

A Geographic Information System can be described as a system that that displays, stores, analyses, retrieves and generates spatial and attribute data (Melesse *et al*., 2003; Coskun and Masaoglu, 2004). GIS provides tools for management, analysis and display of geographical information and a user is provided with a workflow in which tools can be applied in a meaningful sequence (Aspinall *et al*., 2000).

2.4.1 Coupling of GIS with Environmental Models

Hydrologic modelling is a portion of environmental modelling so it is important to have an understanding of environmental models. The application of models to different aspects of the environment including the socio-economic aspects with the aim of gaining insight to such systems is referred to as environmental modelling (Olsson and Pilesjo, 2002). Analyses of decisions and auditing for specific geographical areas require one to appreciate the spatial variability that is inherent in geographic data (Aspinall *et al*., 2000). Environmental models simulate physical processes over time and provide the results for different options but most models do not examine an issue in a spatial context (Pullar and Springer, 2000). GIS therefore becomes useful as it provides an environment for simulation to be run in a geographical context (Pullar and Springer, 2000).

Coupling of GIS with environmental models can be described as loose, tight or entirely integrated (Aspinall *et al*., 2000; Pullar and Springer, 2000). Loose coupling refers to a relationship in which systems are separate and are only related through file exchange performed by the user (Pullar and Spinger, 2000). In tight coupling, GIS serves as an interface to manage and exchange data to a separate modelling system. Full integration implies that a model is implanted as a component in the host GIS application (Pullar and Springer, 2000). Some authors argue that this coupling reduces the quality of environmental models as they must fit within the temporal and geometrical make up of GIS instead of representing real environmental or socio-economic situations (Aspinall *et al*., 2000).

Apart from the application perspective, GIS can also be viewed from the programming interface perspective. This is unlike the case of environmental models which are designed as complete programmes in which the user has to specify initial inputs and model parameters by which the model is implemented without further interaction (Aspinall *et al*., 2000). Coupling of GIS and environmental models is designed in such a way that environmental models act as additional tools developed from a set of analysis tools that they can be applied in sequential steps recorded as work plans expressed as inputs, analyses and outputs (Aspinall *et al*., 2000).

2.5 GIS in Hydrology

2.5.1 Introduction

The integration of GIS with hydrological modelling was one of the initiatives of relating geographical analysis with modelling using GIS (Sui *et al*., 1999). However hydrological modelling is different from other environmental modelling as it has established standards which are recognised by hydrologists and engineers and the results are from time to time applied in regulatory activities hence it requires special analysis (Sui *et al*., 1999).

Proper water resource management requires a clear understanding of water flow and quality and how these are affected by changes in management practices (Maidment, 2002). Models have been applied in the investigation of impacts of land use change on water quality and quantity but further research has to be done in regards to description of spatial process in integrated models at catchment level (Lorz *et al.*, 2007). Hydrologic simulation models represent water flow and quality for different water bodies while GIS supports hydrologic modelling and analysis by providing a description of the physical environment through which water flows (Maidment, 2002).

According to Smith *et al.* (2004), the introduction of GIS and the improved computer capabilities have dealt with the historical obstacles which faced distributed models in the past. The development of distributed models is inspired by the impact of spatial variability of precipitation and catchment properties on runoff response (Smith *et al.* 2004). It is also inspired by the need to accurately simulate discharge and other information at the outlet and at unsampled locations. Complexity of the model does not increase the accuracy of the simulation as the simple distributed models produces almost the same results as the complex distributed model (Smith *et al*., 2004).

According to Aspinall *et al*., (2000) discharge-area relationships are well established for river basins whose discharge have been measured providing an easy way of approximating discharge for unmeasured sub-catchments. It can also be used to estimate discharge for different areas with large catchment areas and the basis for indicators of deviations from established patterns. Drainage areas for gauge sites can be delimited based on terrain using

GIS hydrological modelling tools. The relationship between precipitation and discharge is used to summarise the input-output components of water balance (Aspinall *et al*., 2000). Lastly, changes in the discharge can be traced to changes in land use.

There are several ways in which GIS can support modelling and they are all based on the definition of GIS being, data management, extraction, visualisation, modelling and development of interfaces as shown in the sections below.

2.5.2 Data management

Most hydrologic models are very complex making it very challenging to set them up manually. The advent of GIS in modelling creates a proper and easy to use interface for the organisation of all inputs required. Hydrological modelling involves many sub-models which must be compatible with a common database as there are many processes within the hydrological cycle (Maidment, 2002). GIS has the capability of combining these complex models which represent hydrological processes taking place at a certain region (Maidment, 2002).

Luzio *et al*., (2005) state that GIS is a helpful tool in hydrologic studies and in the development of distributed models as the majority of hydrological models take advantage of it. The improvements in GIS have allowed handling of large datasets of various land surface characteristics (Jain *et al*., 2004). The Digital elevation model (DEM) enables one to derive geomorphologic parameters such as catchment boundaries and stream network (Luzio *et al*., 2005). Arc GIS interface (ESRI, 2008) is very user-friendly hence it safeguards users from the complexity of GIS and enables them to work on the GIS input data in different formats and properties (Luzio *et al*., 2005).

2.5.3 Data analysis and modelling

GIS is used as a tool in hydrological modelling as it can model and analyse spatially related parameters of the hydrological cycle (Melesse *et al*., 2003). GIS aids in the processing, management and interpretation of model inputs. GIS is also able to integrate Remote Sensing data with other spatial data such rainfall distribution, soil maps and topography (Melesse *et al*., 2003). GIS can be incorporated into hydrological modelling for computation of input parameters for existing models, mapping and display of hydrologic models, representation of watershed surface, and identification of hydrologic response units (Melesse *et al*., 2003). In addition, the capabilities of GIS enable representation of spatially and temporally distributed information such as discharge, flow depth and velocity for all the cells (Jain and Singh, 2005). Hydrological modelling has enabled GIS users to go a step further in data analysis and simulation both for research and policy examination while GIS has assisted hydrologists and engineers in designing and implementing models through data inventory, boundary delimitation and visualisation of results (Sui *et al.*, 1999).

2.5.3.1 Flow direction and Accumulation

On a grid network, four point algorithm (eight directions) ensures connectivity of the cells by establishing flow direction in each cell and from one cell to the other all the way to the outlet (Jain and Singh, 2005). A DEM-based surface runoff model requires that a catchment be represented as a matrix of discretised cells each having eight possible flow directions (Jain and Singh, 2005). Flow direction is determined by choosing the steepest descent among the eight possible directions as shown in Figure 2.2. Flow accumulation is calculated as the weight of the all the pixels draining into a downstream pixel (Santasmita and Paul, 2006). Flow accumulation function incorporated into ArcHydro (ESRI, 2009) extension can be used to derive flow accumulation from a DEM. Computational drainage network can be generated by studying flow accumulation starting from upstream cells to downstream cells determined from DEM analysis (Jain and Singh, 2005).GIS-based Flow direction and accumulation can be used to automatically determine streams based on a specified flow accumulation threshold.

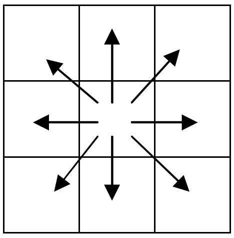

Figure 2.2: Eight possible flow directions in a cell

The flow entering through the corner is considered to enter the downstream cell from its faces converging at the corner of upstream cell. The flow coming from a corner of a square cell is assumed to enter at 45°, and is divided equally between the two faces joining the corner (Jain and Singh, 2005).

2.5.3.2 Catchment Delineation

Catchment boundaries can be used in water-availability, water quality studies, flood forecasting and other engineering and policy applications (Maidment, 2002). Traditionally, catchments were delineated by analysing contour lines on topographic maps in order to locate drainage divides. Arrows would be drawn perpendicular to each contour to represent flow direction based on the steepest descent and a drainage divide would be where the lines diverge (Maidment, 2002). Santasmita and Paul (2006) used the above method for catchment delineation. ArcHydro tools are capable of automatically delineating catchments from DEMs by tracing water flow from cell to cell and identifying all the cells whose drainage flows through the outlet point cell (Maidment, 2002). Automated delineation saves time but manual editing is still required in flat areas with many constructed channels instead of natural drainage channels (Maidment, 2002). The raster grid has made the determination of cell-to-cell flow path easy (Maidment, 2002).

2.5.3.3 Digital Elevation Models

The quality of hydrological modelling in GIS depends on the quality of elevation data. GIS is able to carry out most of the calculations involved in Hydrolgical modelling through the use of Digital Elevation Models (DEMs). A DEM is a type of a Digital Terrain Model (DTM) which is made up of a matrix of cells and the value of each cell corresponds to the elevation at the centre of a point on the earth's surface (Olsson and Pilesjo, 2002). Digital Elevation models have made analysis of topography very easy. Topography is very crucial in distributed hydrological modelling as slope affects flow distribution of both surface and subsurface flow (Olsson and Pilesjo, 2002). Slope also influences the velocity of surface flow. Olsson and Pilesjo, (2002) continues to show that DEMs have made measurement of several hydrological aspects such as flow accumulation and catchment area feasible (Olsson and Pilesjo, 2002).

According to Sui *et al.* (1999) GIS was not integrated into Hydrological modelling until the 1980s when hydrologists required more accurate presentation of terrain. The capabilities of GIS to produce Digital Elevation Models (DEMs) have enabled hydrologists to manage and visualise data in an easier way (Sui *et al.*, 1999). In addition, the procedures and results of GIS-based hydrological modelling are easy to interpret hence, enabling communication with broad groups of stakeholders (Sui *et al.*, 1999).

Digital Elevation Models can either be structured as Triangulated Irregular Networks (TINs), contours, or grids which are the most common structures (Jain *et al*., 2004). Hydrological models together with the capabilities of DTMs provide spatially distributed information about hydrological processes (Jain *et al*., 2004). The grid structure is helpful in the numerical solution of equations governing the rainfall- runoff process (Jain *et al*., 2004).

The resolution of the DEM greatly affects the watershed delineation results which in turn affect some of the subsequent calculations. For instance, coarse DEMs lead to underestimation of the watershed area and a consequent decrease in runoff (Luzio *et al*., 2005). A DEM with high spatial resolution also allows accurate delineation of sub-basins and grids (Moon *et al*., 2004). Other GIS inputs such as land use and land cover also affect simulations depending on the size of a watershed (Luzio *et al*., 2005). There is therefore a need to analyse the accuracy and spatial distribution of inputs and to estimate the resulting uncertainty in the model outputs (Luzio *et al*., 2005). GIS inputs such as land use maps should also be validated by ground surveys during the time of simulation (Luzio *et al*., 2005).

2.5.3.4 ArcHydro

One of the major strides in GIS based hydrological modelling is the development of ArcHydro (ESRI, 2009). This is a geospatial data model that describes hydrological processes and is capable of storing hydrological data in a common understandable structure therefore combination with GIS software capabilities will enhance integration of applications and models (Strassberg *et al*., 2006). Components of surface water systems within ArcHydro include drainage system, hydrography, hydro network and channel system (Strassberg *et al*., 2006). One of the advantages of ArcHydro is that it does not only incorporate the spatial scale but also the temporal scale in both the surface water system and the groundwater system and in between the two systems. Common understanding and characterisation provided by ArcHydro can be used as a common structure for various models, analysis tools and decision support systems (Strassberg *et al*., 2006).

2.5.4 Display

In regard to visualisation, GIS can be used to display data either before the hydrologic analysis is carried out in order to verify the data, or to evaluate the results (Maidment, 2002). GIS can model interfaces through catchment delineation and representation of channel shapes based on DTMs and DEMs. Conventional GIS based models focus on 2-2.5 dimensional representation of subsurface and groundwater systems (Strassberg *et al*., 2006).The capability of ArcHydro to represent 3-dimensional features depends on tools available in ArcGIS (ESRI, 2008). Because of GIS visualisation capability, Sui *et al*., (1999) suggest that the spread of GIS in the society might make hydrological models more transparent and communicative to many stakeholders.

2.6 Surface Runoff Modelling

Modelling of runoff requires proper understanding of runoff processes and factors affecting its occurance. The level of soil moisture at the beginning of rainfall is one of the factors affecting infiltration and the amount of water to be infiltrated during the subsequent storm period (Jain and Singh, 2005). This initial soil moisture saturation is in turn affected by antecedent moisture condition, soil texture and climatic factors such as evapotranspiration rate, and rainfall intensity (Jain and Singh, 2005). Mathematical models which integrate existing knowledge with logical framework are usually used to describe rainfall-runoff processes (Jain and Singh, 2005).

The properties of a catchment such as soil, topography, geology, watershed morphology and land cover are important in determining the amount of rainfall which becomes runoff (Jain and Singh, 2005; Soulsby *et al*., 2006; Winnaar *et al*., 2007) and GIS tools become useful in spatially representing these parameters. GIS is able to facilitate the provision of physical properties for each cell such as land use, topography and soil (Jain and Singh, 2005). These factors not only affect the amount of runoff but flow paths, water storage patterns and residence times (McGlynn *et al*., 2003; Soulsby *et al*., 2006).

2.6.1 Influence of soil on runoff

Soil is the primary regulator of catchment hydrological response due to the fact that it has the ability to absorb, store and release water. This is ability based on the soil pore size which on the other hand is depends on the soil particle size, aggregation and arrangement (Tsheko, 2006) Poorly drained soils with high clay content and a shallow water table usually generate large amounts of runoff unlike well drained soils with low clay content (Winnaar *et al*., 2007). Arid and semi-arid regions often have impervious surfaces or soil crusting leading to Hortonian overland flow instead of surface runoff generated as a result of soil saturation (Lycon et al., 2006 in Winnaar *et al*., 2007).

Soils integrate the influence of topography, climate, vegetation and land use hence they control the partitioning of flow paths, residence time and water storage (Soulsby *et al*., 2006). They are therefore assumed to be the primary determinants of hydrological response units in most catchments where the geology is almost impermeable (Soulsby *et al*., 2006). 'Responsive' soils respond rapidly to precipitation and increase stream runoff through overland or sub-surface flow while 'recharge' soils have a slower vertical drainage to an impermeable surface (Soulsby *et al*., 2006).

2.6.1.1 Hydrological Soil Groups

Soils can be categorized into four groups based on minimum infiltration rate of a bare soil after prolonged wetting. The United States SCS has developed a standard soil classification procedure referred to as Hydrological Soil Groups (HSG) for runoff modelling purposes. Group A consists of sand and aggregated silt with high infiltration rates, while group D refers to soils with low infiltration rate and swell considerably when wet (Gumbo *et al*., 2002). Group B consists of fine to coarse textures soils with moderate infiltration. Group C soils have slow infiltration and are made up of fine textured soils such as clay loam and shallow sandy loam (Vivoni and Sheehan, undated). However, intermediate soils (A/B, B/C, and C/D) can also be in Southern Africa. A description of each group is summarised in Table 2.1.

Table 2.1 Description of Hydrological Soil Groups (LMNO Engineering, Research, and Software, 1999; Gumbo *et al*., 2002)

Soil group	**Texture**	**Storm-flow/runoff potential**	**Final infiltration rate (mm/h)**	**Permeability rate (mm/h)**
A	Sand, loamy sand or sandy loam	Low	25	>7.6
B	Silt loam or loam	Moderately low	13	3.8–7.6
C	Sandy clay loam	Moderately High	6	1.3–3.8
D	Clay loam, silt clay, sandy clay, or clay	High	3	3 <1.3

2.6.2 Influence of Land cover on Runoff

Land cover is another important factor in runoff generation as vegetation affects the amount of water intercepted and subsequently the partitioning of water into infiltration and surface runoff (Winnaar *et al*., 2007). The effect of land cover on runoff generation can be seen through the impact of urbanization since increasing impervious surfaces changes the surface flow paths and the transmission of water into groundwater systems (Barron *et al*., 2009).

Human induced changes on land cover such as deforestation, management of grassland and growth in settlements lead to increased flood generation (Wahren *et al*., 2009)

2.6.3 Influence of Topography on Runoff

Topography also has a great effect on runoff process since it affects among others, flow paths and residence times. As Winnaar *et al*. (2007), indicated slope is an important factor in runoff determination as areas of steep slopes are considered to have high runoff potential. In addition, increased slope usually decreases residence time due to increased gravitational potential but the type soil can cause the inverse to be true if it is well drained 'recharge' soil (Soulsby *et al*., 2006). This was the case with a study focusing on runoff processes, stream water residence times and controlling landscape characteristics in a mesoscale catchment conducted in Scotland by Soulsby and his colleagues (2006). Soulsby *et al*., (2006) found that steep slopes with recharge alluvial soils had more residence times than slopes with similar slope values but different soil types.

2.6.4 Soil Conservation Service Curve Number Method or Natural Resource Conversation Service Curve Number (NRCS-CN)

The Natural Resource Conservation Curve Number method is a runoff estimation technique developed by the United States Department of Agriculture in the 1950s and is normally referred to as the curve number method (Melesse *et al*., 2003). For any rainfall event, some processes have to be satisfied before runoff can take place and the amount of rainfall required for these processes is termed initial abstraction (Melesse *et al*., 2003). These processes include interception, depression storage and infiltration which continues after runoff has begun and increases with increasing rainfall until the maximum retention (Melesse *et al*., 2003). Runoff volume also increases with an increase in rainfall. It is assumed that the ratio of actual retention to maximum retention is equivalent to the ratio of direct runoff to rainfall minus initial abstraction as shown in Equation 2.1 (Melesse *et al*., 2003).

$$\frac{F}{S} = \frac{Q}{P - I} \qquad \text{[Eq 2.1]}$$

Where F is the actual retention after runoff begins in millimetres (mm); S is watershed storage; I is the initial abstraction in mm; and P is total rainfall in mm (Melesse *et al*., 2003).

The actual retention can be expressed as

$$F = (P - I) - Q \qquad \text{[Eq 2.2]}$$

Where Q is runoff while all the other letters retain the meanings indicated above. In this case, I is constituted by interception, depression storage, and infiltration prior to runoff. The empirical relationship between S and I can be expressed as

$$I = 0.2S \qquad \text{[Eq 2.3]}$$

NRCS therefore uses the following rainfall-runoff equation (Equation 2.4):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad (\mathrm{P} > 0.2S) \qquad \text{[Eq 2.4]}$$

S can be related to CN by Equation 2.5:

$$S = \frac{25400}{CN} - 254 \qquad \text{[Eq 2.5]}$$

The curve number is an index expressing runoff response of a catchment to rainfall and is derived based on the relationship of land cover with hydrological soil groups (Winnaar *et al.*, 2007).The land cover refers to cover type, land treatment and hydrologic condition (Winnaar *et al.*, 2007). The curve number value ranges from 1 to 100 and its determination is based on hydrologic soil group, land use and hydrologic conditions (Gumbo *et al.*, 2002; Melesse *et al.*, 2003; Zhan and Huang, 2004). Low curve number value represents low runoff while high curve number value represents high runoff and low infiltration (Melesse *et al.*, 2003; Zhan and Huang, 2004; Winnaar et al., 2007).

The majority of watershed models use curve number method for runoff prediction due to its flexibility and simplicity (Melesse *et al.*, 2003; Zhan and Huang, 2004). The Unite States SCS has developed tables of initial curve number (Appendix A) for different combinations of hydrologic soil groups and land uses (Gumbo *et al.*, 2002) making the calculation of potential runoff easy since these tables are available on the internet and the ArcCN-Runoff tool download package. ArcCN-Runoff tool is an ArcGIS tool designed for catchment-modelling and it is suitable for any polygon shape so as to preserve irregular boundaries (Zhan and

Huang, 2004). GIS enables the user to display and interpret the results of runoff simulation and other hydrological simulations (Pullar and Springer, 2000).

2.7 Dam Site Analysis in GIS

2.7.1 Introduction

International Commission on Large Dams (ICOLD) defines a dam as a barrier across a stream, river, or waterway used to confine and then control the flow of water and the additional structures can include a spillway, outlet works, hydropower plants, and a control facility. There are various purposes for constructing a dam including storage for domestic water supply and irrigation, flood control, recreation, hydropower generation and sedimentation control (ICOLD, 2007). As emphasized by Mwanukuzi (2008), dams are significant water resource management systems as they are used in various regions to regulate and store water for many purposes, the most common one being dependable water supply. The modern dams are usually built for several purposes and therefore referred to as multipurpose dams. These are very cost effective for developing countries since the population is provided with various benefits from one investment (ICOLD, 2007). Multipurpose dam are vital for catchment water resource development (ICOLD, 2007).

Santasmita and Paul (2006) indicate that the selection of a site for a reservoir in inaccessible areas using conventional methods can be difficult, costly and time consuming. It is for this reason that the use of GIS and Remote Sensing should be taken into serious consideration due to their 3-dimensional and spatial capability (Santasmita and Paul, 2006). Application of GIS can reduce the number of potential sites to a handful making further verification manageable (Santasmita and Paul, 2006).

The purpose of a dam is one of the most important factors in deciding on the dam location and size. The criteria for dam site selection should also include socio-economic factors such as distance from croplands and settlements, conveyance costs and gravitation effects (Winnaar *et al*., 2007). Selecting a proper dam site depends on technical, economic as well as environmental considerations (ICOLD, 2007).

The location of dams has previously been based on engineering and economic criteria neglecting the social and environmental considerations. This is no longer acceptable due to increased knowledge of environmental and social concerns which demand equitable sharing of benefits from dam construction (Mwanukuzi, 2008). On the other hand, finding a balance between all the factors of sustainability makes decision making on dam location difficult. Most of the available reservoir planning and decisions tools focus on only physical and engineering aspects not allowing people without much technical understanding to participate fully (Mwanukuzi, 2008). GIS can be used as a decision support tool for dam construction as it is easy for stakeholders to decide on the dam location and size based on different scenarios displayed using GIS (Mwanukuzi, 2008).

The case of Kikunda dam in Tanzania is a good illustration of how stakeholders can be involved in deciding on the dam size. Villagers were engaged through the use of participatory rural appraisal where resource inventory was developed and identified concerns used as criteria for appropriate dam construction (Mwanukuzi, 2008). Representative variables of stakeholders' issues were transformed into maps and each map used as criterion. Each criterion was weighed according to perceived importance by stakeholders while volume was used as a limiting factor (Mwanukuzi, 2008). The volume was determined from a DEM used to outline the land area that would store enough volume of water (Mwanukuzi, 2008). From this study, Kwanukuzi, (2008) concluded that GIS has a great potential in effecting resource allocation decisions. This project is however limited in that stakeholders' concerns were only considered in deciding on dam size and not the location.

2.7.2 Dam height, reservoir capacity and area

Planning a dam requires that storage capacity and inundation area be determined prior to the actual construction process. Dam height is a determinant of both volume and area. The methods of storage capacity estimation include direct reservoir surveys in the case of existing reservoir and indirect methods which normally involve the use of satellite data and topographic maps (Samunyama *et al.*, 2006). Direct field reservoir surveys are labour intensive and time consuming and therefore quite costly. Most of the formulas used to calculate reservoir capacity are based on the general equation,

$$C = K * D * W * T \qquad \text{[Eq 2.6]}$$

where C is reservoir capacity in m^3, D is maximum water depth which is the difference between spillway crest level and the lowest point on the reservoir bed, K is a constant, W is the width at the top of the spillway and T is distance in metres from the dam wall to the point where the river enters the reservoir (Samunyama *et al.*, 2006).

The indirect methods make use of the model relationship illustrated in Equation 2.7.

$$C = aA^b \qquad \text{[Eq 2.7]}$$

Where C is the reservoir capacity in m^3, A represents surface area in m^2 while a and b are calibration constants (Samunyama *et al*., 2006). This can be applied anywhere as long as the error in the results is within the uncertainty of the measured capacity. Millar (2009) calculated reservoir area and volume of the splash dam in the Luckiamute and South Fork Coos Basins, Oregon. The calculations were done in GIS based on a DEM of the dam using Equation 2.8.

$$V = \sum_{i=1}^{n} D_i \times N_i \times A_i \qquad \text{[Eq 2.8]}$$

Where V is the volume, D is the depth (contour elevation – pixel value elevation) and, N is the pixel count at each elevation value, and A is the pixel size (Millar, 2006).

2.8 Case Studies

Winnaar *et al*., (2007) used curve number method to identify potential runoff harvesting sites in the Thukela River Basin, South Africa. Integration and representation of factors affecting runoff such soil, land cover, slope and rainfall were achieved by the use of GIS. Areas with high runoff potential and away from croplands and residential areas were identified to be the most suitable runoff harvesting sites. Eighteen percent of the study area was found to be highly suitable for the location of runoff harvesting systems. This study is different in that the curve numbers were utilised in the determination of runoff potential instead of the actual runoff volume.

Hernández *et al*., (2009) determined the potential runoff of Rio San Pedro sub-basin, Mexico and using the curve number method. GIS and Remote Sensing were used to develop Hydrologic Response Units (HRUs) and to delineate the sub-basin from DEMs. The results showed that the HRUs associated with human activities such as agriculture and built up area contributed to one fifth of the total runoff although they constituted only thirteen percent of the total area and they are within HSG (A) and low relief which is assumed to have high infiltration rates. The second group of HRU which contributed to runoff in the Rio San Pedro sub-basin consisted of forests and the third group constituted wetlands which did not contribute to runoff. Melesse *et al*., 2003 also studied the influence of changes in land cover on runoff and the results revealed that urbanisation increases runoff depth.

Kosgie *et al*., 2008 characterised the dominant field-scale and near-surface hydraulic properties of small holder rainfed agriculture catchments, Potshini catchment, South Africa. The results showed that there is more runoff in areas with conventional tillage than areas with no till since tillage increases the hydraulic conductivity of the soil. Tillage also influences the storage, residence times and lateral flow of water (Kosgei *et al*., 2008)

Coskun and Musaoglu (2004) used Soil Conservation Service Curve Number Method to determine runoff depth of Van Lake basin in Turkey with the aid of Remote Sensing and GIS. Hydrological soils groups derived from soil map of the study area and the land cover classified from Remote Sensing data were used to generate curve numbers. Coskun and Musaoglu concluded that GIS and Remote Sensing can be used in the analysis of runoff depth distribution of a catchment.

Hatzopoulos e*t al*., (undated) used ArcHydro and digital elevation data to identify suitable areas for the location of small dams in the North East part of the Greek Island of Naxos. Digital Terrain Models (DTMs) were created by digitising contours from topographic maps and ArcHydro was used to generate flow direction and accumulation. Runoff volume was calculated for each cell and the storage capacity of the dams computed based on the area and the height of the dam. A total of 107 sites for small dams were identified by the use of GIS techniques.

Santasmita and Paul (2006) utilised GIS to identify the most technically suitable site for a small hydro power station in the Himalayan Region of India. Flow Accumulation and DEM were used to locate sites with suitable elevation and SCS method was used to determine the average monthly runoff of the site. The flow and power generation capacity were also determined. It was concluded that the use of GIS is very cost effective as it can reduce number of sites to a manageable size and these sites can be validated using additional scientific methods.

2.9 Summary

Hydrological models can be described as models which integrate knowledge on hydrologic systems in order to represent different aspects of hydrological cycle. This review has revealed that GIS supports modelling in various ways which are all related to the definition of GIS being a system of data management, analysis, modelling and visualisation. The importance of the ability of GIS to represent terrain in a form of DEMs was also highlighted since most of hydrological calculations such as flow direction and accumulation are based on terrain. The incorporation of spatial variability into hydrological modelling enables automated delineation of hydrological features such as streams and their drainage areas.

It has been found from this review that GIS tools and extensions have proven to make distributed hydrological modelling manageable not only in the definition of flow distribution but also in the simulation of spatially distributed runoff. There are different factors affecting the generation of runoff and these include precipitation, topography, land cover and soil type. GIS manages and analyses these layers of information through the use of tools like ArcCN-Runoff tool which calculates runoff based on curve number method. Curve Number index expresses watershed response to rainfall based on hydrological soil groups and land cover.

It has also been realised that GIS plays an important role in the determination of suitable dam sites and sizes. The purpose of a dam is one of the major determinants of size and location. Previous studies have revealed that identification of a dam site should not only be based on economic and physical aspects but social aspects as well. There are different ways of determining storage capacity but all the methods are based on the relationship between the dam wall dimensions and volume. Simulations can therefore be made using different dam wall heights. It has been seen from this chapter how important GIS is in hydrologic analysis and subsequent decision making.

CHAPTER THREE: MATERAILS AND METHODS

3.1 Introduction

This study is aimed at applying GIS in the determination of flow distribution and accumulation within Phuthiatsane Catchment and to estimate the runoff potential. Below is a description of the study area and the methods used to achieve the objectives of the study through the use of ArcGIS and its extensions ArcHydro and ArcCn-Runoff tool. Datasets required for this study are also described.

3.2 Description of the Study Area

Phuthiatsane South River, which is also known as the Little Caledon River, is a tributary of Caledon River and is located in South Western Lesotho as shown in Figure 3.1. Lesotho is well known for being totally land locked by the Republic South Africa and is located approximately between 28°S and 31°S latitudes and 27° E and 30°E longitudes. The river originates in the highlands but a larger part of its length flows through the foothills and the lowlands (SMEC, 2008). Phuthiatsane drainage basin is normally divided into three sub-basins based on the gauging sites (shown in Figure 3.1), namely Pulane which is the most upstream, Metolong, and Masianokeng which is the most downstream (SMEC, 2008). According to Consulting Engineering Centre (CEC) *et al*., (2003) the main river gauging station is Masianokeng station and the drainage area at this station is 945 km^2. The main channel flows in a south-westerly direction draining the southern part of the catchment (see Figure 3.1).

The terrain of Lesotho is mostly highland with the lowest point being 1400 m AMSL and the highest being 3482 m AMSL (Morake *et al*., 1998). Most of Phuthiatsana catchment area is steep and gets featureless towards the south (CEC *et al*., 2003).

Lesotho is dominated by grassland vegetation but there are some areas with shrubs and forests. There are various land cover types in Lesotho but a large portion of the study area consists of fields for subsistence farming. This is confirmed by SMEC, (2008) which revealed that most of the Metolong households depend on fields. Topographic maps show that there are also a number of settlements in the study area.

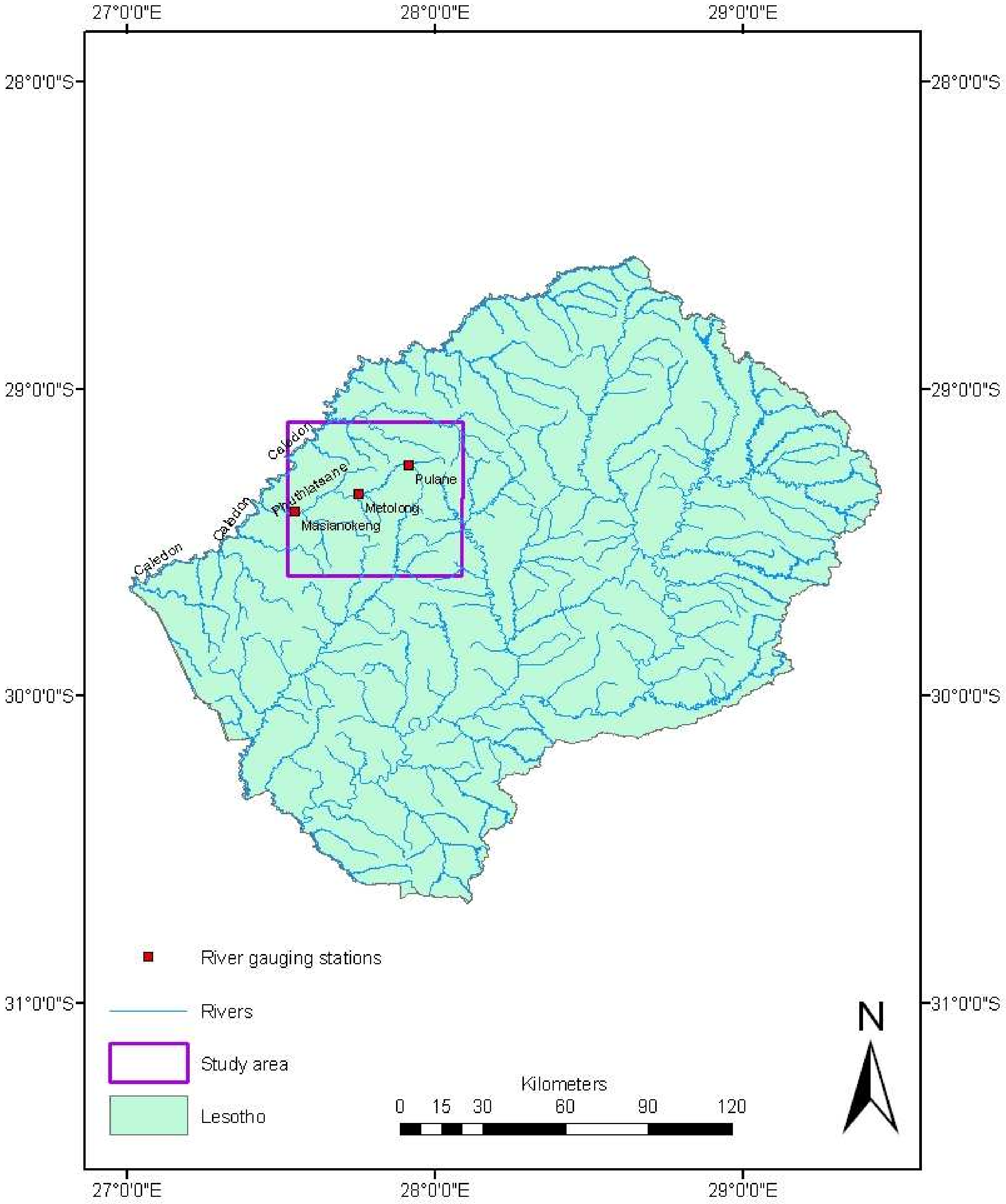

Figure 3.1: Map of Lesotho showing the location of the study area

Sub-humid and temperate climate dominate in Lesotho with warm and rainy summers and cold and dry winters. Lowland temperature ranges from 6.7°C to 21°C while the mean monthly temperature in the highlands ranges from -0.7°C in June to 10.8°C in January (Sabet and Yance, 2000). CEC *et al.*, (2003) show that TY-Phuthiatsane station (see Figure 3.2) is most representative of the study area although it is outside the drainage basin. Mean temperature at this station ranges from 5.9°-6.3°C in June and July to 16.7°C in January.

The rainfall pattern of Lesotho is influenced by the advection of warm moist air from the equator, the orographic effect and the interaction of these two processes (Sabet andYance, 2000). This results in high annual rainfall in the highlands which decreases towards the interior. The Inter-tropical Convergence Zone (ITCZ) causes that annual rainfall to decline more steadily in an easterly direction from the Maluti crest than in a westerly direction from the Drankensberg since the air linked with the ITCZ is more stable approaching from the east than it is from the west (Sabet andYance, 2000). Mean annual rainfall ranges from approximately 500 mm to above 1200 mm. In general, Lesotho experiences an average of 780 mm annual rainfall of which 88% of it falls between September and April while snow covers a good portion of the highlands in winter (Sabet andYance, 2000). The average annual rainfall at the study area is 890 mm (CEC *et al.*, 2003).

Humidity is one of the factors affecting evapotranspiration and it varies from 28% in October to 47% in February and December. CEC *et al.*, (2003) calculated the potential evapotranspiration (ET_o) at the study area using Penman-Monteith Equation and found the mean annual ET_o of 1,251 mm/yr. The average pan evaporation at the study area is approximately 2000 mm/yr (CEC *et al.*, 2003).

3.3 Datasets

Monthly Rainfall data for five rainfall stations (see Figure 3.2) in the study area was obtained from the National Meteorology Services of Lesotho. The majority of the provided rainfall records went as far back early as the 1970s except for TY-Phuthiatsane Station whose records have been documented since 1945. There are however no records for Thaba-Putsoa, Moletsane and Molimo-Nthuse stations from 2004 to present. A summary of rainfall data is provided in Appendix D.

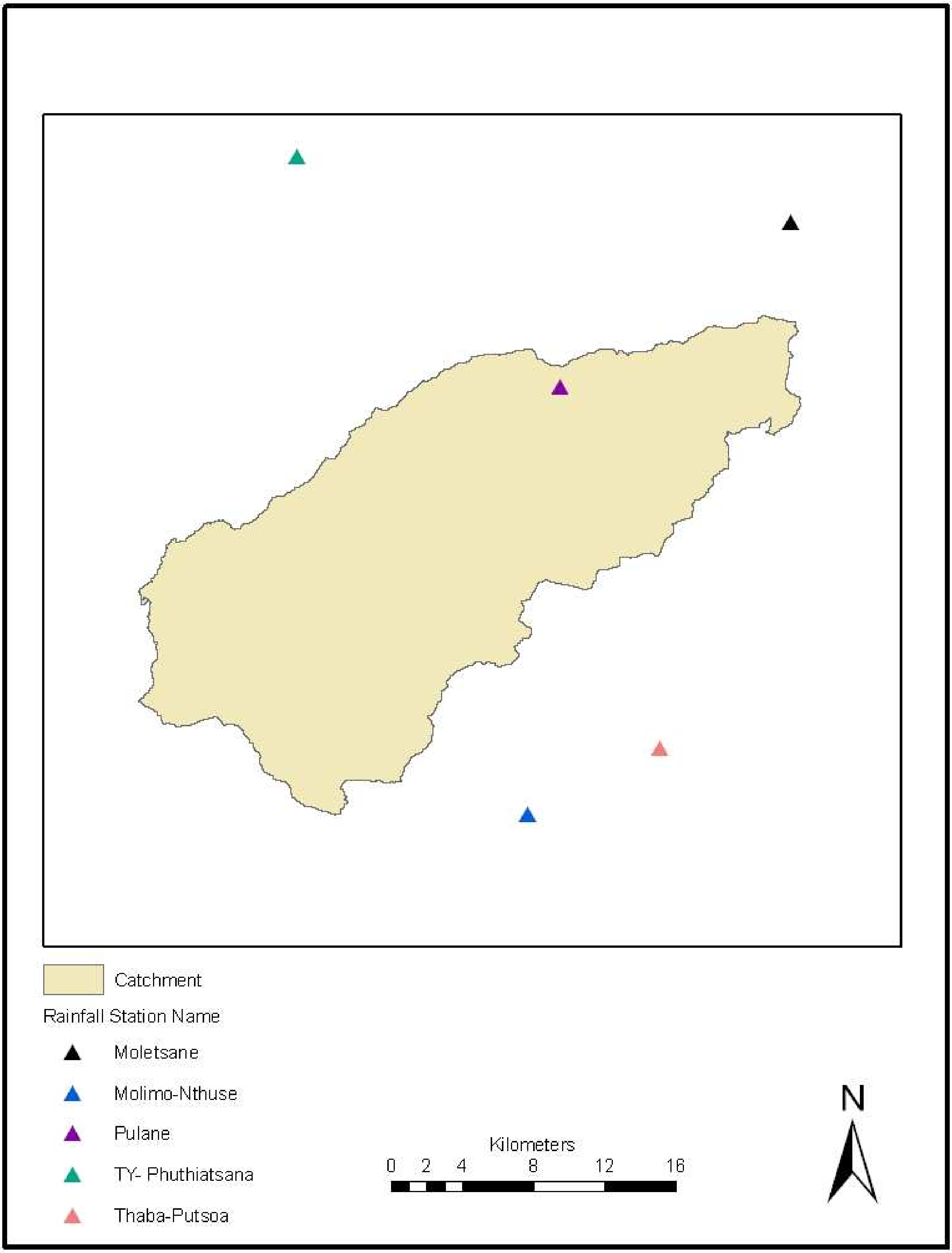

Figure 3.2: Distribution of rainfall stations over the study area

A 30m by 30m DEM of Lesotho was downloaded from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), 2009 website. ASTER is a joint observation project between the United States and Japan headed by the United States National Aeronautics and Space Administration (NASA). Earth Remote Sensing Data Analysis (ERSDAC) is Responsible for the distribution of ASTER data.

The topographic maps with a scale of 1:50 000 were obtained from the Department of Land, Surveys and Physical Planning (LSPP) of the Government of Lesotho. Both soil type and land cover maps (Appendices B and C) were obtained from the Lesotho Ministry of Natural Resources, Department of Forestry and Land Reclamation. The soil type of the provided map is based on FAO classification. All the datasets required for this study were reprojected using World Geodetic System (WGS) 1984. The original projection of a topographic maps and soil type maps was Transverse Mercator Clarke 1880 (Modified).

3.4 Methods

This section describes the methods undertaken in order to achieve the objectives of the study. It also describes how the different tools and functions used in the procedures work. All the datasets in this study were clipped according to the study area in order to reduce the processing time in ArcGIS. The boundaries of the study area were visually determined by looking at the highest elevation points around Phuthiatsane area since these high elevation points were probable to be catchment boundaries. The study area was also digitized in such a way that it included the five rainfall stations that are within the vicinity of Phuthiatsane catchment. ArcHydro tools (ESRI, 2009) were used to derive flow direction, flow accumulation and stream definition grids from a DEM and to subsequently delineate the catchment. The amount of runoff generated within Phuthiatsane catchment was then calculated based on the United States SCS method and the results overlaid with slope map to determine the final runoff potential. Finally, storage capacities and reservoir areas were determined for various dam wall heights at three different sites. The most suitable dam site and size were determined based on the storage capacity and the impact of the reservoir on land cover.

3.4.1 DEM Manipulation

According to Vassilopoulou *et al.*, (2002) a DEM provides a 3D presentation of terrain for maps and GIS databases for various applications and it is also a base for the production of different maps such as 3D maps and slope maps. Spatially distributed models require substantial topographic information hence the use of digital elevation model is very fundamental (Olsson and Pilesjo, 2002). It is for this reason that its accuracy is very critical and key to accurate hydrologic modelling.

Six DEM tiles of Lesotho were downloaded and the two tiles covering the study area were mosaiced together using the merge function of map algebra under Spatial Analyst Tools (ESRI, 2008). ArcHydro extension was downloaded from ESRI, (2009) website and used for large part of this research including determination of flow direction, flow accumulation and watershed delineation. ArcHydro tools have the capability of conceptually connecting the hydrologic elements required for model (Robayo and Maidment, 2005). Pits or sinks are errors in a DEM and they were evaluated and filled using Sink Evaluation and Fill Sinks commands under terrain processing module of ArcHydro. Part of accuracy assessment was carried out by creating contours from the DEM and comparing them with the 30m contour on the topographic maps of the study area. Topographic maps' projection was redefined by importing the projection WGS 1984 projection from a DEM. Subsequent hydrological analysis was then carried out using this DEM.

3.4.2 Determination of Flow Direction and Accumulation

Determination of flow distribution is based on the following principles. The first principle states that a drainage channel starts from close neighbourhood peaks. The second one suggests that the flow of water follows one or more directions of downhill slope. Thirdly, it is assumed that streams do not cross each other and lastly, water will flow until it reaches a sink or an outlet (Olsson and Pilesjo, 2002). The direction is calculated by determining the steepest descent from each cell to the surrounding eight cells (Jain *et al.*, 2004; Djokic, 2008). This is referred to as the D8 method (Djoki, 2009). Flow Direction function under terrain processing of ArcHydro was utilised to produce flow direction grid in Figure 3.3. This flow direction grid defines the direction of a water droplet from the time it reaches the ground to the time it exits the catchment or it gets caught up in a sink (Djokic, 2008). Flow direction in Figure 3.3 has only eight values which means the sinks in the DEM were successfully filled

(Djokic, 2008). Flow direction grid was used as an input in the determination of flow accumulation.

Flow accumulation is the number of upstream cells which drain through a certain cell (Maidment 2002; Santasmita and Paul 2006; Djokic, 2008). Flow accumulation grid in Figure 3.4 can be used to delineate sub-basins and subsequently the whole watershed (Gumbo *et al.*, 2002). Flow accumulation operation which is also under Terrain Processing module was used to calculate flow accumulation. The function calculates Flow accumulation as the weight of the all the cells draining into a cell (Santasmita and Paul, 2006).

Flow accumulation grid in Figure 3.4 illustrates the number of pixels which drain into a given pixel based on flow direction. The flow accumulation in the area ranged from 0 to 1236644 cells. As expected, pixels with low elevation seemed to have more flow accumulation than pixels with high elevation.

3.4.3 Stream definition

The purpose of stream is to identify cells which are drainage lines (Djokic, 2008). As indicated by Jain and Singh, (2005) stream network can be identified by tracing flow accumulation from upstream cells to downstream cells. Flow accumulation grid (Figure 3.4) was used as an input in defining the streams and a threshold of 1200 cells (≈1% of maximum flow accumulation) was specified for this purpose (Djokic, 2008). A threshold in this case refers to the number of cells that have to flow into a cell for it to be identified as a stream and it has to be 1% of the maximum flow accumulation (Djokic, 2008). Stream definition function identifies cells whose flow accumulation is above the specified threshold as streams (Djokic, 2008).This number was varied until the streams on the stream definition grid matched the ones on the topographic maps in order to avoid over generalization of streams. Stream definition function is also found under terrain processing module of ArcHydro (ESRI, 2009).

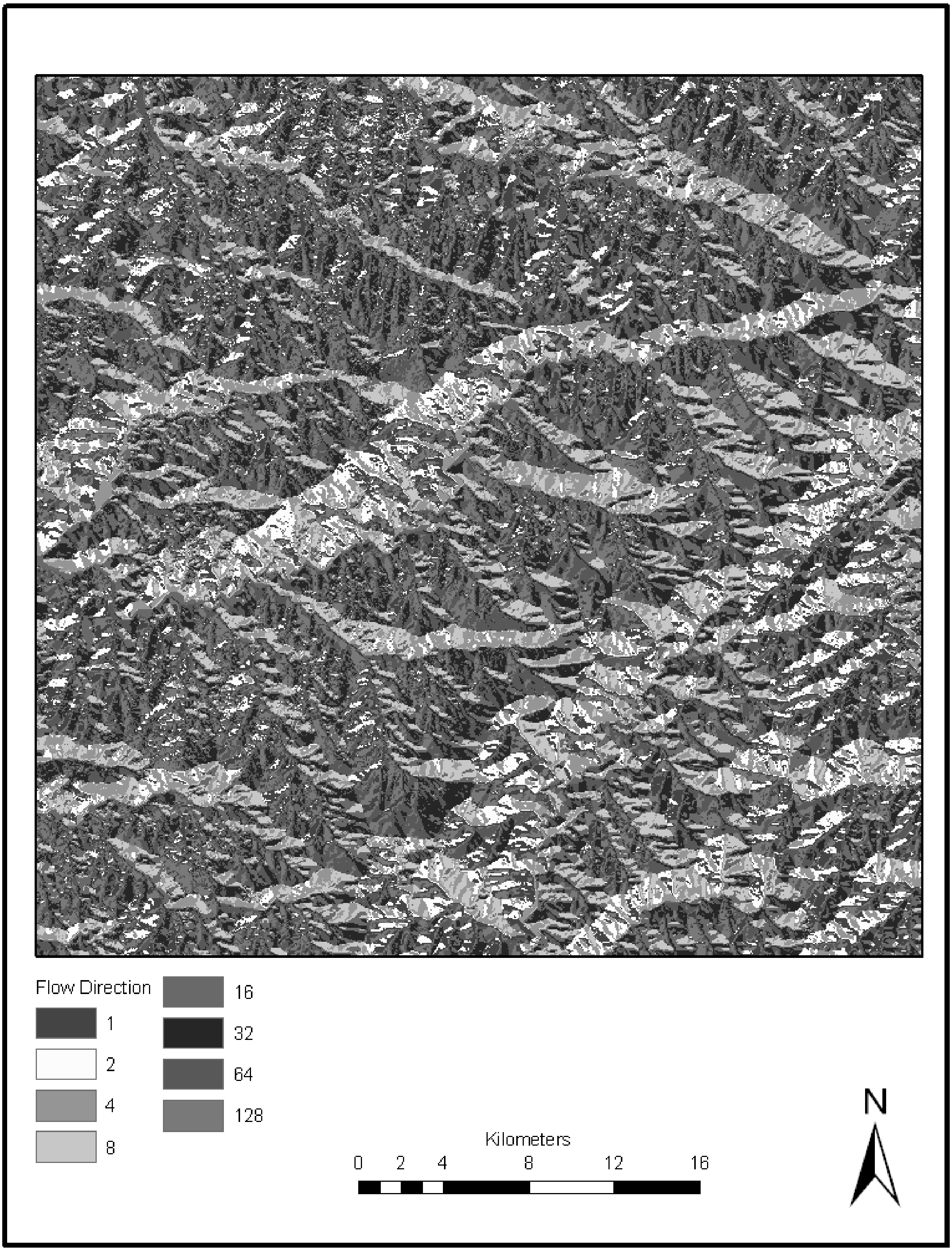

Figure 3.3: Flow direction grid of the study area showing the eight possible directions a drop of water can follow when it reaches the ground surface

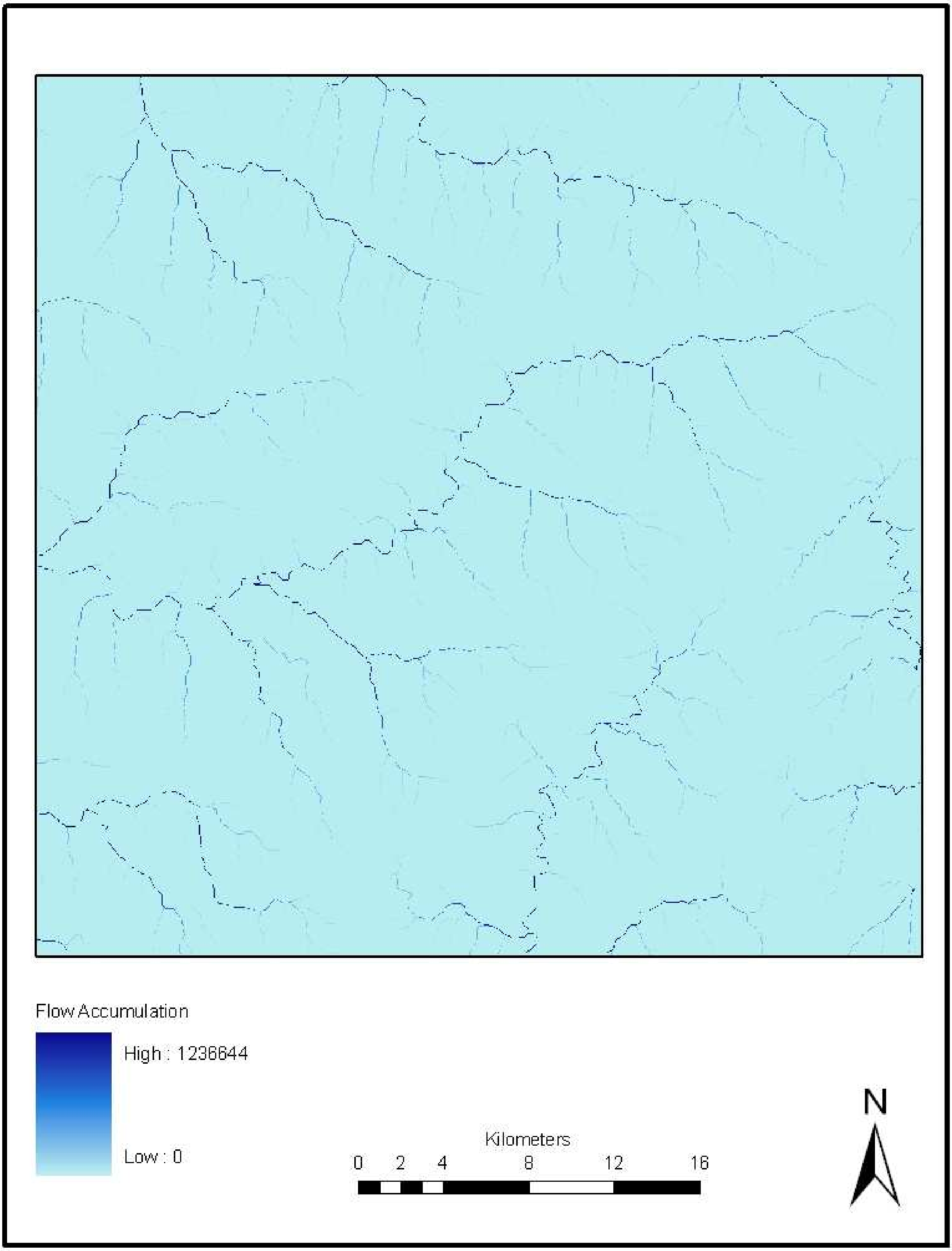

Figure 3.4: Flow accumulation grid of the study area

3.4.4 Delineation of the Catchment

The catchment was delineated based on a DEM using ArcHydro tools (Aspinall et al., 2000; Luzio et al., 2005) .The batch watershed delineation tool under watershed processing was used to delineate the watershed from flow accumulation grid (Gumbo *et al*., 2002). This function requires a number of inputs like flow direction, catchment, adjoint catchment, batch points and stream grid. Both catchment polygons and adjoint catchment were generated using Terrain Processing module while batch points were created using the batch point generation button. The batch watershed delineation function traces water flow from cell to cell and identifies all the cells whose drainage flows through the outlet cell (Maidment, 2002).

3.4.5 Rainfall Data Processing

Mean annual rainfall was calculated for each station (see Appendix D) in Microsoft Excel and the results imported into ArcMap (ESRI, 2008). An event theme of rainfall was created in ArcMap (ESRI, 2008) in order to show their distribution over the study area (see Figure 3.2). An average amount of annual rainfall from the five rainfall stations was calculated and then used in the computation of runoff.

3.4.6 Calculation of Runoff Potential

Computation of runoff response to rainfall can be achieved by the use of GIS and its extensions since they are able to integrate input parameters such as slope, soil and land cover (Melesse *et al*., 2003). This section describes the computation of curve numbers, runoff volume, slope and the final runoff potential.

3.4.6.1 Curve number determination and runoff calculation

Curve numbers were determined using HSG and land cover information (Winnaar *et al*., 2007). Soil and land cover maps shown in appendices B and C were reprojected by importing Aster GDEM projection which is WGS 1984. Soil and land cover datasets were then clipped using the study area polygon so as to reduce the processing time. Hydrologic soil group (HSG) of each soil type within the study area was determined based on literature and the textural and infiltration properties of each type. A field was then added in soils' attribute table in order to incorporate the established HSG.

ArcCN-Runoff tool (Zhang and Huang, 2004) was loaded as .dll file into ArcGIS 9.3 (ESRI, 2008) and data processing continued as follows: Land cover and soils were then intersected using the ArcCN-Runoff tool based on 'class description' in land cover and 'hydrogroup' field in soils attribute table to produce the 'landsoil' layer. The 'landsoil' layer was used as an input in ArcCN-Runoff tool for the development of curve numbers and an average annual precipitation of 855 mm used for the calculation of the resulting runoff. This tool calculates runoff based on the SCS method (Equations 2.4 and 2.5). This keeps spatial variability of soil and land cover hence it is considered to be accurate than using raster grid to calculate runoff or any other dominant or average method to determine curve number (Zhang and Huang, 2004).

3.4.6.2 Calculation of slope and final runoff potential

Spatial analyst (ESRI, 2008) was used to calculate slope in percentage and the output was reclassified into five groups to produce the slope map in Figure 3.5. Steep slopes are represented with ranges of high values like 39 – 219 % and gentle slopes are represented with low values. The output was then overlaid with runoff volume calculated using ArcCN-Runoff tool to determine the overall runoff potential. Areas with steep slopes and high runoff volume were considered to have high runoff potential (Winnaar *et al*., 2007).

3.4.7 Determination of Suitable Dam Sites

The current dam wall dam proposed by CEC *et al*., (2003) is approximately 73 m high and is located at 27°46′34.9″ E 29°209.2″ S. This site was used as the first site in the analysis and two other alternative sites were selected at an approximate interval of 5 km downstream (see Figure 3.6). There are thousands of potential dam sites along the river channel hence 5 km interval was used for simplicity. The alternative sites were located downstream since there would be more negative impacts upstream of the currently proposed site since there are more farmlands. Polygon shapefiles for different dam wall heights were first created in ArcCatalog and projected using WGS 1984. These shapefiles were then added to Arc Map for subsequent analysis.

Contours created at an interval of 10m from an Extracted DEM using contours tool of spatial analyst (ESRI, 2008). The lowest point in terms of elevation was identified at each site and a required dam wall height added to that elevation value in order to identify the contour at which to create the reservoir polygon (Milllar, 2006). For example, the lowest point at site

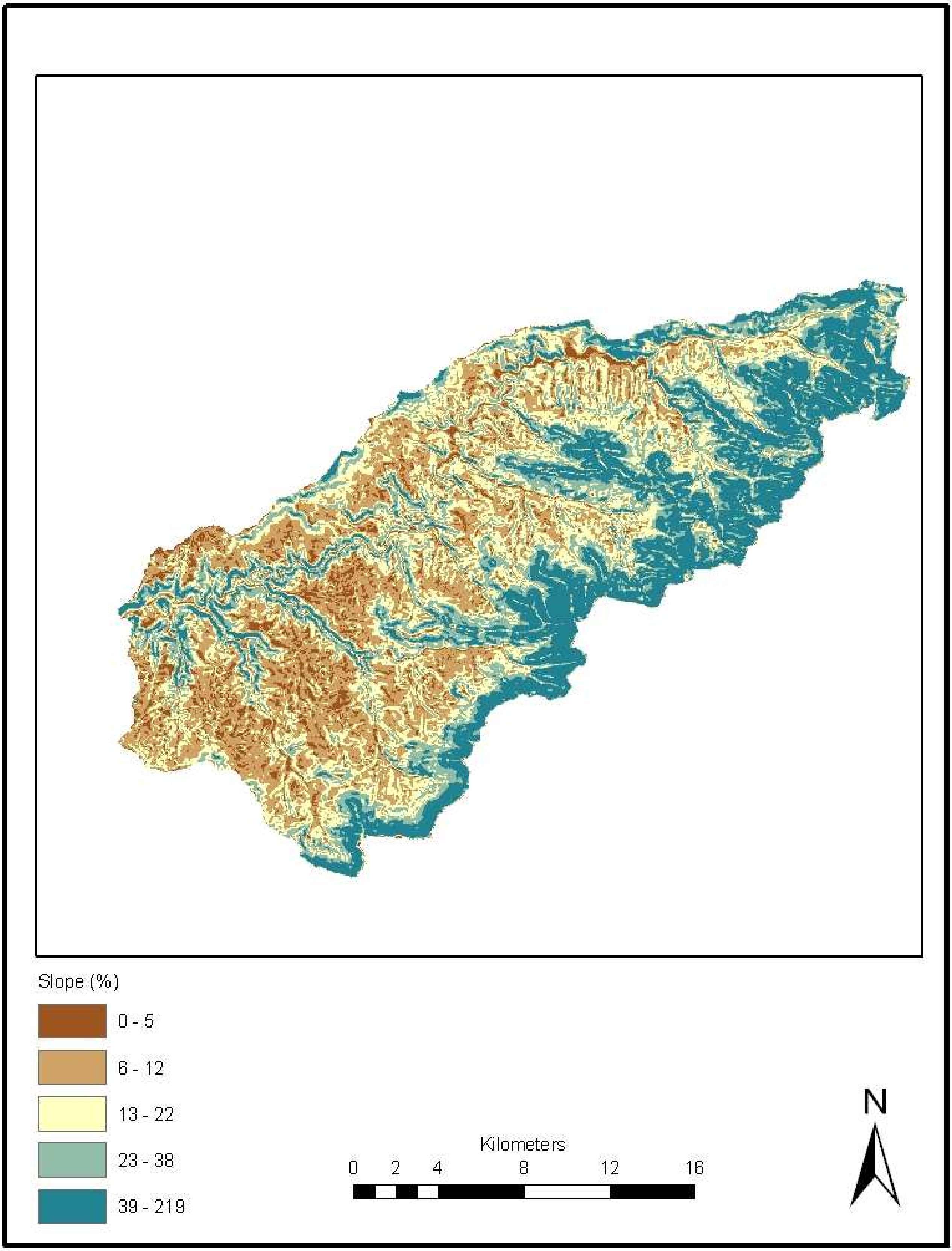

Figure 3.5: Slope % of Phuthiatsane Catchment represented in five classes

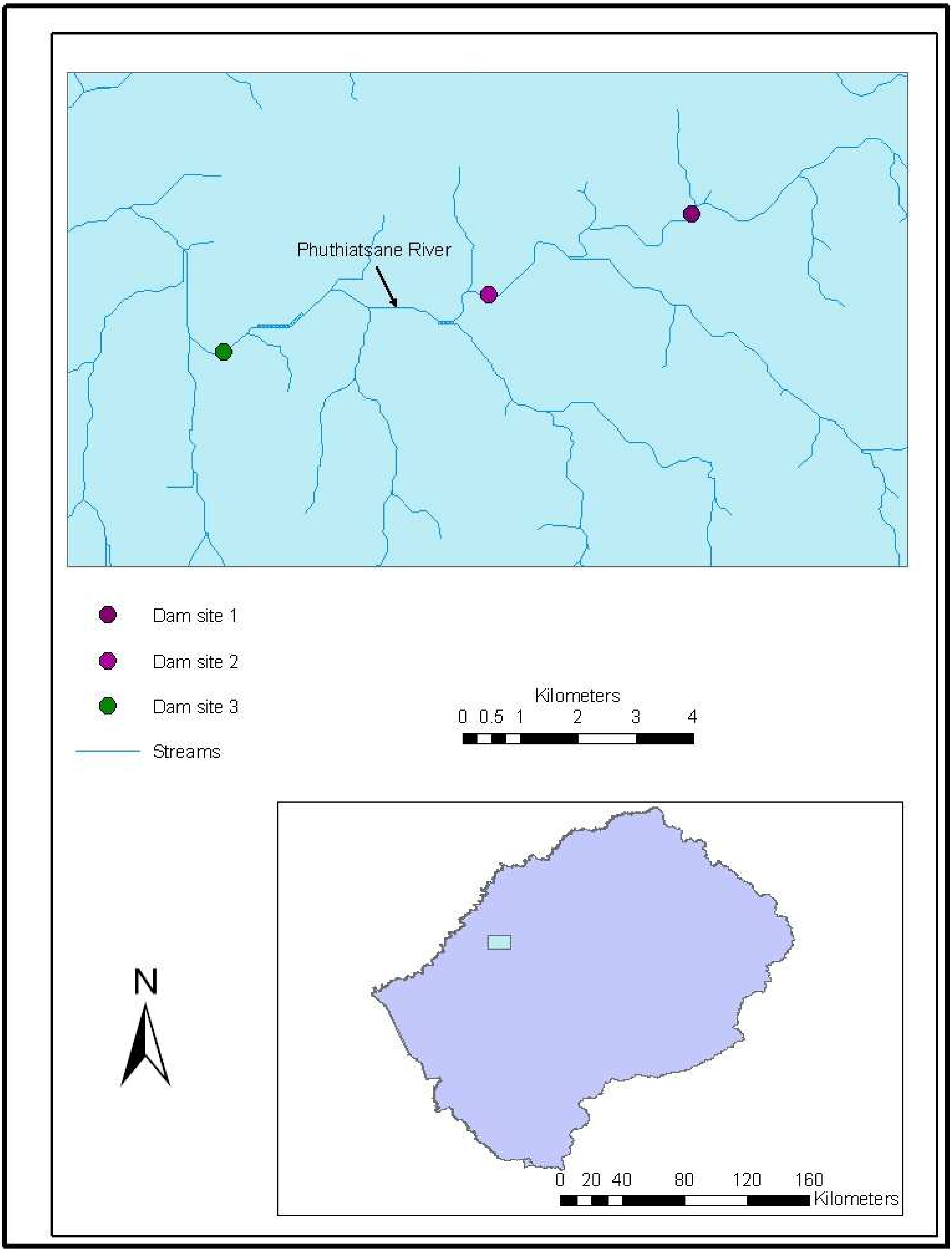

Figure 3.6: Location of the three potential dam sites relative to the map of Lesotho

one was 1620 m and 1620 m + 30 m = 1650 m hence 1650 m contour was traced upstream from dam site and back to dam site so as to create 30m dam polygon and to determine the possible area of flooding. Trace tool of ArcEditor was used for this purpose. This procedure was carried out for 30 m, 50 m, 70 m, and 90 m at all the three sites.

Reservoir capacities and surface areas were determined at each of the three sites based on the dam wall heights of 30 m, 50 m, 70 m and 90 m. Extract by Mask tool of Spatial Analyst Tools was employed to extract a DEM using the reservoir polygons created from the contours since it was easier and more accurate to perform calculations based on the DEM (Millar, 2009). The field calculator was utilised to calculate volume from each DEM based on Millar, (2009) method (see Equation 2.8). This method is also based on the general relationship between dam wall height and volume described in section 2.72 of the literature review. The procedure for calculation of volume and area were undertaken for 30m, 50m, 70m, and 90m dams at all the three selected sites.

Each reservoir polygon was used to clip the land cover Shapefile in order to determine the area of each land cover enclosed by the reservoir. The ‘Calculate Geometry’ function of ArcGIS 9.3 (ESRI, 2008) was used to calculate the area of land cover that would be submerged by each reservoir at different dam wall heights (Millar, 2006). The best dam site was selected based on the dam that would store a significant volume of water with fewer impacts on the environment.

The above methods are summarised in a flow chart illustrated in Figure 3.7.

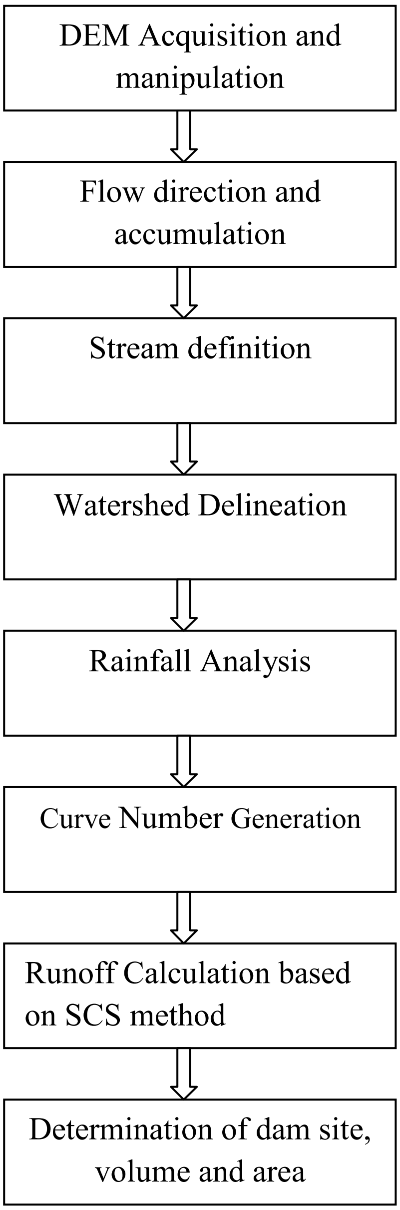

Figure 3.7: Flow diagram showing the steps followed in the study

CHAPTER FOUR: RESULTS AND DISCUSSIONS

This chapter provides the findings of this study, their interpretation and discussions based on the literature review. It is divided into several sections based on the main objectives of the study. A summary of findings is then presented at end of the chapter.

4.1 Flow Distribution

This section focuses on the findings of the determination of flow distribution. The results of accuracy assessment for the obtained findings are also shown.

4.1.1 Digital elevation Model

The quality of hydrologic simulations and calculations is based on the accurate representation of terrain (Olsson and Pilesjo, 2002). Figure 4.1 shows the DEM of the study area in a form of a grid in which every pixel value represents elevation. It can be seen from this DEM that the elevation of the study area ranges from 1460 m AMSL to 2985 m AMSL with the darkest shade representing the lowest elevation and the bright shade representing high elevation. The grid form of a DEM shows how the visualisation capability of GIS can ease hydrologic analysis since one can almost identify catchment boundaries by looking at the highest elevation points.

Hernández *et a*l. (2009), state that a DEM should be accurate enough to capture topographic features that affect the channel patterns. This DEM was accurate since the contour lines generated matched the ones on the topographic maps (Figure 4.2). Figure 4.2 illustrates the contour lines generated from a DEM in comparison with contour lines on a topographic map. The contour lines on the topographic map are symbolised with brown lines and the map is zoomed in order make the contrast between the two sets of contours clear. The offset in some areas was caused by different contour intervals in the topographic map as some sheets had 25 m interval while others had 30 m interval.

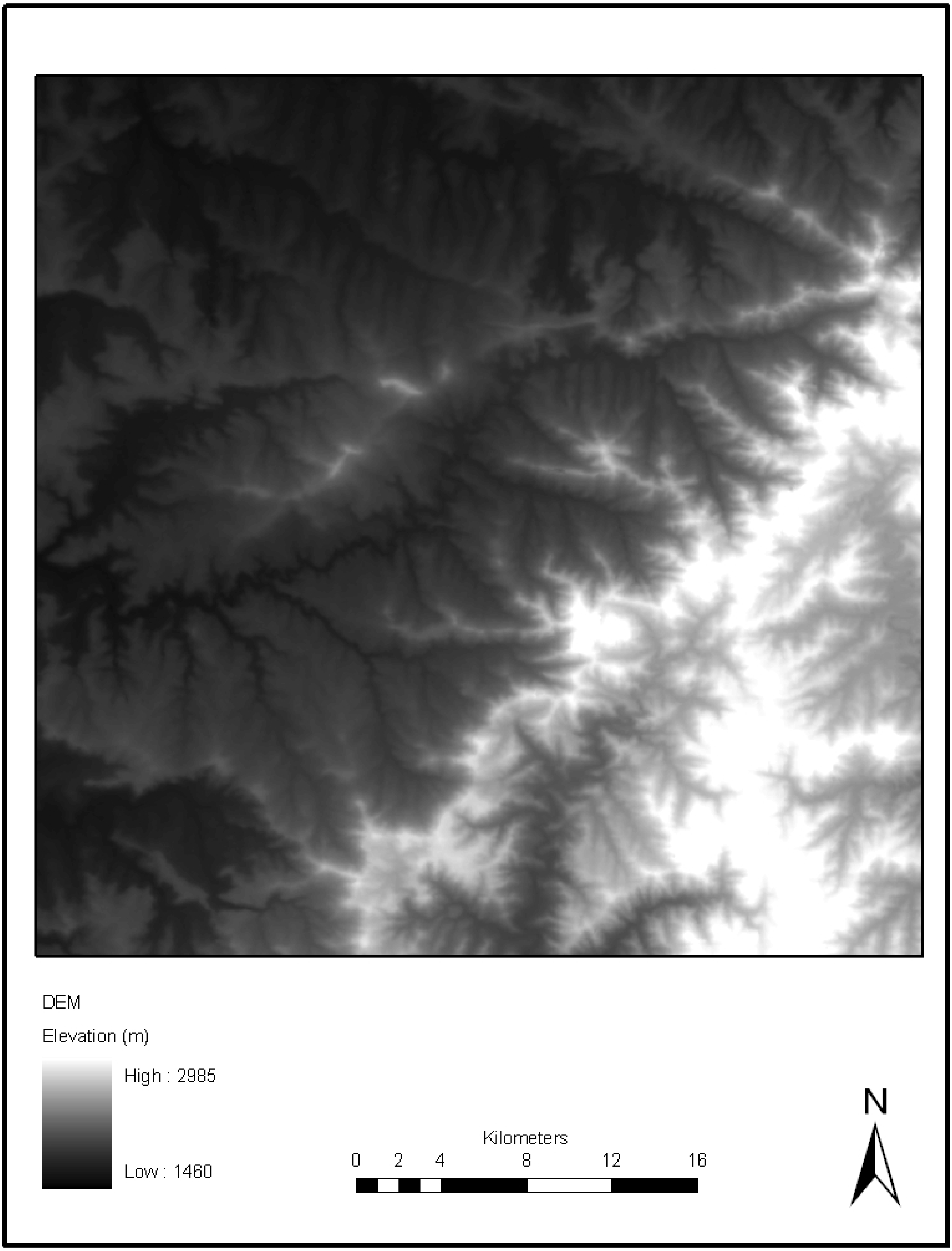

Figure 4.1: A Digital Elevation Model of the study area

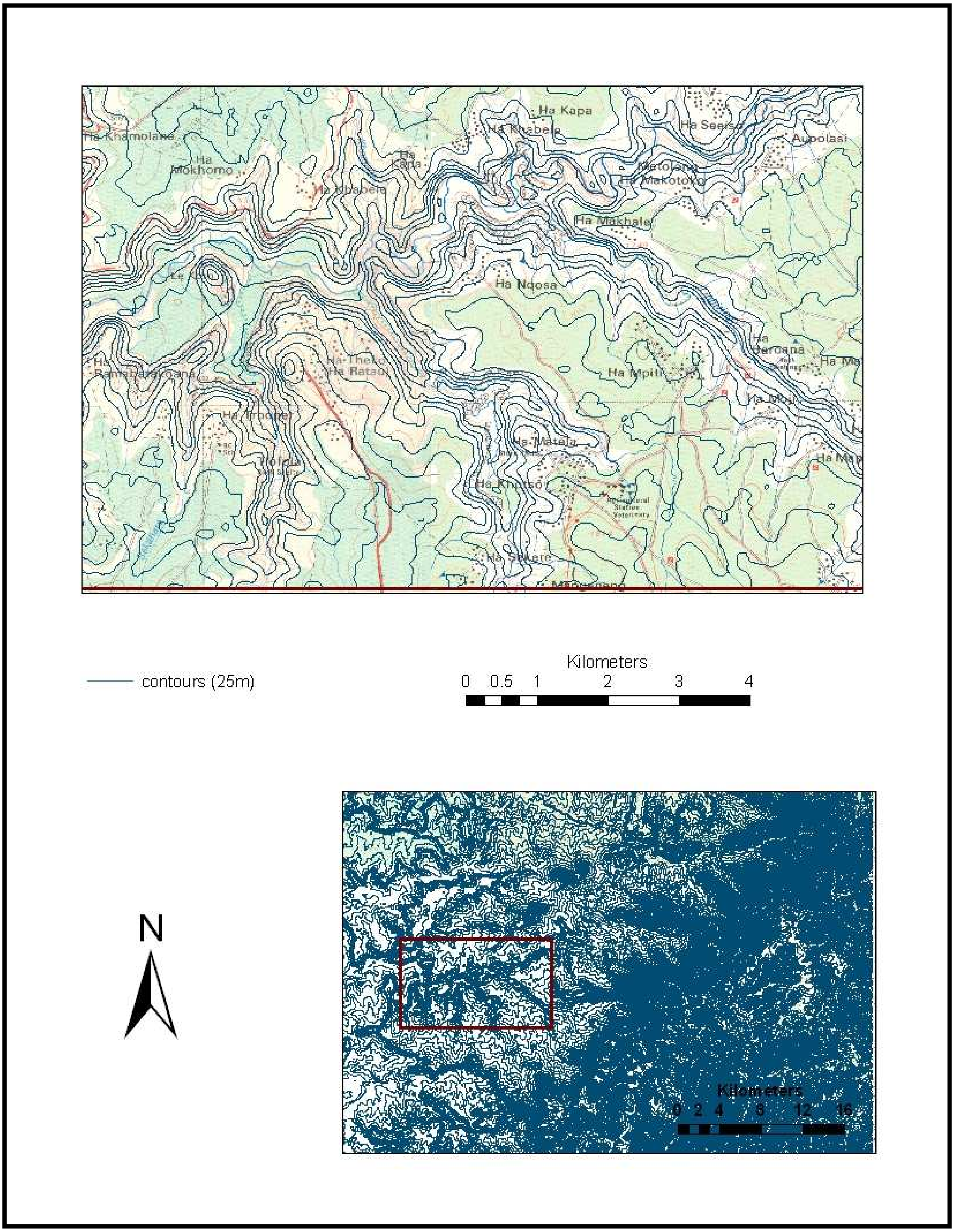

Figure 4.2: Contour lines generated from a DEM at an interval of 25m in comparison with topographic map contour lines

4.1.2 Stream Definition

Automated Stream definition by ArcHydro produced the streams shown in Figure 4.3. The streams were successfully defined and converted to vector. The ArcHydro method of stream definition is reasonably accurate since most of the main streams were successfully delineated. Automated streams usually do not match with mapped drainage patterns in flat areas (Hernández et al., 2009) since pixels with same elevation can have almost the same amount of flow accumulation. This problem was not encountered in this study since the area is dominated by hilly terrain hence there was no confusion in the identification of drainage patterns.

The shape and location of the delineated streams matched the known streams of the study area (Figure 4.4). The known streams were clipped from the South African Rivers shapefile which only shows the major rivers hence, the smaller streams which appear on the delineated streams do not appear on the known streams (Figure 4.4). The known streams are symbolised in dark blue in Figure 4.4 while the delineated streams are symbolised in light blue. The angle and points at which tributaries join the main channel is the same in both defined streams and known streams. The match between the delineated streams and the known streams further verifies the accuracy of the DEM.

4.2 Delineated Catchment

Phuthiatsane Catchment was also successfully delineated using dam site three as an outlet since site three is the furthest site downstream (see Figure 3.6). The delineation of catchment produced an irregularly shaped basin illustrated in Figure 4.6. A DEM is used as a backdrop and it shows that the catchment boundaries were delineated at the highest points defining the drainage divide (Maidment, 2002).

The size of the delineated Phuthiatsane catchment is 468 km^2. This Catchment encloses the entire area covered by Pulane and Metolong sub-catchments and a part of Masianokeng sub-catchment up to approximately 10 km along the river channel. According to the Lesotho Ministry of Natural Resources Water Commission (2010), Pulane has a catchment area of 98 km^2 while Metolong has a catchment area of 250 km^2 making a total of 348 km^2. The remaining 120 km^2 (468 km^2 – 348 km^2) of the delineated catchment area is part of Masianokeng sub-catchment. The rest of Masianokeng sub-catchment is not part of the

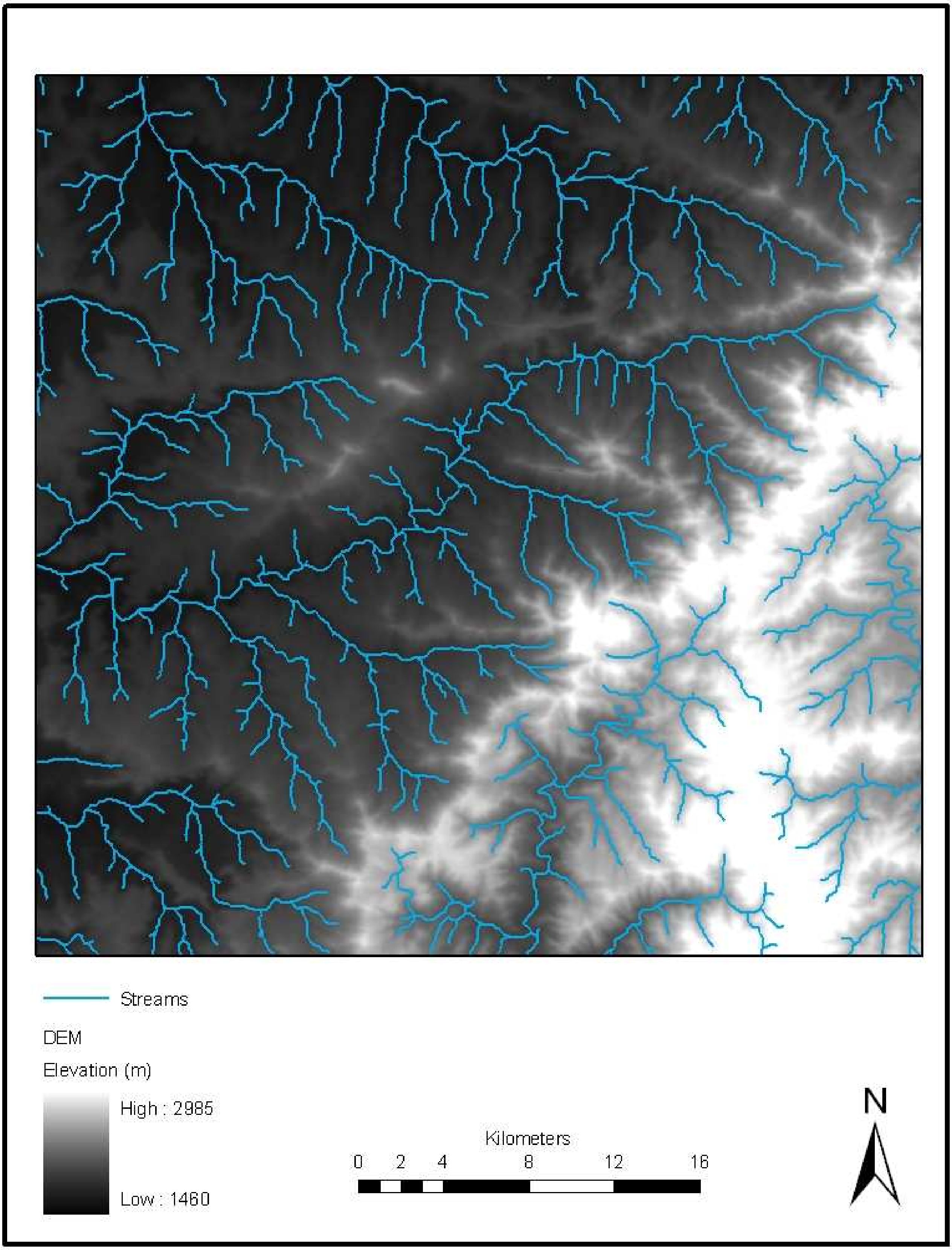

Figure 4.3: Vectorised streams from automated stream definition on a DEM backdrop

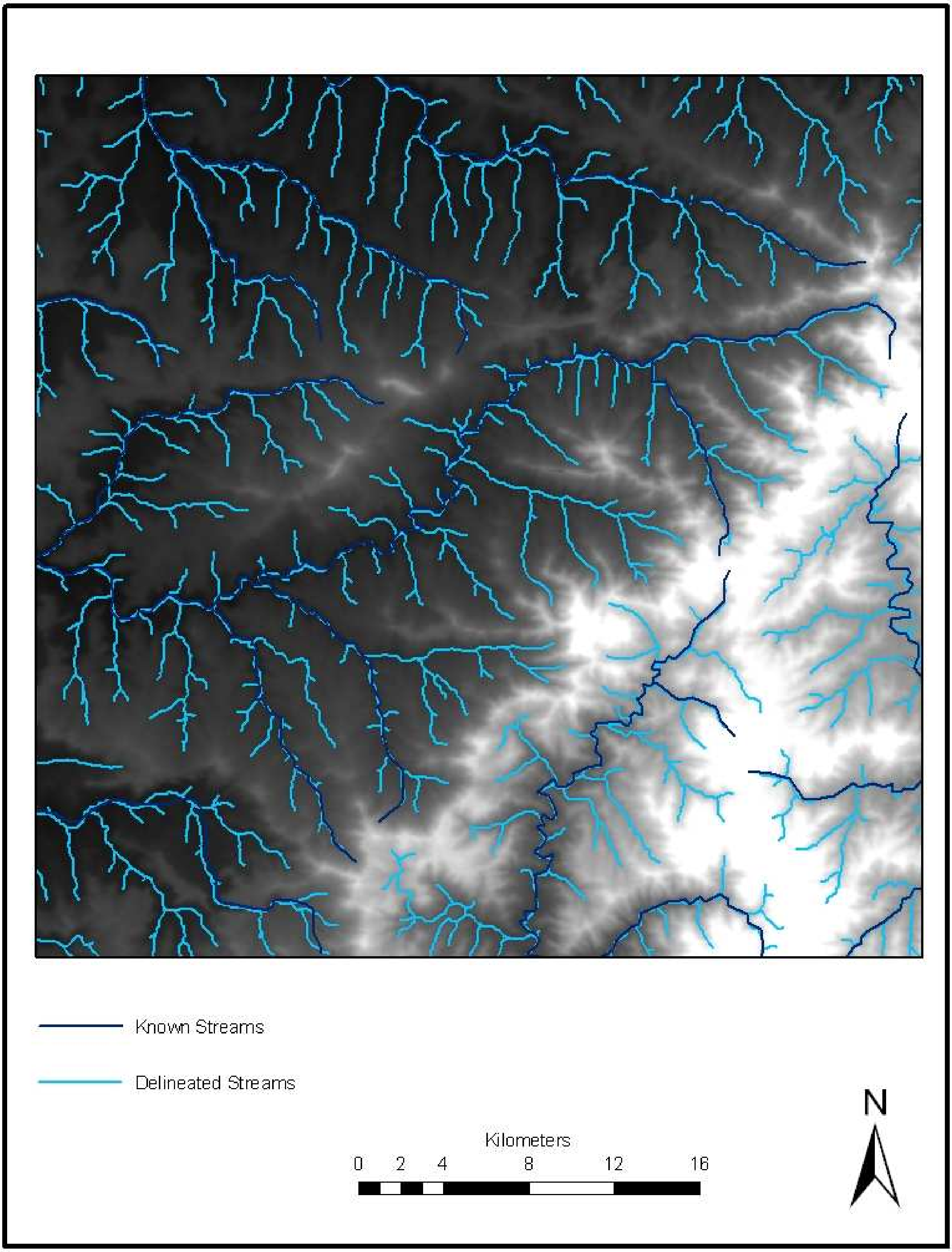

Figure 4.4: Automatically defined streams compared to known streams

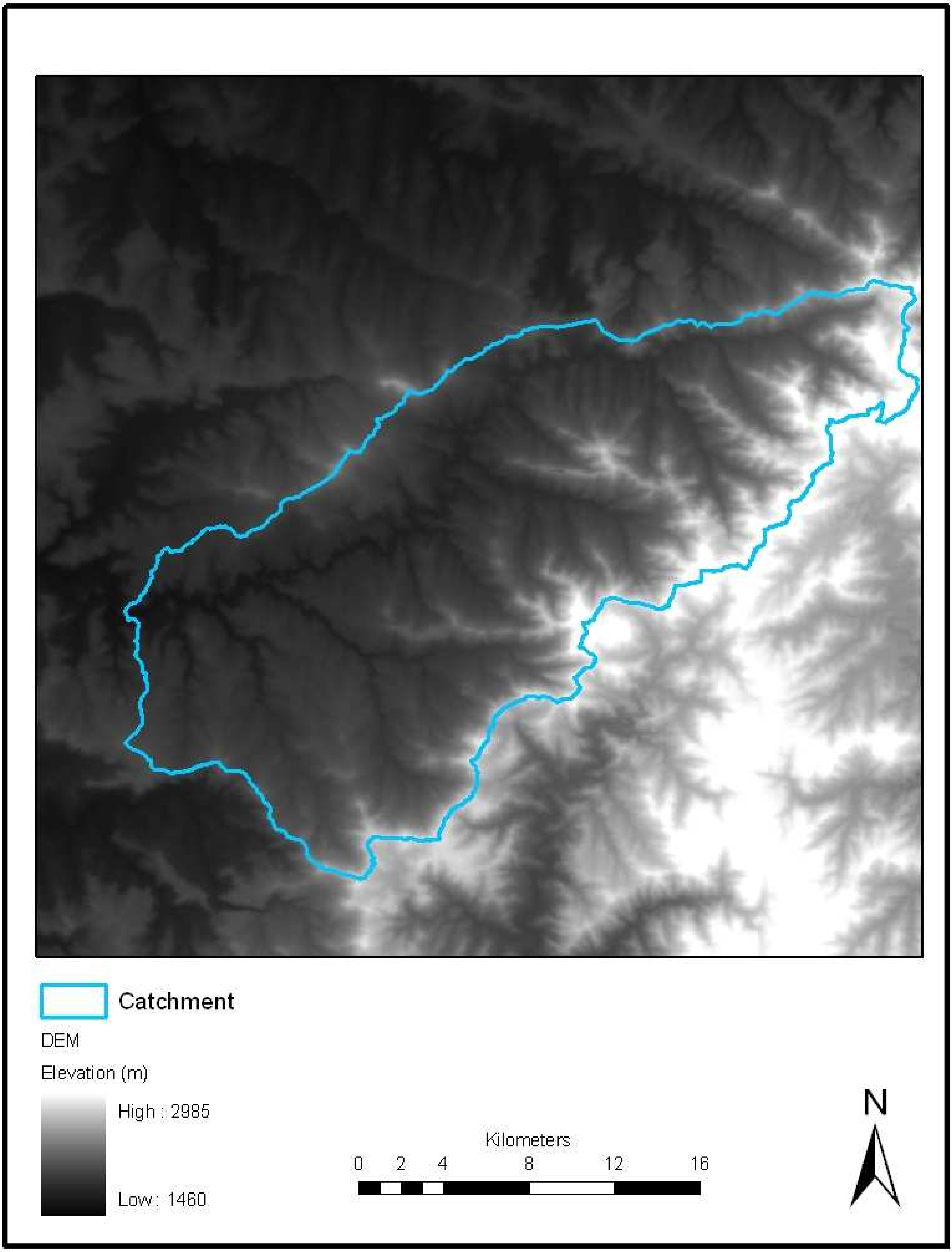

Figure 4.6: Delineated Phuthiatsane Catchment on a DEM backdrop

delineated sub-catchment since an outlet point used in the delineation is within the sub-catchment and not at the end of Phuthiatsane River (where it joins the Caledon River as shown in Figure 3.1).

4.3 Runoff Potential

The amount of potential runoff was calculated using the United States SCS based on soil HSG and land cover types. The study area has all the four HSG (see Table 4.1) but the delineated catchment only has group A and C as shown in Figure 4.7. This is because 71.3% of the catchment is made up of different types of lithosols and which are classified as group A because they are well drained and have a sandy texture. Group A soils have high infiltration rate and hence low runoff potential (Gumbo *et al.*, 2002). Other soils found in the study area include vertisols which fall within group C of HSG. Group C only covers 28.7% of the catchment. Most of the areas with group C of HSG are within a curve number range of 80-91 as shown in the curve number map (Figure 4.8). The high curve numbers (see Figure 4.8) in the catchment area may partly be accredited to the latter types of soil.

The computation of curve numbers produced the curve number map illustrated in Figure 4.8. The lowest curve number in the Phuthiatsane catchment was found to be 35 while the highest was 91. It is important to note that a curve number is coefficient and hence it does not have units. Curve number values were classified into four ranges: 35-36, 37-49, 50-79 and 80-91. The catchment is dominated by curve numbers ranges 50-79 and 80-91. The 37-49 range covers the least proportion of Phuthiatsane Catchment.

Table 4.1 Soil Types found in the study area and their corresponding HSG

Soil Type	Hydrological Soil Group
Claypan soils	D
Fersiallitic soils	B
lithosols on ferromagnesium/sedimentary rocks	A
lithosols on lava	A
lithosols on lava/calcimorphic soils	A
vertisols/calcimorphic soils	C

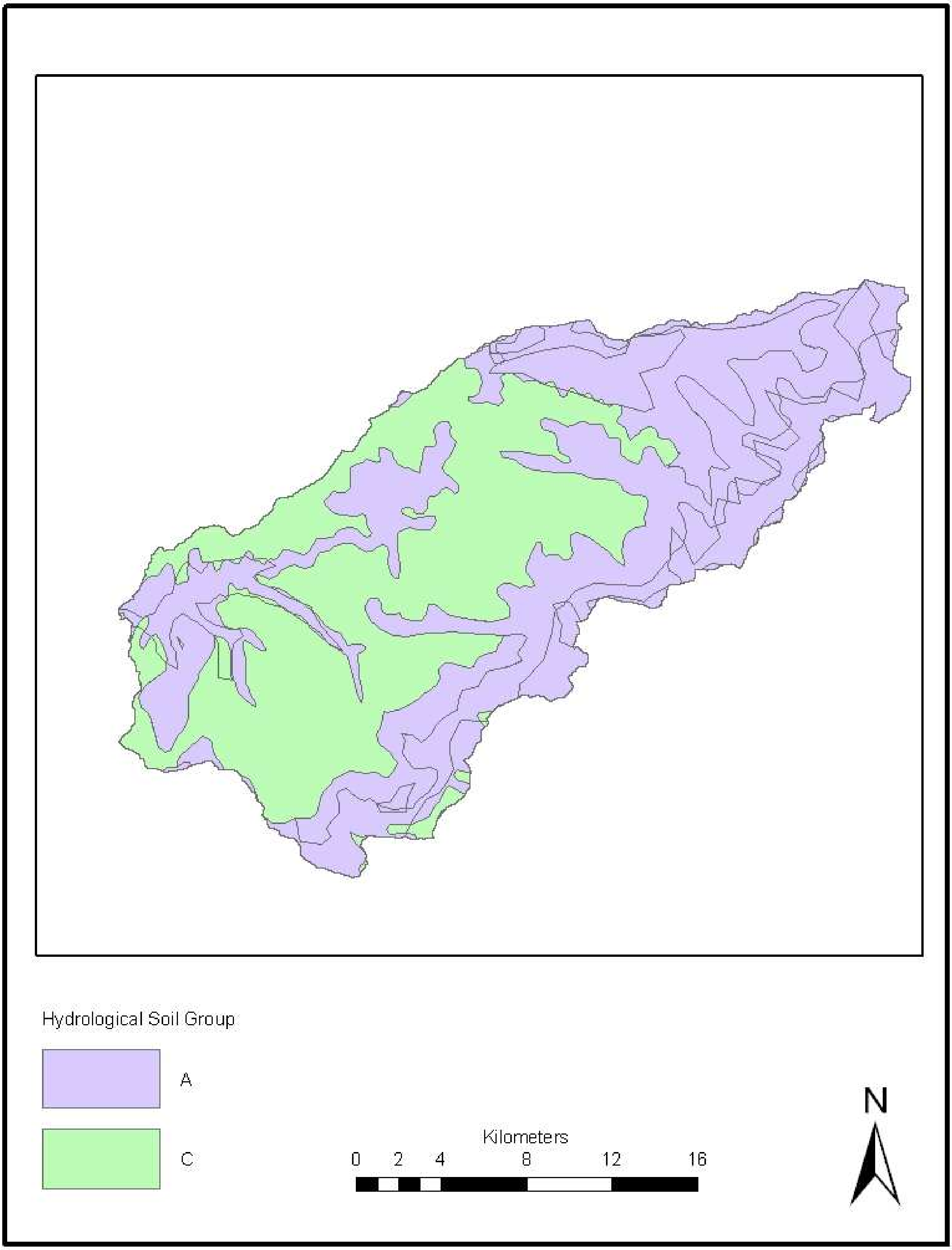

Figure 4.7: Hydrological soils groups found within Phuthiatsane Catchment

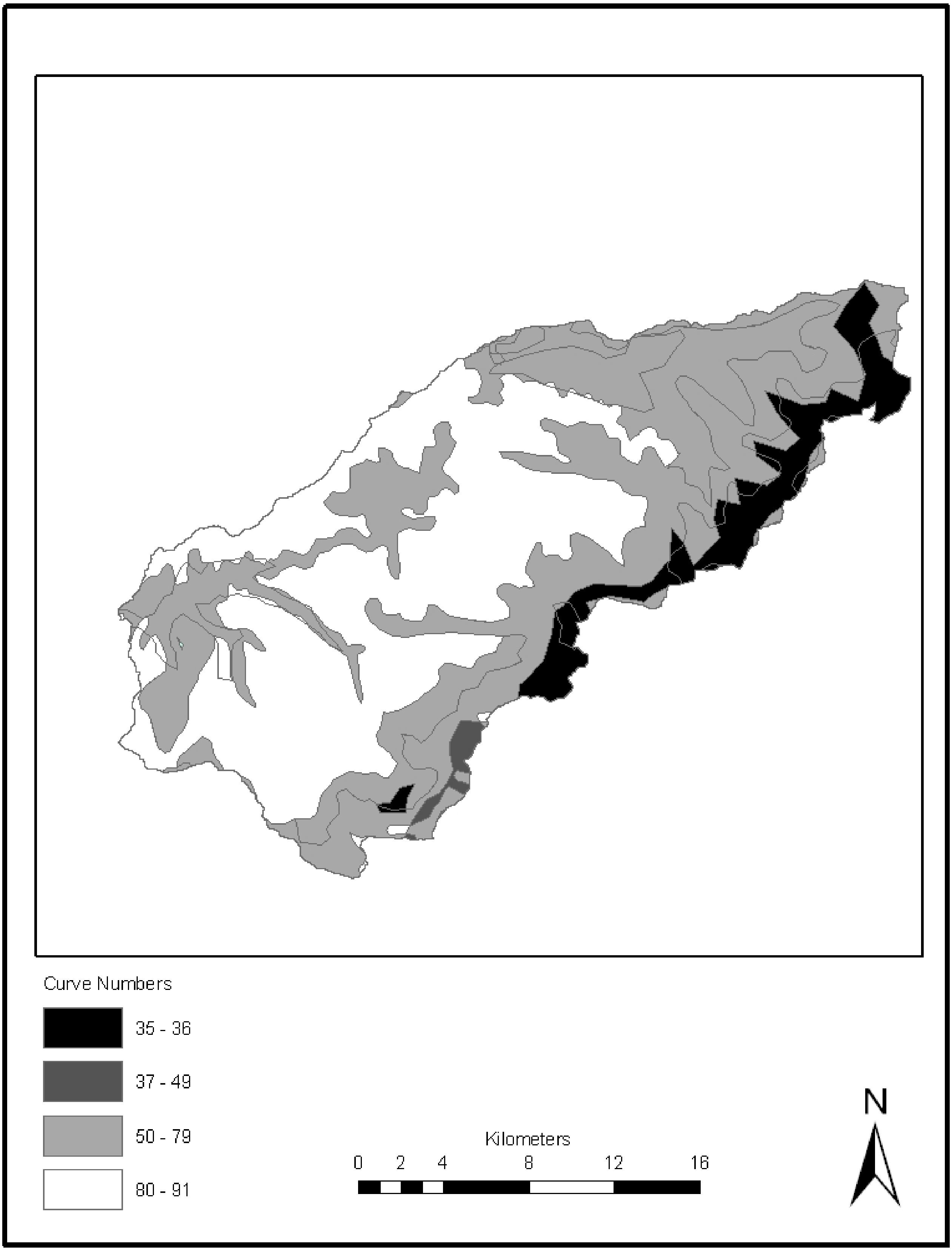

Figure 4.8: A map showing a range of curve numbers and their distribution over the catchment

Figure 4.9 shows a map of potential annual runoff volume in the catchment which ranges from 0.00217 million m^3 (MCM) to 51.878 MCM with an average of 30.943 MCM. Approximately 80% of the study area has runoff ranging from 8.394 MCM to 51.878 MCM. This range is in agreement with the annual average flow of 46.3 MCM found by CEC *et al*., 2003.

The different amounts of runoff produced on different soil types and land covers show the impact of catchment properties on runoff response hence the importance of spatially distributed models (Smith *et al*., 2004). Table 4.2 shows a summary of the average values of curve numbers and the resulting amount of runoff generated on different land cover types. Cultivated area has the highest ratio of runoff volume to area since it covers 93.355% of the total area and produced 94.954% of the total runoff volume. This is comparative to the results found by Kosgie e*t al*., (2008) and Hernández *et al*., (2009). Degraded land also has a high proportion of runoff to area due to high average curve number (81). Degraded land has high curve number because it is often bare and the soil easily gets crusted therefore increasing runoff (Alansi *et al*., 2009). The runoff volume produced on degraded land accounts for 2.149% of the total runoff although it covers 2.146% of the area. The last three groups of land cover namely; forest plantations, shrubland and low fynbos, and unimproved grassland have low proportion of runoff relative to the size of area they cover. The low amount runoff generated in forest plantations is due to increased interception in forest land which reduces the amount to rainfall reaching the ground and the subsequent reduction in runoff (Hundecha and Bárdossy, 2004). The average runoff depth generated for each land cover is directly proportional to the average value of CN for each respective land cover.

Table 4.2 A summary of runoff volume generated on each land cover type in the catchment

Land cover	Area (m^2)	Mean CN	Mean Runoff M^3
Cultivated land	1866650000	80	367269841.377500
Degraded land	42921086.57	81	4750596.861428
Forest plantations	968493.265	36	232817.355
Shrubland and low fynbos	76143096.99	35	17874622.13
Unimproved grassland	12825296.030000	64	4303393.43

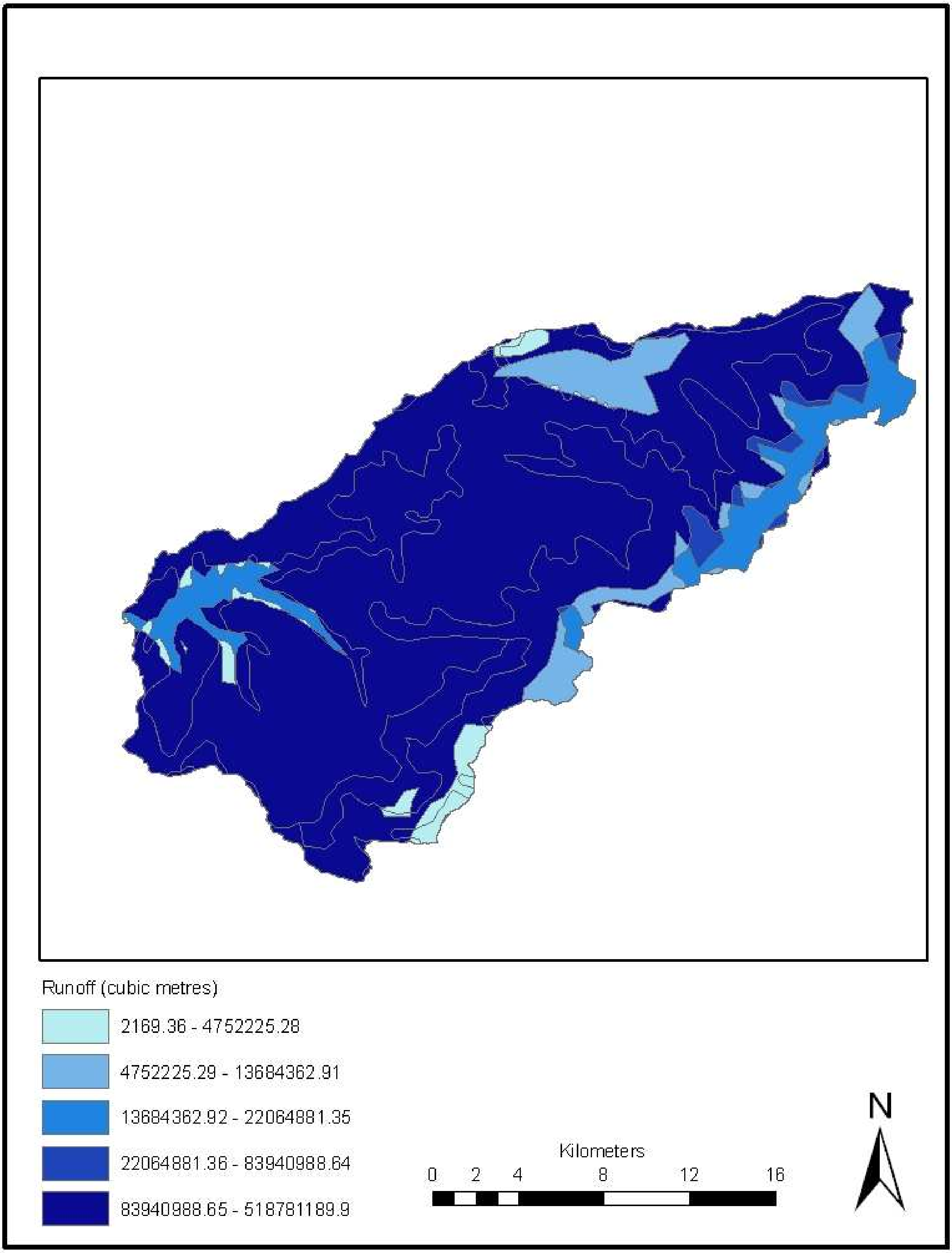

Figure 4.9: Map of Potential Runoff Volume based on SCS method

The runoff volume map (see Figure 4.9) was overlaid with the slope map in Figure 3.5 to produce the final runoff potential map shown in Figure 4.10 since the ArcCN-Runoff tool does not incorporate slope in the calculation of runoff depth and volume. The class with low runoff potential covers 0.90% while medium runoff potential class covers 22.99% of the catchment area. The class with high runoff potential symbolised in blue in Figure 4.10 covers 76.11% of the total catchment area.

4.4 Dam site Analysis Results

This section shows the three potential sites and the storage capacities at each of the four dam wall heights at all sites. The impact of reservoirs on the three proposed sites were analysed based the amount of impact on cultivated land and settlements (Mwanukuzi, 2008 and ICOLD, 2007).

4.4.1 Storage Capacities

Table 4.3 shows the elevation and storage capacity of different dam wall heights in all the sites. The crest[2] length for each dam wall and the coordinates of each dam site are also shown in highlighted rows on the table. The storage capacities for site one reservoir are 35.968 MCM, 101.017 MCM, 237.801 and 502.09 MCM for 30 m, 50 m, 70 m and 90 m dam wall heights respectively. Site two reservoir capacities are 27.235 MCM, 77.526 MCM, 170.027 MCM and 318.017 MCM for 30 m, 50 m, 70 m, and 90 m dam wall heights. The dam at site three has highest storage capacities relative to the dams at the site one and two at all the different dam heights. The storage capacities for site three reservoir are 35.968 MCM, 101.017 MCM, 237.801 MCM and 502.09 MCM for the respective dam wall heights of 30 m, 50 m, 70 m and 90 m (Table 4.3). Fifty meters and thirty meters high dams in all the sites do not have enough capacity to store the volume that would meet the current and future water demand (Table 4.4) in the lowlands of Lesotho. As shown in Table 4.3, all the site three dams have larger storage capacities than their counter dams in site one and two.

There crest lengths at site two are generally larger than the lengths at site one and three for all the dam wall heights with the exception of 90 m dam wall height in site one which has a crest length of 1180 m (Table 4.3). The differences between the crest lengths at each dam height are large in site one and small in site three. For instance, the difference between 70 m and 50 m dams crest length is 312 m (692 m -380 m) and 94 m (611 m – 516 m).

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[2] The top a dam wall

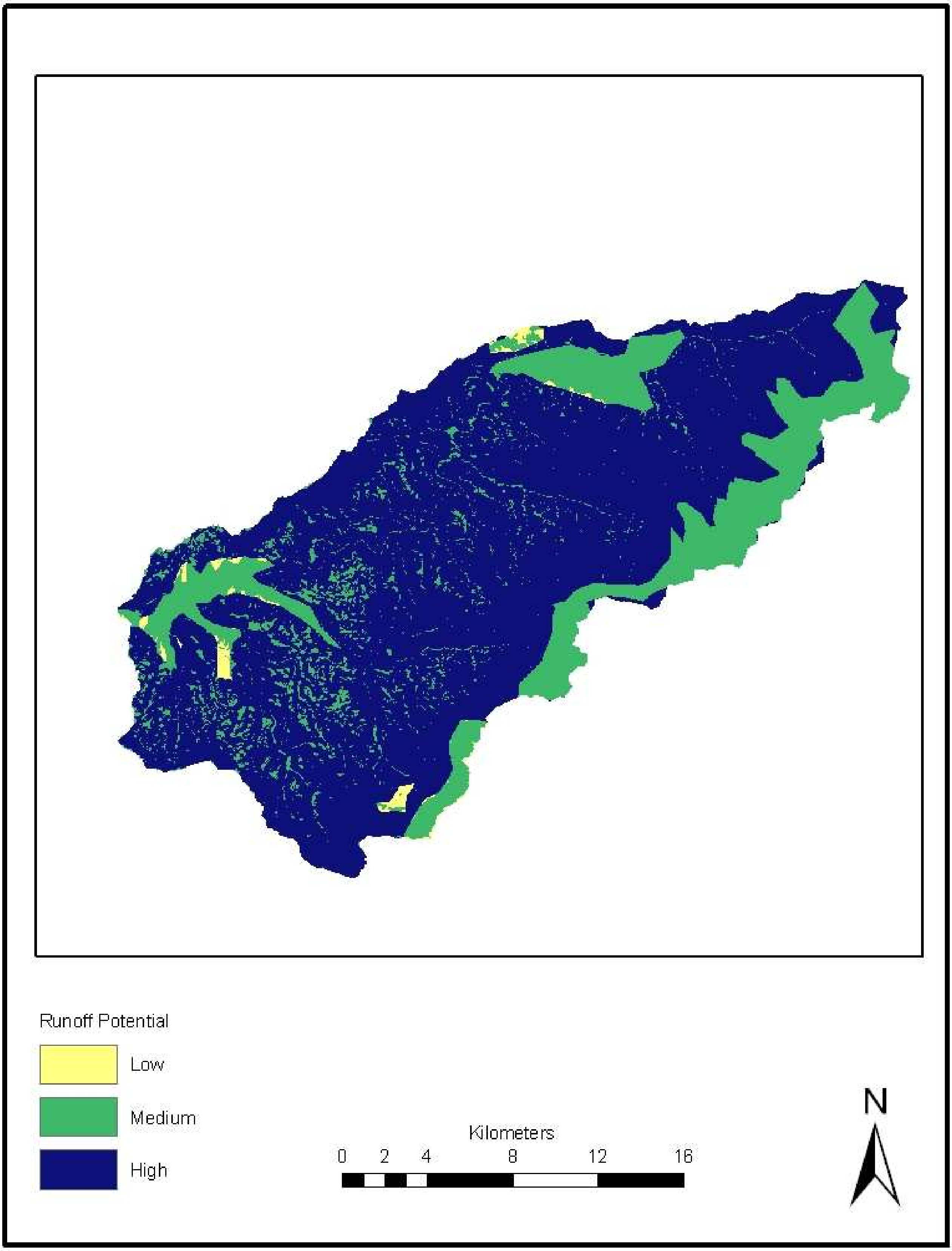

Figure 4.10: Runoff potential of Phuthiatsane classified as low, medium and high potential

Table 4.3 Storage capacities due to different dam wall heights at the three different dam sites

Site Number	Height (m)	Elevation (m)	Crest Length (m)	Volume MCM
Location of site one: 27°46′34.9″ E 29°20′9.2″ S				
1	30	1620-1650	1180	35.968
1	50	1620-1670	693	101.017
1	70	1620-1690	381	237.801
1	90	1620-1710	245	502.709
Location of site two: 27°44′42.4″ E 29°20′55.3″ S				
2	30	1580-1610	868	27.235
2	50	1580-1630	734	77.526
2	70	1580-1650	592	170.027
2	90	1580-1670	560	318.017
Location of site three: 27°42′15.6″ E 29°21′27.5″ S				
3	30	1560-1590	684	69.381
3	50	1560-1610	610	166.243
3	70	1560-1630	516	327.921
3	90	1560-1650	427	565.373

Table 4.4 Predicted Water Demand for the year 2020 (CEC *et al.*, 2003)

Level of Industrial expansion	Total Demand (MCM/day) Domestic and Industrial	Required Future Raw[3] Water Supply (MCM/day)
Low	98.4	68.3
Medium	122.3	92.9
High	141.0	112.0

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[3] The required future raw water supply includes the water for treatment and transmission losses of 2.5% volume in each scenario (CEC, 2003).

4.4.2 Assessment of Impacts on Land cover

The hypothetical reservoir at site one only covers cultivated land and there is a considerable difference in the potential surface area of each reservoir at different dam wall heights. Table 4.5 shows the amount of cultivated land that would be covered by the reservoir at different dam wall heights. The area shown in this table was calculated from land cover maps of the study area. The reservoir will submerge 8.767 km^2, 3.981 km^2 and 2.069 km^2 of cultivated land for 70 m, 50 m and 30 m dam wall heights respectively. Ninety meter dam wall height will cause 16.202 km^2 of cultivated land to be submerged and this is a considerably large area relative to the amount of area that would be submerged by the lower dam wall heights reservoirs. This implies that it would be economically costly as the fields owners would have to be compensated. As indicated by (SMEC, 2007) most households in this area depend on subsistence farming therefore it is important not to affect a large amount of agricultural land.

Table 4.5 Amount of cultivated area that would be submerged by site one reservoir at different dam wall heights

Dam height	**Area km^2**
30m site 1	2.069
50m site 1	3.981
70m site1	8.766
90m site 1	16.202

Figure 4.11 shows the hypothetical reservoir for a dam at four different heights at site one on a topographic map[4] backdrop. Topographic maps show that there are some settlements that will be submerged by the reservoir if the dam wall height would be 90 m, 70 m or 50 m. This implies more costs for relocation of the households. Based on the topographic maps, the reservoir will not affect any agricultural land at 50 m and 30 m dam wall heights. However, the whole of site one and its surroundings is symbolised as cultivated land in the catchment land cover map shown in Figure 4.12. The reservoirs in Figure 4.12 are displayed with land cover in order to illustrate the amount of land cover that would be covered by each reservoir at 70 m dam wall height.

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[4] Most of the features on the topographic maps are not clear due to changes in scale

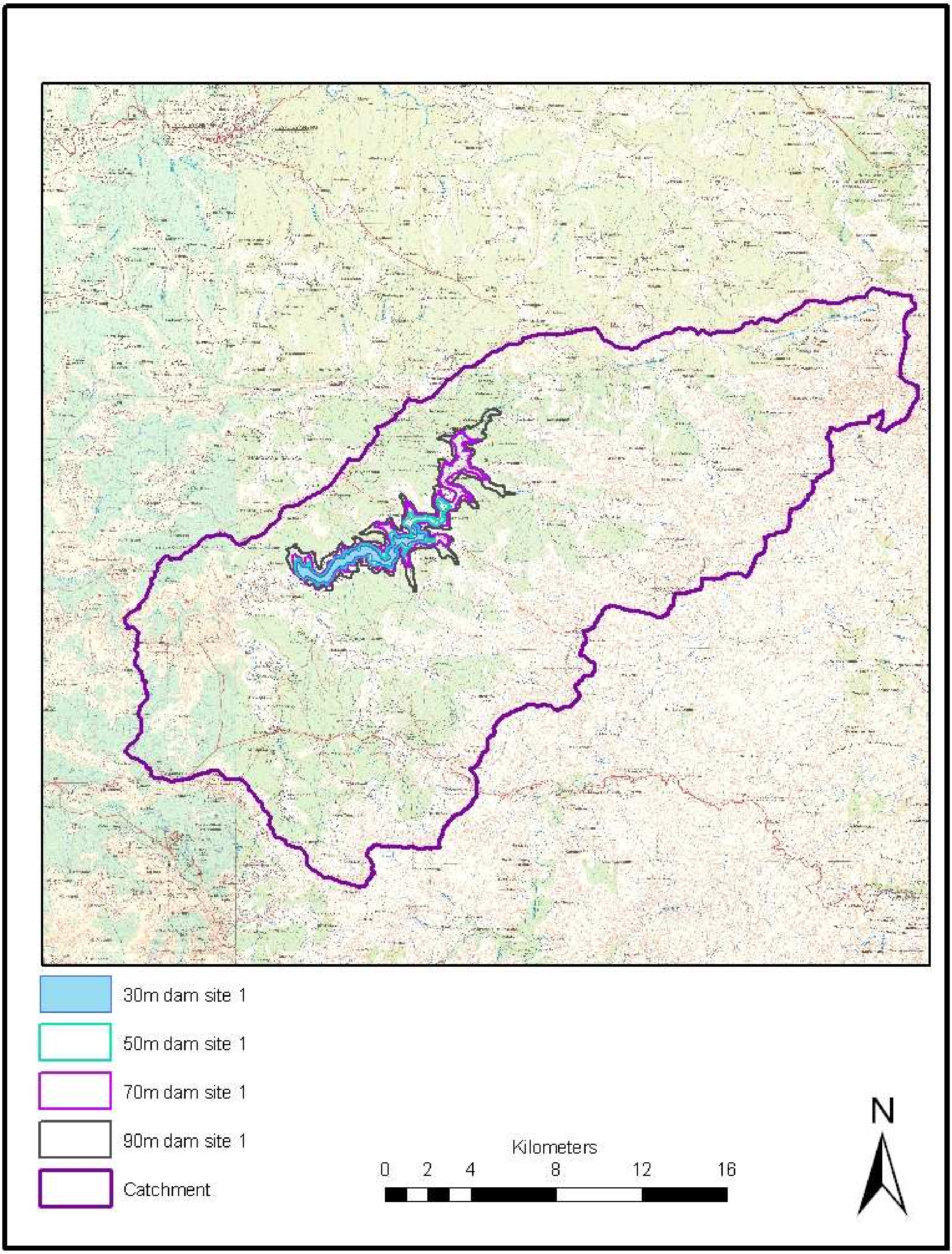

Figure 4.11: Site one map with reservoir polygons for different dam wall heights

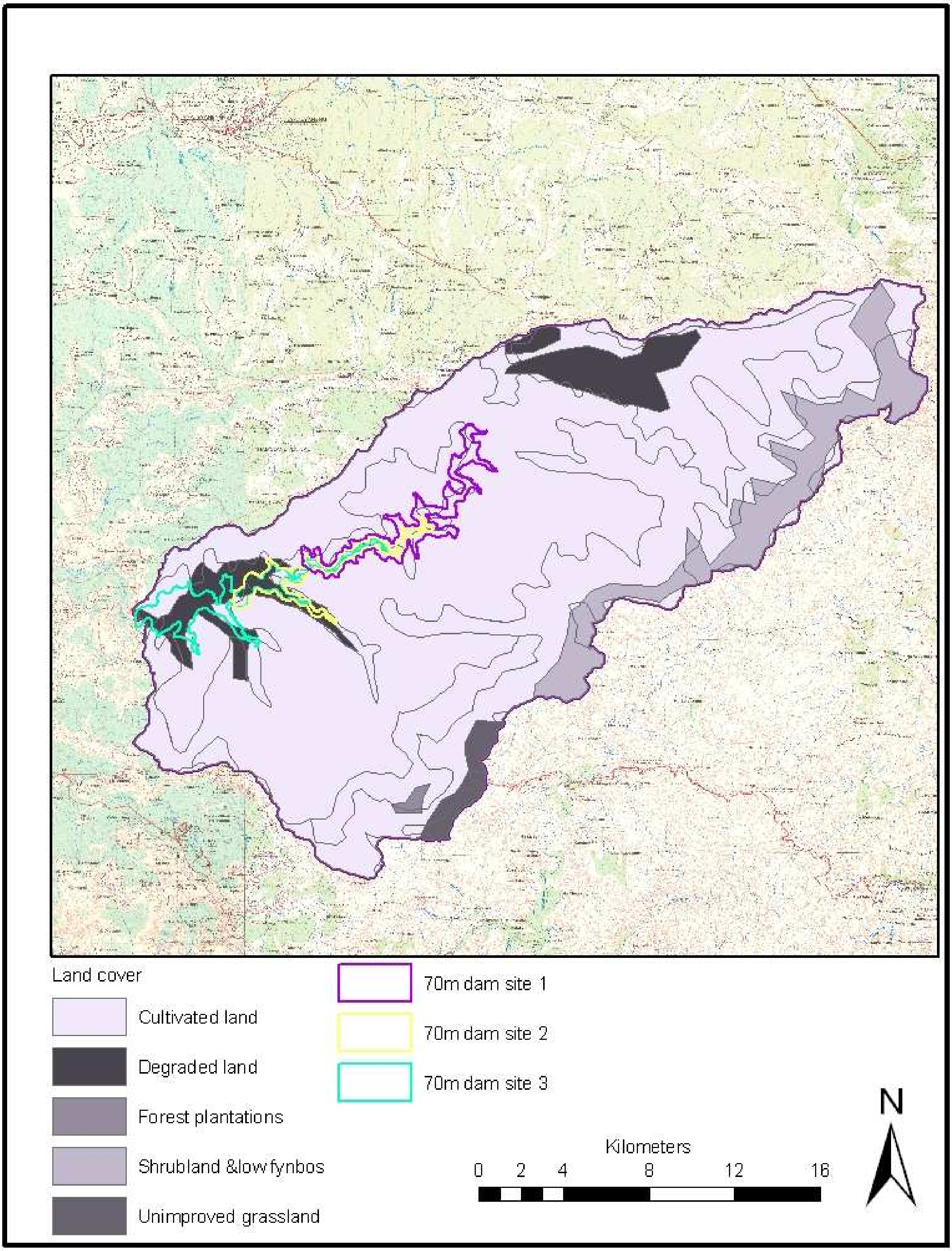

Figure 4.12: Reservoirs for 70m dam wall height on land cover map background

Site two covers both cultivated and degraded land. All the areas that would be submerged by the reservoir at site two are much less than the areas in site one. This is because the areas along the river banks are very steep at site two. The reservoir at site two has lower impacts relative to site one since there is less cultivated land in site two due the presence of degraded land. Table 4.6 shows that the areas of cultivated land that will be inundated by the reservoir are 5.67 km^2, 3.435 km^2, 1.752 km^2 and 0.463 km^2 for 90 m, 70 m 50 m and 30 m dam wall heights respectively. Based on Table 4.5, the reservoir will cover 2.726 km^2, 2.063 km^2, 1.433 km^2 and 0.961 km^2 of degraded land for 90 m, 70 m, 50 m and 30 m dam wall heights. Topographic maps however reflect that there are settlements on the degraded land (Figure 4.13).

Table 4.6 Land cover areas that would be submerged by site two reservoir at different dam wall heights

Dam height	**Land Cover**	**Area km^2**
30m	Cultivated land	0.463
30m	Degraded land	0.961
50m	Cultivated land	1.752
50m	Degraded land	1.433
70m	Cultivated land	3.343
70m	Degraded land	2.063
90m	Cultivated land	5.677
90m	Degraded land	2.726

Unlike site one, there is no much difference in the area covered by each reservoir (see Table 4.6) since the area along the river banks is steep hence the contours are close to each other. This is shown by the close proximity of the polygon outlines to each other and the small difference of calculated area illustrated in Table 4.6. Land cover map shows site two as degraded land. The surface areas and at site two are smaller than those of corresponding dams at site one and three and the storage capacities are significantly small.

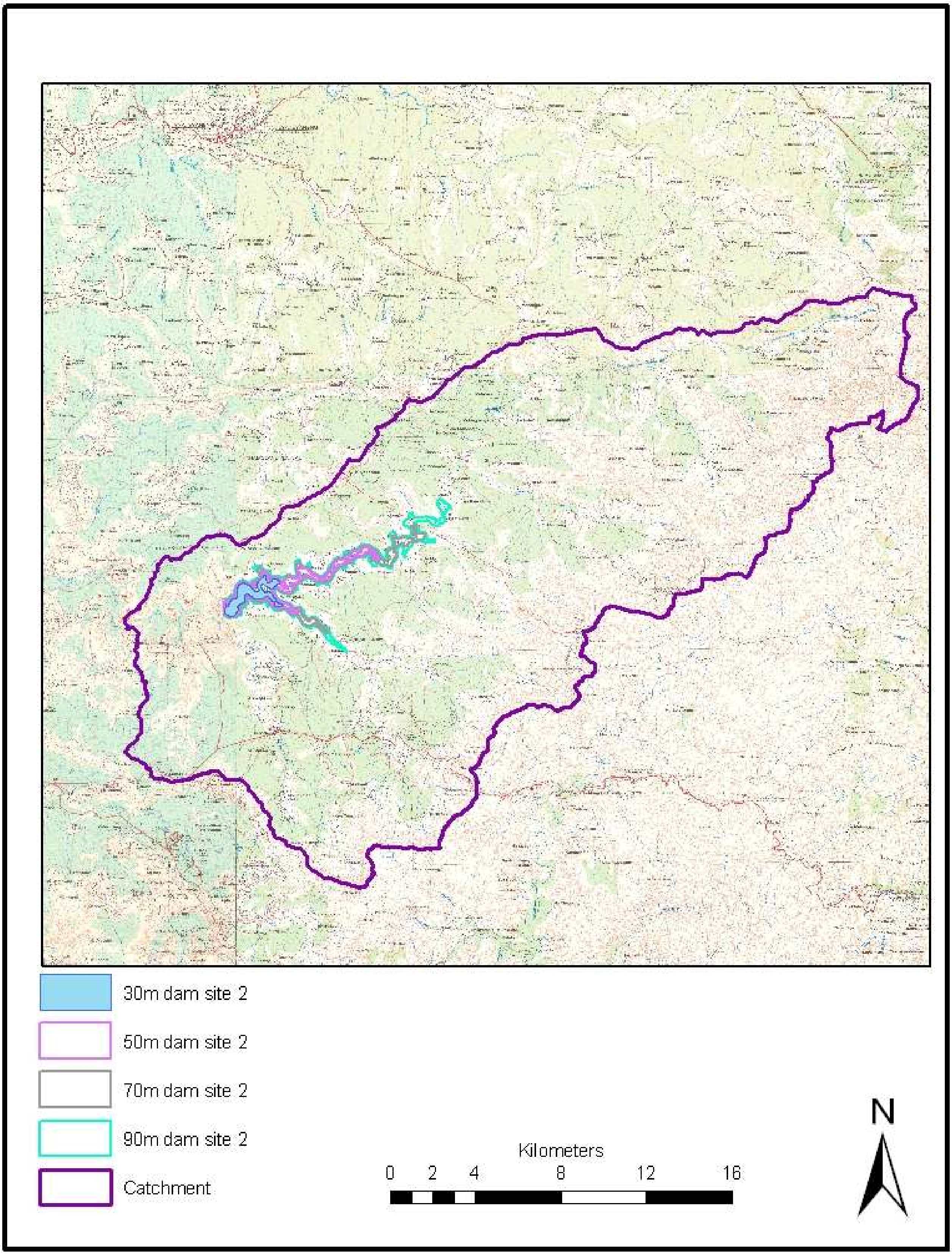

Figure 4.13: Site two reservoir polygons for different dam wall heights

The reservoir at site three also covers both cultivated and degraded land. Site three reservoir will submerge 6.535 km^2, 4.039 km^2, 2.14 km^2 and 1.307 km^2 of cultivated land for the respective dam wall heights of 90 m, 70 m, 50 m and 30 m as illustrated in Table 4.7. These values are slightly higher than corresponding areas in site two but less than site one areas. The degraded land in site three is generally higher than the cultivated land in the same site. Table 4.7 shows that the reservoir will submerge 6.48 km^2, 5.2 km^2, 3.852 km^2 and 2.081 km^2 of degraded land according to the order of decreasing dam wall height. There are also settlements in the area as shown by the topographic maps (Figure 4.14). The degraded land that would be covered by the reservoir at all the heights except 90 m is larger than cultivated. Looking at the land cover map and topographic maps, site three dams cover a very small portion of cultivated land. This implies there will be less impact on agricultural land from which the community's livelihood depends on hence it would be more cost effective to construct a dam at this site. In addition, the crest lengths at four dam wall heights (see Table 4.3) in site three are relatively not that different because the contour lines are not that far apart hence the major influence on the differences in storage capacities is the difference in the stretch of the reservoirs upstream and not the area covered by the reservoirs.

Table 4.7 Land cover areas that would be submerged by site three reservoir at different dam wall heights

Dam height	**Land Cover**	**Area km^2**
30m	Cultivated land	1.387
30m	Degraded land	2.081
50m	Cultivated land	2.140
50m	Degraded land	3.852
70m	Cultivated land	4.0394
70m	Degraded land	5.200
90m	Cultivated land	6.535
90m	Degraded land	6.438

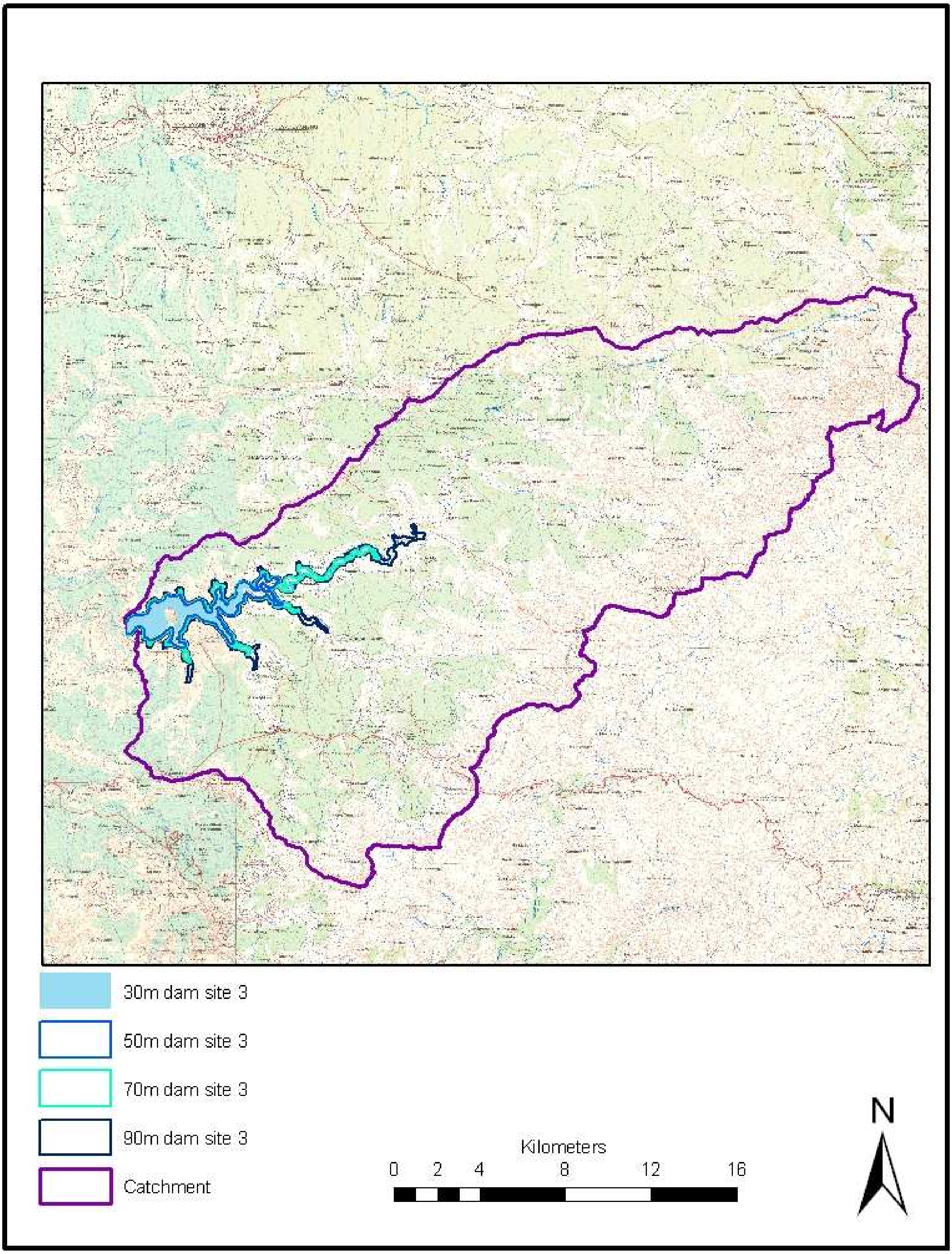

Figure 4.14: Site three map with reservoir polygons for different dam wall heights

The 70m dam wall height was considered to be the most suitable dam height for all the sites since it yields high storage capacities with reasonable level of impact on land use. The decision on best dam site was therefore based on 70m dams. Both site two and site three are located on an area with medium runoff potential. The discharge at site three is however assumed to be higher than the discharge at site one since site three is further downstream. The fact that site three is more towards downstream can be a disadvantage since sedimentation can reduce the life span of a dam.

Site two was eliminated from the three options because it has very low storage capacities yet the impact is almost equal to that of site three. The amount of rainfall is almost the same in all the sights so rainfall was not considered to be one the main determining factors. Site three was considered to be the best dam site since it has the largest storage capacity with less impact on farm land and settlements. Site one would be the best site if hydro power generation would be included as one of the purposes of dam construction in this area since it has the highest altitude. However, storage is the major purpose hence, 70m dam wall height at site three (illustrated in Figure 4.15) is considered to be the most appropriate option.

4.5 Summary of findings

The results of this study have confirmed that simulation of hydrological processes has been made easy due to the spatial analysis capabilities provided within a GIS environment. The capabilities of ArcHydro tools to model hydrology have been fundamental in this study. The flow distribution has been defined through the use of a DEM to produce flow direction, flow accumulation and subsequent stream network definition. The defined streams matched the streams on the topographic map and this confirmed that accurate stream definition can be achieved by specifying the threshold which equals the 10% of the maximum flow accumulation (Djokic, 2008). The catchment of Phuthiatsane River was successfully delineated with a catchment area of 468 km^2.

Runoff analysis resulted in an annual runoff volume ranging from of 0.00217 MCM to 51.878 MCM with an average of 30.943 MCM. The results were obtained using the United States SCS method which is a widely utilised method based on the development of curve numbers for different land cover and HSG combinations (Melese *et al*., 2003). The high curve number value (80) for cultivated land confirmed that conventional tillage increases the amount of runoff (Kosgie *et al*., 2007). Degraded land in the study area had the highest value of curve number since there is usually high runoff in bare open space (Alansi *et al*., 2009).

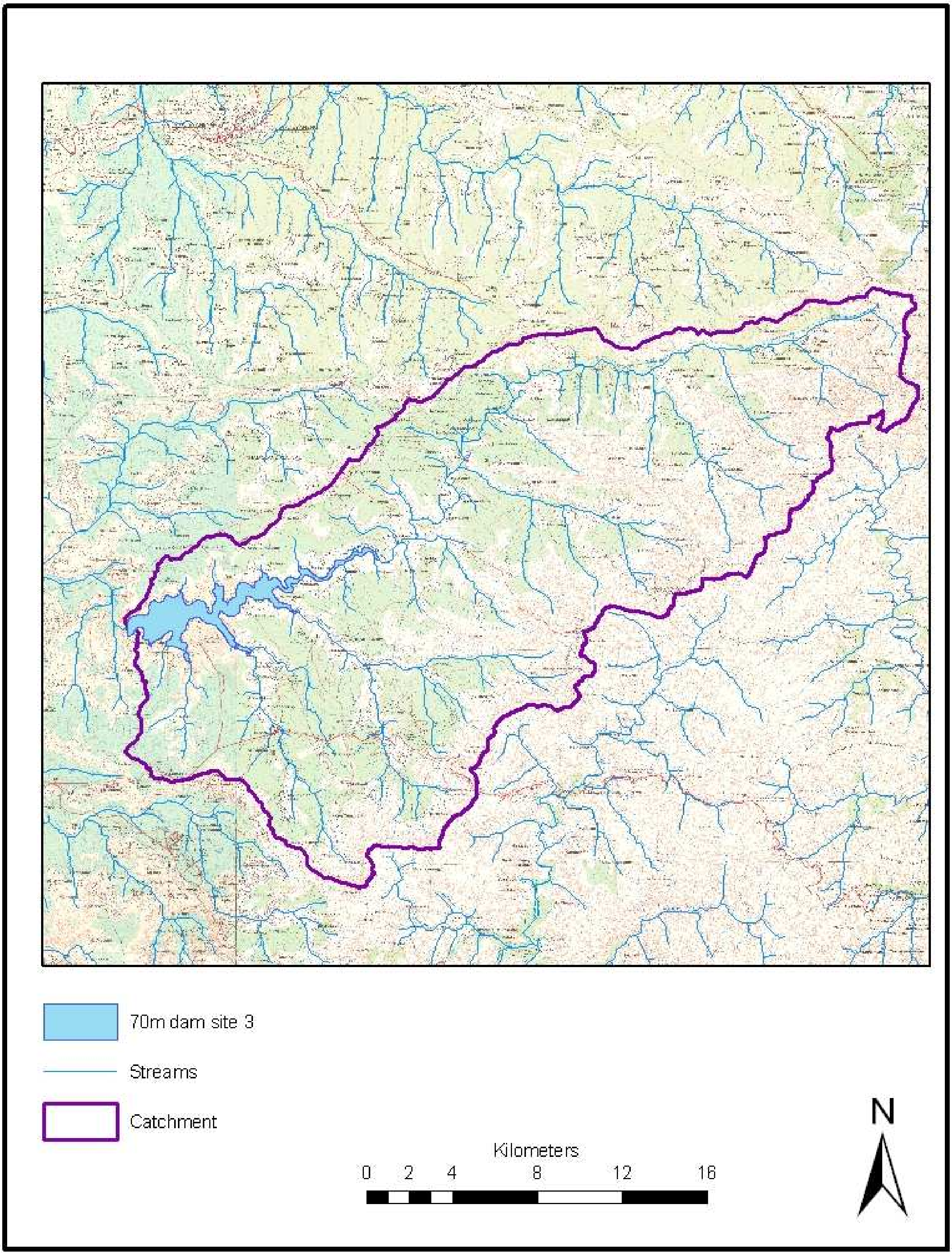

Figure 4.15: The most suitable site and reservoir size

The other reason is that degraded land in the study area falls within an area with group C of HSG. The annual runoff volume map was overlaid with the slope map derived from a DEM in order to obtain the overall runoff potential. Phuthiatsane catchment is dominated by areas with high runoff potential. Both site two and site three dams area located in areas of medium runoff potential as compared to a dam at site one which is located within an area of high runoff potential. Site two and three are however located downstream where there is high discharge

The final step was to identify the most suitable site to locate a dam with high storage capacity but with low impacts on the agricultural land and residential areas. Three different sites which are approximately were selected along the river channel and the reservoir areas and storage capacities determined. Reservoir area and the storage capacities were calculated for different dam wall heights at each site. The dam is currently being constructed at site one which is the site selected by CEC, 2003. However, based on the results of this study, site three is the most suitable site since it has the highest storage capacity and relatively low impact on land use.

CHAPTER FIVE: CONLCUSIONS AND RECOMMENTDATIONS

5.1 Conclusions

It can be concluded from the findings of this study that the application of GIS in hydrological modelling can be used to accurately model Phuthiatsane Catchment. The ability of GIS to represent spatially distributed variables has enabled accurate determination of flow distribution and automated stream definition in the study area. Phuthiatsane catchment has been successfully delineated and through the use of ArcHydro (ESRI, 2009). This catchment covers an area of 468 km^2 as it does not include approximately three quarters of Masianokeng sub-catchment.

The average annual runoff calculated using the United States SCS in GIS environment ranged from 0.00217 MCM to 51.878 MCM and the average found by CEC *et al*., (2003) is within this range hence the result obtained in this study are accurate. The incorporation of slope into runoff analysis showed that 76.11% of Phuthiatsane Catchment has high runoff potential. The distributed results runoff can be used on in catchment management to monitor the different factors affecting the generation of runoff.

It can also be concluded that the determination of dam sites, storage capacities and the resulting reservoir impacts in a GIS environment can easily be made due to the analytical and visualization capability of GIS to display the majority of factors involved in decision making. Based on the storage capacities and the level of impacts, site three was considered to be the most suitable site for dam construction. It was concluded that the 70 m high dam at site three is appropriate for water storage for the purposes of water supply as it has a large storage capacity (327.921 MCM) and relatively fewer impacts on land use.

The objectives of this study have been achieved. However, the study was limited in that ArcCN-Runoff tools used in the computation of curve numbers and runoff does not incorporate the spatial variability of rainfall. In addition, Lesotho topographic maps, land cover and soil maps (1994) provided were very old so the information depicted might have changed. However, the results obtained in this study are fairly accurate in as far as the accuracy of the data used since they are not very different from what was found in previous studies by CEC *et al*., (2003) in regard to the size of the delineated catchment.

5.2 Recommendations

The results have shown that hydrological modelling using GIS could easily be undertaken therefore, the approach used in this study can be utilised in the feasibility studies of dams yet to be constructed. The results of this study can also used for the purposes of water resource management since they represent hydrological processes at every point within the catchment. It is recommended that further research should be conducted to further investigate the applicability of GIS based hydrological modelling in Lesotho. ArcCN-Runoff tool can be improved in such a way that it takes the spatial variability of rainfall into account. In addition recent satellite images should be used in the identification of land cover since they are more detailed and updated.

It is also recommended that further studies should include ground truth surveys in order to validate the results. Stakeholders play an important role in decision making and the consideration of their concerns in deciding on the appropriate location and size of a dam can greatly enhance the results and minimise the impacts. Finally, it is recommended that incorporation of hydro power station should be taken into consideration as combining water storage with hydro power generation would be economically and environmentally beneficial for a developing country like Lesotho.

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APPENDICES

Appendix A United States Soil Conservation Service (SCS) Index Table showing curve number values for different combinations of land use and Hydrological Soil Group

ID	**LAND USE**	**A**	**B**	**C**	**D**
0	Open Space (Poor)	68	79	86	89
1	Open Space (Fair)	49	69	79	84
2	Open Space (Good)	39	61	74	80
3	Impervious	98	98	98	98
4	Roads (Paved)	98	98	98	98
5	Roads (Paved w/ditch)	83	89	92	93
6	Roads (Gravel)	76	85	89	91
7	Roads (Dirt)	72	82	87	89
8	Urban Desert (Natural)	63	77	85	88
9	Urban Desert (Artificial)	96	96	96	96
10	Urban (85% imp)	89	92	94	95
11	Urban (72% imp)	81	88	91	93
12	Residential (65% imp)	77	85	90	92
13	Residential (38% imp)	61	75	83	87
14	Residential (30% imp)	57	72	81	86
15	Residential (25% imp)	54	70	80	85
16	Residential (20% imp)	51	68	79	84
17	Residential (12% imp)	46	65	77	82
18	Urban (Newly graded)	77	86	91	94
19	Fallow (Bare)	77	86	91	94
20	Fallow (CR - Poor)	76	85	90	93
21	Fallow (CR - Good)	74	83	88	90

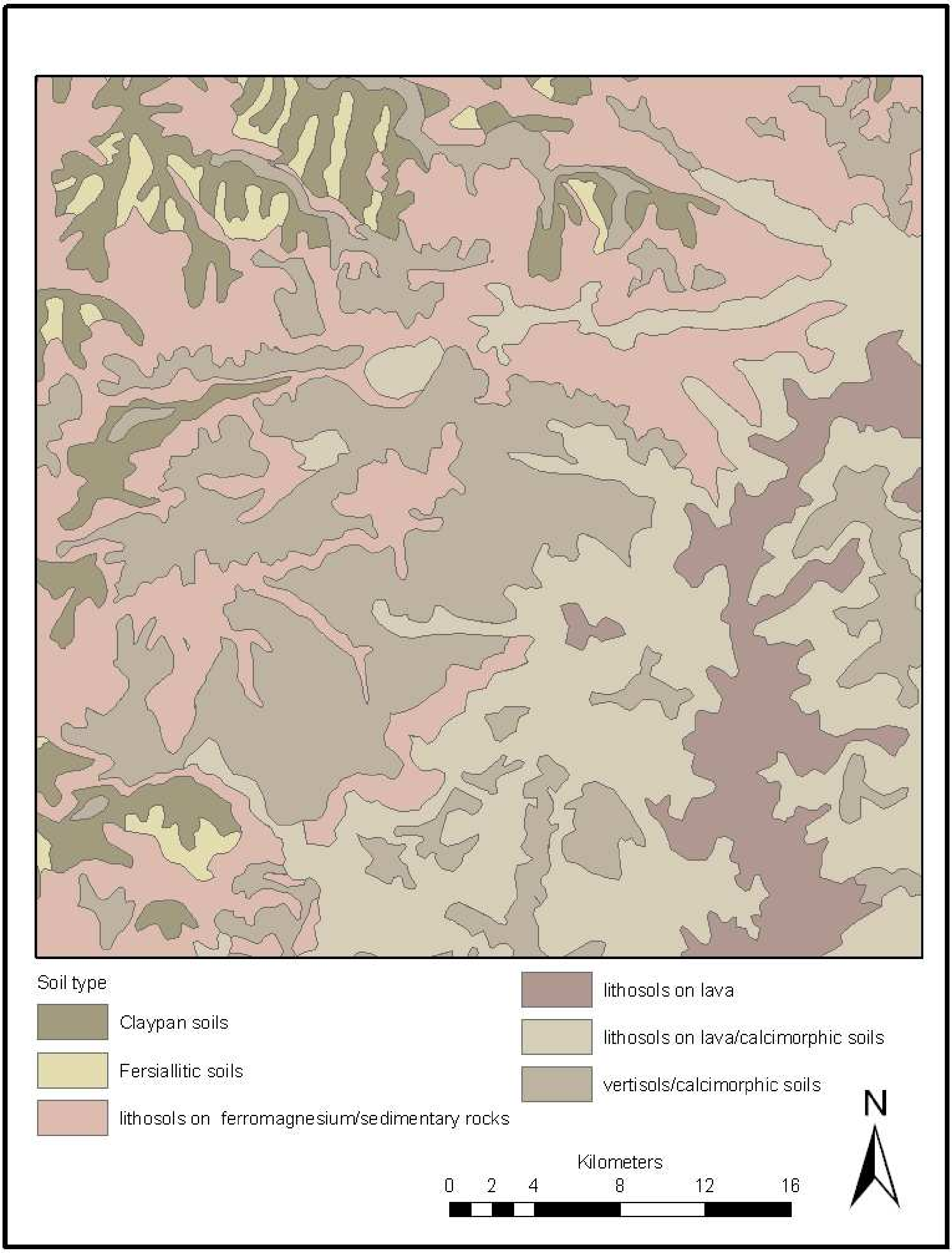
22	Row Crop (SR - Poor)	72	81	88	91
23	Row Crop (SR - Good)	67	78	85	89
24	Row Crop (SR + CR - Poor)	71	80	87	90
25	Row Crop (SR + CR - Good)	64	75	82	85
26	Row Crop (C - Poor)	70	79	84	88
27	Row Crop (C - Good)	65	75	82	86
28	Row Crop (C + CR - Poor)	69	78	83	87
29	Row Crop (C + CR - Good)	64	74	81	85
30	Row Crop (C & T - Poor)	66	74	80	82
31	Row Crop (C & T - Good)	62	71	78	81
32	Row Crop (C & T + CR - Poor)	65	73	79	81
33	Row Crop (C & T + CR - Good)	61	70	77	80
34	Small Grain (SR - Poor)	65	76	84	88
35	Small Grain (SR - Good)	63	75	83	87
36	Small Grain (SR + CR - Poor)	64	75	83	86
37	Small Grain (SR + CR - Good)	60	72	80	84
38	Small Grain (C - Poor)	63	74	82	85
39	Small Grain (C - Good)	61	73	81	84
40	Small Grain (C + CR - Poor)	62	73	81	84
41	Small Grain (C + CR - Good)	60	72	80	83
42	Small Grain (C & T - Poor)	61	72	79	82
43	Small Grain (C & T - Good)	59	70	78	81
44	Small Grain (C & T + CR - Poor)	60	71	78	81
45	Small Grain (C & T + CR - Good)	58	69	77	80
46	Close Seeded (SR - Poor)	66	77	85	89
47	Close Seeded (SR - Good)	58	72	81	85
48	Close Seeded (C - Poor)	64	75	83	85

49	Close Seeded (C - Good)	55	69	78	83
50	Close Seeded (C & T - Poor)	63	73	80	83
51	Close Seeded (C & T - Good)	51	67	76	80
52	Pasture (Poor)	68	79	86	89
53	Pasture (Fair)	49	69	79	84
54	Pasture (Good)	39	61	74	80
55	Meadow	30	58	71	78
56	Brush (Poor)	48	67	77	83
57	Brush (Fair)	35	56	70	77
8	Brush (Good)	30	48	65	73
59	Woods - Grass (Poor)	57	73	82	86
60	Woods - Grass (Fair)	43	65	76	82
61	Woods - Grass (Good)	32	58	72	79
62	Woods (Poor)	45	66	77	83
63	Woods (Fair)	36	60	73	79
64	Woods (Good)	30	55	70	77
65	Farmstead	59	74	82	86
66	Rangeland (Herbaceous - Poor)	30	80	87	93
67	Rangeland (Herbaceous - Fair)	30	71	81	89
68	Rangeland (Herbaceous - Good)	30	62	74	85
69	Rangeland (Oak-Aspen - Poor)	30	66	74	79
70	Rangeland (Oak-Aspen - Fair)	30	48	57	63
71	Rangeland (Oak-Aspen - Good)	30	30	41	48
72	Rangeland (Pinyon-Juniper - Poor)	30	75	85	89
73	Rangeland (Pinyon-Juniper - Fair)	30	58	73	80
74	Rangeland (Pinyon-Juniper - Good)	30	41	61	71
75	Rangeland (Sagebrush - Poor)	30	67	80	86

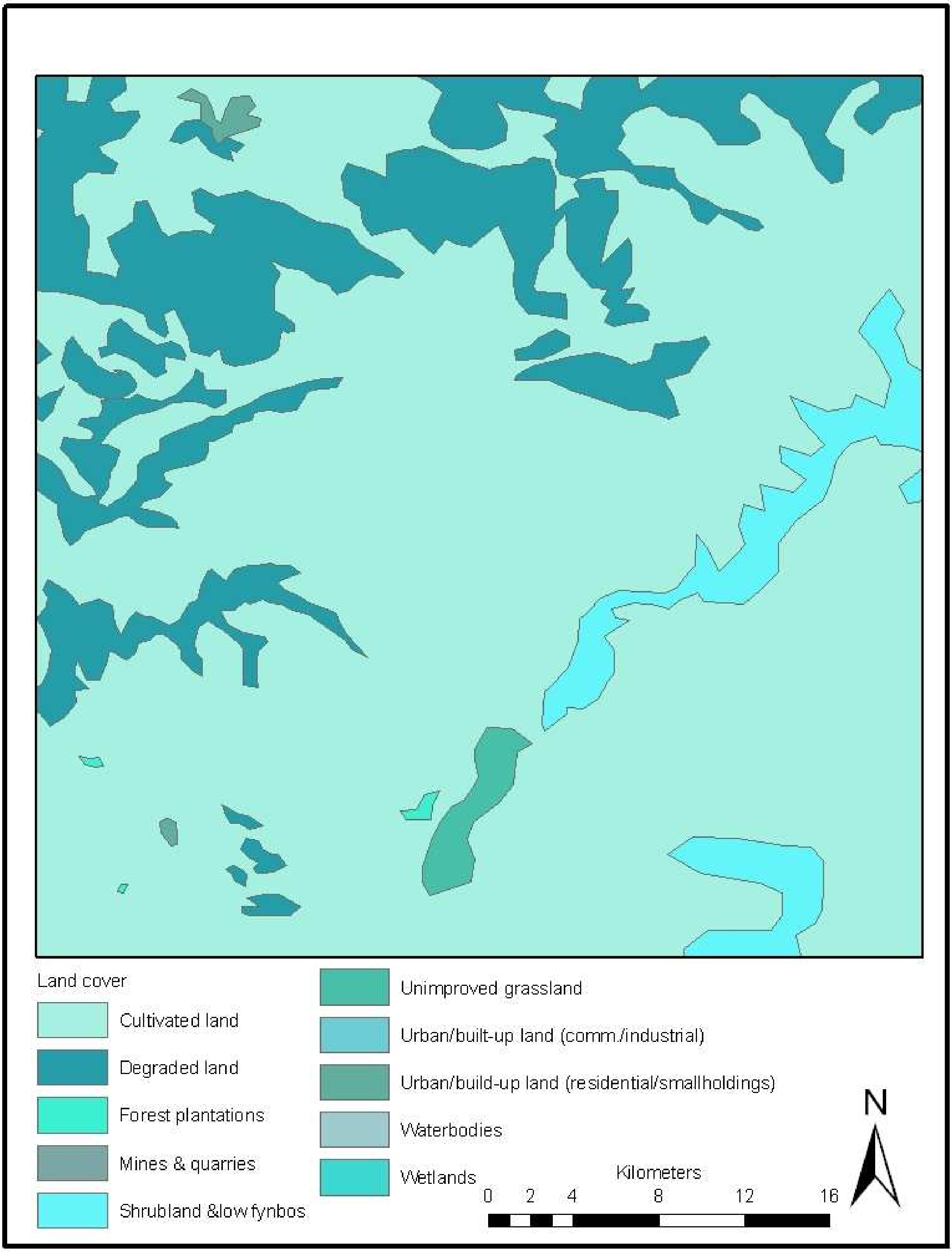
76	Rangeland (Sagebrush – Fair)	30	51	63	70
77	Rangeland (Sagebrush - Good)	30	35	47	55
78	Rangeland (Desert Shrub - Poor)	63	77	85	88
79	Rangeland (Desert Shrub - Fair)	55	72	81	86
80	Rangeland (Desert Shrub - Good)	49	68	79	84
81	21Agriculture	77	86	91	94
82	11Residential	61	75	83	87
83	32Rangeland	49	69	79	84
84	41Deciduous Forest	36	60	73	79
85	42Evergreen Forest	40	66	77	85
86	43Mixed Forest	38	63	75	82
87	17Urban	68	80	88	94
88	74Rock	100	100	100	100
89	75Gravel Pit	35	45	55	65
90	82Herbaceous Tundra	52	60	67	75
91	85Mixed Tundra	58	67	73	80
92	11Residential	57	72	81	86
93	12Commercial and Services	89	92	94	95
94	13Industrial	81	88	91	93
95	14Transportation and Communications	83	89	92	93
96	15Industrial and Commercial	84	90	92	94
97	16Mixed Urban or Built-up Land	81	88	91	93
98	17Other Urban or Built-up Land	63	77	85	88
99	21Cropland and Pasture	49	69	79	84
100	22Orchards Groves Vineyards Nurseries	45	66	77	83
101	23Confined Feeding Operations	68	79	86	89
102	24Other Agricultural Land	59	74	82	86

103	31Herbaceous Rangeland	49	69	79	84
104	32Shrub and Brush Rangeland	35	56	70	77
105	33Mixed Rangeland	35	56	70	77
106	41Deciduous Forest Land	36	60	73	79
107	42Evergreen Forest Land	36	60	73	79
108	43Mixed Forest Land	36	60	73	79
109	51Streams and Canals	0	0	0	0
110	52Lakes	0	0	0	0
111	53Reservoirs	0	0	0	0
112	54Bays and Estuaries	0	0	0	0
113	61Forested Wetland	30	55	70	77
114	62Nonforested Wetland	30	58	71	78
115	71Dry Salt Flats	74	84	90	92
116	72Beaches	50	50	50	50
117	73Sandy Areas other than Beaches	63	77	85	88
118	74Bare Exposed Rock	98	98	98	98
119	75Strip Mines	77	86	77	86
120	76Transitional Areas	77	86	91	94
121	77Mixed Barren Land	77	86	91	94
122	81Shrub and Brush Tundra	48	67	77	83
123	82Herbaceous Tundra	68	79	86	89
124	83Bare Ground Tundra	77	86	91	94
125	84Wet Tundra	35	56	70	77
126	85Mixed Tundra	35	56	70	77
127	91Perennial Snowfields	0	0	0	0
128	92Glaciers	0	0	0	0

Appendix B Soil Type Map of the Study Area



Appendix C Land Cover Map of the Study Area



Appendix D Summary of Rainfall Data from the Rainfall Stations within the Study Area

Station name	Location		January		February		March		April	
	Latitude	Longitude	mean	max	mean	max	mean	max	mean	max
TY-Phuthiatsana	-29.13	27.78	120.8	361.0	97.1	243.4	101.2	334.7	58.1	141.0
Moletsane	-29.17	28.03	128.63	359.9	98.87	217.3	106.18	207	61.63	137.7
Molimo-Nthuse	-29.47	27.90	132.97	316.1	127.47	270.6	115.37	231.8	73.45	191.5
Pulane	-29.25	27.92	131.51	380.5	126.63	249.2	97.3	267.5	62.69	171.7
Thaba-Putsoa	-29.43	27.97	153.67	354	133.14	255.1	123.89	275.8	80.58	236.9

Station name	May		June		July		August	
	mean	max	mean	max	mean	max	mean	max
TY- Phuthiatsana	28.4	90.0	14.6	62.7	8.4	67.9	18.8	92.0
Moletsane	22.46	88	13.79	61.4	11.48	58.6	28.205	121.1
Molimo-Nthuse	26.78	130.9	19.39	91.6	14.82	69.8	28.79	94.8
Pulane	24.64	99.8	19.329	137	10.31	75.5	45.28	122.2
Thaba-Putsoa	33.27	215.1	16.82	85.7	10.69	44	38.78	216.9

Station name	September		October		November		December		Annual
	mean	max	mean	max	mean	max	mean	max	mean
TY- Phuthiatsana	28.4	155.1	77.9	256.0	91.6	220.8	91.6	212.0	734.8
Moletsane	33.46	135.2	78.17	166.8	93.37	205.4	119.79	197.8	796.03
Molimo-Nthuse	43.2	196.5	96.79	202.7	100.72	220	111.25	298.7	890.99
Pulane	34.62	160.5	86.21	215	108.79	280.5	102.71	240	850.01
Thaba-Putsoa	58.84	186.9	108.94	259.7	114.13	241.9	132.67	249.6	1005.44