University of Nairobi

School of Engineering

Application of GIS for Estimation of Water Runoff Volume in Water Collection Sites

Case Study: Northern Collector Water Tunnel

BY

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Declaration

I, Noah Kimeli, hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

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Name of student	Signature	Date

This project has been submitted for review with my approval as university supervisor.

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Name of supervisor	Signature	Date

Dedication

Most importantly, this research project is devoted to my loving parents, Joseph K. Chebii and Milka J. Songol who have always believed in me throughout my academic life. Secondly, to my siblings Alex, Fredrick, Festus, Maryline, Weldon and Eliah who have always encouraged me towards accomplishing this research project. Lastly, to the entire family at large. God bless you!

Acknowledgement

I thank the Almighty God for health, sanity, intelligence and spiritual nourishment since the start of this course up to this level. I likewise thank my family for their unending affection, encouragement and support i.e. emotionally, physically, financially and spiritually. I also thank all my lecturers who have worked tirelessly to ensure that I am equipped with vast knowledge and skills that are relevant in the current competitive and dynamic digital generation. To my able supervisor B. M. Okumu, I say thank you for your enormous timely help and guidance all through. Special thanks to my friends and colleagues for their individual input into my research together with their encouragement and support.

Abstract

Surface runoff is a single most significant hydrological variable that is utilized in many civil works, planning for optimal usage of reservoirs, shaping rivers and flood control. Prediction and quantification of catchment runoff is a basic challenge in hydrology. In this study, estimation of floodwaters by Soil Conservation Services-Curve Number (SCS-CN) method using GIS was conducted. The important parameters include land use map, hydrologic soil groups, daily rainfall data and Digital Elevation Model (DEM). The land use data was derived from Landsat satellite images. Hydrological Soil Group (HSG) thematic map was also prepared based on the soil type, infiltration rate and percentage slope. A spatial union between the land use and HSG datasets was created to obtain Soil-Vegetation-Land use (SVL) complex which was then assigned the Antecedent Moisture Condition II (AMC II) Curve Numbers (CN) values based on respective classes. Weighted-CN was calculated as the product of CN-values and percentage areal coverage of respective classes hence resulting in a runoff potential map. Using daily precipitation data recorded in a weather station, sum of five-day prior precipitation was computed to give the AMC for each day. Revision of weighted AMC II was done based on AMC results. Direct daily runoff depth in the watershed was then computed using SCS-CN equation. The depth was later converted to runoff volume. It was revealed that runoff potential of the watershed is increasing at a very slow rate due to insignificant changes in land use. The annual runoff volume was found to range between 7,120,686.458M^3 during the period of low rains to 95,632,370.51 M^3 during heavy rains. When daily runoff was computed from these results, the daily floodwaters volume was found to be comparable with the NCT value that was used to validate the results.

Keywords: Surface runoff, SCS-CN, GIS, HSG, SVL complex.

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List of Acronyms

Above Sea Level:	ASL
Antecedent Moisture Condition:	AMC
Curve Number:	CN
Geographic Information Systems:	GIS
Geospatial Hydrologic Modelling Extension:	HEC-GeoHMS
Hydrologic Soil Cover Complex:	HSCC
Hydrological Soil Group:	HSG
Infiltration Rate:	IR
Land Use Land Cover:	LULC
Northern Collector Water Tunnel:	NCT
Soil Conservation Services-Curve Number:	SCS-CN
Survey of Kenya:	SoK
United States Department of Agriculture:	USDA

CHAPTER 1: INTRODUCTION

1.1 Background

Runoff is the flowing or draining of rain water from a catchment area though a surface channel after satisfying all surface and sub-surface losses (Bhange, et al., 2014). Rainstorms usually generate runoff whose occurrence and quantity are determined mainly by the distribution, duration, intensity and the characteristics of the rainfall event. Also, soil type, vegetation cover, slopes and catchment type affects the occurrence and volume of runoff.

The essence of estimating surface runoff is to provide important information on planning of water conservation measures, reducing the flooding hazards downstream which result in sedimentation, recharging the ground water zones, and assessment of water yield potential of the watershed. Watershed or catchment is an area covering all the land contributing runoff water to a common point known as pour point (Bhange, et al., 2014).

Successful planning for a precipitation harvesting system must entail determination of Runoff behaviour. Early researchers on water harvesting often reported outcomes as an "annual percentage" which was pronounced as the proportion rainfall that ran off annually (Evett & Dutt, 1985). However, (Shanan & Tadmor, 1979) warned against the use of annual runoff percentage in the design of micro-catchment systems. (Hollick, 1982) stated the weakness grieved by the annual runoff percentage as inability to gives an indication of the relationship between rainfall intensity, runoff and duration hence limiting extrapolation to drought years or new areas.

Recently, GIS and remote sensing has proved to play a vital role in runoff modelling and identification of optimal sites for water harvesting or recharging structures (Padmavathy, et al., 1993; El-Awar, et al., 2000; Ravishankar & Mohan, 2005; De Winnaar, et al., 2007). Hydrological modelling can hardly be performed without the incorporation of GIS as a tool due to its capacity to manage a large amount of spatial and attribute data (Bhange, et al., 2014).

Attempts to estimate land cover parameters essential for runoff generation from remotely sensed data to up-scale field-based studies have been reported to be successful. Recent advances in spatial data processing in a GIS environment and remote sensing of land use/cover have led to the use of remotely sensed data in hydrological modelling (Senay & Verdin, 2004). Most of the work on adoption of remotely sensed data in hydrologic modelling has involved the use of SCS-CN runoff model due to its dependence on landcover material which is crucial when it comes to runoff.

The most widely used approach for fast and accurate determination surface runoff within a watershed is the Curve Number method (SCS-CN). It involves the use of a simple empirical formula and readily available tables and curves. The curve numbers are determined by the hydrologic soil group (HSG) and land use. A small curve number means little runoff and high infiltration while a high curve number implies high runoff and low infiltration. The most unique thing with this method is its ability to incorporate the land use factor in the computation of runoff from precipitation data (Shadeed & Almasri, 2010).

Water harvesting is a process of gathering and storing of surface runoff from a catchment area. It is a common practice in arid and semi-arid regions because they act as a source of water for diverse purposes when alternative sources such as wells, springs or streams dry up (Fraiser, 1980). (Rockstrom, 2000) presented an overview of different water harvesting methods in smallholder farms in Eastern and Southern Africa. Through this research, it was emphasized that ponds are among water storage structures that are rated highest in minimizing the danger of crops failing due to unpredictable rainfall in comparison to other water harvesting techniques.

The SCS-CN approach has constraints that can be calibrated or modified for localized conditions. These constraints include the threshold antecedent soil moisture values (Mitchell, et al., 1993) and the initial abstraction (Sharama & Kumar, 2002). With modifications that assigned appropriate curve numbers to local specific cover types, researchers such as (Artan, et al., 2001) together with (Colombo & Sarfatti, 1997) have successfully demonstrated the application of the SCS CN Technique for estimation of runoff in African environments.

Water has proved to be a vital necessity in social and economic development. The human population of Kenya and more specifically Nairobi City is ever increasing thereby raising the water demand required for domestic, industrial and other uses. However, the amount of rainfall, surface and sub-surface water sources available has either remained constant or declined over time. This has resulted in over-exploitation of these water sources hence leading to declining water table levels and water quality deterioration. Harvesting of surface runoff is hence the only untapped potential that can be utilized to salvage the situation by increasing water availability and recharging the water table in the process.

1.2 Problem Statement

The Northern Collector Water Tunnel has been surrounded by many Controversies. However, the primary concern raised pertains the viability of the project based on the availability of the floodwaters along the three rivers (Irati, Gikigie, and Maragua) being focused on the project. Some of the project critics question the volumes of water along those rivers during the rainy seasons and have raised concerns that the project might interfere with the normal flow of the three rivers.

As per the design specifications of the intake structures elaborated in NCT commissioning booklet, it's clear that the Project will mostly abstract flood waters. This will help in lessening adverse effects of flooding downstream and associated landslides. Moreover, to guarantee constructive results in terms of water use with minimal effects downstream during heavy rains, the NCT project design has been limited to cumulatively abstract only forty three percent of the maximum floodwaters leaving fifty seven percent available for other investments in the storage infrastructure. This will ensure irrigation and storage reservoirs are not affected.

The Athi Water board dispute is that only "excess" flood water will be diverted to the tunnel. But what exactly is "excess"? It is due to this reason that this study is going to utilize geospatial techniques (GIS and Remote Sensing) and try to quantify the "excess" floodwaters that are under dispute. From multitemporal drainage patterns observation, the average maximum floodwater at the three rivers abstraction points according to NCT booklet is estimated to be 1,198,368m3/day, and NCT will abstract 513,388 m3/day. However, the process of arriving at the values has not been justified. This study estimated the runoff volumes for four epochs with varying rainfall amount.

1.3 Objectives

1.3.1 The Overall objective

To estimate the annual runoff potential of Northern Collector Water Tunnel project watershed by applying Soil Conservation Service-Curve Number (SCS-CN) method using GIS.

1.3.2 The specific objectives

- To investigate the impacts of changes in land use/cover on the rate of runoff
- To assess the relationship between the amount of rainfall and corresponding resultant runoff
- To investigate the applicability of SCS-CN method to the Kenyan environment.

1.4 Justification for the Study

For a watershed to be properly managed, it is essential that the amount of runoff yield should be accurately estimated to establish its potential hence minimising chances of overexploitation which might result in adverse impacts (Gajbhiye, 2014). The water supply from rivers and other available sources is not sufficient and has been overexploited. Thus, for the usage of available water to be made efficiently to meet the people's need and demand, other methods of water harvesting should be devised. Harvesting of flood water is one of the upcoming options which has not been fully exploited.

This research shades light on the average volume of annual flood waters that are capable of being harvested from the ongoing NCT project hence justifying its viability to the critiques. The use of geospatial techniques has proved from existing literature to have successfully been applied to investigate and model hydrology (Bhange, et al., 2014; De Winnaar, et al., 2007; Gajbhiye, 2014). The results of all these literatures show successful research with positive outcome representing the watershed runoff capacity.

Knowing the volume of the surface runoff within the study area will enhance the knowledge on the amount that can be harvested hence an indication of its ability to meet the demand gap that is currently experienced in Nairobi city. This will also act as a benchmark and an indication of the amount of deficit that will still exist after project completion. Knowing the shortage will help in planning strategies on other potential sources that can fill the gap.

The estimation of runoff volume can also act as an informational tool and assist in flood control, land use planning, locating suitable water storage structures, drainage systems design and for warning purposes in case of hazards.

1.5 Scope of work

Since the three rivers that NCT project is focused on are known to be falling within the same watershed, this research focused first at delineating the watershed. The watershed boundary generated was then treated as the extent of interest where all the analysis is done. SCS-CN method was used as the method to determine the runoff volume that occurs from precipitation. To achieve this, land use and land cover classification was done and HSG generated from the soil classes. CN grid was then generated using hydrological modelling software available as an extension in ArcGIS software. Runoff was then calculated using daily precipitation data recorded in the nearest weather station.

Runoff was determined for four epochs (years; 2000, 2003, 2010 and 2015). All these epochs had different amount of rainfall ranging from high to low levels. This was intended to establish the fluctuations that are likely to occur in the amount of flood waters that are likely to be harvested within the watershed. To achieve this, land use/cover classification was performed for all the epochs. This was necessary because changes in land use has a significant impact on the runoff.

The research considered only the major watershed formed by the three rivers focused in the NCT project to determine the combined flood waters contributed by the combined sub watersheds at the pour point. The confluence of the three rivers was treated as the pour point where the flood waters from the three rivers exit the watershed. This is the point where the runoff volume was determined.

The approach differs from the existing situation in the NCT project being implemented because the project utilises intakes at each river and uses tunnels to allow the water flow by gravity from one river to the next river intake. This implies that the project abstracts water from the sub watersheds rather than the major watershed. The major watershed was chosen for this research because it reflects on the wholistic nature of the water to be harvested and easy comprehension when treated as one. Also, due to their small areal coverage, the sub watersheds could require high resolution data which was out of reach. Lastly, the volume available for validation of the results is a combined value of the three rivers without statement on value for each river.

The research however does not in any way dwell on the location or design of the collector tunnel. It only determines the potential yield in terms of flood waters. It does not also estimate the potential volume of each river other than the combined volume which results after the three rivers have joined together.

1.6 Organization of the Report

The report has five chapters and a list of appendices. Chapter one provides an overview of the area of study by providing some background information. It also states the gaps to be filled under the problem statement including overall and specific objectives. The justification and scope of work is also dealt with under this section of the report.

Chapter two covers the literature reviewed during the research process. It considers the runoff formation process and explains different factors that determine rate of water runoff. It also explains different methods of determining surface runoff.

Chapter three presents the materials and methods of the research. The area focused by the study is first depicted geographically and explained vividly. The materials are explained in terms of the data and software that were used. The methodology is then summarised in a flow chart then explained logically starting from the respective datasets and the analyses performed on them until final runoff depth is arrived at. The conversion of the runoff depth into runoff volume is also explained.

Chapter four delivers the results of the research and discusses them. The results are explained in terms of the findings on the factors that were considered including the watershed, the soil map, land use/cover maps and statistics, curve number maps, runoff depth, runoff volume and validation of the findings. All these findings are discoursed under the discussion section.

Chapter five has two sections. The first section is the conclusive remarks of the research and the second being the recommendations on areas that were perceived to be better fostered through research.

CHAPTER 2: LITERATURE REVIEW

2.1 Rainwater runoff

This refers to the gravitational flow of a portion of precipitation on or below the surface of the earth (Rientjes, 2004). This occurs ideally within a watershed, which is an area draining water through a single exit point known as the pour point. The final amount of water available for runoff is determined by the surface and subsurface loses that occur to the level of reaching water balance state for the excess amount to occur as runoff (Mishra & Singh, 2003). These water flow and accumulates within the lowest points of the channel which act as flow paths to drain away as stream flows or rivers.

Runoff is directly affected by the rainfall amount, ground permeability, vegetation covers and slope of the surface. Some human activities over time have also been found to increase runoff. Some of these activities include urbanization and large infrastructure networks. These human practices increase the percentage of impervious surface which discourages percolation hence forcing most precipitation water to flow straight away into streams or drains.

The increasing amount of water runoff has led to increase in the negative impacts that accompany them. They include soil erosion and deposition, pollution of water and soil, loss of agricultural chemicals like fertilizers and floods in the downstream (Ward & Robinson, 1990). This has necessitated impose on mitigation measures which to some extent are expensive. The measures can be in many forms ranging from flood controls to land use planning and control. They are all aimed at minimizing the hazards which might occur (Morgan, 1995).

2.2 Surface runoff in a watershed

This stands for the part of rain water that is retained after interception loss, infiltration, evapotranspiration and surface storage. This water then flows to a stream through the earth's surface (Morgan, 1995). Vegetation canopy intercept some of the falling rain and what remains thereafter falls onto the ground surface as through fall (White, 1997). The intercepted rainwater may either evaporate or drop to the ground if rainfall proceeding is heavy and continuous. Leaf drainage and stem flow can also occur because of canopy storage capacity being exceed. This is a clear indication that the vegetation cover together with rainfall trend of a place in a way determines the quantity of rainwater losses (Dingman, 2002). The water lost in this process is known as interception loss.

The precipitation drops that touches the soil surface can either penetrate, evapo-transpire or become stored in depressions within the ground surface. What remains after all this becomes the surface runoff. It is a common occurrence after the soil saturation is achieved. After surface storage becoming full and precipitation rate being higher than infiltration rate, gravitational flow of water occurs (Morgan, 1995; Ward & Robinson, 1990; Mishra & Singh, 2003). Sometimes the soil might be already saturated by previous storms hence most of the precipitation becomes runoff.

2.3 Properties of soil influencing infiltration

This explains the rate of water absorption by the soil after downpour. This generally act as a way of ground recharge and in the process determining water availability for runoff (Schwab, et al., 1981; Morgan, 1995). Several properties of the soil including soil porosity, texture, structure of the soil aggregates, organic matter content, and moisture holding capacity (Solomon, 2005; Morgan, 1995) come into play to determine infiltration status.

For water to flow through the soil, its porosity acts as the determining factor together with related aspects like particle size and aggregates arrangement (Dunne & Leopold, 1978). The geology and areas landforms contribute to the soil structure of a place (Hillel, 1980). Manmade activities aimed at better management of a watershed can as well influence the soil properties (Brady & Weil, 1996; White, 1997).

The determining factor for soil to be able to allow water down its profile through infiltration is called hydraulic conductivity (White, 1997). Forces responsible for the process are suction and gravitational head gradient. Suction is important at start of rain when the soil is dry while the later force comes into play after the soil becoming saturated with water. Saturated hydraulic conductivity will occur when the rainfall amount exceeds the rate of soil absorption hence causing ponding. Any water added to the soil will exceed capacity of storage hence resulting in surface runoff (White, 1997; Hillel, 1980).

Saturated soil hydraulic conductivity varies with soil types. Soils rich in clay content tend to have less values than course texture soil such as sand. This make clayey have lower infiltration rate of up to 5mm/h compared to coarse textured soils like sand which will have 200mm/h (Morgan, 1995). Compact soil will have lower conductivity when compared with loose soils (Hillel, 1980).

2.4 Land Use and Land Cover Changes in relation to surface Runoff

Human developments and vegetation cover influence the processes through which rain water pass through before encountering the soil surface. These processes obviously lead to a series of water loses until a water balance state is achieved for runoff of excess water to take place. In this way, significant changes are taking place in the rate at which runoff is generated and these changes mostly lead to increased runoff which in the process leads to increased soil erosion and land degradation (Morgan, 1995).

Soil compaction alters the soil profile by distracting the arrangement of components such as particles and aggregates (Schwab, et al., 1981). It also makes the soils tightly packed thus lowering the infiltration rate and leads to generally a different structure from what existed (Hillel, 1980). Such human practices are believed to drive the dynamism in the rate at which runoff volumes of developing areas is changing rapidly and causing unexpected hazards such as floods in some rapidly developing places (Dijck, 2000; Hillel, 1980).

The vegetation act as a blanket that covers the soil and prevents it from exposure and in the process, enhances infiltration of water into the soil. Negative changes in land use/cover leaves the soil uncovered hence increasing susceptibility to detachment when heavy precipitation fall due to direct contact (Hillel, 1980; White, 1997). In the process, flowing water cause clogging of finer particles pore spaces of the soil creating thin compact layer preventing infiltration of water into the soil (Schwab, et al., 1981). This eventually leads to increased water runoff on the surface.

Vegetation therefore is well known for reducing flow velocity of water hence reducing impact it causes on the soil. The soil structure is there for preserved due to less impact. Plant roots and dead leaves further strengthens the soil particles by holding them together. This leads to hardening of the soil structure thus inhibiting infiltration of water into the soil (Schwab, et al., 1981). This will lead to increased surface runoff.

2.5 Runoff modelling

There are several methods that has been devised to quantify runoff (Beven, 2000; Dingman, 2002). The most common approach being gauging a stream canal then measuring its water flow pattern over time. This method however does not take into consideration variation in land management practices such as LULC changes and soil on the magnitude at which runoff is created from diverse areas in a watershed. Because of the significant influence of dynamics in the catchment in terms of spatial and temporal heterogeneity, an ideal method should consider them during quantification process.

Mathematical formulas are widely used to model the real process of runoff under normal circumstances. This makes other models to be more precise when compared with others. Each model usually has the factors under consideration described mathematically in a form that can make quantifiable predictions (Beven, 2000; Rientjes, 2004). The factors involved vary widely over small distances. It is never possible to consider all factors at all instances due to the variations but instead, the mean of values showing similarity is utilized. This is a clear indication of one of the many assumptions that are involved in these models whether empirical, physical or both (Beven, 2000).

Physical models are hard to accomplish because most of the parameters are achieved through measurement or observation. This implies that the process is prone to errors and blunders due to limitation of the investigator, instrument or environmental factors (Deursen, 1995; Pfeffer, 2003). The errors introduced will finally contribute to the overall inaccuracy of the model hence limiting its reliability (Deursen, 1995). Simple empirical models on the other hand tend to be more general. This often leads to omission of some information (Beven, 2000). The two explanations justify that there is no single precise model that can fully accommodate all factors involved in nature to reflect the actual natural process of runoff.

For better result to be achieved, it should first start with identifying the problem at hand. Then recognition of the nature of the watershed should follow. Finally, simulate surface runoff while taking into consideration changes in LULC (Ward & Robinson, 1990; Deursen, 1995; Beven, 2000). This process can give better forecast by detecting areas which contribute more runoff. The information can be a valuable resource when planning for better catchment management practices. The choice of a suitable model will majorly be driven by the target of a research and other factors like accessibility of data, time and money.

2.6 Types of Runoff Models

They are broadly categorised into two classes namely lumped/ distributed and deterministic/ stochastic models (Ward & Robinson, 1990; Beven, 2000).

The lumped modelling methods consider a watershed as an individual unit with only one mean value representing it entirely and generates unique forecast values (Beven, 2000). Distributed modelling approach make spatially distributed forecast where variables are visualized by varying or invariable grid cells carrying the averaged values unlike lumped method which uses only one averaged value (Rientjes, 2004). Each grid cell is applied the equation hence giving distinct results for each cell hence facilitating monitoring of factors affecting runoff that vary with space such as land use and land cover (Beven, 2000).

Stochastic/probability models focus at the possibility of hydrologic variable occurring (Ward & Robinson, 1990). Its input and output variables are in form of probability density distribution. The possible outcome of this method is uncertain and random but this is allowable due to the risk that is presented by model input variables (Beven, 2000; Rientjes, 2004).

Most runoff models utilize deterministic models which dwell on the imitation of the physical procedures taking place in the cycle that take place from precipitation to runoff. Only a single set of values are entered per variable into the model hence resulting into single set of values (Rientjes, 2004).

2.7 Soil Conservation Service-Curve Number (SCS-CN) Method

The SCS-CN approach was utilized for the accomplishment of the research. This method entails the use of an equation to make estimates of runoff depth that occurs after precipitation. The equation is empirical based and was developed in United States through observations on rainfall runoff data collected from different regions over extended duration of time (Beven, 2000; Mishra & Singh, 2003; Shadeed & Almasri, 2010). The selection of this method for this study was arrived at due to the simplicity and less demands when it comes to data requirements. It is further boosted significantly by the accessibility of readily tabulated CN values (Appendix A) for a broad range of soil groups and land use/cover patterns which act as a guideline (Mishra & Singh, 2003).

The approach looks at the time distribution of precipitation and the initial precipitation losses to interception by objects, surface storage in pools and soil infiltration rate that diminish over a period of a rainfall occurrence (Gerlach et al., 2003). Some amount of rainfall will not contribute to a runoff till all the demands of the initial abstraction (I_a) are met. Hence the potential runoff is given by ($P-I_a$). After water becoming available for a runoff, some extra amount of water remains in the drainage area which is less or equivalent to the potential maximum retention (S).

Equation 3-1 below summarizes how rainfall, initial abstraction, the potential maximum retention and the additional water retained are expressed mathematically. When this method is applied in an iterative environment, it will result in surface runoff values varying both with location and time (Deursen, 1995; Shadeed & Almasri, 2010).

The universal equation of SCS-CN method (Mishra & Singh, 2003):

$$Q = \frac{(P-I_a)^2}{(P-I_a+S)} \qquad (2\text{-}1)$$

Where;

Q = runoff (inch)

P = rainfall (inch)

I_a = Initial abstraction (surface storage, interception, and infiltration, inch)

S = potential maximum retention (inch)

The I_a can further be expressed by the following empirical equation:

$$I_a = 0.2\,S \qquad (\,2\text{-}2)$$

Substituting equation 3-2 into equation 3-1 gives:

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \qquad (2\text{-}3)$$

P is a measurable quantity and can easily be obtained. However, S is hard to determine. As a result, the runoff curve number is used to establish S based on the following relationship:

$$S = \frac{1000}{CN} - 10 \qquad (2\text{-}4)$$

Where;

CN = runoff Curve Number

Appendix A is the table with values where the *CN* is derived from basing on the soil condition, land use/cover, and treatment of an area. This is where it is referred to as localization of the variables to reflect an area being studied. The larger the CN value, the greater the runoff potential and vice versa. The initial wetness of the soil, also known as AMC can also be put into consideration in this approach. Once the *CN* is identified based on land use/cover and the type of soil in an area, equation 3-5 below can then be used to adjust the *CN* values for moisture condition (AMC).

$$CN_{adj} = \frac{23CN}{10+0.13CN} \qquad (2\text{-}5)$$

This equation is used for a study in which the daily precipitation data is not available.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location and Description

The research focuses on the Northern Collector Water Tunnel (NCT) project which is situated within Murang'a county in central Kenya. The county resides in a total area of 2,558.8Km^2. NCT anticipates harnessing floodwater from three rivers shown in Figure 3.1 below, namely Maragua, Gikie, and Irati, which are within the same watershed with their source being Aberdare forest. The area extends between latitudes 0º33'30" S and 1º5'20" S, and longitudes 36º41'00" E and 37º25'20" E. Its proximity to Nairobi city and the fact that it has numerous rivers has made it to be recognized as the primary source of water to meet the rising demand.

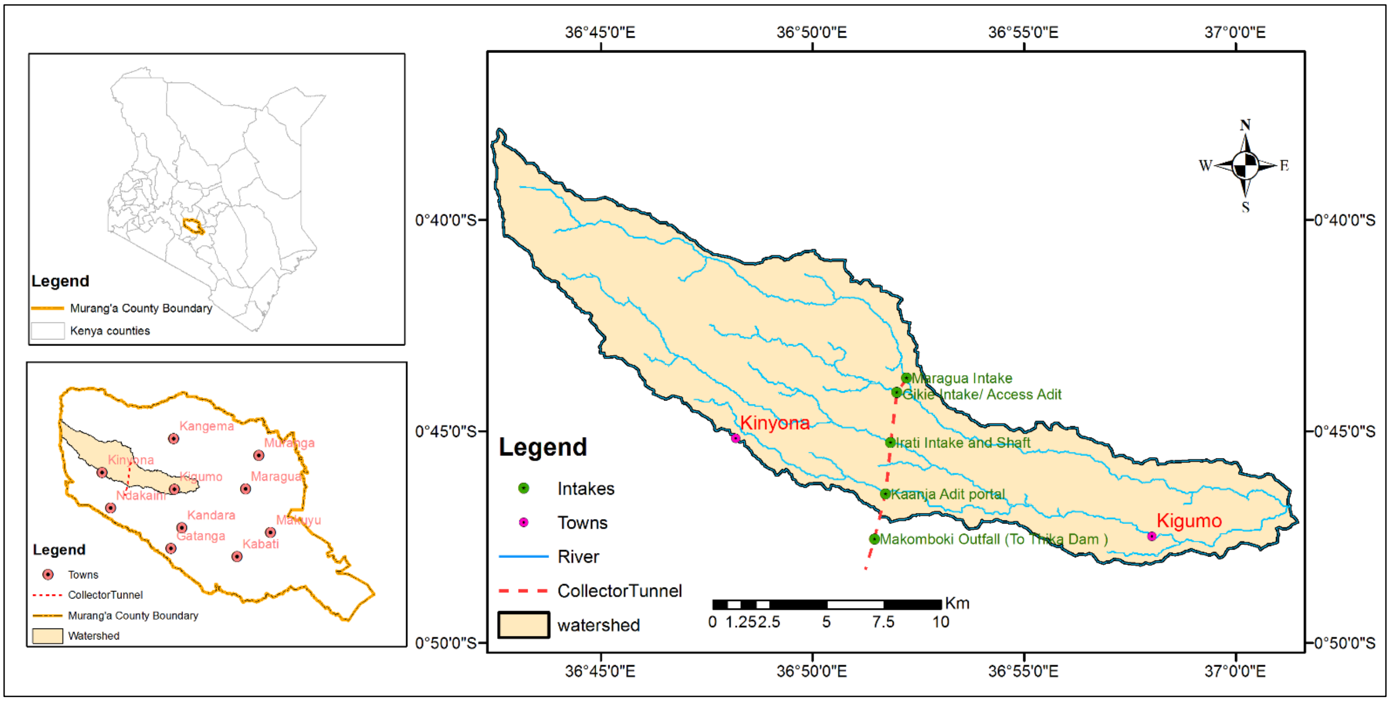


Figure 3.1: The Study Area

The watershed being within the Aberdare ranges and proximal to Mount Kenya, experiences an equatorial type of climate making it wet and humid. The months of March, April, and May receive long rains while October and November receive short rains.

The watershed falls approximately 3,353m Above Sea Level (ASL) and experience extremely dissected topography which is drained by numerous rivers flowing from the Aberdare ranges to join the great River Tana. The soils are mainly volcanic hence highly productive and significant for agricultural activities. This explains why tea is the main crop grown within the watershed.

3.2 Materials

The materials used in the study are categorized into data and software. They are summarised in the following two subsections:

3.2.1 Data

The topographic map at the scale of 1:50000 prepared by Survey of Kenya (SoK) was utilized for delineation of rivers within the watershed and to digitize boundaries. The Landsat imagery with 30m resolution downloaded from USGS website was used to prepare the land use/cover (LULC) map of the watershed. Soil map made through Kenya soil survey of 1987 on 1:50000 was utilized. 30m resolution Aster DEM data was used to generate the slope and determining the extents of the watershed.

Table 3.1: Data and their sources

Type of Data	Scale/Data Resolution	Source of Data
Rainfall	Daily Nyeri Station Precipitation	Kenya Meteorological Department
Landsat data	30m (2000,2003,2010,2015)	www.earthexplorer.usgs.gov
Soil	1:250,000	ILRI (Kenya soil survey 1987)
Toposheets	1:50,000	Survey of Kenya
Aster DEM	30m	DRSRS

3.2.2 Software

ArcGIS 10.4 software was utilized for creating, handling and generation of different layers and maps. ERDAS Imagine 2014 was utilized in generating LULC maps due to its better accuracy in land use/cover analysis compared to other GIS software. The Geospatial Hydrologic Modelling Extension (HEC-GeoHMS) for ArcGIS was used for hydrologic modelling. Microsoft excel was utilized in mathematical computation of runoff depth from the daily rainfall data.

The modelling approach that was used to model runoff is the Soil Conservation Service-Curve Number (SCS-CN) Method. The approach was selected because of its elementary nature in terms of data necessary and due to the element that it considers the impact of land use/cover dynamics while deriving the parameters (CN) used to compute excess precipitation.

3.3 The Methodology

The runoff was predicted with the help of hydrological model utilizing USDA (United States Department of Agriculture) procedure for estimation of surface runoff using SCS-CN (Soil Conservation Service Curve Number) method. Figure 3.2 below shows the methodology adopted;

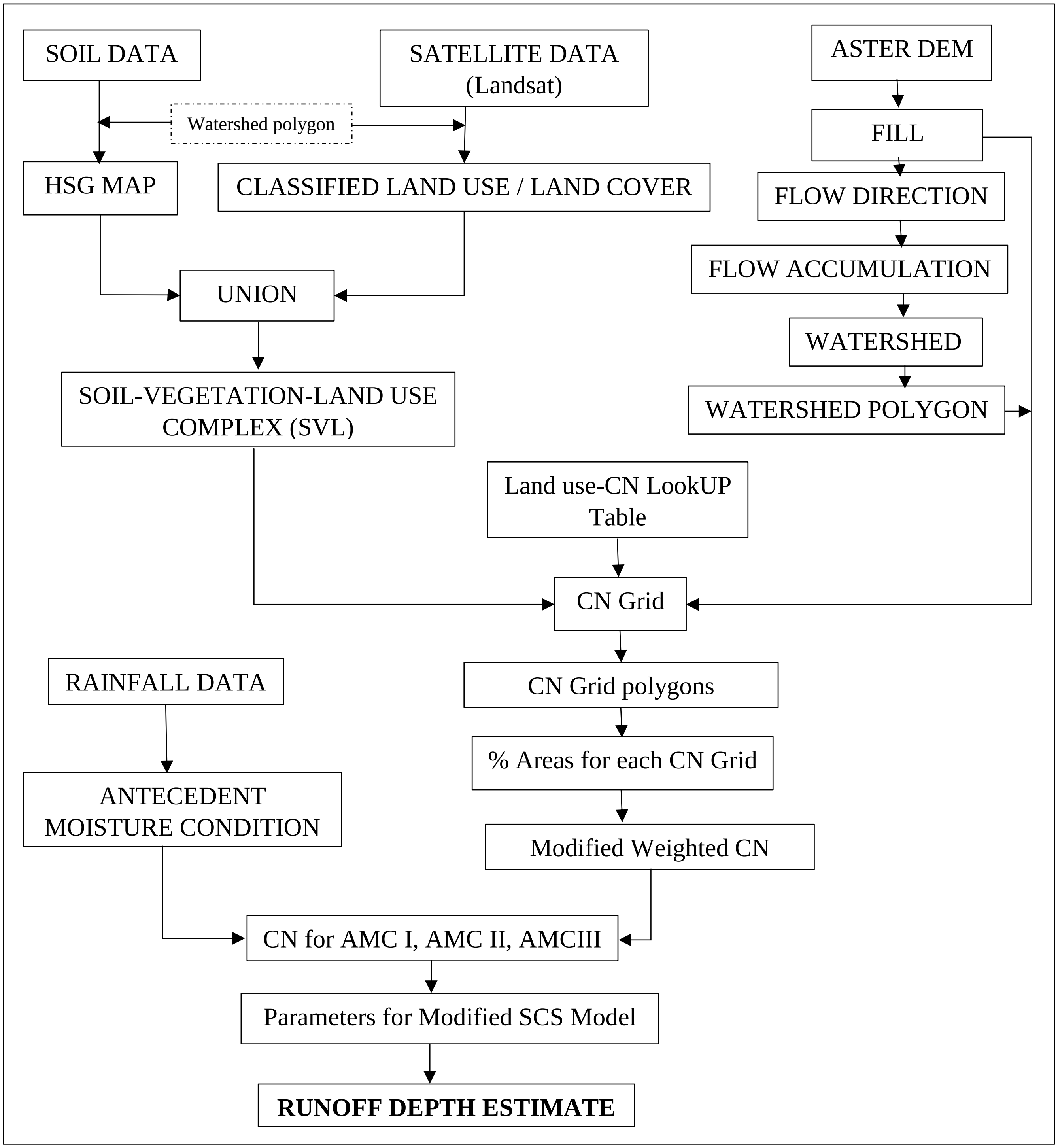


Figure 3.2: The methodology flow diagram

3.3.1 Watershed Delineation

The extraction watershed extent for the three rivers was done using ArcGIS 10.4 software. To accomplish this, *ArcToolbox* was opened from the main menu. *Spatial Analysis Tools > Hydrology* was expanded to view the important tools required for the process. First, the *Fill* hydrology tool was used to eliminate imperfection (sink) in the DEM. The DEM was specified as input and the fill layer as the output. *Flow Direction* tool was used to create grids representing flow direction within the cells. The filled DEM was used as the input and the output is the Flow Direction Raster.

Flow Accumulation tool was then used to calculate the flow into each cell. Flow direction raster was specified as the input at this stage and flow accumulation raster as the output. The flow accumulation raster was reclassified into two classes, one with accumulation values less than 5000 and another class with values greater than 5000. The values greater than 5000 represented the stream paths which form the river. The point where the three rivers under consideration exited was identified as the pour point of the watershed. A new point feature class representing the pour points was then created by right clicking the geodatabase and selecting *New > Feature Class*. Editor for the new feature class was started and the pour point digitized. The edits were saved and editing mode stopped.

Snap Pour Point tool was used to establish the three sub-watersheds. Flow accumulation raster was specified as the input together with the pour points created and the resulting layer represents the watershed with defined pour pont. Finally, the watershed tool was clicked and specification of flow *direction raster* and *feature pour point* data as inputs and the output will be the raster representing the watershed. The watershed raster created was then converted to polygons using the tool from *ArcToolbox > Conversion > From Raster*.

3.3.2 Preparation of Various Thematic Maps

The different thematic maps that were prepared using ERDAS Imagine 2013 and Arc GIS 10.4 are the soil map, land use/cover classification maps and the curve number maps.

3.3.3 Soil Map

SCS developed soil classification system that consists of four groups, which are identified as A, B, C, and D according to their lowest infiltration rate. ***Group A*:** Soil having high penetration rate and low runoff potential when thoroughly wet. Water is conveyed freely through the soil; ***Group B*:** Soil having moderately moderate infiltration rate and low runoff potential when thoroughly wet. Water conveyance through the soil is medium; ***Group C*****:** Soil having low penetration rate and moderately high runoff potential when thoroughly wet. Conveyance of water is somewhat restricted through the soil; ***Group D*****:** Soil having very low infiltration rate and a bit high runoff potential when thoroughly wet. Water conveyance is limited through the soil.

Based on (Mishra & Singh, 2003), the soil was categorized into their respective HSG as shown in Table 3.2 while considering texture, percentage slope and infiltration rate (IR) of the soil. A field was added in the soil attribute table and the respective hydrological groups keyed in.

Table 3.2: The Hydrological Soil Group Classes within the study area

Texture Class	%Slope	**IR (Inches/Hour)**	**HSG**
Clay	Over 16%	0.03	D
Clay Loam	Over 16%	0.06	C
Sand Clay	Over 16%	0.08	C
Silty Clay	Over 16%	0.05	D

Because the Curve numbers are assigned by HEC-GeoHMS ArcGIS extension which uses lookup table to perform computations, four additional fields required to normalise the respective HSG were added as percentages. The fields were labelled PctA, PctB, PctC and PctD standing for abbreviations to the percentages of the soil groups. A value 100 is assigned where CN field value coincides with percentage values for example C and PctC or D and PctD. All other fields are assigned a value of zero. The fields were useful when assigning Curve Numbers with the help of lookup tables during computations.

3.3.4 Land Use Land Cover (LULC) Classification

Land use/cover classification was done using unsupervised classification method by use of four classes namely Forest, Agriculture, Built up areas and Shrubs/Rock. This method of classification was chosen due to its unique ability to distinguish clearly and precisely all reflectance values contained in a multispectral imagery. Each image was classified separately by use of Erdas Imagine software as follows:

All the Landsat images were first layer stacked using the tool found under *Raster* > *Spectral* > *Layer* Stack option. All the bands were added independently as input files after choosing *'.Tiff'* format under the *files of type* option. Output location for the resulting multispectral imagery was then specified and union function was chosen. This was repeated for all the epochs.

The multispectral imagery was then loaded to the viewer window by right clicking on viewer and choosing *open raster layer* then browse to directory and opening it. The watershed shapefile was also loaded in the same window through the same process as for the multispectral imagery but choosing the *Open Vector Layer* option instead. Select tool from *Raster > Select* was then used to highlight the shapefile then the selection was copied and pasted to *Aoi* (Area of interest) using Copy and Paste option available under the *Home tab*. The *Aoi* was then saved by right clicking it in the contents menu and choosing *save as Aoi* option.

Subseting of the layer stacked images was then done using the tool found under *Raster > Subset & Chip > Create Subset Image.* Multispectral images from the layer stack was chosen as input. Output location was specified and Aoi created specified as the extent. This step was repeated for all the four epochs under consideration in the study.

The classification of the year 2000 Landsat imagery started with the launch of *Raster > Unsupervised > Unsupervised Classification* tool from the main menu. The subset for year 2000 was chosen as *Input Raster File* and the resulting classified raster layer saved the output. *K means* method of classification with *eight classes* was used for this epoch. The eight classes were later recoded into four classes using *Raster>Thematic>Recode* tool. The recoded image was later smoothened using neighbourhood tool from *Raster>Thematic>Neighbourhood* using majority pixels and 3x3 window size.

Classification for the years 2003, 2010 and 2015 was performed similarly as explained above (in year 2000 classification) but the number of classes generated through unsupervised classification vary. Nine classes were generated for the year 2003, sixteen classes for the year 2010 and seven classes for 2015. The choice of the number of classes was based on complexity of the reflectance of the respective images. Recoding was done on all images to achieve the required four classes that had been identified for this study. The recoded images were also smoothened using a majority pixels 3x3 window size. The statistics of land use and land cover were extracted from the raster attribute tables of respective classified and recoded images.

Accuracy assessment was then performed using ten random points per class. Google earth aerial images was used as ground truth data during the accuracy assessment.

3.3.5 Soil-Vegetation-Land Use (SVL) complex

This refers to the layer resulting from the overlay of LULC and HSG maps through a spatial Union. To achieve this, the LULC maps were first converted from raster to polygons in ArcGIS software using *Raster to Polygon* tool found in *ArcToolbox>Conversion Tools>From Raster>Raster to Polygon.* The input being the recoded images while the output being the resulting polygons. A new field was added in the land use attribute table then each land use was assigned unique Land use code in form of values ranging from one to four. These values would be required in HEC-GeoHMS processing.

LULC polygons and HSG were joined through ArcGIS spatial analyst *Union* tool found under *Geoprocessing* tools. Land Use and Soil layers were selected as inputs and the output being the union of the two layers. All polygons which did not overlay appeared with negative geometry in the attribute table and were deleted. The land use and HSG attributes will be mutually available for every polygon within the study area after the union of the two layers.

3.3.6 Generating Curve Number (CN) Grid

HEC-GeoHMS extension of ArcGIS was utilized at this stage since it involves hydrological modelling. To generate the CN map, the fill DEM, SVL complex and CNLookUp table are required as input datasets. The curve numbers for different cover classes and respective hydrological soil groups (Table 3.3) are pre-defined based on (Mishra & Singh, 2003) as shown in Appendix A. The CNLookUp table for this case is a table representing the AMC II values in different HSG as shown in Table 3.4 below. It works by creating a new raster by looking up values found in another field in the table of the input layer. For this case, the SVL complex polygon layer with land use number one and HSG D will be assigned a CN of 96 while a polygon of land use number four with the same HSG will be assigned a CN of 89.

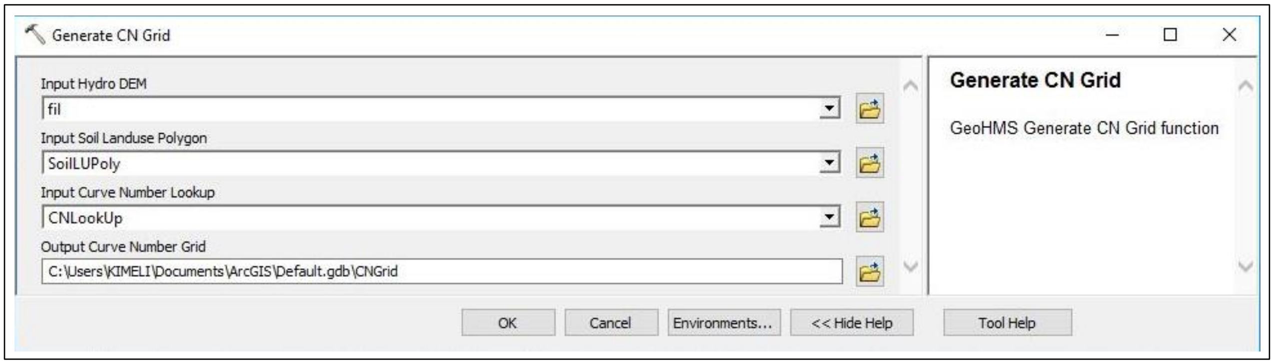
Table 3.3: Runoff curve numbers for hydrologic cover complexes (AMC II and Ia=0.02S) (Mishra & Singh, 2003)

Class	**Land use Description/treatment**	**Hydrologic Condition/% impervious area**	**Hydrologic Soil Groups**			
			A	**B**	**C**	**D**
Shrubs and Rocks	Arid and Semiarid rangelands: Herbaceous	Poor		80	87	93
Forest	Humid rangelands or agricultural uncultivated lands: Woods or forest land	Poor	45	66	77	83
Built-up	Developing areas: Newly graded areas (pervious areas only, no vegetation)		77	86	91	94
Agricultural	Row crops: Contoured	Good	65	75	82	86

Table 3.4: The LookUp table used to assign the AMC II CN to SVL complex

LULC		HSG			
LUValue	Description	A	B	C	D
1	Shrubs/Rock		80	87	93
2	Forest	45	66	77	83
3	Built-up	77	86	91	94
4	Agriculture	65	75	82	86

From HEC-GeoHMS toolbar in ArcGIS, go to *Utility>Generate CN Grid* then a dialog box was launched prompting for inputs and output location. Specify fill DEM, SVL and CNLookUp table respectively as input and browse to where to save the CN grid and name it then save as illustrated in Figure 3.3. The soil map and land use map were selected for a union. A map with new polygons representing the SVL complex map resulted. The corresponding CN values for each polygon of the complex map were then assigned.


Generate CN Grid

Input Hydro DEM: fil

Input Soil Landuse Polygon: SoilLUPoly

Input Curve Number Lookup: CNLookUp

Output Curve Number Grid: C:\Users\KIMELI\Documents\ArcGIS\Default.gdb\CNGrid

Generate CN Grid

GeoHMS Generate CN Grid function

Figure 3.3: Screenshot of the tool for generating CN Grid

Hilly areas are significant in terms of rainfall-runoff response. The rapid runoff response from steep slopes results in non-availability of water in peak demand periods, even if the average rainfall is high. For this reason, fill was derived from the DEM, which is the sink free DEM considered to be free from imperfections. This fill is important in the process of generating CN values because it played a significant role in determining the runoff direction and accumulation.

3.3.7 Preparations of CN Grid for Runoff Estimation

a) CN Grid polygons

The raster CN Grids generated were first converted to polygons to determine the total areas covered by specific CN. The areas are required to be used when calculating the weights.

b) Percentage areas for each CN Grid

At this stage, the areas obtained for the various CN are converted into a fraction of the total area of the watershed. This is equivalent to assigning a weight to each CN based on the total area it covers.

c) Modified Weighted Curve Number (CN)

All the percentage areas are multiplied by their curve number and divided by 100. The products of all the areas are added to give one overall weight representing the entire watershed. This is the modified weighted curve number that stands as the Mean CN representing entire watershed.

d) Assigning of AMC I and AMC III CN to weighted AMC II CN (in c) above

Since the weighted curve number value obtained was for AMC II, the other two AMC values were assigned from the table of AMC shown in Appendix B.

3.3.8 The Rainfall Data

In this research work, daily precipitation data documented over time in a weather station within vicinity from the watershed was used. Daily rainfall data was chosen because the AMC of the soil can only be computed using total precipitation for five successive days preceding a storm. The data was readily available in excel sheet hence making the computations easier.

3.3.9 Antecedent Moisture Conditions (AMC)

The Antecedent Moisture Condition (AMC) is simply the water content present in the soil at a specific time. It is the crucial effect on the flow responses in these systems during wet weather.

It was determined by summing the total rainfall recorded in five consecutive days before a storm. The AMC value is envisioned to imitate the consequence of infiltration on both the rate of runoff and volume according to the infiltration curve. An increase in the index means an increase in the runoff potential. The SCS established three antecedent soil-moisture conditions and categorized them as I, II, III, according to rainfall limits and soil conditions for dormant and growing seasons as shown in Table 3.5 below. This technique was helpful in rectifying the influence of soil moisture on the runoff potential of the area. It is also important to note that a greater percentage of the watershed was covered with forest and tea plantations hence for this reason, a growing season was assumed in the study.

Table 3.5: AMC for determination of CN value (Mishra & Singh, 2003)

AMC	Total Rain in Previous 5 days	
	Dormant Season	**Growing Season**
I	Less than 13 mm	Less than 36 mm
II	13 to 28 mm	36 to 53 mm
III	More than 28 mm	More than 53 mm

3.3.10 Estimation of Runoff Depth Using parameters for SCS Model

The runoff was calculated using rainfall data from Kenya Meteorological Department. The SCS Model also known as the Hydrologic Soil Cover Complex (HSCC) Model, is a useful and extensively used process for estimation of runoff. The model utilizes runoff producing capability expressed by a numerical value (Curve Number) varying between 0-100. This model was utilized in the study.

To materialize this, CNs were first assigned based on computed AMC that represents five-day precipitation. Potential maximum retention (S) was then computed using the equation (2-4). Subsequently, initial abstraction (surface storage, interception, and infiltration) was computed using equation (2-2). For all values with precipitation greater than the initial abstraction (Ia), the runoff depth was computed using equation (2-3) (Mishra & Singh, 2003). The result was daily runoff depth for all the specific days of the year.

3.3.11 Calculating the Runoff Volume

To convert the computed runoff depth into runoff volume, the units of the depth and watershed area were first harmonised. Thereafter, the area of the watershed was multiplied with the obtained runoff depth to give the resultant volume of excess water that will pass through the pour point of the watershed after precipitation (Bedient & Huber, 1992).

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 The Watershed

The total area of the watershed was found stretch approximately 208.3 square kilometers with its starting point at the peak of Aberdare ranges and the pour point of the three rivers being around Kigumo market within Murang'a County. The watershed has three major Sub watersheds in which the collector tunnel will be abstracting water from them. Figure 4.1 shows the watershed, rivers and the collector tunnel.

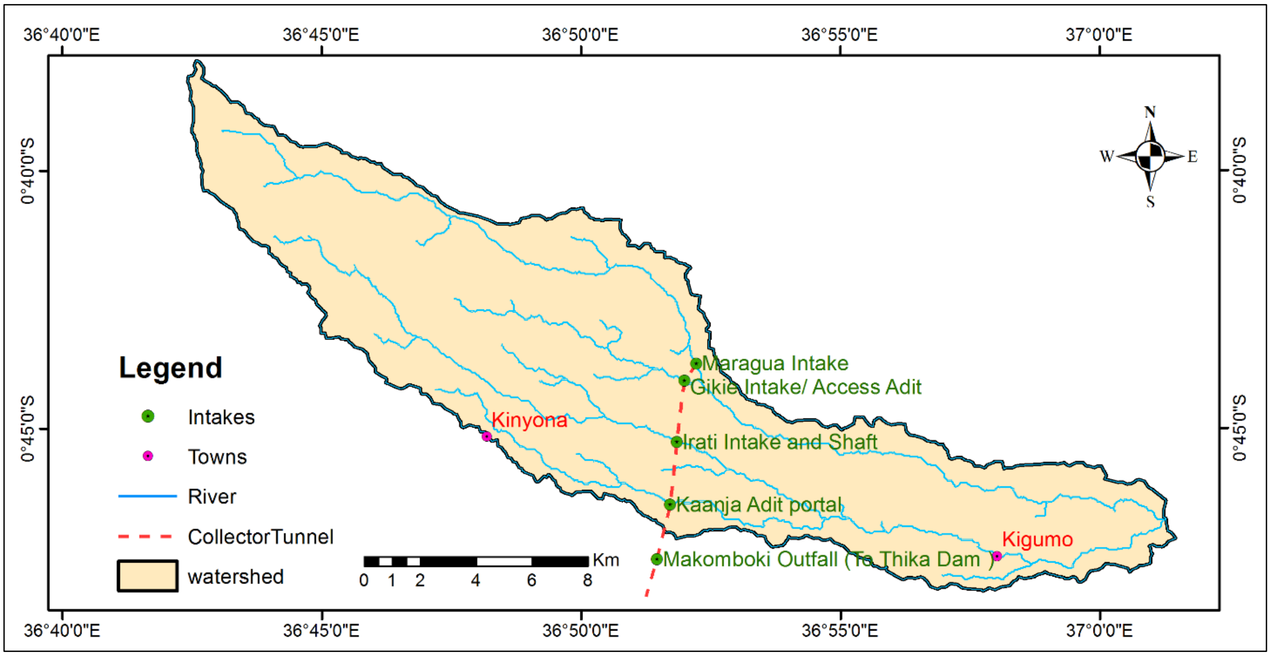


Figure 4.1: The Watershed and the Location of the Collector Tunnel

4.1.2 The soil Map

Clay soil of types montmorillonitic and kaolinitic were found to dominate the watershed as shown in Figure 4.2 below. Kaolinitic soil majorly concentrated on the lower parts of the watershed and comprised of types clay and silt clay textured soil falling under HSG D. Montmorillonitic soil were found to dominate the upper parts where the watershed starts and comprises of clay loam and sand clay textured soil falling under HSG C.

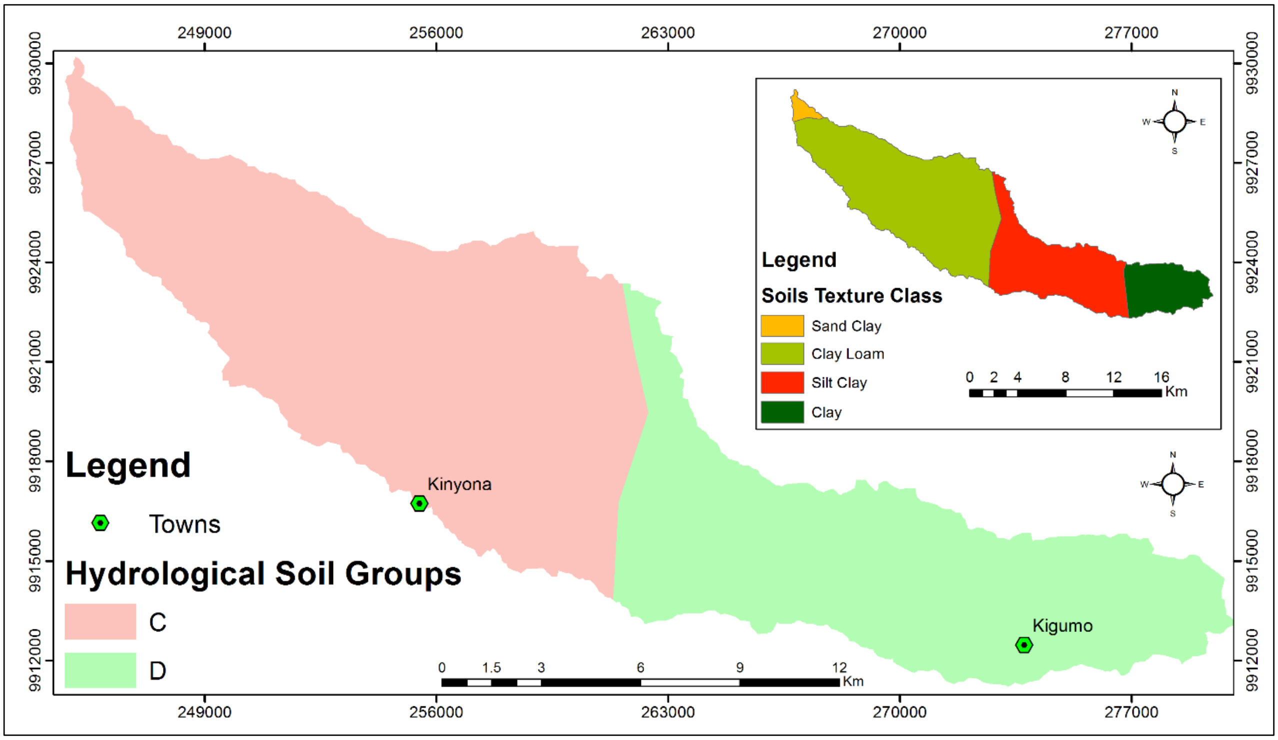


Figure 4.2: Hydrological Soil Group (HSG) Map with an Inset showing the Soil Texture Classes

4.1.3 Land use Land Cover Maps

The Overall Classification Accuracy of classification for the years 2000, 2003, 2010 and 2015 was found to be 87.5%, 97.5%, 90.0% and 87.5% respectively. Both the producer and user accuracies was also found to be greater than 70% in all the years. The user accuracies for the years 2000 and 2010 was slightly low because of limited clouds and cloud shadows that were obstructing some areas. These clouds remained after attempts to eliminate them however they were manually reclassified during classification with the help of ground truth data. Accuracies over 70% implies that the LULC results are reliable and reflect what is on the ground and the changes that occurred over time. Appendix C shows the accuracy assessment results for the different years.

The maps in Figure 4.3 and Figure 4.4 show the results of LULC that were obtained for the watershed over the four epochs that were studied.

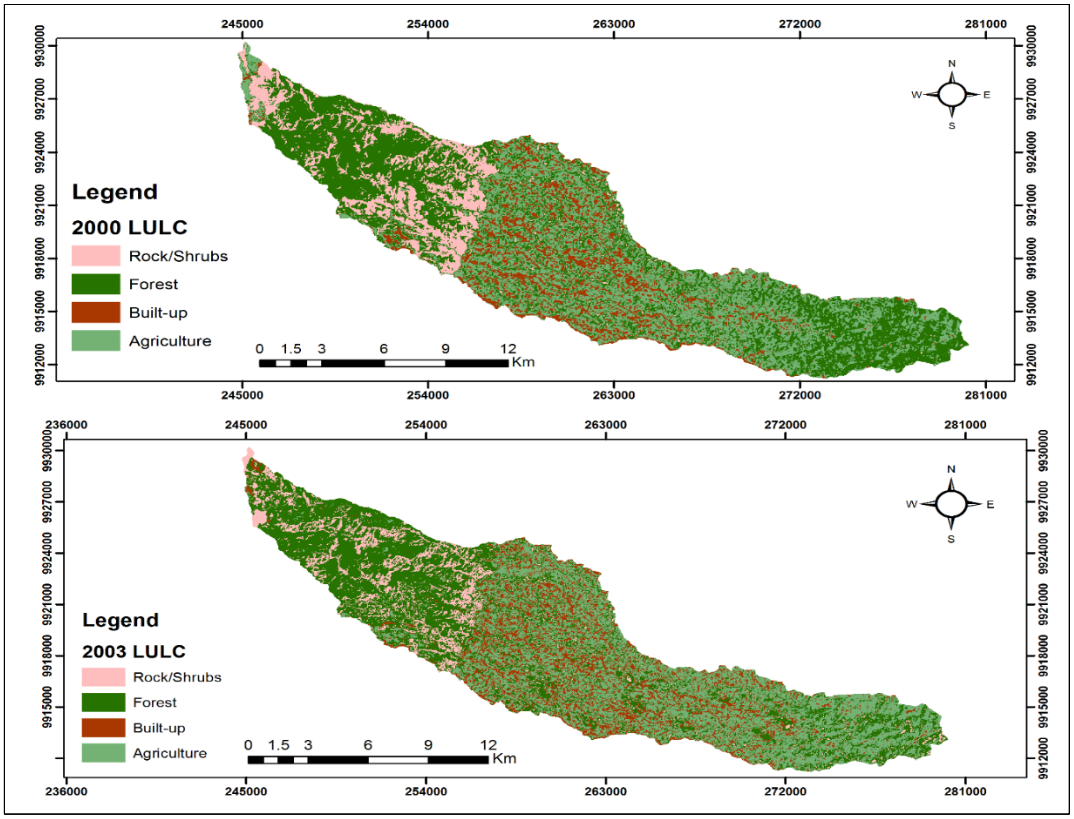


Figure 4.3: LULC maps for the years 2000 and 2003

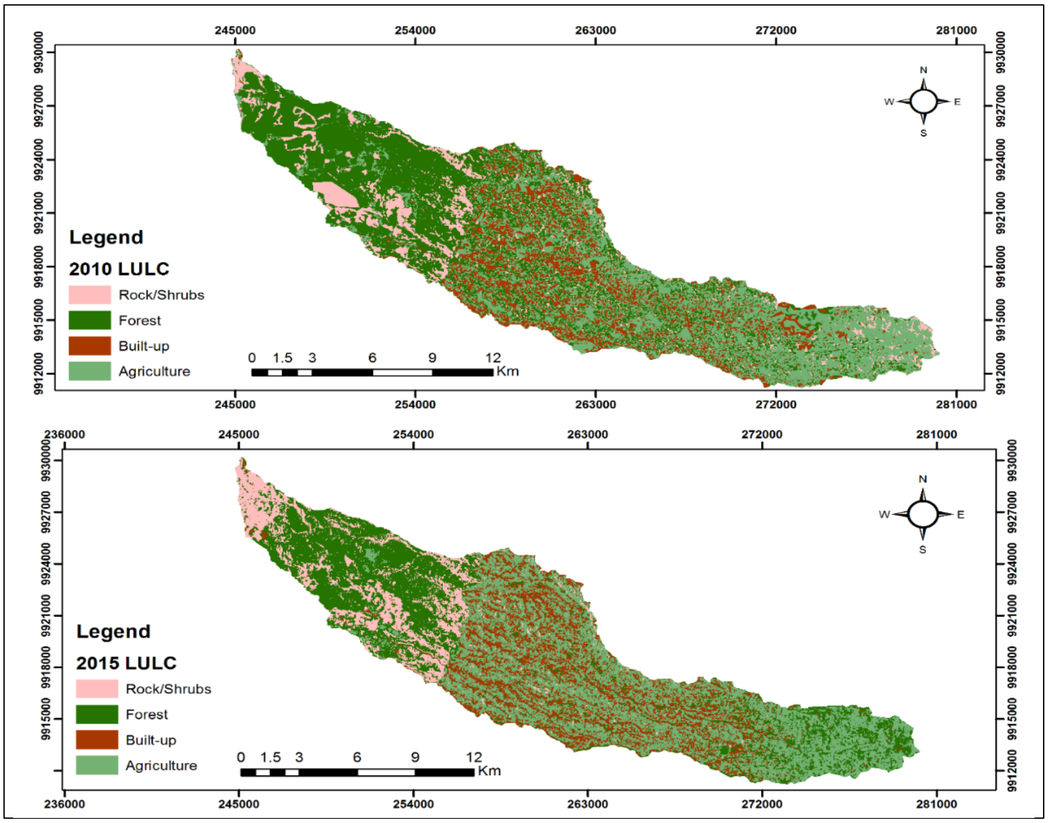


Figure 4.4: LULC maps for the years 2010 and 2015

The statistics of LULC results were derived and tabulated as shown in Table 4.1. Since the Landsat data used to perform LULC classification was 30m resolution, the total area of the classified images varied a bit due to discrepancies encountered at the edges during masking of the images to obtain only the parts covering the watershed.

Table 4.1: Statistics of LULC results for different years

Land Cover Types	**Area (Hectares)**			
	2000	**2003**	**2010**	**2015**
Shrubs and Rock	2639.34	2306.09	2423.16	2643.05
Forest	8530.38	7941.06	8228.7	6220.71
Built-up	2416.68	2984.71	3023.64	3777.14
Agriculture	7389.54	7678.15	7306.47	8269.11
Total	**20975.94**	**20910.01**	**20981.97**	**20910.01**

The chart in Figure 4.5 below visually conveys the results in Table 4.1.

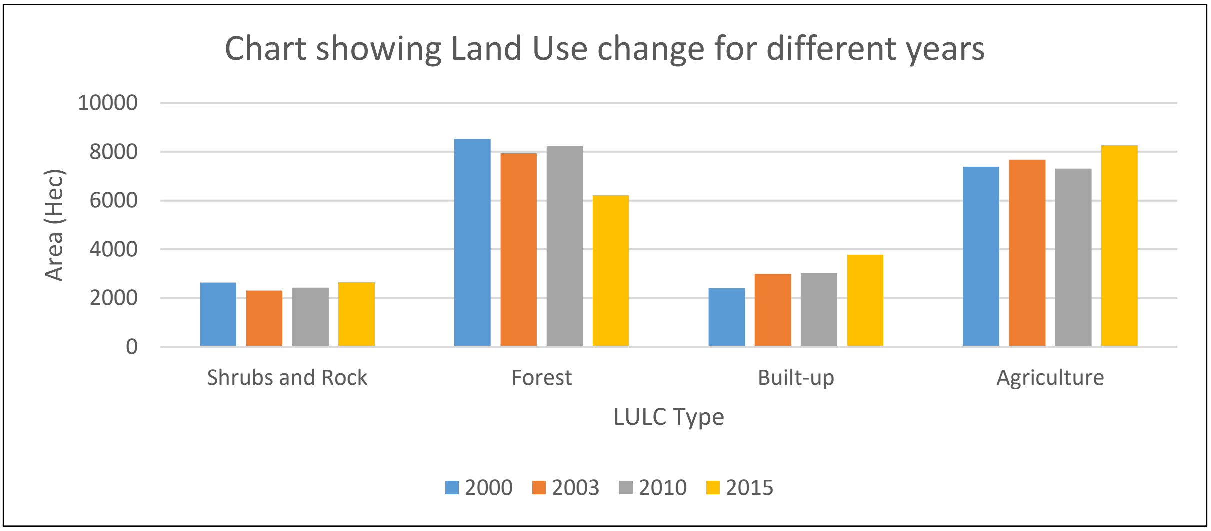


Figure 4.5: Chart showing Areas occupied by various classes in different years

Shrubs and rocks were found to occupy the least area within the watershed. Since the watershed is within the slopes of Aberdare ranges which is characterised by ridges and valleys, the alternating Shrubs and rocky vegetation are found mainly along the ridges and at the peak. Their coverage was found to be less variant over the period of study. Their areal coverage remained almost the same over the entire duration despite small variation which might have been caused by their responses to changes in weather conditions because images of different months were used to perform analysis. Also, these vegetation falls mostly within Aberdare forest which is a protected area meaning limited interferences.

Forest was found to be decreasing in size over time. There were limited changes within the conserved parts of Aberdare forest however most dynamics were occurring within the settlement areas where forested land was being cleared and converted into agricultural land as evidenced by the inverse trend of agriculture when compared with the trend of forest. The trend anomaly in the year 2010 might be due to the presence of clouds in the image that was used. Despite the clouds being masked and manually classified, some error residue might have remained which explains the irregularity. Forest is occupying the largest area compared to other classes however agricultural land is increasing and might dominate soon if this trend persists.

Built-up area is increasing steadily though at a slower rate. Some of the cleared forest and agricultural land might have been converted into settlement areas. This is what might have resulted into increase in the built-up areas. Some of the bare lands especially cultivated land was found to be classified as built-up areas despite attempts to separate. This was made difficult by the fact that the two classes had almost similar reflectance.

Agricultural land is generally increasing over the years with 2015 recording the highest area of land under agriculture. The trend of changes in agricultural land is gradual due to the challenge of correctly representing different types of land under different crops which are at different stages of growth. To overcome this complexity and minimise the struggle of trying to classify agriculture types, unsupervised classification with more classes was performed then the classes were recoded into four classes.

4.1.4 The Curve Number Maps

Since the watershed had two HSG and four LULC classes were considered in the study, eight curve numbers were derived as shown in the CN maps in Figure 4.6 and Figure 4.7.

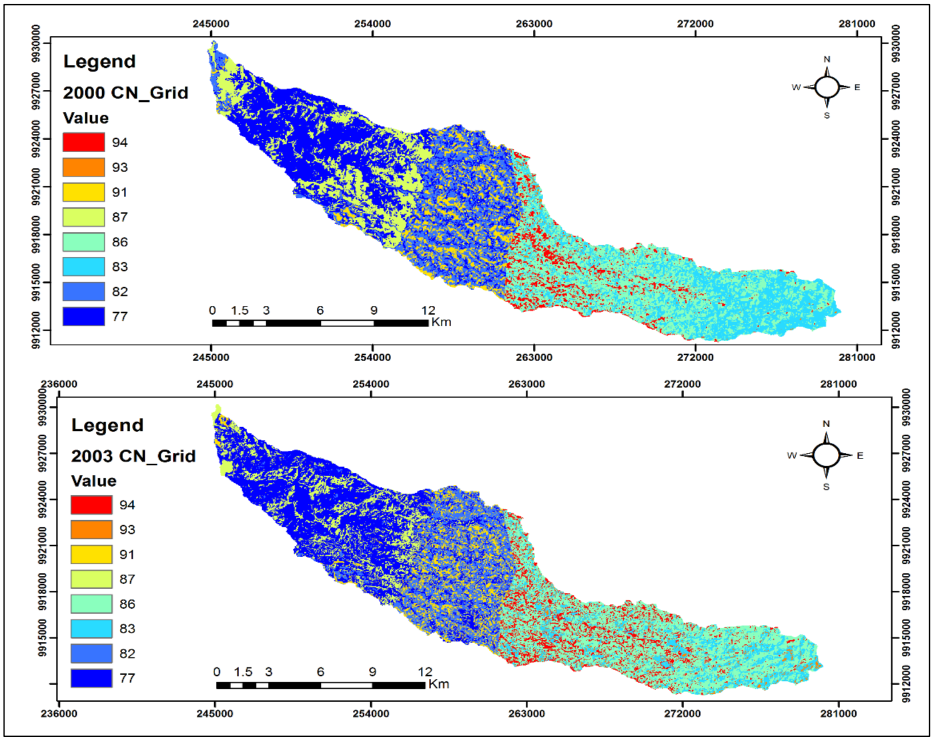


Figure 4.6: The Curve Number map of different SVL complexes for the years 2000 and 2003

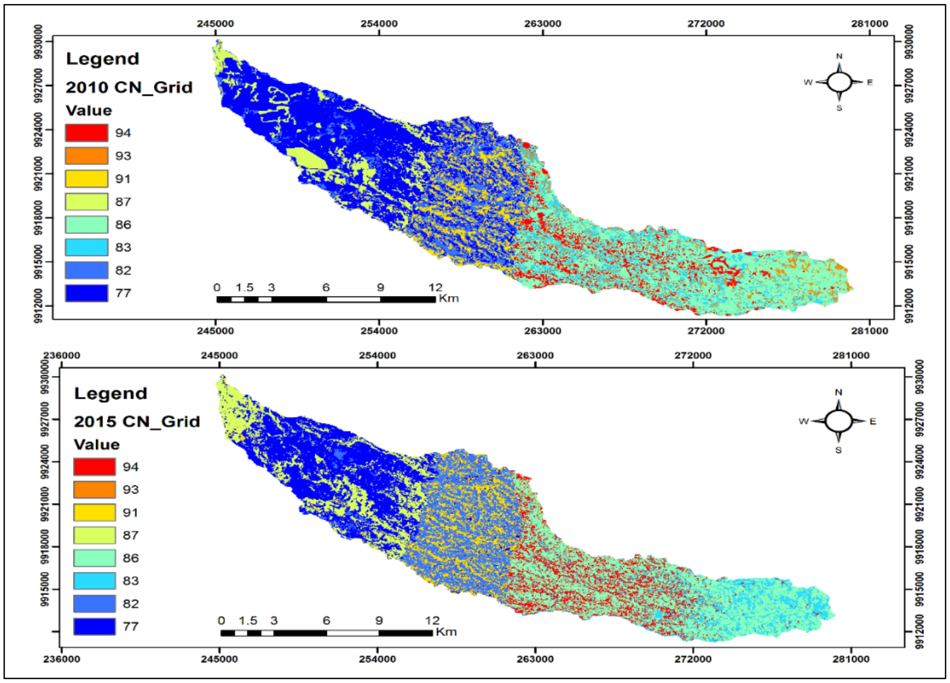


Figure 4.7: The Curve Number map of different SVL complexes for the years 2010 and 2015

The CNs represent land use/cover classes falling in both hydrological groups for example, forest falling in HSG C will have a CN value of 77 while the same forest falling in HSG D will also have a curve number value of 83 as specified in Table 3.3. Similarly, all other classes will have two values under the two HSG. This makes the four classes generate a total of eight CN values each representing unique SVL complex as shown in Table 4.2. The area of each SVL complex is determined because the percentage coverage is required to be used to calculate the overall weighted Curve Number.

Table 4.2: The SVL complex of the watershed for the various years

SVL Complex	***CN (For AMC II)***	**2000**		**2003**		**2010**		**2015**	
		Area (Hectares)	***% Area***	***Area (Hectares)***	***% Area***	***Area (Hectares)***	***% Area***	***Area (Hectares)***	***% Area***
1	77	5219.6	25.0	5980.1	28.7	6574.7	31.5	4624.2	22.2
2	82	3076.0	14.8	2771.7	13.3	2268.1	10.9	3140.0	15.1
3	83	3257.7	15.6	1953.3	9.4	1615.3	7.8	1553.5	7.5
4	86	4346.4	20.9	4931.4	23.7	5063.3	24.3	5155.0	24.7
5	87	2556.4	12.3	2031.9	9.7	1849.0	8.9	2568.0	12.3
6	91	1376.3	6.6	1445.9	6.9	1537.0	7.4	1897.4	9.1
7	93	52.8	0.3	245.5	1.2	509.8	2.4	56.5	0.3
8	94	953.4	4.6	1481.0	7.1	1422.1	6.8	1846.3	8.9
Total		**20838.7**	**100.0**	**20840.9**	**100.0**	**20839.2**	**100.0**	**20840.9**	**100.0**

The above tabulated results can be visually represented as shown in Figure 4.8. The chart summarises the statistics of variability of specific SVL complex over the four epochs focused in the study. It is clearly evident that as the percentage area coverage increases for most complexes while others decrease despite some small fluctuations.

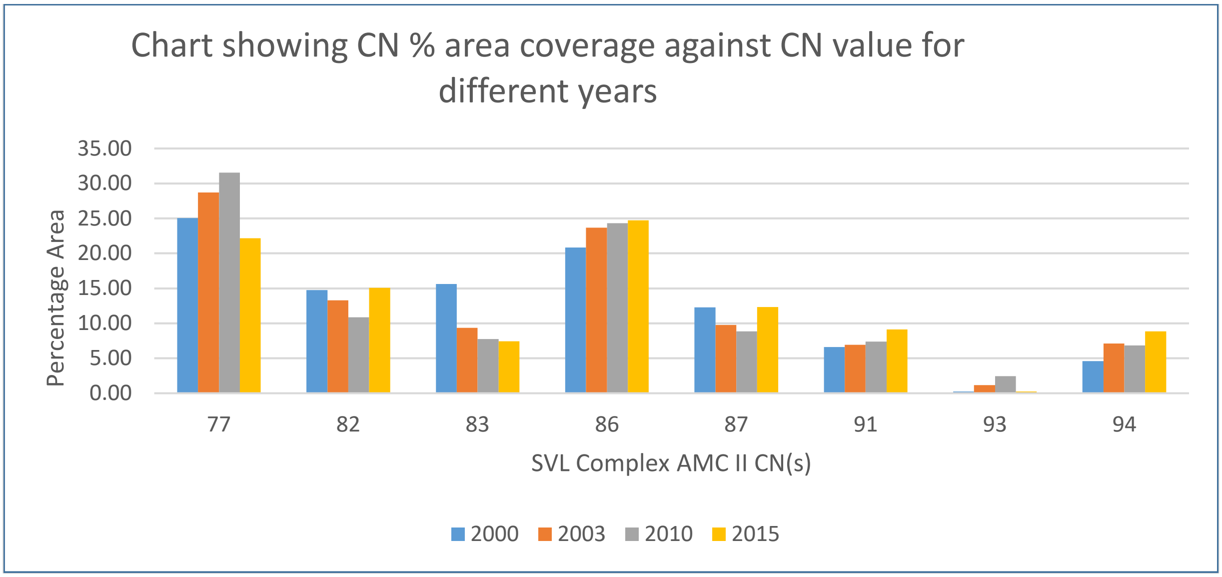


Figure 4.8: Chart showing the percentage area distribution of SVL complex CN for different epochs

The percentage areas of the different SVL complexes were then used to weight the CN for the various SVL complexes. The intention was to obtain one weighted CN representing entire watershed uniquely. Table 4.3 summarises the process of obtaining the weighted CN.

Table 4.3: Table showing the computation of the Weighted Curve Number for all the four epochs

SVL Complex	***CN (for AMC II)***	**2000**		**2003**		**2010**		**2015**	
		% Area	***Weighted_CN (AMC II)***	***% Area***	***Weighted_CN (AMC II)***	***% Area***	***Weighted_CN (AMC II)***	***% Area***	***Weighted_CN (AMC II)***
1	77	25.05	19.29	28.69	22.09	31.55	24.29	22.19	17.08
2	82	14.76	12.10	13.30	10.91	10.88	8.92	15.07	12.35
3	83	15.63	12.98	9.37	7.78	7.75	6.43	7.45	6.19
4	86	20.86	17.94	23.66	20.35	24.30	20.90	24.74	21.27
5	87	12.27	10.67	9.75	8.48	8.87	7.72	12.32	10.72
6	91	6.60	6.01	6.94	6.31	7.38	6.71	9.10	8.28
7	93	0.25	0.24	1.18	1.10	2.45	2.27	0.27	0.25
8	94	4.58	4.30	7.11	6.68	6.82	6.41	8.86	8.33
SUM		***100.00***	***83.52***	***100.00***	***83.70***	***100.00***	***83.67***	***100.00***	***84.48***
Rounding Off		**W_CN ≈84**		**W_CN ≈84**		**W_CN ≈84**		**W_CN ≈84**	

From the sum of the overall weighted CN shown in Table 4.3 above, before rounding off the weighted value, it is evident that the weighted CN is increasing gradually from the year 2000 as illustrated in Figure 4.9. The weighted Curve Number was found to increase through small values that when rounded off remains to be 84 for all the epochs. The reason for round off is to obtain a significant definite weighted CN that can be used to extract AMC I and AMC III from the table in Appendix B.

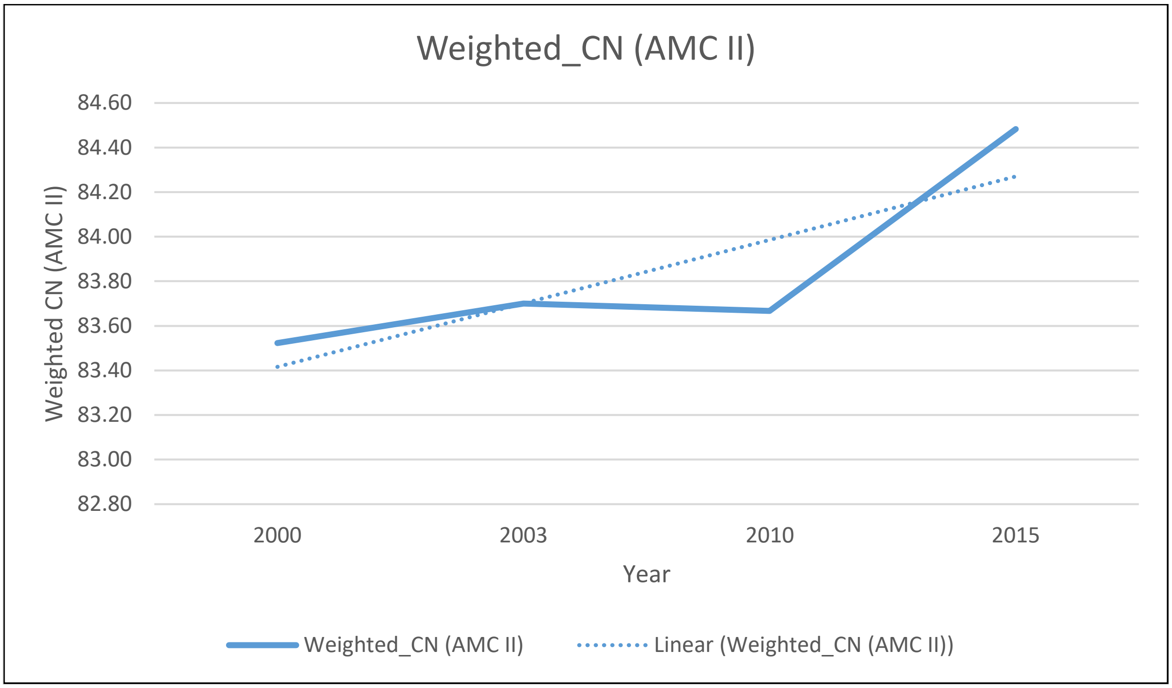


Figure 4.9: The graph showing the trend of Curve Numbers before Round off

Although small increase in the value of the annual weighted curve numbers before round off is evident, a constant value of 84 for all the epochs after round off implies that only negligible changes can occur in the watershed within a period of 15 years that was considered in the study. As far as the CN values are increasing at a slower rate, runoff will also be increasing at an equivalent rate. But since the final rounded off value is equal for all the epochs, it implies that runoff was not affected significantly by the changes that occurred in the watershed within the duration considered.

The rounded off Weighted CN (AMC II) values in Table 4.3 for all the four epochs were then assigned respective AMC I and AMC II values using the table in Appendix B. The final weighted AMC values in Table 4.4 were obtained.

Table 4.4: The Weighted AMC value for the four epochs

YEAR	AMC II	AMC I	AMC III
2000	84	68	93
2003	84	68	93
2010	84	68	93
2015	84	68	93

4.1.5 Runoff Depth

Table 4.5 summarises the runoff depth (Q) values that were obtained after the calculations. It is evident that the average rainfall of the area is approximately 1100mm per year which results in a runoff depth of slightly over 200mm. This implies that approximately 20% of the precipitation is converted into runoff. Precipitation that is less than 1000mm like for the year 2000 was found to contribute the least runoff amounting to 6.07% of the total precipitation.

Table 4.5: The Summary of Runoff Depth Results

Year	Days with Runoff	Precipitation (P_mm)	Runoff (Q_mm)	Runoff Volume (M^3)	% of water turned into Runoff
2000	9	562.61	34.17	7120686.458	6.07
2003	26	1386.59	458.89	95632370.51	33.09
2010	29	1171.96	230.00	47931004.59	19.62
2015	32	1161.03	200.81	41848719.13	17.30

4.1.6 Runoff Volume

Runoff volumes of 7120686.458M^3, 95632370.51 M^3, 47931004.59 M^3 and 41848719.13M^3 were obtained for the years 2000, 2003, 2010 and 2015 respectively as summarised in Table 4.5. The runoff volume is directly proportional to the amount of precipitation received (Figure 3.1). The number of days annually with runoff can be less but contribute more runoff volume as evident in the year 2003.

4.1.7 Validation of the Results

The findings were validated by comparing the values obtained with the river depth analysis result that was obtained during the research conducted at the feasibility study stage of the NCT project.

The average runoff volume obtained from the days that were found to contribute runoff from all the four epochs was found to agree with the NCT daily runoff estimate results for the phase one project. Table 4.6 shows the computed daily runoff based on the number of days that were found to contribute runoff and the documented NCT daily runoff values in the commissioning booklet for the phase one of the project.

Table 4.6: Comparison between the study findings and NCT values

STUDY FINDINGS				***VALIDATION VALUE***
Year	**Days with Runoff (Days/Year)**	**Runoff Volume (M3/Year)**	**Daily Runoff (M3/Day)**	***NCT Daily Runoff (M3/Day)***
2000	9	7120686.46	791187.38	*1,198,368* ***(43% to be abstracted: 513,388)***
2003	26	95632370.51	3678168.10	
2010	29	47931004.59	1652793.26	
2015	32	41848719.13	1307772.47	

4.2 Discussion of the Results

The three rivers contributing water to the collector tunnel were found to lie within one watershed with an area of approximately 208.3 square kilometres. The tunnel cuts across the watershed tapping water from all the rivers through intakes as shown in Figure 4.1. The flood water will be abstracted from the sub watershed before they reach the pour point of the major watershed.

From Figure 4.2, two HSG namely C and D were found to dominate the watershed. The soils at the northern part of the watershed were found to be of HSG C meaning they have highest runoff potential in the watershed. This is because it lies at the peak of Aberdare where rocks and mountain vegetation dominate hence limiting infiltration and favouring runoff. The southern parts of the watershed were found to be dominated by HSG D which has low runoff potential. This is majorly due to presence of agricultural lands in this section. The crops require more water hence increasing the rate of infiltration which in turn leads to lower runoff potential.

Land use/cover changes within the watershed were found to be minimal within the period of fifteen years that was considered in the study as shown in Table 4.1 and Figure 4.5 . This was clearly evident especially with land uses that cause significant changes in runoff such us built-up areas and shrubs and rocks. The impact of these insignificant changes is reflected directly in the CN values which determine runoff potential. Figure 4.9 shows the trend of the weighted CN that was obtained from the four epochs that were studied. It is apparent that the weighted CN is increasing with time. However, the rate at which it is increasing is very low, from 83.52 in the year 2000 to 84.48 in the year 2015 (Table 4.3). When these values are rounded off, they become a weighted CN value of 84 implying that the change is so small to create a difference. This confirms that the land use/cover changes in the area has little impact on surface runoff within a span of fifteen years.

The study area was found to have high rainfall of approximately 1100mm annually (Table 4.5). However, it can fall below 1000mm for some drought years like in the year 2000. Despite rainfall occurring in up to one hundred days in a specific year, only thirty days on average were found to contribute water runoff amounting to approximately 20% of the total precipitation. Figure 4.10 summarises the amount of rainfall and the resultant runoff depths.

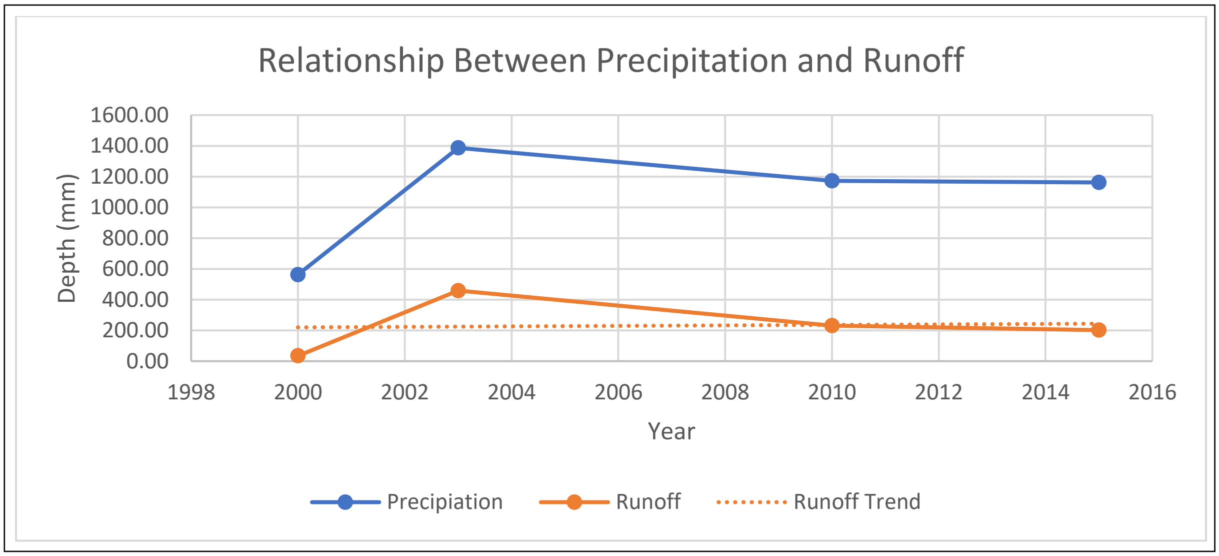


Figure 4.10: Relationship between Precipitation and Runoff depths

Since the watershed is within the Aberdare ranges, the area is often covered with clouds almost throughout the year. This made it difficult to study a single month for the four epochs that were considered because the images with least cloud cover were considered. However, this did not affect the research because the images used were selected based on season they were acquired.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The potential volume of annual floodwaters for the Northern Collector Water Tunnel according this this study was found to range from low values like 791187.38 M^3 during years with low precipitation to as high as 3678168.10 M^3 during years with high precipitation (Table 4.6). Since the project is aimed at abstracting only 43% of the daily floodwaters which is equivalent to 513,388 M^3/day, this implies that the project will still not exhaust the flood waters during dry years with lowest rainfall like the case of the year 2003 which had the lowest runoff volume of 791187.38 M^3/day. This value is higher than the volume to be abstracted per day meaning some flood water will still be available to flow. This proves that areas downstream will not affected by the project.

The changes in land use/cover within the watershed focused in the study are gradual and no significant change took place within the fifteen years epoch. This is confirmed by the stagnation of weighted CN value in all epochs. From Figure 4.9, the value of the CNs increasing at small decimal values is a clear evidence of the limited changes that are taking place. The runoff potential is directly proportional to these changes. It can be inferred that, although the runoff within the watershed is anticipated to increase according to this finding, it will take many years before a visible change takes place.

More precipitation will result in increased surface runoff especially if it rains consecutively for many days. This is because the antecedent moisture condition(AMC) of the soil is a crucial factor determining runoff which is computed from the sum of five-day preceding precipitation. This means that rains falling for more than five consecutive days raises the AMC hence increasing the chances of more runoff.

In summary, SCS-CN method has proved to work well when localised and applied to other places outside the United States of America like this case of the Northern Collector Water Tunnel project in Kenyan. The findings are comparable with the results obtained through measurement of the volumes of the rivers during dry season and wet seasons then estimating the runoff volumes. The application of this method can therefore be extended to other projects aiming at harvesting flood waters in Kenya.

5.2 Recommendations

Due to unavailability of a weather station within the watershed, the weather station data used was from the nearest weather station in Nyeri town which is approximately 20Km away. Although both areas experience similar climatic conditions, better results could have been obtained if a weather station could have been established within the watershed. This could ensure better accuracy for the precipitation information for the watershed. This could be further improved if more than one weather stations are established within the watershed.

Daily runoff volume for the watershed has been estimated based on the number of days that contributed runoff annually. This method of estimating daily runoff assumes that all the flood water flows away within the same day the precipitation occur. However ideally, runoff can last for some days after the precipitation. Therefore, there is need to distribute the flood waters according to some criteria that can be furthered through research.

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APPENDICES

7.1 Appendix A

Table 7.1: Runoff curve numbers for hydrologic cover complexes (Antecedent moisture condition II and Ia=0.2 S) (Mishra & Singh, 2003)

SI No.	Land use Description/Treatment	Hydrologic Condition/% impervious area	Hydrologic Soil Groups			
			A	B	C	D
	Urban					
1.	Residential:					
	Average lot size- 1/8 acre or less	65*	77	85	90	92
	1/4 acre	38*	61	75	83	87
	1/3 acre	30*	57	72	81	86
	1/2 acre	25*	54	70	80	85
	1 acre	20*	51	68	79	84
	2 acre	12*	46	65	77	82
2.	Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
3.	Streets and roads:					
	Paved with curbs and storm sewers (excluding right-of-way)		98	98	98	98
	Paved, open ditches (including right-of-way)		82	89	92	93
	Gravel (including right-of-way)		76	85	89	91
	Dirt (including right-of-way)		72	82	87	89
4.	Western desert areas:					
	Natural desert landscaping (pervious areas only)		63	77	85	88
	Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
5.	Urban districts:					
	Commercial and business areas	85	89	92	94	95
	Industrial districts	72	81	88	91	93
6.	Developing areas:					
	Newly graded areas (pervious areas only, no vegetation)		77	86	91	94
	Idle lands					
7.	Open spaces, lawns, parks, golf courses, cemeteries, etc.					
	Grass cover on 75% or more of the area	Good	39	61	74	80
	Grass cover on 50% to 75% of the area	Fair	49	69	79	84
	Agricultural					
	Cultivated lands:					
8.	Fallow:					
	Bare soil Straight row	…….	77	86	91	94
	Crop residue cover	Poor	76	85	90	93

		Good	74	83	88	90
9.	Row crops:					
	Straight row	Poor	72	81	88	91
	Straight row	Good	67	78	85	89
	Crop residue cover Straight row	Poor	71	80	87	90
	Crop residue cover Straight row	Good	64	75	82	85
	Contoured	Poor	70	79	84	88
	Contoured	Good	65	75	82	86
	Crop residue cover Contoured	Poor	69	78	83	87
	Crop residue cover Contoured	Good	64	74	81	85
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
	Crop residue cover Contoured and terraced	Poor	65	73	79	81
	Crop residue cover Contoured and terraced	Good	61	70	77	80
10.	Small grain:					
	Straight row	Poor	65	76	84	88
	Straight row	Good	63	75	83	87
	Crop residue cover Straight row	Poor	64	75	83	86
	Crop residue cover Straight row	Good	60	72	80	84
	Contoured	Poor	63	74	82	85
	Contoured	Good	61	73	81	84
	Crop residue cover Contoured	Poor	62	73	81	84
	Crop residue cover Contoured	Good	60	72	80	83
	Contoured and terraced	Poor	61	72	79	82
	Contoured and terraced	Good	59	70	78	81
	Crop residue cover Contoured and terraced	Poor	60	71	78	81
	Crop residue cover Contoured and terraced	Good	58	69	77	80
11.	Close-seeded legumes or rotation meadow:					
	Straight row	Poor	66	77	85	89
	Straight row	Good	58	72	81	85
	Contoured	Poor	64	75	83	85
	Contoured	Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
	Uncultivated lands:					
12.	Pasture or range:	Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	Contoured	Fair	25	59	75	83
	Contoured	Good	6	35	70	79
13.	Meadow- continuous grass, protected from grazing, and generally mowed for hay	Good	30	58	71	78
	Brush-brush weed grass mixture with brush being the major element	Poor	48	67	77	83

		Fair	35	56	70	77
		Good	30	48	65	73
14.	Farmsteads- buildings, lanes, driveways, and surrounding lots	…..	59	74	82	86
Woods and forests						
	Humid rangelands or agricultural uncultivated lands:					
15.	Woods or forest land	Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77
16.	Woods-grass combination (orchard or tree farm)	Poor	57	73	82	86
		Fair	43	65	76	82
		Good	32	58	72	79
	Arid and Semiarid rangelands:					
17.	Herbaceous	Poor		80	87	93
		Fair		71	81	89
		Good		62	74	85
18.	Oak-aspen	Poor		66	74	79
		Fair		48	57	63
		Good		30	41	48
19.	Pinyon-juniper	Poor		75	85	89
		Fair		58	73	80
		Good		41	61	71
20.	Sagebrush with grass understory	Poor		67	80	85
		Fair		51	63	70
		Good		35	47	55
21.	Desert shrub	Poor	63	77	85	88
		Fair	55	72	81	86
		Good	49	68	79	84

7.2 Appendix B

Table 7.2: Curve numbers for three antecedent moisture conditions (Mishra & Singh, 2003)

ID	**AMC II**	**AMC I**	**AMC III**
1	100	100	100
2	99	97	100
3	98	94	99
4	97	91	99
5	96	89	99
6	95	87	98
7	94	85	98
8	93	83	98
9	92	81	97
10	91	80	97
11	90	78	96
12	89	76	96
13	88	75	95
14	87	73	95
15	86	72	94
16	85	70	94
17	84	68	93
18	83	67	93
19	82	66	92
20	81	64	92
21	80	63	91
22	79	62	91
23	78	60	90
24	77	59	89
25	76	58	89
26	75	57	88
27	74	55	88
28	73	54	87
29	72	53	86
30	71	52	86
31	70	51	85
32	69	50	84
33	68	48	84
34	67	47	83
35	66	46	82
36	65	45	82
37	64	44	81
38	63	43	80
39	62	42	79
40	61	41	78
41	60	40	78
42	59	39	77
43	58	38	76
44	57	37	75
45	56	36	75
46	55	35	74
47	54	34	73
48	53	33	72
49	52	32	71
50	51	31	70
51	50	31	70
52	49	30	69
53	48	29	68
54	47	28	67
55	46	27	66
56	45	26	65
57	44	25	64
58	43	25	63
59	42	24	62
60	41	23	61
61	40	22	60
62	39	21	59
63	38	21	58
64	37	20	57
65	36	19	56
66	35	18	55
67	34	18	54
68	33	17	53
69	32	16	52
70	31	16	51
71	30	15	50
72			
73	25	12	43
74	20	9	37
75	15	6	30
76	10	4	22
77	5	2	13
78	0	0	0

7.3 Appendix C

7.3.1 Appendix C1

Table 7.3: Accuracy assessment table for the year 2000 image

2000						
Overall Classification Accuracy =87.50%						
Overall Kappa Statistics =0.8333						
Unclassified	Rock	Forest	Built-up	Agriculture	**Total**	User
Rock	10	0	0	0	10	100
Forest	0	10	0	0	10	100
Built-up	0	0	7	3	10	70
Agriculture	0	1	1	8	10	80
Total	10	11	8	11	40	
Producer	100	90.91	87.5	72.73		

7.3.2 Appendix C2

Table 7.4: Accuracy assessment table for the year 2003 image

2003						
Overall Classification Accuracy =97.50%						
Overall Kappa Statistics = 0.9667						
	Rock	Forest	Built-up	Agriculture	**Total**	User
Rock	10	0	0	0	10	100
Forest	0	9	0	1	10	90
Built-up	0	0	10	0	10	100
Agriculture	0	0	0	10	10	100
Total	10	9	10	11	40	
Producer	100	100	100	90.91		

7.3.3 Appendix C3

Table 7.5: Accuracy assessment table for the year 2010 image

<table>
<tr><td colspan="7">2010</td></tr>
<tr><td colspan="7">Overall Classification Accuracy =90.0%</td></tr>
<tr><td colspan="7">Overall Kappa Statistics = 0.8667</td></tr>
<tr><td></td><td>Rock</td><td>Forest</td><td>Built-up</td><td>Agriculture</td><td>Total</td><td>User</td></tr>
<tr><td>Rock</td><td>10</td><td>0</td><td>0</td><td>0</td><td>10</td><td>100</td></tr>
<tr><td>Forest</td><td>0</td><td>9</td><td>0</td><td>1</td><td>10</td><td>90</td></tr>
<tr><td>Built-up</td><td>0</td><td>0</td><td>7</td><td>3</td><td>10</td><td>70</td></tr>
<tr><td>Agriculture</td><td>0</td><td>0</td><td>0</td><td>10</td><td>10</td><td>100</td></tr>
<tr><td>Total</td><td>10</td><td>9</td><td>7</td><td>14</td><td>40</td><td></td></tr>
<tr><td>Producer</td><td>100</td><td>100</td><td>100</td><td>71.43</td><td></td><td></td></tr>
</table>

7.3.4 Appendix C4

Table 7.6: Accuracy assessment table for the year 2015 image

<table>
<tr><td colspan="7">2015</td></tr>
<tr><td colspan="7">Overall Classification Accuracy =87.50%</td></tr>
<tr><td colspan="7">Overall Kappa Statistics = 0.8333</td></tr>
<tr><td></td><td>Rock</td><td>Forest</td><td>Built-up</td><td>Agriculture</td><td>Total</td><td>User</td></tr>
<tr><td>Rock</td><td>10</td><td>0</td><td>0</td><td>0</td><td>11</td><td>100</td></tr>
<tr><td>Forest</td><td>0</td><td>9</td><td>0</td><td>1</td><td>11</td><td>90</td></tr>
<tr><td>Built-up</td><td>0</td><td>0</td><td>8</td><td>2</td><td>8</td><td>80</td></tr>
<tr><td>Agriculture</td><td>0</td><td>0</td><td>2</td><td>8</td><td>10</td><td>80</td></tr>
<tr><td>Total</td><td>10</td><td>9</td><td>10</td><td>11</td><td>40</td><td></td></tr>
<tr><td>Producer</td><td>100</td><td>100</td><td>80</td><td>72.73</td><td></td><td></td></tr>
</table>

7.4 Appendix D

Table 7.7: Sample of Daily Rainfall-Runoff Computation for the year 2000 from Weather station data

Day	Month	Year	Daily rainfall (mm)	5-day cumulative rainfall	Season	AMC condition	Curve number (CN)	Surface retention (S)	Daily Runoff (mm)
21	11	2000	0.762	12.446	G	AMC I	68	110.1176471	0
22	11	2000	21.082	13.208	G	AMC I	68	110.1176471	0
23	11	2000	0	33.528	G	AMC I	68	110.1176471	0
24	11	2000	14.986	32.766	G	AMC I	68	110.1176471	0
25	11	2000	9.906	36.83	G	AMC II	84	44.57142857	0.001086435
26	11	2000	34.036	46.736	G	AMC II	84	44.57142857	8.157741334
27	11	2000	6.096	80.01	G	AMC III	93	17.61290323	0.241393039
28	11	2000	0.762	65.024	G	AMC III	93	17.61290323	0
29	11	2000	7.112	65.786	G	AMC III	93	17.61290323	0.482589746
1	12	2000	0.762	57.912	G	AMC III	93	17.61290323	0
2	12	2000	6.096	48.768	G	AMC II	84	44.57142857	0
3	12	2000	13.97	20.828	G	AMC I	68	110.1176471	0
5	12	2000	0	28.702	G	AMC I	68	110.1176471	0
6	12	2000	0	27.94	G	AMC I	68	110.1176471	0
7	12	2000	0.762	20.828	G	AMC I	68	110.1176471	0
8	12	2000	0.762	20.828	G	AMC I	68	110.1176471	0
9	12	2000	10.922	15.494	G	AMC I	68	110.1176471	0
10	12	2000	4.064	12.446	G	AMC I	68	110.1176471	0
11	12	2000	0.508	16.51	G	AMC I	68	110.1176471	0

12	12	2000	2.032	17.018	G	AMC I	68	110.1176471	0
13	12	2000	5.08	18.288	G	AMC I	68	110.1176471	0
14	12	2000	0	22.606	G	AMC I	68	110.1176471	0
15	12	2000	0	11.684	G	AMC I	68	110.1176471	0
16	12	2000	0	7.62	G	AMC I	68	110.1176471	0
17	12	2000	70.104	7.112	G	AMC I	68	110.1176471	12.87816262
18	12	2000	22.098	75.184	G	AMC III	93	17.61290323	8.930949988
19	12	2000	0	92.202	G	AMC III	93	17.61290323	0
20	12	2000	0.762	92.202	G	AMC III	93	17.61290323	0
21	12	2000	0	92.964	G	AMC III	93	17.61290323	0
22	12	2000	0	92.964	G	AMC III	93	17.61290323	0
23	12	2000	0	22.86	G	AMC I	68	110.1176471	0
24	12	2000	0	0.762	G	AMC I	68	110.1176471	0
25	12	2000	0	0.762	G	AMC I	68	110.1176471	0
26	12	2000	0	0	G	AMC I	68	110.1176471	0
27	12	2000	7.112	0	G	AMC I	68	110.1176471	0
28	12	2000	0	7.112	G	AMC I	68	110.1176471	0
29	12	2000	0	7.112	G	AMC I	68	110.1176471	0
30	12	2000	0	7.112	G	AMC I	68	110.1176471	0
31	12	2000	0	7.112	G	AMC I	68	110.1176471	0
TOTAL			562.61						34.16836112