HYDROLOGIC ANALYSIS OF MALEWA WATERSHED AS A BASIS FOR IMPLEMENTING PAYMENT FOR ENVIRONMENTAL SERVICES (PES)

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Hydrologic Analysis of Malewa Watershed as a basis for Implementing Payment for Environmental Services (PES)

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

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DEDICATION

This work is dedicated to my late father John Alfred Ondulo Aduda for his inspiration and mentorship. The discipline towards work that you instilled in me will live and I will propagate your legacy for the rest of my life, rest in peace. It is also dedicated to all who are struggling to conserve and preserve the environment for the future progeny, to my family members and Cecilia Anyango.

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ABBREVIATIONS

ALPHA-BF	Base flow alpha factor
ARS	Agricultural Research Services
ASCE	American Society of Civil Engineering
BAU	Business as Usual
Bgl	Below ground level
BIOMX	Biological mixing efficiency
CN 2	Initial SCS runoff curve number for moisture condition II.
DEM	Digital Elevation Model
E_{NS}	Nash Sutcliffe Efficiency
ETM	Enhanced Thematic Mapper
ETM+	Enhanced Thematic Mapper plus
FAO	Food and Agricultural Organization
FLOW_IN	Average daily streamflow into reach during a time step (m3/s).
FLOW_OUT	Average daily streamflow out of reach during a time step (m3/s).
GIS	Geographical Information System
GW_Q	Groundwater contribution to streamflow (mm) Water from the shallow aquifer that returns to the reach during a time step
GWQMN	Threshold depth of water in to occur the shallow aquifer required for return flow
GW-REVAP	Ground water coefficient
HRU	Hydrological Response Unit
ILRI	International Livestock Research Institute
JICA	Japanese International Corporation Agency
KMD	Kenya Meteorological Department
KSS	Kenya Soil Survey
Landsat	Land Observation Satellite
LEAA	Lambert Equal Area Azimuthal
MWI	Ministry of Water and Irrigation
MSS	Multi spectral Scanner
PES	Payment for Environmental Services

PRECIP	Total amount of precipitation falling on the subbasin during a time step (mm H_2O)
mcm	million cubic meters
R^2	Coefficient of Determination
RCMRD	Regional Centre for Mapping of Resources for Development
SCS	Soil Conservation Services
SED_IN	Sediment transported with water into reach during a time step (metric tons).
SED_OUT	Sediment transported with water out of reach during a time step (metric tons).
SEDCONC	Concentration of sediment in reach during a time step (mg/L).
SLOPE	Average slope steepness (m/m)
SLSUBBSN	Average slope length (m)
SOL-AWC	Available water capacity of the soil layer (mmH_2O/mm soil)
SOTER	Soil and Terrain Database
SURQ	Surface runoff contribution to streamflow during a time step (mm H2O).
SWAT	Soil and Water Assessment Tool
SWIR	Short Wave Infrared
SYLD	Sediment yield (metric tons/ha). Sediment from the subbasin that is transported into the reach during a time step
TM	Thematic Mapper
USDA	United State Department of Agriculture
USGS	United States Geological Survey
USLE-C	Cover and management factor
USLE-P	The support practice factor
WWF-EARPO	World Wide fund for nature-Eastern Africa Regional Project Office
WYLD	Water yield (mm H_2O). The net amount of water that leaves the subbasin and contributes to streamflow in the reach during a time step

ABSTRACT

The Malewa River Basin is important to development and livelihoods, supporting tourism, floriculture, small-scale farmers, dairy and pastoralism. The area faces key threats such as declining water levels in the Lake Naivasha, catchment degradation, pollution, water conflict, poverty and inequitable access to natural resources and markets. The research was aimed at undertaking situation analysis and hydrological baseline studies focusing on land-use and water relationships. The main study objective was to evaluate the impact of different land use and farming systems on the water, sediment and nutrient yield of River Malewa and to identify target sub-basins for implementing Payment for Environmental Service (PES) on a pilot basis. The following were identified as the major possible buyers of PES; Nakuru water and sewerage company, Naivasha water and sewerage company, Olkaria Geothermal plant (OGP), flower farmers and large scale water abstractors such as Manera farm, Delemare farm, the lake Naivasha riparian owners association, etc. The major sellers in PES scheme would be the small scale upstream landowners around Geta, and Wanjohi locations farmers around Kipipiri range, amongst others.

Land-use changes over a timeframe of thirty years were studied using satellite images. The trends in land-use were analyzed using IDRIS Kilimanjaro software. Landsat images for 1973, 1987, and 2003 were used to determine land cover and land cover change. A criterion was developed based on parameters such as annual rainfall, water yield, population density, water conflicts, and pressures on vegetation and water bodies to select the target areas for PES implementation. Hydrological effects of specific land use changes and best management practices in the selected priority catchment were analyzed using the Soil and Water Assessment Tool (SWAT) model run on a monthly time step. Extensive continuous flow data over 10-year period from three locations within the basin were used for model calibration and validation. Sensitive model parameters were adjusted within their feasible ranges during calibration to minimize model prediction errors for monthly flows. A modeling framework was developed to represent the Best Management Practices (BMPs) with the Soil and Water Assessment Tool (SWAT) model and evaluate their impact on the water quantity and quality of the target watersheds.

Over the thirty years timeframe of study, it was noted that there has been spatio-temporal change in landuse. There has been expansion in agricultural lands and built-up areas with reduction of forests and grasslands which are fragile ecosystems. These changes exert influence on the ecosystem as a whole, because they affect water cycle, biodiversity, radiation budgets and many other processes. Based on the parameters, two sub-catchments with areas of 121 km^2 and 112 km^2 respectively within the upper catchment near GETA and Wanjohi were identified to be suitable for PES implementation.

At the main gauging station 2GB01; monthly calibration resulted in model prediction of average flow within 19% of the measured average flow while the monthly Nash-Sutcliffe (E_{NS}) measure was 0.58. These results indicated acceptance level of the model to predict monthly flow in the basin. The model was then used to run scenario analyses for the selected target areas. Six scenarios were tested namely 100 % horticultural crops (carrot, cabbage, sweet potatoes and onions distributed equally), 100% high density residential areas, 100% forest, a combination of forest and range brush in the ratio of

53% to 47%, Best Management Practices (BMPs) i.e. 1, 5 and 10 m filter strips and conservation farming with USLE_P values of 0.1, 0.5 and 1.0). The P values of 1.0 indicate no erosion control, 0.65 indicates contour farming and 0.1 indicates terraces. Land management practices with these P values were tested for their effect on streamflow and sediment load.

The results from land-use indicate that there has been land-use change mainly conversions from forest to agriculture and from range brush to agriculture. From the scenario analyses, it was observed that forest cover is the best with regards to water quantity and quality. The implementation of BMPs indicated that water quality can be greatly improved for example, the BMPs decreased the average monthly sediment yield at Wanjohi sub-basin outlet from 457.16 kg/ha (without BMPs) to 11.73 kg/ha for the best BMP (USLE_P=0.1.Without the BMPs, total organic N yield predicted by the SWAT were 2891 Kg/ha for Wanjohi and 472 Kg/ha for Geta. After the implementation of the BMPs, there was a significant decrease in organic N in both sub-basins. The decrease for Wanjohi sub-basin was from 2891 kg/ha to 77.18, for contour terrace (USLE_P=0.5), the decrease for Geta was from 472.34 kg/ha to 167.06 kg/ha for contour terrace (USLE_P=0.1) and 358.78kg/ha and 240.1kg/ha for filter width of 5m and 10m respectively

From the study, it is recommended that a filter strip of 5m should be implemented in Geta and Wanjohi sub-basins as a start for PES implementation. Implementation of 5 m vegetated filter strips in the pilot watersheds would reduce sediment yield from 457.16 kg/ha (without BMPs) to 11.73 kg/ha at Wanjohi sub-basin and from 424.56 kg/ha with no best management practices (BMPs) to 18.9 kg/ha in Geta sub-basin with BMP installed.

There is need for further research on impacts of different agricultural land-use systems if they are to form part of PES implementation, also basin wise studies from upstream to downstream basins need to be undertaken to show the impact of BMPs on water quality and streamflow at the Malewa river mouth into the Lake Naivasha.

CHAPTER I

1 INTRODUCTION

1.1 Overview of Payment for -Environmental Services

Watersheds provide mankind with economically significant goods and services. The hydrological services provided by forests, such as clean and regulated water flow, and reduced sedimentation, for example, are typically only noted when natural disasters, flooding, siltation of reservoirs and scarcity of water occur as a result of the removal of forest cover. Land users typically receive no compensation for the services their land generates for others, and so do not take them into account in making land use decisions.

Payment for environmental services (PES) schemes focus on environmental services for which there is an existing market demand, or for which such demand can emerge under appropriate conditions. Existing services fall within four categories: water services, carbon sequestration, biodiversity conservation and landscape beauty. PES systems present a series of advantages and opportunities which make them a promising mechanism to improve the conditions of water resources in watersheds.

Water services were the main target for this study. The list of water services provided by forest ecosystems that are considered under existing PES schemes include:

- Water flow regulation: maintenance of dry season flows and flood control;

- Water quality maintenance: sediment load control, nutrient load control e.g. phosphorous and nitrogen, chemical load control, and salinity control;
- Erosion and sedimentation control;
- Land salinization reduction/water table regulation; and
- Maintenance of aquatic habitats (e.g. maintaining water temperature, shading rivers/streams, ensuring adequate woody debris in water) (Landell-Mills, *et al*, 2002).

This study dwelt mainly on water flow regulation and water quality maintenance. Water services provided by forests are complex and often only partially understood. Forest services to watersheds depend on several site-specific factors, such as terrain, soil composition, tree species, vegetation mix, climate and existing management regimes. In addition, watersheds may experience seasonal, annual or multi-year fluctuations that make it virtually impossible to project and quantify the provision of specific levels of water services at any given time (FAO, 2004). A useful tool to estimate the actual supply of environmental services is the use of models to estimate the marginal change in the service provision associated with the transformation of land use.

1.2 Problem Statement

The Malewa catchment is important to development and livelihoods, supporting tourism, floriculture, horticulture, small-scale farmers, dairy and pastoralism. The basin is faced with key threats such as declining water levels in the lake, catchment degradation, pollution of the lake, conflict over water, poverty, inter basin water transfer, forest encroachment, poor land management practices, over abstraction of water, and inequitable access to natural resources and markets.

Past studies show that lake evaporation is higher than the rainfall (Farah, 2001), so that the lake is solely dependent on the discharges from the basin. Therefore, the changes in the upper areas of the basin can greatly influence the lake water quantity and quality. The greatest threats to Lake Naivasha result from an increased water demand throughout the watershed. Horticultural farms introduced in the late 1970s around Lake Naivasha have changed the nature of agriculture around the lake substantially. Flower farms occupy 1560 hectares, which is 31% of the total irrigated area around the lake (Sayeed, 2001).

The Lake Naivasha Management Plan (LNRA, 1999) has mentioned that the amount of water abstraction each year is a threat to sustainable utilization of lake water. At the same time growing flower farms increases the water demand of the basin. Because of this, economic value for irrigation and the recent drop of water level, the water balance of Lake Naivasha has been of wider interest. High population growth and use of inappropriate farming technologies by the upstream users are some of the major concerns. Understanding the past and present water balance would facilitate the development of future management scenarios which would maintain the lake sustainably.

Previous hydrological studies in the basin were hampered by lack of properly distributed spatial inputs such as rainfall and topography. Average rain gauge density of the basin is 1 per 230 km^2. The uneven spatial distribution of the rain gages leads to a data scarcity situation in upper parts of the basin. Further, the quality of available topographic information is a barrier to proper hydrological investigation of the basin. The following are some of the key research areas, ground water and water abstraction, pollution loading, water balance, water resource management and its allocation, lake bathymetry, hydrogeology, geology, catchment degradation, soil surveys, water quality, land use, rainfall-runoff relationships, ecological functions of wetlands, geospatial studies using GIS and remote sensing, and socio-economic studies. Most of these studies have been done solely around the lake with few done basin-wise. The need to protect the runoff regulating functions of forests is becoming explicit as human settlements spread into forested lands.

A difference of opinion exists about the probable nature and extent of land-use effects on biological resources and water quality (USDA Forest Service, 1988, Reid, 1993, CEQ, 1997; MacDonald, 2000). An important component of this debate is the concept of Cumulative Effects, which states that two or more influences of land use, or changes on two or more parcels of land, can interact to produce a magnified effect on the functioning of an ecosystem or other resource, even if each influence alone would have been relatively small or benign. Among the entire set of cumulative effects that have been described, are adverse influences on water quality and biological resources that arise from the way watersheds function, and particularly from the ways that disturbances within a watershed can be transmitted and magnified within channels and riparian habitats downstream of disturbed areas. Many of these cumulative watershed effects (CWEs) occur at considerable distance downstream from the original site of landscape alteration, and are mixed with other effects that are not driven by land use. The land-use signal may thus be hard to define in quantitative terms. Cumulative watershed effects (CWEs) have been of great concern to resource managers and regulators in forested mountain regions, where the goals of timber harvest may conflict with other social goals for water quality or biodiversity.

Regulation of land use practices alone is often ineffective in land degradation controls as they tend to place a disproportionate share of the burden on upstream land users without giving them a corresponding access to benefits. For example, it is common for a country to claim ownership of forested areas, and to protect watersheds through policies that exclude local populations from access to resources on which they have traditionally relied, which may lead them to occupy more marginal land areas (Tomich *et al.*, 2004). This study was commissioned by WWF-EARPO in Malewa River basin with the aim of assessing impact of different land management practices on the quantity and quality of water flowing into Lake Naivasha and consequently to recommend target sub catchments where Payment for Ecosystem Services (PES) Scheme can be implemented.

1.3 Research Questions

The study aimed at answering the following questions:

- Which land use or land management practices in the target sub-basins can be supported through a PES scheme in order to improve the quantity and quality of water flowing into Lake Naivasha?
- What are the biophysical impacts of upstream land uses on downstream water resources in Malewa watersheds?

- Which sub-catchment(s) of Malewa Basin are/is the most critical or vulnerable with respect to water quantity and quality, and when conserved will have the greatest impact on water quantity and quality?
- Is SWAT model capable of simulating the hydrological changes within the Malewa watershed and can it be used for PES analysis?

1.4 Main Objective

The research objective was to evaluate the impact of different land use and farming management systems on the hydrology of identified sub-basins of Malewa Basin for pilot payment for environmental services (PES).

1.4.1 Specific objectives

The specific objectives were:

~~4.0~~1. To analyze the landuse/land cover changes that has occurred in the Malewa river basin over the last 30 years.

~~5.0~~2. To identify key target areas for implementing pilot PES scheme.

~~6.0~~3. To simulate water, sediment and nutrients flow in Malewa River basin using the Soil and Water Assessment Tool (SWAT) in order to assess the potential impacts of different land-use changes and best management practices (BMPs) on catchment hydrology (water flow and quality) for improved water and land use practices.

1.5 Justification

Different forms of land use can generate a variety of environmental services. The environmental services are those goods or services that in a direct or indirect fashion are obtained due to the existence of an ecosystem such as natural forest. The forest provides the environmental service of capturing and retaining water, and avoids landslides and soil erosion, particularly in terrain with steep slopes. (Johnson *et al*, 2004)

Land uses with high levels of tree cover, for example, can help regulate water flows in a watershed and reduce the risk of catastrophic flooding or landslides. Land users, however, typically do not receive any compensation for such environmental services. As a result, landusers usually ignore them in making their land use decisions often leading to land uses that are socially sub-optimal. Remedial measures are often imperfect and expensive - often far more expensive than preventive measures. It's worth noting that regulatory approaches are extremely difficult to enforce and may impose high costs on poor land users.

Efforts to develop systems in which land users are compensated for the environmental services they generate have gained momentum in recent years. In this way, land users would have a direct incentive to include these services in their land use decisions, resulting in more socially-optimal land uses. Human intervention and natural phenomena cause change in land cover day by day. Accurate land cover information is essential for many applications like natural resource management, planning and monitoring programs. In a forestation programs, there would be need to know which are the areas where forest is degrading or areas with less forest and suitable for planting. To value costs and benefits of changes in specific land use practices, the ideal situation would be able to identify how those changes will affect the availability of specific resources of concern, and their value to users hence the study was undertaken to identify hydrological changes that are occurring as a result of landuse change and to propose probable mitigation measures that can be undertaken under market mechanism in this case PES.

CHAPTER II

~~3.1~~2.0 Background of the Study Area

~~3.2~~2.1 Introduction

The Malewa basin is situated in the central Rift Valley, Naivasha District in Kenya about 100 km northwest from Nairobi (Figure 2.1). It lies between 36°15′E-36°30′E longitude and 00°40′S-00°53′S latitude. The altitude ranges from 1900-3980m.a.m.s.l.

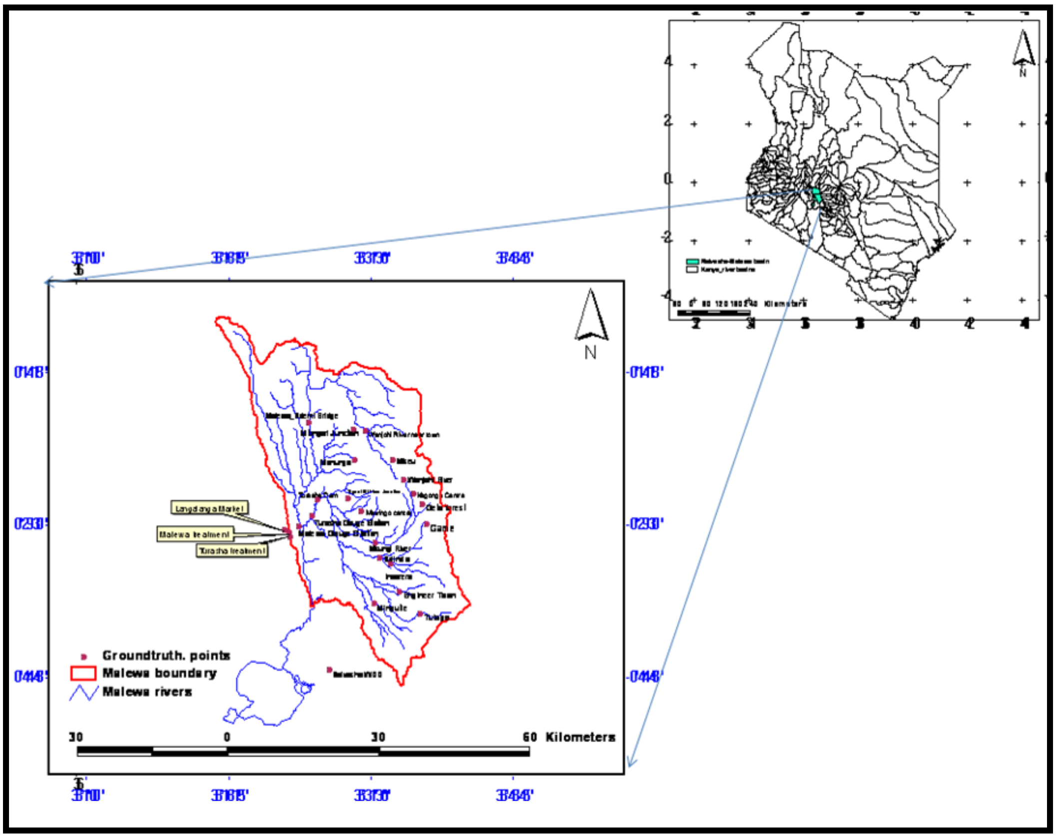


Figure 2.1: Location of the study area (River Malewa basin).

~~3.3~~2.2 Climate

The Lake Naivasha basin belongs to a semi-arid type of climate. The rainfall distribution is bimodal (Figure 2.2 and 2.3). The long term mean annual rain varies from 600 mm at Naivasha town to 1700 mm at the slopes of the Nyandarua Mountains. The Nyandarua plateau experiences a yearly rainfall ranging from 1000 mm and 1300 mm (Becht and Higgins, 2003). Longer rainy season occurs in March-May and short rainy seasons occur in October-November (Kamoni, 1988). February, July and December are the driest months of the year. The lowest temperatures are experienced in July, while the highest temperatures occur in March. The potential evaporation is about twice the annual rainfall in the semi arid area while in the upper humid areas, rainfall exceeds potential evaporation in most parts of the year (Farah, 2001). The annual temperature range is approximately from 8°C to 30°C.

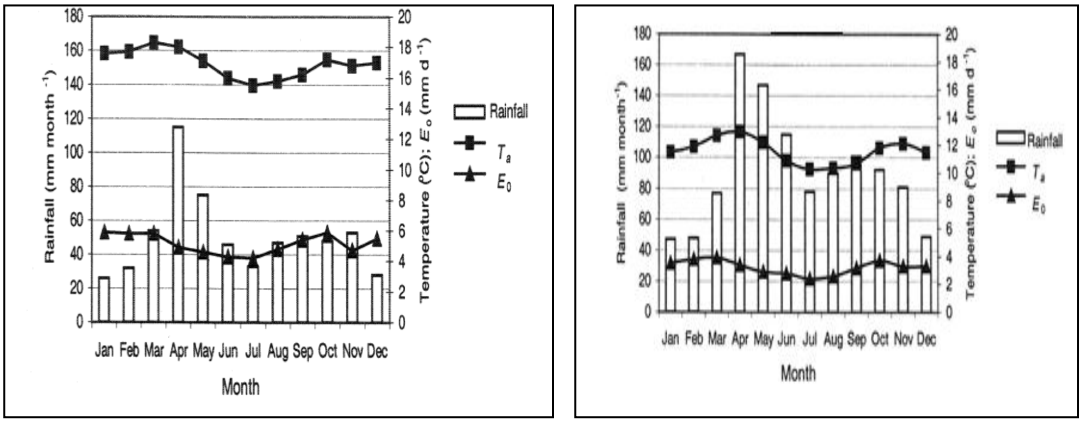


Figure 2.2: Monthly average rainfall, average daily temperature (1931-1983) and average daily reference E_0 (1974-1983) at Naivasha town at altitude 1906 m and at North Kinangop at 2620 m (Source: Farah, 2000)

~~3.4~~2.3 Vegetation

Landcover in the basin is greatly influenced by rainfall. The vegetation can be broadly classified into:

- Forest,
- Scrub/Bush-land/native,
- Bare/range brush/moorland,
- Grassland/scrubland, and
- Agricultural land (small intensive/sparse)

The land cover of the basin is broadly categorized into four groups, namely Agriculture, Grass, Bush/scrub land and Forest. In the Nyandarua ranges, predominant land cover classes are forest and crops. The main crops are maize, potatoes and wheat. In addition there are many other vegetables grown by smallholder farmers in the middle part of the basin. In the lower catchments, there are extensive areas of grass/scrubland and bush land, which are used for livestock grazing (Muthawatta, 2004).

~~3.5~~2.4 Soils

The soils in Naivasha are complex due to the influence of extensive relief variation, volcanic activity and underlying bedrocks (Sombroek *et al.,* 1980). The soils can be grouped into three groups. These are; 1) soils developed from lacustrine deposits; 2) volcanic; and 3) lacustrine-volcanic. (Sombroek *et al.,* 1980, Siderius, 1998; Atkilt, 2001; and Nagelhout, 2001) These soils are highly susceptible to both erosion and compaction (Kiai and Mailu, 1998). The fragility of the area and various human activities seems to accelerate land degradation in the west and southern area of the basin (Hennemann, 2001). From the Kenya soil terrain (SOTWIS Ver. 1), the soils of the study area were classified into 10 different soil categories based on the FAO classification (Figure 2.3).

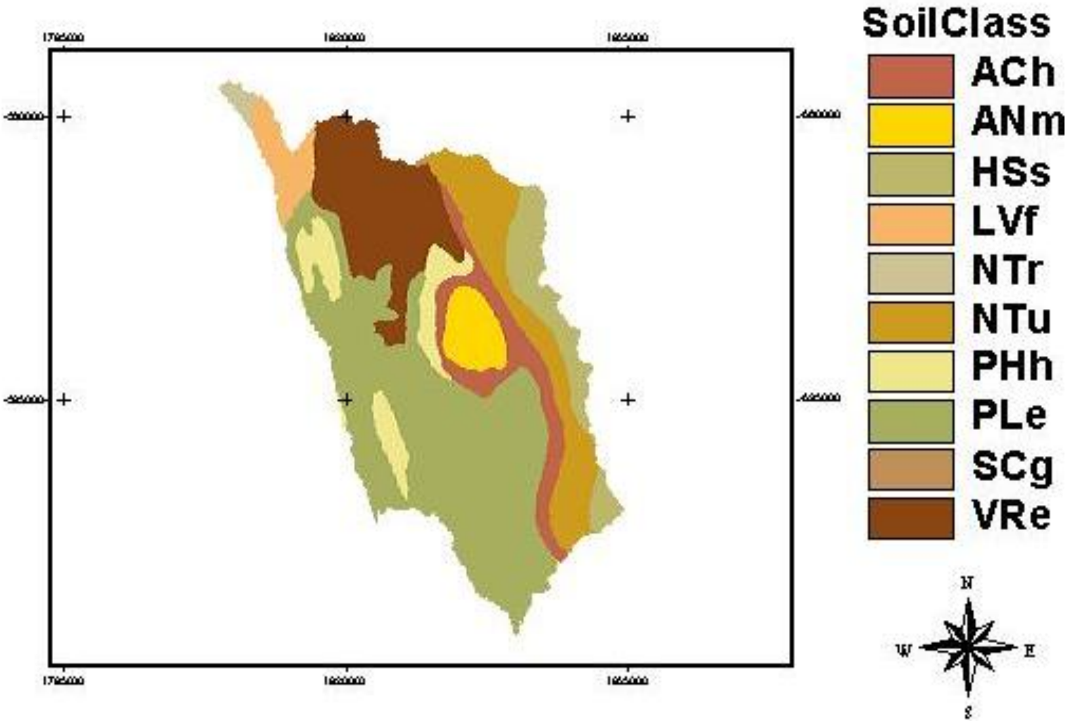


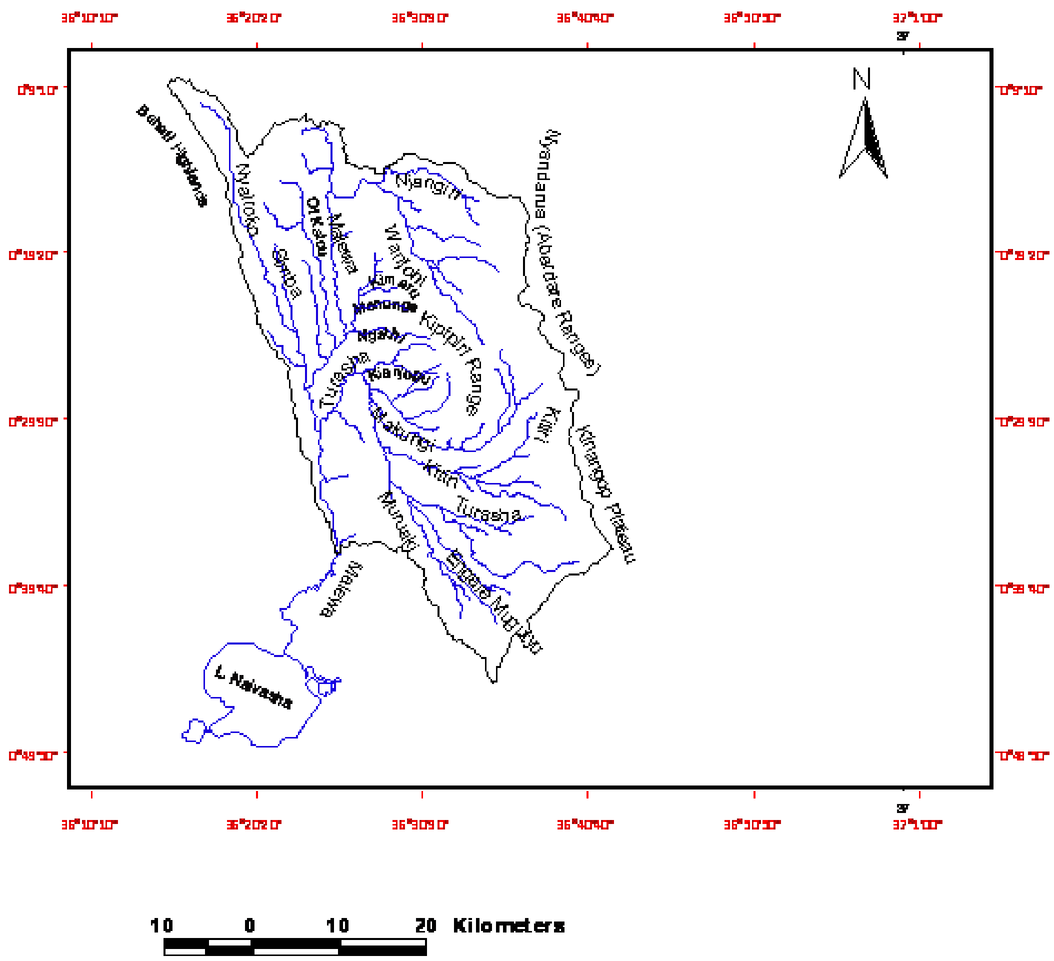
Figure 2.3: Soil distribution in study area

(Note: ACh is Haplic Acrisol, ANm is Mollic Andosols, HSs Terric Histosols, LVf is Ferric Luvisols, NTr is Rhodic Nitisols, NTu is Humic Nitisol, PHh is Haplic Phaeozem, PLe is Eutric Planosols, SCg is Gleyic Solonchak, and VRe is Eutric Vertisol)

~~3.6~~2.5 The Drainage Networks

The Malewa River Basin comprises an area of 1705 km^2 which is approximately 50% of the larger Lake Naivasha Basin (3387 km^2). Drainage into the Malewa river starts from the steep forested eastern slopes from the Kinangop plateau (2483 m a.m.s.l.) and the Aberdares (3960+ m a.m.s.l.) with average annual rainfall of 1087.5 mm (Salah, 1999). Initial flow takes place in a westerly direction via a number of steeply graded tributaries that, at the lower slopes of the range, developing into four main tributaries namely, Mugutyu, Turasha, Kitiri, and Mukungi. All these four rivers flow north-south before turning west and joining the River Malewa. River Turasha is the most important tributary and joins the Malewa approximately 8 km east of Gilgil town (Figure 2.4). The tributaries of the Malewa river forms a very dense dendritic drainage pattern except in the Kipipiri area where they have a radial flow pattern due to the conical shape of the volcanic Kipipiri range (Graham, 1998). River Wanjohi tributary and Malewa tributary flow northward before turning west the south from Ol Kalou.

Figure 2.4: The Drainage Pattern of Malewa Watershed



~~3.7~~2.6 Geomorphology

The study area is situated within the large African rift system and its geological evolution has influenced the geomorphology and hydrogeology in the area. Two major geomorphological groups can be observed (Graham, 1998).

The rift margins:

These are North-South oriented and comprises of the Mau Escarpment in the west and Kinangop Plateau in the east. The Kinangop plateau lies in the south-eastern part of the area between the Aberdares range and the rift floor (Figure 2.5).

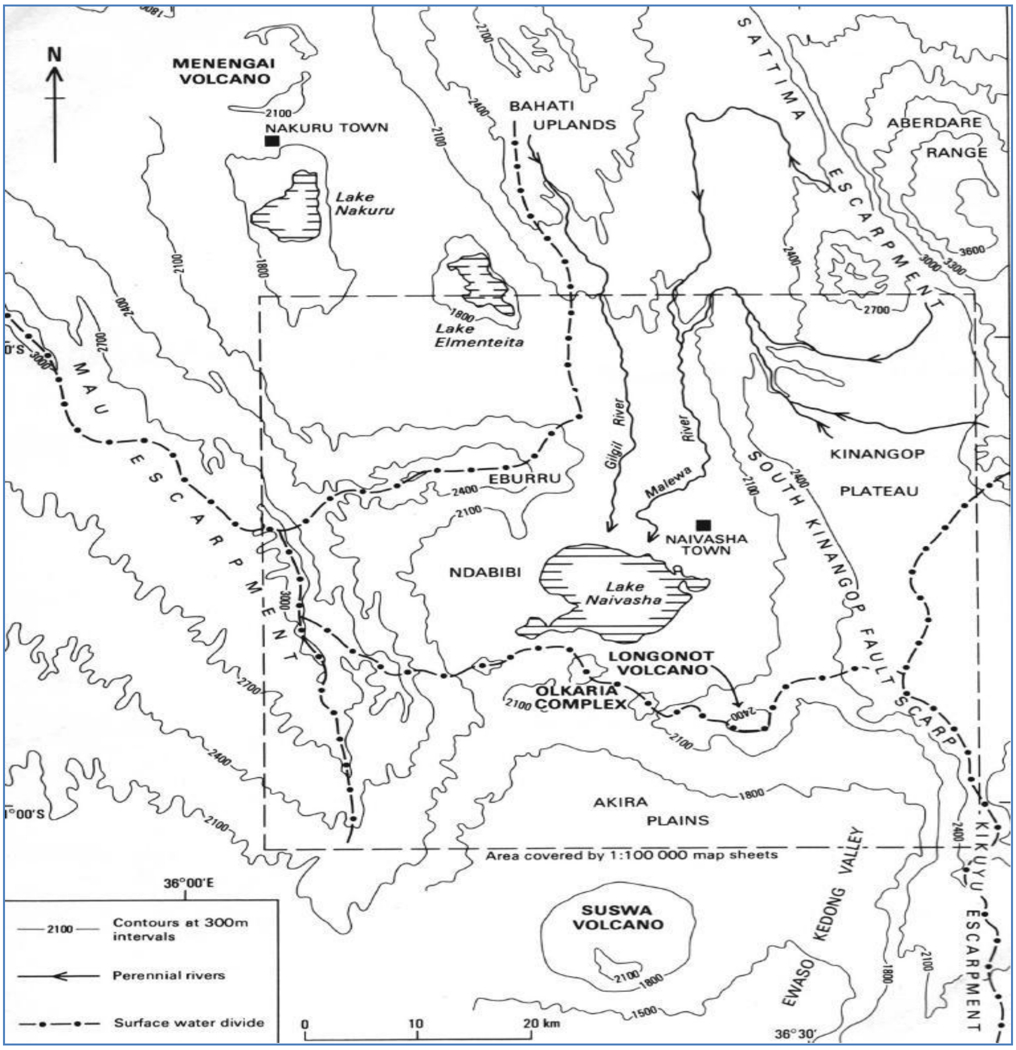


Figure 2.5: Detailed Physiographic Map of the Lake Naivasha Basin (Adopted after Clarke *et al.*, 1990)

It is a broad flat plain ranging in height from 2379 m to a maximum elevation of about 2740 m above mean sea level. Its western margin is defined by the north-north-west trending South Kinangop fault scarp which ranges in height from 100 m to 240 m. It is steeply incised by the tributaries of Malewa River. Along much of its length, this scarp has very steep or vertical rock face above less steep talus slopes. The crest of the scarp is between 500 and 600 m high relative to the rift floor, but is separated from the floor by a series of down faulted platforms.

The north-north-west trending Mau Escarpment forms the western edge of the Naivasha basin attaining maximum elevation of just over 3080 m at some localities but is over 3000 m for 36 km of its length within the map area, decreasing in height both north and south.

Rift floor plain

The rift floor forms part of the Gregory Rift Valley. It is diverse in its structures and topography where numerous volcanic cones and craters, scarps and lakes are found. It reaches its highest elevation (near 2000 m) in the vicinity of Elementeita and Naivasha. High points are formed by mount Longonot and Eburu, both of which rises over 2745 m above mean sea level. On the western and south-western shores of the Lake Naivasha numerous volcanic craters exist. The Lake Naivasha covers an area of approximately 145 km^2 and stands at an elevation of 1882.4 m a.m.s.l (October 1997). The lake is smooth floored and has a mean depth of 4.7 m (Graham, 1998).

~~3.7.1~~2.6.1 Geology

The study area is located in the Eastern section of the African Rift Valley (Gregory Rift). The basin has been subjected to numerous tectonic episodes and is characterized by prominent morphological and structural features. The geology of the area is characterized by volcanic rocks and Quaternary lacustrine deposits. Table 2.1 gives a summarized stratigraphy of the area. Time scale used is that most generally used in East Africa, with the beginning of the Miocene, Pliocene and Pleistocene epochs being placed at 25, 12, and 2.5 Ma (Million years) respectively (Graham, 1998).

Table 2.1: Summarized Stratigraphy of Lake Naivasha basin.

Name of formation (fmn) or (Mem)	Age	Major Outcrops	Lithology
Simbara Series	Miocene	The Aberdares	Basaltic agglomerates and autobreccias
Kinangop Tuff	3.4-4.5 Ma BP Pliocene-early Pleistocene	Eastern Rift margin	Ignimbrite succession; mostly welded trachytic tuffs, palaeosols and weathered zones at top of most beds
Limuru Trachte Fmn	1.66-2.65 Ma BP Pliocene-Early Pleistocene	Eastern Rift margin	Lava flows of trachyte and composition. Some flows have abundant feldspar phenocrysts
Karati Basalt Fmn	< 1.5 Ma BP Pliocene-Early Pleistocene	Adjacent to North Karati settlement and Naivasha Town	Olivine basalt lava, scoriaeceous blocks and lapilli
Sattima Series	Pliocene-Middle Pleistocene		Volcanic series; phonolite, olivine alkali-trachyted, mugearites and fissile basalts
Laikipian Basalt	Early Pleistocene-Upper Middle Pleistocene	The Aberdares National Park	Non porphyearitic basalts
Lake Sediments		Oserian Farm, Sulmac Eastate	Pumiceous granule-pebble gravel, coarse sand gravely sand, silt and clay
Alluvial deposits	< 0.45 Ma BP Mid/Late Pleistocene-Holocene	Gullies and small internally draining basins	Silt, fine sand, some ferruginous coarse sand and boulder gravel
Eburru pumice	Recent?	Widespread over Western Eburru extending onto the adjacent Mau Escarpment	Grey pumice lapilli and/or ash beds most of which have a palaeosols and or weathered zone at the top. Blocky pumice deposits occur in the cratered summit area of Eastern Eburru. Pumice accompanied by obsidian and trachyte lava lithics. Occassional beds rich in feldspar crystals and highly feldspar porphyearitic lapilli. some bedded ash deposits low in the exposed succession (Source: Graham, 1998)

3.7.22.6.2 Hydrogeologic Setting

The hydrogeology of Lake Naivasha has been described as complex by Clarke *et al,* (1990). While it is lower than the rift escarpments, it lies on the highest elevation of Rift Valley Floor. Ojiambo, (1992) recognized two systems operating in the area.

- The Lake Naivasha subsurface seepage and the cold shallow groundwater system.

- The hot highly mineralized deep geothermal systems.

Piezometric plots and isotopic results show that underground movement of water is occurring both axially along the rift and laterally from the bordering highlands into the rift. Analysis of piezometric maps (Figure 2.6) and aquifer properties of the rocks in the area show that much of the subsurface outflow from the Naivasha catchment is to the south, via Olkaria-Longonot towards Suswa. Shallower aquifers may form a significant conduit for southerly flow.

The hydrogeology of the Naivasha Basin is simple in concept but complex in detail. At its simplest, the system can be regarded as having three main zones: the recharge, transit and discharge zones.

- The recharge zones are at the periphery of the Basin; in the east the highlands of the Nyandarua Mountains and Kipipiri; Eburru in the North West; and the Mau Escarpment to the west.
- The transit zone covers all that area between 2,400 and 2,100 m a.m.s.l;
- The discharge zone covers the basal part of the Basin, culminating in the Lake itself. This is the most complex part of the basin in hydrogeological terms.

The recharge zone provides baseflow generation in streams and rivers and deep percolation to aquifers, almost certainly fault-controlled. Groundwater movement is dominated by faults and the weathered upper parts of individual lava flows and associated pyroclasts.

In the discharge zone (the basal part of the basin) there is generally a two-part aquifer system: a shallow aquifer from 10 to 40 m below ground level (bgl), and a second deeper aquifer – sometimes separated by clay layers or basalt lava flows but in hydraulic continuity with the shallow aquifer – below about 50 m bgl (Tsiboah, 2002). Aquifer material includes fine, medium and coarse sands, gravels, pebbles and fractured volcanics.

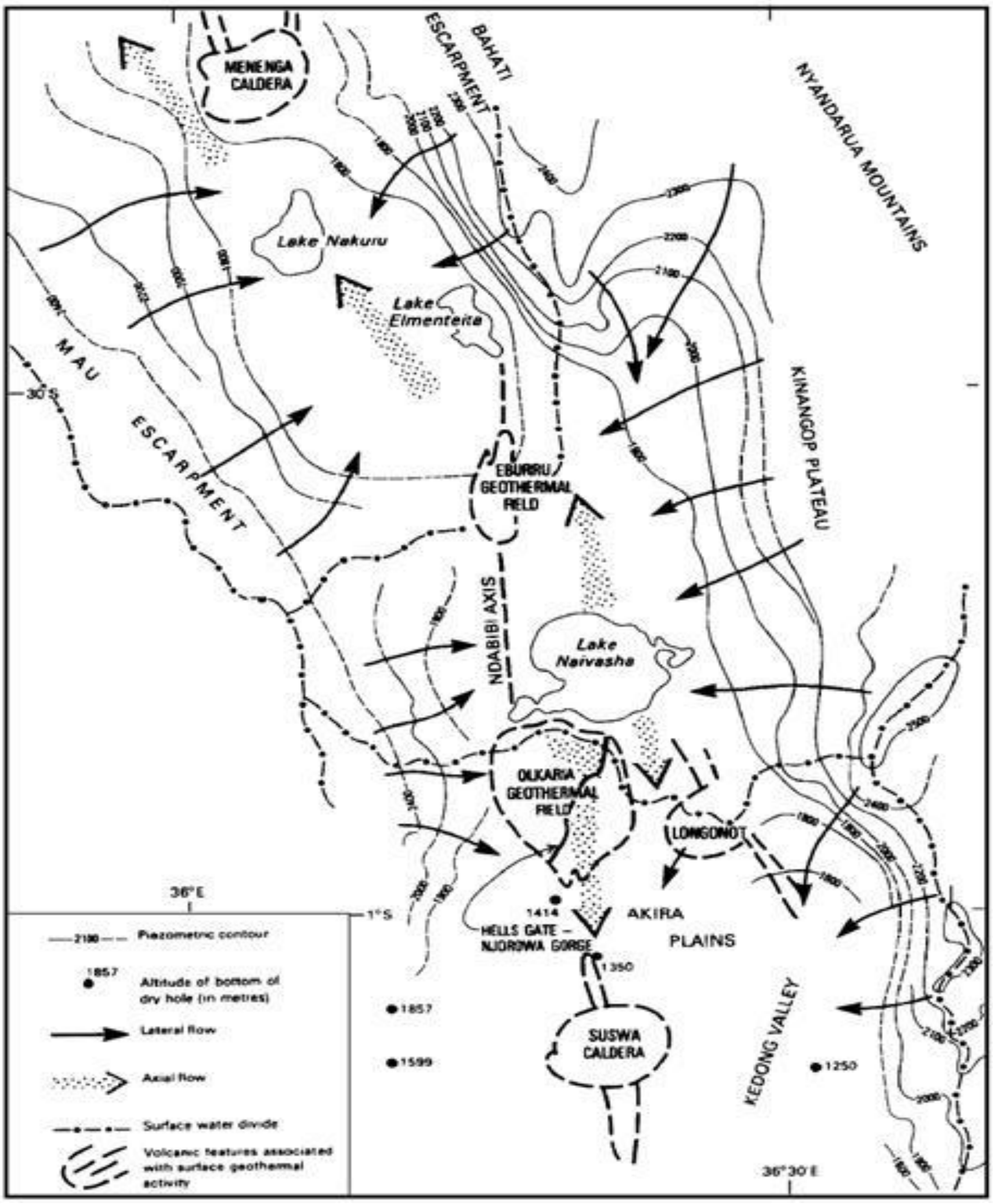


Figure 2.6: Piezometric Map of Lake Naivasha and Vicinities (Taken from Clarke *et al* (1990)

CHAPTER III

~~4~~3 REVIEW OF LITERATURE

~~a)~~3.1 Introduction

The main driving force in the Lake Naivasha basin and the surroundings is the agricultural production with uncoordinated development in the area (Alfarra, 2004). It can be further pointed out that, the main problem in the area is caused by a number of identified water uses in agriculture sector, which is the driving force in the area. According to (Alfarra, 2004), water is misused by over-irrigation in fodder, grass and vegetable farming, although flower farms, a high income source for the area, are accused of causing the problem. The main problem is not the shortage of water but the management of the lake. The author recommended that a basin wide legally mandated body involving all levels be established to oversee water use. Other strategies include capacity building of stakeholders on water natural resources management policies, water rights and enforcements of laws.

Salah, (1999) reported that importing water into the basin is practically impossible; development of the basin water status could be accomplished by reallocation among uses, not users, decreases the non-process depletion, and decrease the non-beneficial depletion. Naivasha basin could be considered as a fully committed water basin as the amount of outflow is negligible. Considering *water quantity, quality, and productivity*, he made the following conclusions

~~a)~~1. The environmental assets, e.g. forest, and natural vegetation are the largest consumers of water.

~~b)~~2. Both agricultural and industrial sectors are pushing on a serious pressure onto the environment. Although clear segregated values about the sub-sectors and their contribution were not involved in his studies, the aggregation was favorable slightly overwhelming the agricultural pressure over the industrial one in some parameters and the vice versa in others. Domestic pressure would partly disappear if a proper sewage treatment facility was in place

~~c)~~3. The most money earning sector was the tourism sector and then the flower industry which in a way or another launches a double edge effect, most economic, but most polluting. On the other hand, the largest water consumer was not contributing to the economic return directly. In fact, they are economically contributing by their existence so they support a certain wildlife for which the tourists visit the area.

The water balance of Lake Naivasha has been calculated from a model based upon long-term meteorological data of rainfall, evaporation and river inflows (Becht and Harper, 2002). The most accurate predictions of lake level were derived from the data sets of river discharges known to be from the most-reliable time period and gauging stations. There model estimated a current annual abstraction rate of 60×10^6 m^3 $annual^{-1}$, a figure perhaps six-times higher than that calculated as a 'safe' yield in the 1980s. They further recommended that there is an urgent need to accurately measure all abstractions and provide consistent, reliable, hydrological and meteorological data from the catchment, so that a 'safe' yield may be agreed upon by all stakeholders and sustainable use of the lake waters to be achieved.

Fayos, (2002) reports that the availability of water resources is determined by the behaviour of the hydrological cycle at the catchment level, the alteration of any mechanism or process within the cycle (for instance, change of infiltration and percolation rates, increase of runoff and sediment load, etc.) directly or by affecting any of the factors which condition those processes will have effects in the quantity and quality of the water resources within the catchment.

Lukman, (2003) found out that the SWAT model predicts, without abstractions, that the climate change would affect the lake water levels 4 meters lower than the condition without any climate change. Abstraction of the lake would accelerate the lake water level depletion. Further, the major effects of climate change on the Lake Naivasha area and the water resources will be through changes in the *hydrological cycle, temperature and precipitation.* These factors are the controlling parameters of the lake water level and lake water volume and finally the water availability.

Bhandari, (2005) found out that monthly rainfall data showed less correlation and annual rainfall data showed good correlation coefficient (=0.5) these can be attributed to the fact that precipitation data contains errors due to measurement accuracy (approximation uncertainty) and the spatial variability (ambiguity & likelihood uncertainty) of precipitation. Precipitation errors are mainly classified into three parts: orographic effects, gage measurement error, and spatial sampling error. Gage and sampling error are described as random error, and orographic effects are systematic errors, so they can be modeled and removed from the data.

The errors in the individual measurement accumulate when using these point measurements to estimate areal average precipitation in watersheds. The annual mean data contains aggregated error which is distributed over the entire period, while monthly data, the errors are more magnified due to disaggregation. So, annual rainfall data was selected for the study purpose. In his case study for validation purpose, station Naivasha District Office (station id 9036002) was selected, as it was having the best quality daily rainfall record. Observed mean rainfall for Julian day 120 of this station was compared with the rainfall for Julian day 120 generated using weather generator model (WXGEN) for the same station location (Table 3.1).

Table 3.1: Rainfall for Julian day 120 generated using weather generator (WXGEN)

	Rainfall (mm)
Observed	3.6
Simulated	3.1

The author further pointed out that the difference (= 0.5 mm) between the observed and simulated rainfall for Julian day 120 was insignificant. Thus he inferred that:

- Weather generator input parameters can be accurately spatially and temporally modeled and
- Spatially correlated weather generator model address the problem of the variation of rainfall data.

A study conducted by Mmbui, (1999) using historical inflow data from 1932 to 1998 estimated the lake levels based on simple water balance model and found out that the model output correlated well with the lake levels before 1984. The author further pointed out that the long-term water balance of the basin is as follows, rainfall as 95 mcm/month, surface water inflow as 220 mcm/month, evaporation as 260 mcm/month and calculated groundwater outflow of 4.6 million m^3 per month with lake abstraction of about 57 million cubic meters/month. The author further estimated long-term average total combined inflow from the Rivers Malewa, Gilgil, Turasha, Karati and surface runoff into the lake approximated at 2.26 mcm/month. Podder, (1998) estimated annual average inflow from Malewa as 214.7 mcm. Total inflow to the lake shows that, contribution to the lake is as follows:

- 40% from Malewa River
- 20% from Gilgil River
- 40% from Turasha River

Al-Sabbagh, (2002) analyzed stream flow data of the Turasha and Malewa sub-basins and concluded that, the data for the gauging stations 2GB1, 2GB5, 2GB4, 2GC4, 2GC5 and 2GC7 are reliable for streamflow analysis.

Abdulahi, (1999) observed that the change in groundwater storage is insignificant, accounting for 0.1% of the lake storage. Also, Lake Naivasha is losing water to the aquifers at a rate of about 55 million-cubic meters per annum, over a period of 1958 to date. Further study by Graham (1998) on groundwater recharge estimation of Malewa Catchment, indicates that baseflow vary between 60 and 290 mm/year. An average annual baseflow contribution of 60mm/year was calculated as inflow to Lake Naivasha. This represented approximately 8% of the effective rainfall that occurs over the catchment. Total inflow, i.e. baseflow and surface inflow to the Lake was estimated to be 137 mm/year.

Graham further pointed out that groundwater recharge based on streamflow analysis indicates that recharge primarily comes from the upper catchment areas of Ol Kalou. However, there are some groundwater losses in the vicinity of Ol Kalou which can be attributed to the abstraction of groundwater from wells or to grid faulting along the rift floor which acts as conduits which channel flow along the rift floor. Baseflow across the Kinangop Plateau area did not show any evidence of being affected by fault found within the area. Baseflow analysis estimates an annual average recharge value of 60mm/year. Groundwater recharge over the catchment areas appeared to be quite varied and it was observed that the recharge primarily occurs over the areas which are at a higher elevation and which have relatively high rainfall. These areas corresponded to the rift margins of the Kinangop plateau and the Aberdares where groundwater recharge ranged from 112-290 mm/year. In the rift Valley where semi-arid conditions exist, recharge was significantly less and varied between 49 and 69 mm/year. Total recharge over the River Malewa was estimated to be 137 mm/year.

Nalugya, (2003) reported that there is high recharge values estimates in areas that are mainly dominated by grassland type of vegetation and low values in areas covered by shrubs and thick vegetation. Owor, (2000) reported that the regional groundwater flow patterns are to the south and south-eastern part and lesser to the north and north-eastern part of the basin. Transmissivity and groundwater recharge in the area had been modeled using available data from individual wells. A recharge of 20-25 $mmyear^{-1}$ was estimated for the rest low gradient area, which is underlay by the mixture of sediments and re-workable volcanic materials. He recommended that in order to have a clear description of the groundwater flow patterns, estimation of spatial variation of recharge is required.

Gaudet and Melack, (1987) estimated 44 mcm/year and 12 mcm/year for groundwater outflow and abstraction respectively which sum up to 56 mcm/year. Ojiambo, (1996) re-evaluated mean value from different studies and gave a value of 39 mcm/year for abstraction that sum up to 51mcm/year. Mmbui, (1999) used 55 mcm/year for groundwater outflow in his water balance model without abstraction for their studies on groundwater outflow and abstraction for the Lake Naivasha Basin. Behar, (1999) found a similar lake seepage loss of 55 mcm per annum since 1958. Ramirez, (1999) found aquifer transmissivity values varying from less than 1 m^2/day to more than 5000 m^2/day. He estimated storativity values between 0.01 and 0.15. Trottman, (1998) in the study of the groundwater storage change in response to fluctuating levels of the lake found active groundwater storage zones of up to 1-2 km from the lake shores. Podder, (1998) estimated the long-term average inflow from the Malewa catchment 1960 – 1990 into Lake Naivasha at about 215 mcm /year. Groundwater recharge estimation of the Malewa catchment by Graham, (1998) found annual baseflow contribution to the lake to average 60 mm/year representing about 8% of effective precipitation. Baseflow and surface inflow to lake was about 137 mm/year. Ashfaque, (1999) estimated daily average evaporation from the lake at 5.96 mm using the evaporative fraction approach, whereas the pan evaporation gave 5.46 mm with a standard deviation of 1.28 mm for the period 1958-1999.

Fayos, (2002) found out that, some of the conflicts that exist and worry the stakeholders are formed by problems not founded on scientific data, for example in the case of the potential problem of siltation of rivers and lakes. Some stakeholders, mainly downstream water user, are alarmed about what they believe to be a high increase of sediment load coming from the rivers into the lake. This conflict raises a high degree of concern in the society nowadays, but exploring the existing data and the analyzed information of some other researchers, it is concluded that the alarm around this conflict is exaggerated and that threats of siltation does not seem so high nowadays An indication of the sediment concentration is given by a couple of samples taken in Turasha river in October 2001 which gave a sediment concentration of 0.11 kgm^{-3}.

Ringo, (1999) further found out that the general pattern of the soils in the study area to be related to topography and parent material. On flat areas (interfluves), Planosols were found with imperfect to poor drainage conditions and clay pan subsoil with bleached and coarser topsoils. On sloping ground better drained soils were found such as Andosols, Phaeozems and Luvisols. Gleysols were found in the wet bottomlands.

It was observed that the erosion hazard ranges from very low (0-5 t/ha/year), to low (5-12 t/ha/year) and medium (12 - 25 t/ha/year), which covers 70%, 23% and 7% of the studied area respectively. The relative low values of the erosion hazard were attributed to the current land use, which contribute to the better vegetation cover and result into a very low C-factor of USLE (mainly <0.1). It was also found that topography covered gentle undulating slopes (0-5%) and undulating slopes (5-10%) which was 60% and 15% of the studied area respectively. With the presence of vegetation and many drainage waterways, the slope length (overland flow production) was reduced. Relatively low slope percentage and or shortened slope length resulted into the low topographic factors (LS with the average < 1) which contribute also to the low erosion hazard. Soil erodibility was found to be relative low, ranging from low to moderate and this attributed to the relatively high amount of clay and high organic matter in the topsoils. Rainfall was found to increase from west (788 mm/year) to east (1167nm / year) with an erosivity of 325 N/h and 427 N/h respectively.

Rupasingha, (2002) reported that Malewa River supplies long-term suspended sediment concentration of 0.23 kg/m^3 and 0.26 kg/m^3 from 1932-1990 and 1957-1990 respectively. Measured concentrations during 2001 fieldwork gave an average suspended sediment concentration along the Malewa River at about 0.21 kg/m^3. Long-term estimated annual average suspended sediment load of Malewa is about $42.8x10^3$ tons and 55.9 $x10^3$ tons for the periods from 1932-1990 and 1957-1990 respectively. Based on latter figure, total estimated suspended sediment load to the lake through Malewa, from 1957 to 2001 is about 2.5 $x10^6$ tons.

According to Rupasingha, (2002), the sediment input in Lake Naivasha in the period 1957 – 2001 was 19.0 million m^3, which, if spread evenly over the depositional area of lake bottom (89.23 km^2 at 1884 m a.m.s.l.) would give an average thickness of 0.21 m. The total mass of sediment accumulated in the lake was estimated at $7.07x10^6$ tons for the 44 year period from 1957-2001. Out of this, 5.75 $x10^6$ tons was determined as inorganic mineral matter and 1.32 $x10^6$ tons of organic matter. A comparison of the lake sedimentation with suspended sediment fluxes of Malewa and Gilgil rivers reveals that the Malewa river wash load contributes to 35% of the lake sedimentation. This implies that 65% of the sediment mass is transported either as bed load, a fraction also by the much smaller Gilgil river, or by another active sediment source. Considering the whole drainage basin of Lake Naivasha, the estimated long-term watershed sediment yield was about 39.5 metric $tons/km^2/year$ and 48.0 $tons/km^2/year$ from 1957 to 2001 for respectively inorganic mineral and total sediment. Assuming that the active contribution for lake sedimentation is only from the hydraulically connected sub basins, i.e. Malewa and Gilgil river systems, the long-term average annual watershed sediment yield (of these watersheds) will draw around

74 tons/km^2/year. Between 1957 and 2001, this accounted for a 7 % reduction of the lake volume capacity (using the 1957 bathymetry and 1985m a.m.s.l. as lake reference level). For this 44-year period, the annual volume depreciation rate was about 0.0016% only.

Kitaka, *et al,* (2002) reported that the loss of phosphorus from the catchment of Lake Naivasha, Kenya, was 0.2 kg ha^{-1} $annual^{-1}$, 76% of it particulate in a `normal' year of wet and dry periods. It rose to a mean of 1.8 kg ha^{-1} $annual^{-1}$, 90% of which was particulate, in the months following the extreme rainfall which followed the 1997–1998 El Niño event in the Southern Atlantic. Total and particulate phosphorus were positively correlated with suspended solids and with discharge, and conductivity was negatively correlated with discharge. The magnitude of losses poses both threats to the water quality of Lake Naivasha and to the sustainable soils resources of the catchment.

~~b)~~3.2 Concepts of Payment for Environmental Services (PES)

Ecosystems provide a whole range of valuable environmental services, such as water services, biodiversity conservation or carbon sequestration. However, these services are usually lost or deteriorated since landowners often do not receive any compensation for providing these services and, therefore, they are ignored in decisions related to the land use (FAO, 2004). The concept of payment for environmental services (PES) is a promising solution to incorporating market based mechanisms in decisions related to land use, which has caused significant interest over the last years. However, putting theory into practice is not an easy task (Pagiola and Platais, 2003).

Often it is assumed that land use practices have significant impacts on water resources and affect the downstream population in the watershed (FAO, 2004). Payments by the downstream population to the upstream population for "hydrological services", such as good quality of water, less sediments or a more regular flow regime are some of the mechanisms to internalize these impacts. However, there is much controversy on the direction and extent of such impacts, their influence in the relations between the different resource users in the watershed and the mechanisms to distribute costs and benefits among the various users. Hence there is need for a careful assessment and monitoring of land-water relations for implementing payment systems for environmental services in watersheds.

The effects of land use on water resources vary according to local conditions. The assessment is difficult due to large delays between cause and effect and the interference between anthropic and natural impacts caused by for example climatic changes. These limitations make it difficult to draw general conclusions about the relations between land and water use in watersheds. However, some experiences show that land management impacts on watershed hydrology and sedimentation are observed more clearly in small-scale watersheds of about tens of square kilometers. Some land management effects on water quality can be observed also at larger scales.

Gathering of reliable information on interactions between land use and water-related services in watersheds is expensive and it can be obtained only in the long term. There are some generalizations about these poorly reliable interactions, which are obtained from extrapolations of experimental results from the farm scale to the watershed scale.

~~i)~~3.2.1 Definition of PES

Payment schemes for environmental services (PES) are flexible compensation mechanisms by which service providers are compensated by service users (FAO, 2004). The concept PES has received much attention in several Latin American countries in the last few years as an innovative tool for financing investments in sustainable land management (FAO, 2004). However, there are important challenges to be met, e.g. identification and quantification of the environmental service, performance monitoring, as well as the sustainability of the schemes.

In a watershed context, PES schemes usually involve the implementation of market mechanisms to compensate upstream landowners in order to maintain or modify a particular land use which is affecting the availability and/or quality of the downstream water resource. Usually this compensation is generated from payments made by downstream water users. Providers and users of the service are located in the same watershed.

For this study, the following definitions were adopted

> *Providers* – economic agents whose productive activity generates, as a positive externality, the service for which the payment system has been created.
>
> *Users* – Economic agents, who benefit from the service through a consumer good, e.g. water.
>
> *Environmental services* refers to positive externalities – affecting a consumer good – associated with particular environmental conditions, e.g. a certain land use.

Water services – these includes such functions as flood control, erosion control, sedimentation control, water quality control, soil salinization control, maintenance of aquatic habitats, and maintenance of dry season flows)

In the specific case of PES schemes in watersheds, the service usually relates to the maintenance of the availability and/or quality of water. The providers are upstream land users, whose land use is to be modified or conserved to render the service, and the users are downstream consumers – companies or individuals – of the water resources.

The basic idea of PES schemes is to create a market for an environmental good, which usually is priceless. Economically speaking, PES schemes require the allocation of titles *de jure* or *de facto (absolute)* on environmental externalities benefiting third parties (environmental service). Thus, the system identifies economic agents in charge of "positive" environmental externalities, or service "providers", and the benefited agents (or users). The establishment of cause-effect relations is required between the land use - upstream - and the water resource conditions - downstream in the watershed. In addition, PES schemes intend to establish an information flow between service providers and users to facilitate the market exchange between both types of agents.

Two types of PES schemes can be distinguished (FAO, 2004). The first type relates to services at the global or the broad geographical scale and has the purpose of using market instruments to pay for services whose users are not limited to the local level, e.g. biodiversity conservation, scenic beauty, carbon sequestration and others. The second type of PES schemes is designed to compensate providers by means of a local market, in which generally users are better defined and limited to a particular geographical area, which is close to the location where providers carry out their productive activities (FAO, 2004). PES systems for water services in watersheds belong to the latter category.

~~c)~~3.3 Advantages and Opportunities of PES Schemes in Watersheds

The advantages and opportunities of PES in a watershed are depicted in Table 3.2.

Table 3.2: Advantages and opportunities of PES in Watersheds (Adapted from FAO, 2004)

SN	Advantage/opportunity	Explanation
1	PES schemes can serve as an instrument to educate the population about the value of the natural resources	PES schemes set a price for environmental services, which were previously priceless. This causes users and providers to associate a market value to such services, which should lead to a more efficient use of the water resource, and recognition of the benefits of particular land uses which provide the required environmental service
2	PES schemes can facilitate the solution of conflicts and the reaching of consensus among the actors involved	PES systems can contribute to solving conflicts about the alternative uses of land and water resources by fostering the information flow between providers and users of the services and considering economic compensation mechanisms
3	PES schemes can enhance efficiency in the allocation of natural, social and economic resources.	One of the basic assumptions underlying the schemes is that the use of market mechanisms increases the efficiency in resources allocation. As in other markets, efficiency can be increased if the required institutional conditions are in place, including a sufficient degree of competition, information availability and the lack of externalities, among others. The design of PES schemes should make certain that these conditions are met to ensure that market mechanisms have a positive effect on the efficient allocation of resources.
4	PES schemes can generate new sources of funding for the conservation, restoration and valuation of natural resources.	The appropriate implementation and execution of a PES scheme requires an important number of preliminary studies to establish relations between the land use and the water resources, and to estimate the economic value of the service. These studies may constitute a significant contribution to the knowledge of the ecosystems involved, as well as an important input for its conservation. On the other hand, ideally PES schemes should be self-financed. Therefore, they should constitute a local – and mostly private – financing source for the better use or protection of the natural resources.
5	PES schemes can create indicators for the relative importance of natural resources by means of the valuation of environmental services.	As previously stated, PES schemes can generate useful knowledge about human impacts on the condition of water resources in watersheds, as well as the economic importance of these impacts and other resources.
6	PES schemes allow the transfer of resources to socio-economically vulnerable sectors providing environmental services.	PES schemes are more suitable for increasing the efficiency of resource allocation than to deal with inequality problems in income allocation, since they are based on the use of market tools. However, these systems, if explicitly designed for this purpose, can contribute to poverty reduction. In many cases, upstream service providers belong to marginalized social groups. Therefore, a financial compensation might help to raise low incomes to a certain extent. In some cases, low compensation values to providers may imply considerable increases in incomes. In other cases, however, providers belong to rather high socio-economic layers and do not depend greatly on the environmental

		service payments to improve their income.

~~i)~~3.3.1 Assessment of PES

Once identified, environmental services need assessment in order to value them correctly. The difficulty of identification is due partly to the variety and complexity of conditions in the field (Pagiola, *et al.*, 2002; FAO, 2004 and PROFOR, 2005). Hydrological benefits, for instance, are function of many factors e.g. the rainfall regime, the type of soil and vegetation and topography. Working out a program can thus prove to be complex. Another difficulty lies in the fact that there can be a diversity of objectives being sought in one same place. Indeed, regulating water flows to prevent flooding and the effects of the dry season require different actions. A basic assessment of opportunity costs can help set PES rates competitively and target limited resources to the particular sectors where they can really make a difference.

A baseline is necessary for buyers of environmental services to set up PES programs and later assess them; otherwise the risk is that they may be paying for something that would have happened anyway. Moreover, for PES to have the desired effects, they must reach land users in a way that motivates them to change their practices to more sustainable ones. The lack of information – about how to quantify environmental services, about buyers and sellers, about how these markets work, about how to design and monitor payments systems is generally the biggest obstacle to the development of markets for PES (PROFOR, 2005). For specific case of PES schemes in watersheds, the service usually relates to the maintenance of the availability and/or quality of water. The providers are upstream land users, whose land use is to be modified or conserved to render the service, and the users are downstream consumers – companies or individuals – of the water resources.

~~d)~~3.4 Design of PES Schemes in Watersheds

FAO, (2004) gives a detailed description of how PES can be designed. In order to evaluate the feasibility of a PES, studies regarding supply and demand for environmental services must be carried out, as well as economic assessments of the technological changes needed in order to provide environmental services. Several environmental services have been identified in watersheds and with significantly different assessment methods. There is global demand for some of the services while others such as water services correspond to local demand.

The process of studying PES involves understanding the science behind the impact of land use changes have on hydrological regime of a watershed. Figure 3.1 illustrates the paths necessary to translate the theoretical aspects of PES into practice. The study aim was to focus on water service hence Figure 3.2 is a sub-set of Figure 3.1. It shows the flow paths followed in understanding the impacts that landuse changes have on hydrological regime i.e. understanding water service provision.

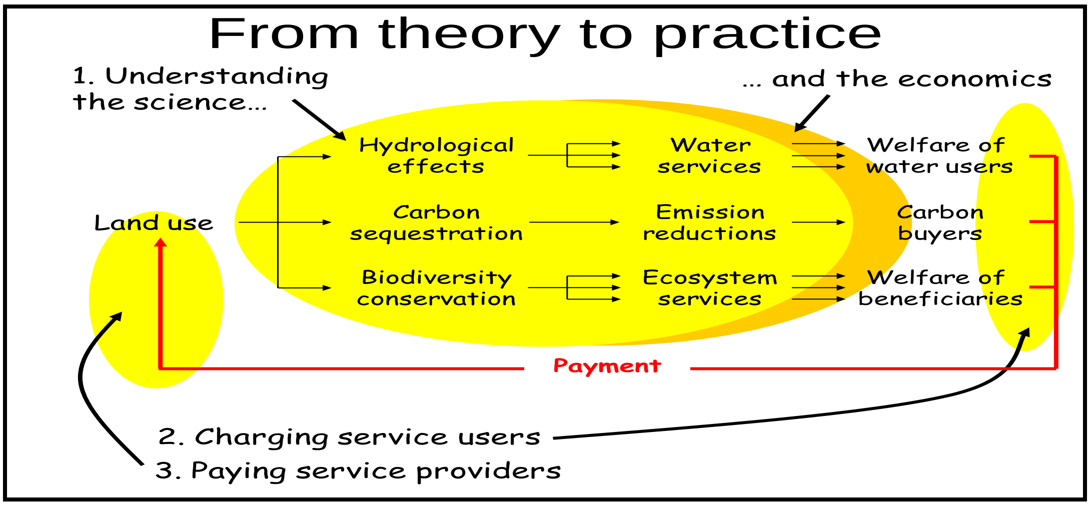


Figure 3.1: Understanding the science and the economics of PES

(Source: Pagiola, 2003)

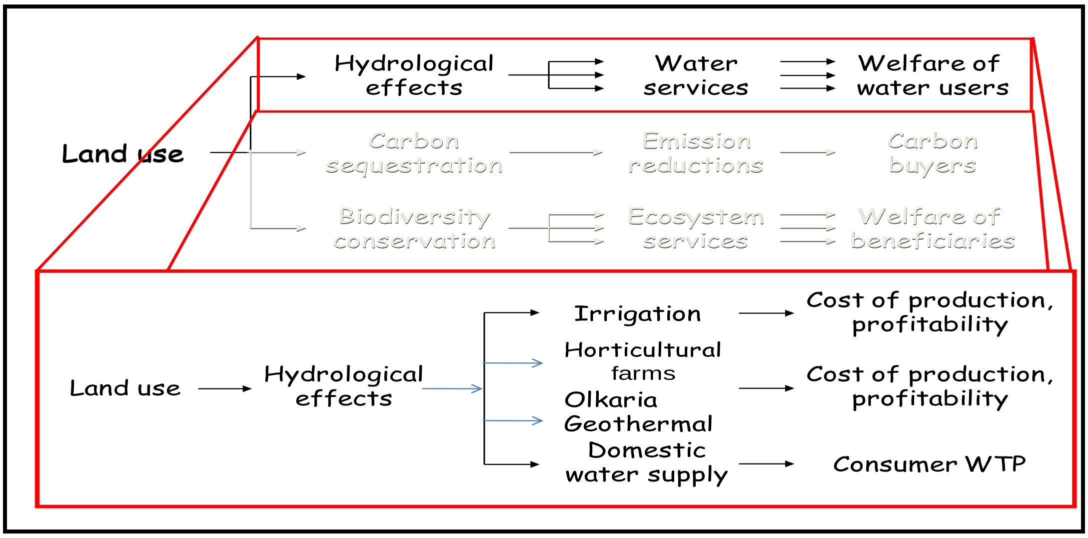


Figure 3.2: Understanding service provision (Source: Pagiola, 2003)

As for design of incentives, PES does not necessarily involve cash payments; these can be fiscal incentives, credits or others. Incentives provided by a payment for environmental services scheme may be individual or collective. In order to encourage service providers to conserve natural resources, the incentives offered should match the current income of the service providers from productive activities.

In terms of land use promoted by PES, forestry systems are generally favored, with special recognition of the services provided by trees, especially native species. However, agro-forestry, forestry-grazing and conservation agriculture systems are recognized as appropriate for the provision of environmental services in watersheds as well as the provision of production options for rural communities. PES can be a tool for the consolidation of decentralization processes since these consolidate and strengthen local institutions, among other benefits. An example of the basic steps of a PES process is illustrated in Figure 3.3

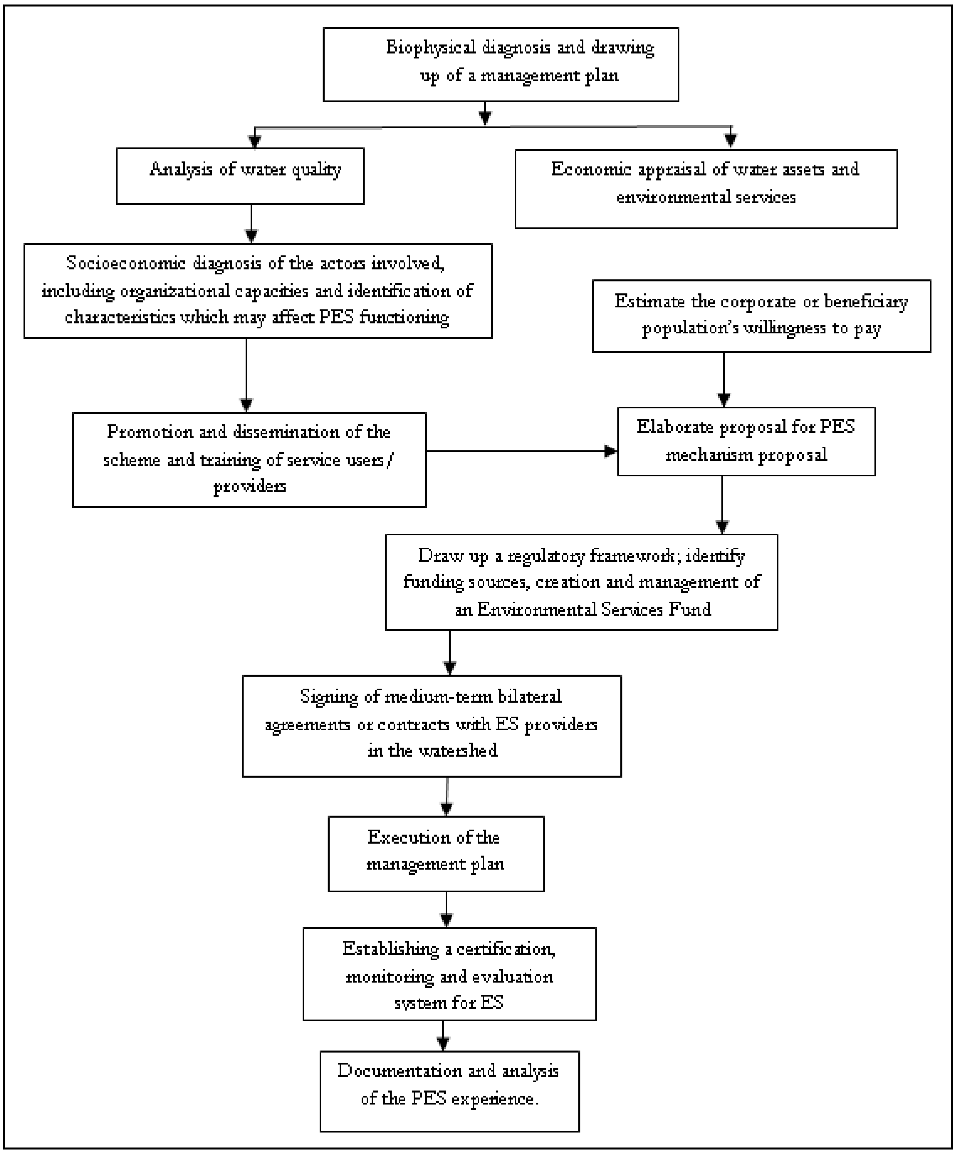


Figure 3.3: Basic steps of a PES process (Adapted from FAO, 2004)

~~e)~~3.5 Identification and quantification of water-related environmental services

The basis of any water-related PES scheme is the assumption that a change or preservation of a specific land and water use in the upstream part of the watershed will be beneficial to downstream water users in terms of water availability or quality. These beneficial uses are thus defined as environmental services to downstream users. Which services downstream users may beneficially utilize, depend very much on the type of water use, the hydrological regime and geological features of the watershed, as well as climatic factors (Kiersch, 2005).

Watershed services include, flow regulation, maintenance of water quality, control of soil erosion and sedimentation, and maintenance of the hydrological functions provided by forests/ecosystem. Environmental services are defined as goods or services that in a direct or indirect fashion are obtained due to the existence of an ecosystem such as natural forest. Forest provides the environmental service of capturing and retaining water, and avoids landslides and soil erosion, particularly in terrain with steep slopes (Johnson *et al.*, 2002)

~~f)~~3.6 Catchment Characterization

Catchment characterization involves obtaining summaries of a number of topographic, climatic and environmental (physiographic) parameters for each catchment in the analysis. The range of parameters to be investigated is limited by the availability of complete and uniform data sets for the region. The uniformity of data sets across all catchments is important to ensure that there are consistent and comparable results (Nathan*, et al.*, 2000).

The first step is to develop catchment or sub-catchment boundary coverage. This can include catchments with water monitoring gauges, nested catchments and ungauged catchments. These catchments may be derived through GIS analysis of digital elevation data (if it is of sufficient quality) or digitized from topographic maps. Each catchment requires a unique identifier. The available data vary from country to country and region to region. The core data sets include: Stream data, Soils, tree cover (generally derived from satellite image analysis), DEM (various sources and grid sizes), climate data (various sources, including the Department of Meteorology and groundwater data sets (Nathan *et al.*, 2000).

~~g)~~3.7 Hydrological Assessment

A simple method to assess hydrologic impacts of different land uses is to compare streamflow characteristics of different catchment areas with contrasting land use types. This would enable comparison of the hydrologic response of a catchment consisting of degraded lands where watershed management is to be introduced with catchments that already have the desired land use characteristics anticipated to be achieved. Such a comparison may lead to wrong conclusions as shown by Bruijnzeel, (1990) after reviewing the catchment water balance studies related to land use transformation in the tropics.

In measuring water yield in small catchments Richardson, (1982) reported considerable differences in total water yield in Madagascar suggesting catchment leakage. Qian, (1983) and Dyhr-Nielsen, (1986) have shown that in the tropics, another factor complicating the evaluation of hydrologic effects of land cover transformation is the strong interannual variability of weather. An effective method evolved to overcome the above problems encountered in catchment water balance studies is the "paired catchment method," where hydrologic comparison is made between two (or more) catchments of similar size, geology, slopes, exposure, and vegetation, and situated close to one another. Here the "control" is left unchanged while land use changes are effected in the "experimental" or "treatment" catchment (Roche, 1981 and Hewlett and Fortson, 1983) in (Jalal Barkhordari, 2003). In addition to the comparison made after treatment, a comparison is also made during the initial calibration phase of several years before changes in land use are effected in the control catchment.

In recent years there has been an increasing trend to predict hydrologic changes brought about by land cover transformations in the tropics by robust models employing data obtained during relatively short but intensive measuring periods (Shuttleworth, 1990 and Institute of Hydrology, 1990).

~~i)~~3.7.1 Hydrological models

Effective hydrological modeling of watersheds is an essential tool in the management of land degradation and its off-site impacts, such as those associated with salinity and nutrient problems. Various methods have been used in the past to model processes and responses in catchment hydrology. Catchment hydrology models can be considered crudely as either, physical, conceptual or empirical. Each of these modeling approaches suffers from certain inadequacies (Wheater *et al*., 1993.)

Many hydrological modeling studies have achieved excellent correlation between the modeled and observed streamflow, especially during the calibration period (Chiew and McMahon, 1994; Post and Jakeman, 1996). This correlation is often reduced during subsequent simulation periods with little or no correlation occurring in some catchments. Beven, (1997) states that model calibration should immediately imply uncertainty. Often this uncertainty is most likely due to the failure to take the spatial distribution of input variables or parameters into account and/or poor representation of the hydrological processes being modeled. In many cases model parameters have been successful in obtaining a good fit to the observed response even when the physical process underlying the model is questionable.

The complexities of the environment and data collection restraints have seen many researchers favor lumped conceptual models. This is because most models, especially distributed ones, are over parameterized with respect to the information required to calibrate them. If however distribution takes place at the largest possible scale less information is required for parameter estimation. For instance surface hydrology such as infiltration and recharge needs to be modeled at the management scale, whereas routing can be carried out at the sub-catchment or catchment scale. Similarly subsurface discharge needs to be proportioned at the land management scale, but routed at the sub-catchment or hydro geomorphic unit (HGU) scale.

Because hydrologic models require different types of data depending on the processes modeled (Cruise *et al.*, 1993), not every GIS is suitable for a specific model. The main elements of the extraction of a drainage network required for water quality monitoring include watershed segmentation, identification of drainage divides and the network of channels, characterization of terrain slope and aspect, and routing of flow of water Lyon, (2003). Techniques are available for the extraction of these parameters from a digital representation of the topography, a Digital Elevation Model (DEM), whereas the manual determination is a tedious, time-consuming, error-prone and often highly subjective process (Lyon *et al.*, 2003).

~~ii)~~3.7.2 Model Selection

Watershed models are utilized to better understand the role of hydrological processes that govern surface and subsurface water movement. Moreover, they provide assessment tools for decision making in regard to water quality issues. Watershed models have been classified into various categories including empirical vs. physically-based, event-based vs. continuous, and lumped vs. distributed-parameter models. Selection of a suitable model depends on several factors such as capability to simulate design variables (runoff, groundwater, sediment yield, nutrient yield, etc.), accuracy, available data, and temporal and spatial scales.

Empirical models are developed based on statistical relationships between design parameters and watershed characteristics. These relationships are obtained from regression analysis using observed data. Application of these models will likely be limited to the same statistical conditions over which the observed data are acquired. An example of such model includes USLE model. Physically-based models are grounded in physical principles of conservation of mass, energy, and momentum. These models are preferred because they provide a better understanding of the processes in the watershed. Many models utilize both empirical and physically-based relationships to represent hydrologic and water quality processes within a watershed, and may be labeled as process-based models example includes Soil and Water Assessment Tool (SWAT).

Lumped models consider a watershed as a single unit for computations, and watershed parameters are averaged over this unit, while distributed-parameter models partition a watershed into subunits (subwatersheds, HRUs, or grids) for simulation purposes, and homogeneous properties are assumed for each subunit. As a result, the number of input parameters increases significantly. However, the spatial variability of watershed parameters such as land use, soil series, and management actions are more easily represented in distributed-parameter models.

In addition to spatial scale, watershed models utilize different temporal scales for computations. Event-based models usually require small time steps, at times in the order of seconds. These models are suitable for analyzing influence of design storms. Larger time steps, in the order of days, are usually sufficient for continuous models that are appropriate for long term assessment of hydrological and land use change and watershed management practices.

Computer modeling can be one of the more effective and efficient methods for predicting the quantity and nature of runoff, and the effectiveness of best management practices (BMPs). However, computer simulations and models have inherent limitations that users should be aware of and should factor into their decision-making processes. Usually, the best source for finding model limitations is the user manual, but sometimes this is not the case.

Borah, (2002) reviewed eleven continuous-simulation and single-event watershed scale models including the ones mentioned above. The study provides a better understanding of the mathematical bases of the models. Among all, the Soil and Water Assessment Tool (SWAT) model is the only continuous/process-based/distributed-parameter model that contains both sediment and nutrient components and is capable of representing BMPs at a watershed scale.

SWAT was selected for this study because of its ability to simulate land management processes in larger watersheds. SWAT is a physically based simulation model developed to simulate continuous-time landscape processes and streamflow with a high level of spatial detail by allowing the river/watershed to be divided into subbasins or subwatersheds. Each subbasin is divided into several land use and soil combinations called Hydrologic Response Units (HRUs) based on threshold percentages used to select the land use and soil (Arnold *et al.*, 1998).

~~h)~~3.8 Water Quality

The availability and quality of freshwater supplies for human and ecological needs are critical factors influencing the health and livelihoods of all people in a nation. Continued growth in human population and water use, continued degradation of water supplies by contamination, and greater recognition of the legitimate needs for freshwater in order to support critical ecosystem functions will lead to increasing scarcity and conflict over freshwater supplies in coming years. Water conflicts, which once were confined largely to the arid parts of the country, are now becoming increasingly common in the humid parts, as well. The potential for alterations in climate creates an even stronger need for reliable information about the status of freshwater resources (Nicole and Mathias, 2003).

Perennial inflows from Malewa catchment transport water, nutrients, and various other dissolved and suspended constituents to the Lake Naivasha (Sara Higgins, per.com 2006). Some of these constituents may have the potential to directly impact human health by degrading the water quality while others may affect the ability of the ecosystem to absorb these constituents, ultimately having a detrimental impact on the flora and fauna supported by the stream and the lagoon system. The common, easily measurable constituents that may result in degraded water quality include nitrogen, phosphorus, fecal coliform bacteria, and enterococcus bacteria (Nicole and Maggie Mathias, 2003). These constituents are all naturally occurring but if found at high concentrations or in excessive amounts can cause degraded water quality conditions.

~~i)~~3.8.1 Sediments

Many factors influence the sediment production in natural catchments. Factors such as rainfall intensity, local soil, geomorphology, cover type and farming practices will exert an important influence on the precise magnitude of the increase in sediment yield that will occur in particular area as a result of land use activities. Other factor related to deposition in a catchment can reduce the sediment yield.

The effect of land use on sediment yields are closely linked to those of climate and physiography. Its effects can be isolated and it is clear that major contrasts in sediment yield may be attributed to the influence of land use (Hadley, 1985). When studying the effect of land use on sediment yield, the temporal dimension must also be considered in many areas of the world, the impact of human activity may be relatively recent, whereas others may have experienced a long history of land use change extending back over several thousand years.

The absence of long-term records of sediment yield generally precludes detailed analysis of the effects of a documented history of land use change on the records of sediment yield, although a study of sediment load records from the Colorado river undertaken by Hadley, (1974) was able to suggest that the 50 percent reduction in loads after 1941 resulted from a reduction in grazing pressure. Meade and Trimble, (1974) were also able to undertake tentative comparisons of sediment loads during years near 1910 and 1970 for several rivers draining to the Atlantic coast of the USA, but they found it difficult decipher the influence of improve land management practice in recent years due to the effect of remobilization of sediment deposited in valley bottoms during earlier periods of accelerated erosion.

The natural variability of long-term records of annual sediment yield may also obscure trends produced by changes in land use. Vernhoff and Yaksich, (1982) were unable to detect any significant modification in sediment regime of the Maumee River at Waterville Ohio 'USA' over the period 1951-1977 despite significant urbanization and changes in land management. In the case of tributaries of the Yellow River, the presence of highly erodible loss soils, the lack of vegetation cover and semi-arid climate re major controlling variable (Walling, 1981). Dunne, (1979) and Schumm and Harvey, (1982) studied about the relationship between the magnitudes of sediment yield and climatic parameters. They concluded:

- Reduce uncertainty surrounding the effects of land use by representing relationship between sediment yield and annual runoff for individual land use classes.

- The positive trend of the relationship between annual sediment yield and precipitation and Runoff suggests that the increase in Erosivity. Associated with increased precipitation or runoff levels is not off set by increased protection by the vegetation cover, although the effect of human activity and land use practices in reducing this cover must also be considered.

A useful general perspective on the influence of human activity of erosion fields above the natural base line can be obtained by considering the various parameters employed in the universal soil loss equation (USLE) (Wischmeyer and Smith, 1965, 1978). In the equation the cover and management factor 'C' expresses the influence of land use practice. Wilson's, (1973) indicated that, the most important on-climatic variable influencing sediment yield is land use. The human influence on erosion processes is so pervasive that attempts to study sediment yield variation are likely to be unsuccessful unless land use factors are considered. Euananon and Suwanna, (1994) used multiple regression analysis for determining the relationship between land use changes and stream flow and suspended sediment they mentioned that the true form of the functional relationship between sediment yield and the, independent, variables is not known and can never be expected to be fully clarified. Simple graphical correlations between dependent and independent variables are often used to test what type or relationships are the most appropriate (Yevjevich, 1972).

~~i)~~3.9 Overview of Issues Related to Land Use Change

Land is the stage on which all human activity is being conducted and the source of the materials needed for this conduct. Human use of land resources gives rise to "land use" which varies with the purposes it serves, whether they be food production, provision of shelter, recreation, extraction and processing of materials, and so on, as well as the bio-physical characteristics of land itself. Hence, land use is being shaped under the influence of two broad sets of forces – human needs and environmental features and processes. Neither one of these forces stays still; they are in a constant state of flux as change is the quintessence of life. Changes in the uses of land occurring at various spatial levels and within various time periods are the material expressions, among others, of environmental and human dynamics and of their interactions which are mediated by land. These changes have at times beneficial, at times detrimental impacts and effects, the latter being the chief causes of concern as they impinge variously on human well-being and welfare.

Assessments of landuse changes depend on the source, the definitions of land use types, the spatial groupings, and the data sets used. Changes in the uses of land which cause major concern are associated with conversion to and from cropland as well as with forest clearance. Considering major environmental problems such as desertification, eutrophication, acidification, and climate change, and eustatic sea-level rise, greenhouse effect, and biodiversity loss in all of them and in myriad other less publicized and less visible, land use change caused by human activities is implicated to a greater or lesser extent. The impacts of these environmental problems are serious both in the short and in the long term. In the short term, food security, human vulnerability, health and safety are at stake; in the longer term, the viability of earth is being threatened. Hence, the impetus to study global environmental change in general and particularly land use change. Generally the purpose for conducting landuse change analyses is to:

- Predict future changes in land use.

- Impact assessment of landuse change on its various environmental and socio-economic impacts at all spatial levels.
- "What should be"; in other words, the purpose is to prescribe land use configurations that ensure the achievement of particular goals i.e. "sustainable land use solutions".
- Evaluating either past, present or future (policy-driven) changes in patterns of land use in terms of certain criteria such as environmental deterioration (or improvement), economic decline (or growth), or social impoverishment; or, more generally, against the criterion of sustainability.
- Regardless of its purpose, a reliable and consistent analysis of land use change requires that certain prerequisites are satisfied; namely, that the basic terms used in the analysis are clearly defined, land use classification systems compatible with the purpose of the analysis are used, valid theories frame the analysis, and the analytical techniques used can represent realistically the particular land use change issues under consideration.

The description of land use, at a given spatial level and for a given area, usually involves specifying the mix of land use types (Table 3.3), the particular pattern of these land use types, the areal extent and intensity of use associated with each type, the land tenure status (Bourne, 1982; Skole, 1994).

Meyer and Turner, (1994) state that "By *land cover* is meant the physical, chemical, or biological categorization of the terrestrial surface, e.g. grassland, forest, or concrete, whereas *land use* refers to the human purposes that are associated with that cover, e.g. raising cattle, recreation, or urban living".

Table 3.3: Example of land cover and associated types of land use

Type of Land Cover	*Types of Land Use*
Forest	Natural forest Timber production Recreation Mixed use-timber production and Recreation
Grassland	Natural area Pastures Recreation Mixed use-pastures and recreation
Agricultural land	Cropland-annual crops Orchards, groves-perennial crops Recreation/tourism Mixed uses
Built-up Land	City Village Archaeological sites Industrial area

Land use relates to land cover in various ways and affects it with various implications. As Turner and Meyer, (1994) state: "A single land use may correspond fairly well to a single land cover: pastoralism to unimproved grassland, for example. On the other hand, a single class of cover may support multiple uses (forest used for combinations of timbering, slash-and-burn agriculture, hunting/gathering, fuelwood collection, recreation, wildlife preserve, and watershed and soil protection), and a single system of use may involve the maintenance of several distinct covers (as certain farming systems combine cultivate land, woodlots, improved pasture, and settlements). Land use change is likely to cause land cover change, but land cover may change even if the land use remains unaltered" (Turner and Meyer, 1994). Meyer, (1995) adds the important point that "changes in land cover by land use do not necessarily imply a degradation of the land" (Meyer, 1995, 25 cited in Moser, 1996).

In the study of the interaction of grasslands with the physical processes of global change, for example, Graetz, (1994) emphasizes the need "to retain the definition of grassland by ecological attributes (vegetation structure and composition) rather than by its principal use, livestock production. Land use cannot be directly related to these forms of global change because it is a qualitative descriptor. Land use categories are abstract typologies that, although useful, cannot be meaningfully included in process models seeking to forecast the time and space patterns of global change.

~~i)~~3.9.1 Land Use Change and Land Cover Change

In analysis of land use and land cover *change*, it is first necessary to conceptualize the meaning of *change* to detect it in real world situations. At a very elementary level, land use and land cover change means *(quantitative) changes in the areal extent (increases or decreases) of a given type of land use or land cover*, respectively. It is important to note that, even at this level, the detection and measurement of change depends on the spatial scale; the higher the spatial level of detail, the larger the changes in the areal extent of land use and land cover which can be detected and recorded.

Literature distinguishes between two types of change: conversion and modification (Turner *et al*., 1995, Skole, 1994). *Land cover conversion* involves a change from one cover type to another. *Land cover modification* involves alterations of structure or function without a wholesale change from one type to another; it could involve changes in productivity, biomass, or phenology (Skole, 1994). Most of the land cover changes of the present and the recent past are due to human actions – i.e. uses of land for production or settlement (Turner *et al.,* 1995). More specifically, Meyer and Turner, (1996) suggest that "Land use (both deliberately and inadvertently) alters land cover in three ways: *converting* the land cover, or changing it to a qualitatively different state; *modifying* it, or quantitatively changing its condition without full conversion; and *maintaining* it in its condition against natural agents of change".

L*and use change* may involve either (a) *conversion* from one type of use to another – i.e. changes in the mix and pattern of land uses in an area or (b) *modification.* Modification of a particular land use may involve changes in the intensity of this use or alterations of its characteristic qualities/attributes – such as changes from low-income to high-income residential areas (the buildings remaining physically and quantitatively unaltered), changes of suburban forests from their natural state to recreation uses (the area of land staying unchanged), etc. In the case of agricultural land use, Jones and Clark, (1997) provide a qualitative typology of land use changes: intensification, extensification, marginalization and abandonment (Jones and Clark, 1997).

The specification of the spatial and temporal levels of detail is of crucial importance for the analysis of both changes as: (a) it guides the selection of the types of land use and land cover that are analyzed, (b) it determines the drivers and processes of change that can be detected and, thus, (c) it affects the identification *and* explanation of the linkages between land use and land cover within particular spatio-temporal frames. As regards the latter, the point is that *local* level land use changes may not produce significant *local* land cover change (and, consequently, significant environmental impacts). However, they may accumulate across space and/or over space and produce significant land cover changes at higher (e.g. regional or national) levels. This is the case, for example, of agricultural land conversion to urban uses that results from the decision of the individual land owners to convert their farmland to non-farm uses. Similarly, land use changes may be more qualitative rather than quantitative at lower levels of spatial and temporal detail but they show up as quantitative changes at higher levels and in the longer run. For example, gradual and incremental changes in the types of crops grown at the farm scale or in the quality of land management may result in the long run in abandoned agricultural land or seriously degraded farmland (in other words a change in category from productive to nonproductive land).

~~ii)~~3.9.2 Land Use/Land cover and scenario Change

Land-use refers to human activities that are directly related to land, making use of its resources and interference in the ecological processes that determine the functioning of land-cover (Veldkamp and Fresco, 1996). Land-cover refers to the surface appearance of the landscape, which is mainly affected by its use, its cultivation and the seasonal phenology. The highest amplitude for this dynamic occurs predominantly for arable land, but as well for other landuse types. Landuse/land-cover pattern are highly dynamic and rarely stable in equilibrium.

Alterations in land-use exert an influence on the ecosystem as a whole, because they affect water cycle, biodiversity, radiation budgets and many other processes (Riebesame, 1994). Although land-use changes mainly happen locally in small parts of the landscape, they may cause regional to global effects as a result of accumulation. Variations of land-use are raised by modified biophysical or human demands that arise from changed natural, economical or political conditions (O'Callaghan, 1996). The consequences are either modification or conversion: modification implies a change of condition within a type, caused by different cultivation techniques or management strategies; conversions include a transition from one land-use type to another.

~~iii)~~3.9.3 Scenario Analysis

Designing scenarios is a widely spread technique in environmental studies. The scenario is to be understood as a projection instead of a prediction. Besides the geophysical the anthropogenic aspects need to be considered. Designing such scenarios consists of determining land-use trends, which are miscellaneously originated, and the spatial transformation of these trends into spatially distributed land-use patterns. Impact studies of environmental changes, often neglect neighbourhood relationships and the position of land-use alterations, by shifting percental amounts of land-use types only. Effects of land use changes on runoff characteristics of a watershed have been studied using several types of models, which varied from strictly empirical to physical-based distributed models (Beven, 1989). Reciprocity in hydrologic processes and the mosaic landscape are scale-dependent and nonlinear, and due to such relations the success of both physical and empirical cause-effect modeling is increasingly questioned (Beven, 1989).

Investigating natural, potential, and human-induced impacts on hydrologic systems commonly requires complex modeling with evolving data requirements, plus massive amounts of one to four dimensional data at multiple scales and formats (Hay and Knapp, 1996). Most hydrologic models are traditionally based on cause-effect relationships inferences developed for the temperate region but the sustainable management of vulnerable and extreme regions, such as the tropics, demands a new holistic and transparent approach relying on first principles and integration of processes and landscape patterns (Gumbricht, 1997).

Considering the requirements of various models, their major constraints are the knowledge gap in hydrology-related processes and parameter values, the cost involved and time consumed even if minimum data requirements are to be achieved, and the problems in calibration and validation of such models with reliable historical data.

~~iv)~~3.9.4 Remote Sensing and GIS

For studying land cover classes, some of the information sources are field survey, existing maps, statistical data, existing documents or available literature and remote sensing images. Traditional methods of land cover mapping have been limited to field surveys, which are time-consuming and uneconomical. Satellite images are the most economical way of getting data for different times. The multitude of existing software helps getting information from satellite images also in manipulating the information. Remote sensing offers the possibility of covering a large spatial area with a high temporal frequency. It also provides a spatial distribution of the constituents, which direct sampling cannot economically accomplish. Spatial distributions provide deeper insight into many of the hydrologic and biological processes.

There are many hydrologically relevant parameters that can be determined by using remote sensing data (Hochschild *et al.*, 2000). Remote sensing can supply input and validation data for hydrological models and concentrate on water balance and water demand. One of the key points in the remote sensing applications is the use of different image sources for improving the results. By fusion of data of different spectral, temporal and spatial information as well as with ground measurements, it is possible to combine the various advantages of the different sources.

CHAPTER IV

4.0 METHODOLOGY

Figure 4.1 depicts the methodology process. The scope of the research study involved three main activities namely: 1) Pre-Fieldwork Preparation; 2) Fieldwork; and 3) processing and reporting.

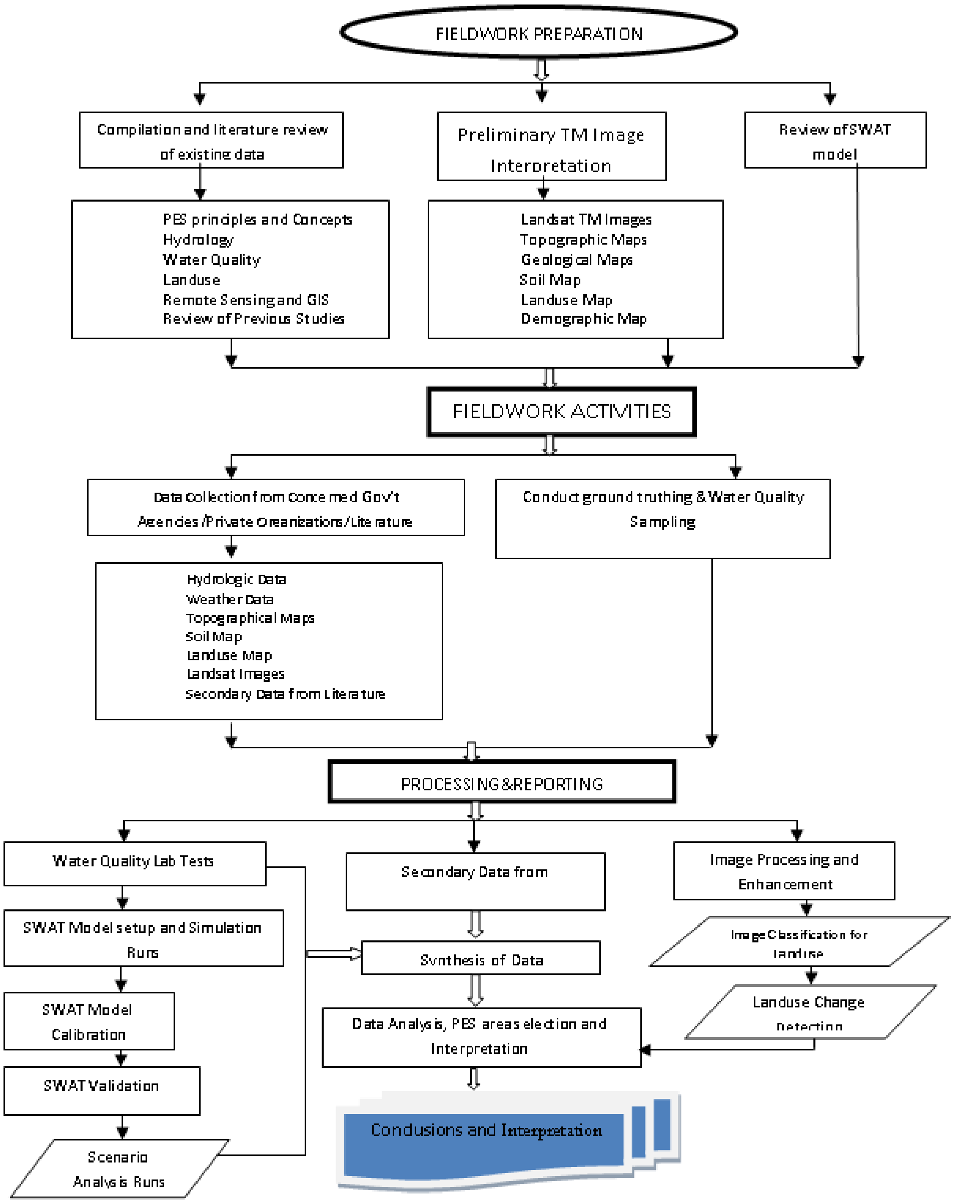


Figure 4.1: Flow Chart of Methodology

~~0~~4.1 Materials Used

The following data were available for the research study:

- Geological Map, 1:100000 by Clarke, M. C. G. *et al.*, 1990 from literature
- Topographic Maps, 1:250000 (Nyeri sheet) and 7 sheets of 1:50000 maps
- Various Geological, Hydrological, and Geophysical and PES Reports

~~0~~4.2 Available Data for the Study

Required input data included: Digital Elevation Model (DEM), landuse/landcover map, soil map and soil data, weather data, topographical sheets, Landsat images, water quality data (nutrients and sediment) and stream flow data. These data were from various sources, which include Internet, Ministry of Water Resource Management and Irrigation (MWI), Kenya Meteorological Department (KMD), Kenya Soil Survey and Regional Centre for Mapping Resources for Development (RCMRD). Land use/land cover map was obtained from the International Livestock Research Institute (ILRI). GIS database were found at and Kenya Soil Survey. Tables 4.1, 4.2 and 4.3 illustrate the sources of data used in the study.

Table 4.1: Summary of available data

Digital Spatial Dataset	Source	Description
Landsat Image, 1987	RCMRD (Landsat Imagery)	Boundaries associated with land use classifications
Landsat Image, 2003	RCMRD (Landsat Imagery)	Boundaries associated with land use classifications
Landsat MSS Image, 1973	RCMRD (Landsat Imagery)	Boundaries associated with land use classifications
90m resolution DEM for Kenya	RCMRD (Landsat Imagery)	Topographic relief mapping; supports watershed delineations and modeling
Kenya Country Shapefiles	ILRI website	Spatial shapefile
Soils (SOTWIS)	KENSOTER website	Soils information including soil component data and soils
Land Use and Land Cover	RCMRD (Landsat Imagery)	Boundaries associated with land use classifications
Weather Stations Data	Kenya Met Department	Location of selected meteorological stations and associated monitoring information used to support modeling
Streamflow data (see appendix 4)	Ministry of irrigation and water (MIW)	Daily data for seven gauging stations

Table 4.2: Source Data for Landsat images

Year	Sensor	Height (Km)	Number of bands	Resolution (m)
1973	MSS	917	4	30*30
1987	TM	705	6	30*30
2003	ETM	705	7	30*30

Available data that were used for modeling are depicted in Table 4.2 and Table 4.3. Mandatory GIS input files needed for the SWAT model include the digital elevation model (DEM), land cover, and soil layers. The following GIS data were used to develop the Beaver Watershed Model to simulate watershed response from 1972 to 2003.

Table 4.3: Model input data sources for the Malewa Watershed

Data Types	Scale	Source	Data description/properties
Topo-sheets	1:50,000 and 1:250,000	Survey of Kenya	Boundary, drainage, geo-referencing
Soils (KENSOTER SOTWIS version 1)	1:1M	ISRIC	Soil physical properties e.g. bulk density, texture, saturated conductivity, etc.
Land use	1:250,000	1980 Landsat data by the Japan International Co-operation Agency, JICA, National Water Master Plan, Kenya	Land use classification valid for 1980
Weather		KMD	Daily precipitation and temperature,(9036002, 9036025, 9036054, 9036062, 9036183, 9036241, 9036281, 9036290, 9036336)
Stream flow		Ministry of water and Irrigation	Daily stream flow (2GB01, 2GB03, 2GB04, 2GB05, 2GB07, 2GC04, 2GC05, 2GC07) for a period starting from 1959-2003
BMP			Pre- and post-management information

4.2.1 Land Use Change Detection

Several methods have been developed to extract land-cover change information from remotely sensed data. Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh, 1989). Change detection is an important process in monitoring and managing natural resources and urban development because it provides quantitative analysis of the spatial distribution of the population of interest. In this study, delta or post classification comparisons was used because the available data was acquired in different seasons by different sensors with different spatial resolution.

4.2.2 Landuse/landcover classification

Classification Process

The following sequences of operations were used (Figure 4.2):

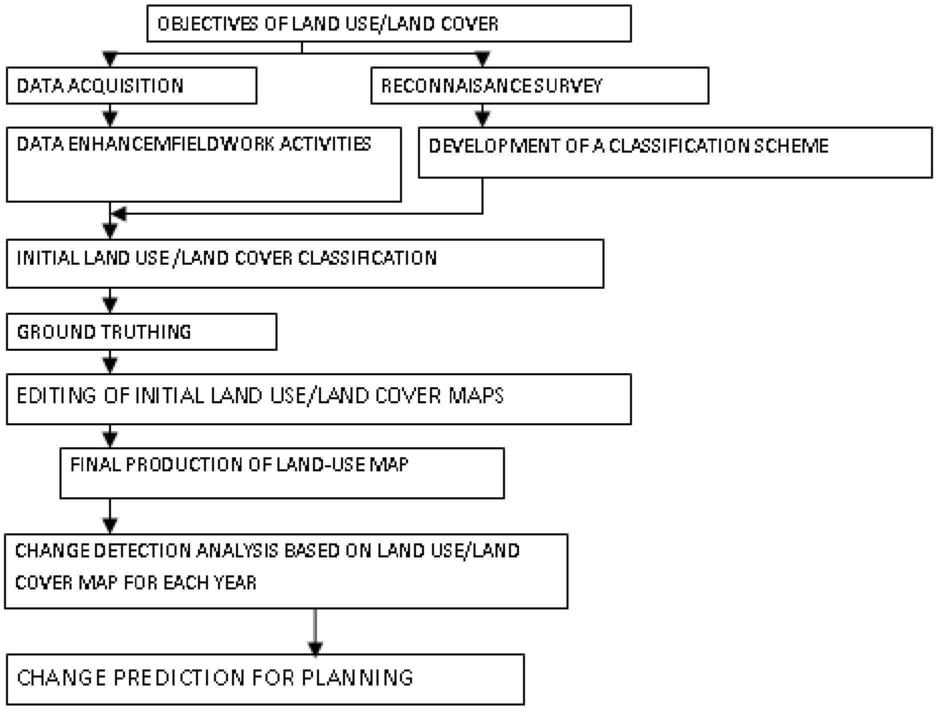


Figure 4.2: Flow chart for Landuse Change Detection Methodology

Idrisi Kilimanjaro was used for the image classification and Maximum Likelihood Classifier used to determine the land classification.

4.2.3 Study area extraction

The images bands were imported to IDRISI in Geo referenced tiff (GEOTIFF) format. The bands imported were 1, 2,3,4,5 and 7 of both images to IDRISI environment using band by band procedure. The delineated catchment boundary was then imported as vector data from the Arc View shape file format. The catchment boundary was overlaid with the different bands using the overlay command. The resulting image windows were reduced using the window command which extracts a sub image from a larger image or a group of images.

4.2.4 Composting and Signature development

Bands combinations ideal for mapping land cover are bands 2, 3 and 4. Combination of these bands shows very clearly the land cover features. There are different bands ideal for different studies as indicated in the Table 4.4. The three bands were combined as red, green and blue bands respectively using the 'COMPOSITE' command in IDRISI task bar to produce a 24 bit false-color composite image.

Table 4.4: Spectral resolution of Landsat TM bands and some of their applications (Source: CLARK LAB, 2001)

Band	Wavelength Range (µm)	Application
1	0.45- 0.52 (blue)	Soil/vegetation discrimination; bathymetry/coastal mapping; cultural/urban feature identification.
2	0.52 - 0.60 (Green)	Green vegetation mapping (measures reflectance peak); cultural/urban feature identification
3	0.63 - 0.69 (red)	Vegetated vs. non-vegetated and plant species discrimination (plant chlorophyll absorption); cultural/urban feature identification
4	0.76 - 0.90 (Near IR)	Identification of plant/vegetation types, health, and biomass content; water body delineation; soil moisture
5	1.55 - 1.75 (Short wave IR)	Sensitive to moisture in soil and vegetation; discriminating snow and cloud-covered areas
6	10.4 - 12.5 (Thermal IR)	Vegetation stress and soil moisture discrimination related to thermal radiation; thermal mapping (urban, water)
7	2.08 - 2.35 (Short wave IR)	Discrimination of mineral and rock types; sensitive to vegetation moisture content

4.2.5 Signature identification and image classification

Multi-spectral classification was carried out to identify signatures based on the training sites using the 'MAKESIG' command in IDRISI. With supervised classification, the user develops the spectral signatures of known categories, such as water bodies, forest, etc and then the software assigns each pixel in the image to the cover type to which its signature is most similar. All six bands (1, 2,3,4,5 and 7) were used as input data to create the signatures. During signature development, the command creates signature files for each informational class created from training sites. The maximum likelihood (MAXLIKE) command was then used to classify the whole image. The command extracts and analyzes the pixels in the whole image and groups them according to training sites pixels. The default color presentation can be changed by designing a color palette. GIS analysis in the main menu can be performed on the final map to calculate attributes such as area and perimeter from the final map.

4.2.6 Defining of the Training Sites

This was done by using the on-screen digitized features. A color composite image of band 2, 3 and 4 was used in digitizing. Generally, one should aim to digitize enough pixels so that there are 10 times as many pixels for each training class as there are bands in the image to classify. For each training class five points representing the same feature were selected and digitized.

4.2.7 Training site and signature development

A false color composite of bands 4, 3, and 2 was used to identify possible training sites, guided by the former predefined training sites. The training sites were digitized and saved as vector polygons while maintaining the key characteristics of the training sites, such as uniformity or homogeneity as much as possible, avoiding mixed pixels, ensuring at least 100 pixels for each landuse/land cover category, and evenly distributed over the study area (Campell, 1996; CLARK LABS, 2001).

4.2.8 Extracting of Signatures

Signature development was done using the MAKESIG module in Idrisi32 release 2 image processing software for each landuse/land cover category of the defined training sites. In this process, signature files containing statistical information about the reflectance values of the pixels within the training sites for each class or landuse /land cover category are created, using the six bands of LANDSAT 7 ETM+ scene.

Signature evaluations were made using the signature compare module (SIGCOMP) in a graphic output showing the means, minimum and maximum reflectance values for each band of the defined training sites. Using these plots similar signatures and overlapping signatures for each band were detected. A clear category separations (looking at the distance between the means), were observed in the red band 3, near infrared band 4 and middle infrared bands 5 and 7, but not in the blue band 1 and green band 2.

After the training site areas have been digitized, the next step was to create statistical characterizations for information obtained in first step. These are called signatures in Idrisi (CLARK LABS, 2001). With this module, categorization of information for each pixel is possible. In this step, the goal was to create a signal (SIG) file for every informational class. The SIG files contain a variety of information about the land cover classes they describe. Each SIG file also has a corresponding SPF file that contains the actual pixel values used to create the SIG file. These include the names of the image bands from which the statistical characterization was taken, the minimum and mean values on each band, and the full variance /covariance matrix associated with that multispectral image band set per class.

4.2.9 Classification of the Image

The classification of the image is the third and the final step. When training sites are known to be strong, the MAXLIKE procedure is used (Richards, 1995). Supervised classification using the maximum likelihood classifier was applied for classifying the image. It is the most common supervised classification method used with remote sensing image data (Richards, 1995). The maximum likelihood algorithm with equal probability of occurrence was (used in the classification exercise, because it is powerful and produces the best results if defined training sites are very good particularly their uniformity (Janssen *et al.*, 1990; Roy *et al.*, 1991; Deppe, 1998; Congalton *et al.*, 1998). In the maximum likelihood method the distribution of reflectance values in a training site are described by a probability density function, developed on the basis of Bayesian statistics (IDRISI Kilimanjaro Guide, 2004). This method uses the training data as means of estimating means and variances of the classes, which are then used to estimate the probabilities.

4.3 Water Quality Analysis

Water quality parameters presented in Table 4.5 were estimated using grab water samples from various upstream and downstream tributaries of the Malewa Catchment and analyzed at JKUAT Civil Engineering Laboratory using the indicated methods.

Table 4.5: Water Quality Parameters and methods of analysis

Parameter Measured	Analysis Method
PO_4, mg P/L	ascorbic acid method
NO_3, mg N/L	palintest method
Sediment load mg/Liter	filtering and solids dried at 103^0-105^0C

For detailed procedures adopted see Appendix 1.

4.4 Hydrologic Modeling

4.4.1 SWAT Model

The SWAT hydrological model was used for hydrological analysis and included many parameters Table 4.5 that impact on hydrology and to simulate the flows on the study area. Figure 4.3 presents a diagram of the SWAT process.

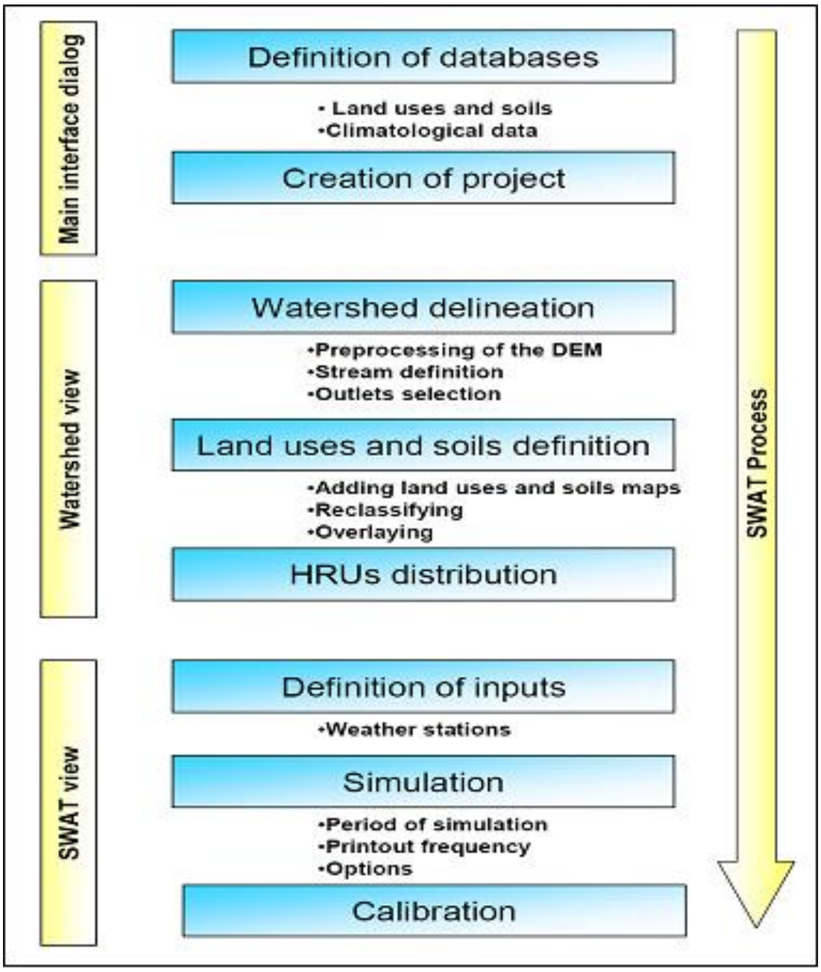


Figure 4.3: Representation of the SWAT model process

Table 4.5 shows the parameters that can be used for sensitivity analysis and adjusted during calibration.

Table 4.5: SWAT Parameters

	Parameter	Description	Min	Max	Units	SWAT input e
1	CN2	Initial SCS runoff curve number for moisture condition II	35	98		MGT
2	SLOPE	Average slope steepness	0	0.6	M/m	HRU
3	SLSUBBSN	Average slope length	10	150	m	HRU
4	ESCO	Soil evaporation compensation factor	0	1		HRU
5	CH-N1	Manning's "n" value for tributary channels	0.008	30		SUB
6	CH-S1	Average slope of tributary channels	0	10	m/m	SUB
7	CH-K1	Effective hydraulic conductivity in tributary channel alluvium	0	150	Mm/hr	SUB
8	CH-N2	Manning "n' value for the main channel	0.008	0.3		RTE
9	CH-S2	Average slope of the main channel along the channel	0	10	m/m	RTE
10	CH-K2	Effective hydraulic conductivity in main channel alluvium	0	150	Mm/hr	RTE
11	GWQMN	Threshold depth of water in shallow aquifer for return flow to occur	0	5000	Mm	GW
12	ALPHA-BF	Base flow alpha factor	0	1	Days	GW
13	GW-DELAY	Ground water delay time	0	500	Days	GW
14	GW-REVAP	Ground water "revap" time	0.02	0.2		GW
15	SOL-AWC	Available water capacity of the soil layer	0	1	Mm/mm	SOL
16	CH-EROD	Channel erodibility factor	0	0.6	Cm/hr/pa	RTE
17	CH-COV	Channel cover factor	0	1		RTE
18	SPCON	Linear coefficient for calculating maximum sediment re-entrained	0.001	0.01		BSN
19	SPEXP	Exponent	1	1.5		BSN
20	PRF	V peak rate adjustment factor for sediment routing in channel network	0	2		BSN
21	USLE-P	USLE equation support practice factor	0.1	1		MGT
22	USLE-C	Maximum value of USLE equation for cover factor for water erosion	0.001	0.5		CROP DAT
23	SOL-LABP	Initial soluble P concentration in soil layer	0	100	Mg/kg	CHM
24	SOL-ORGP	Initial soluble P concentration in soil layer	0	4000	Mg/kg	CHM
25	SOL-NO3N	Initial NO3 concentration in soil layer	0	5	Mg/kg	CHM
26	SOL-ORGN	Initial organic N concentration in soil layer	0	1000	Mg/kg	CHM
27	RS1	Local algae settling rate at 20^{0c}	0	2	m/day	SWQ
28	RS2	Benthic (sediment) source rate for dissolved P in the reach at 20^{0c}	0.001	0.1	Mg/m^2day	SWQ
29	RS4	Rate coefficient for organic N settling in the reach of 20^{0c}				
30	RS5	Organic P settling rate in the reach at 20^{0c}				
31	BC4	Rate constant for mineralization of P to dissolve P in the reach at 20^{0c}				
32	A10	Ratio of chlorophyll –a to algae biomass				
33	A11	Fraction of algal biomass that is nitrogen				
34	A12	Fraction of algal biomass that is phosphorous				
35	RHOQ	Algal respiration rate at 20^{0c}				
36	K-P	Michaelis menton rate saturation constant for phosphorus				

The preliminary step was the definition of the databases (dbf tables) i.e. soil and land use parameters, and climatological data. Each table had to be defined clearly using the nomenclature provided in the SWAT user's manual. The climatological data were added in different files presenting each parameter and the location of their meteorological station.

The watershed delineation process builds the streams and the sub-basins using the Digital Terrain Model. The burn-in option permits the use of an existing digitized stream network. The digitized stream network when uploaded into the SWAT model after conversion from geographic coordinates to Lambert Azimuthal Equal Areas, shifted by one pixel to the left hence was not used.

For the land use and soil definition, raster or shape files were added to the Watershed view in ArcView 3.2 and linked to the SWAT database. To use the maps provided, the SWAT interface requires a table linking the values represented to types already defined in the hydrological model. For the land use, some default categories are already provided in this version of SWAT with two themes: land cover and urban land. As an example, Table 4.6 represents the look-up table for the land use database. The land use mapped in the shapefile is linked to default categories present in SWAT.

Table 4.6: Relation between the land use map and the SWAT database

Land use shapefile	SWAT database
Forests, woodland	FRST Forest-Mixed
Agricultural Land	AGRL Agricultural Land – Generic
Infrastructures	UINS Institutional
Heath land, Brush land,	RNGB Range – Brush
Residential	URMD Residential – Medium Density
Marshland, peat bog	WETN Wetlands – Non Forested
Water	WETN Wetlands – Non Forested
Rocks	RNGB Range – Brush
Sands and Pebbles	FRST Forest-Mixed

The land use 'Water' exists in the SWAT database but it is advisable to use Wetlands because this special land use could create errors in the computation of the hydrological network (Renaud, 2004).

In SWAT, a watershed is divided into multiple sub watersheds, which are then further subdivided into HRUs that consist of homogeneous land use, management, and soil characteristics. The HRUs represent percentages of the subwatershed area and are not identified spatially within a SWAT simulation. The water balance of each HRU in the watershed is represented by four storage volumes: snow, soil profile (0 to 2 meters), shallow aquifer (typically 2 to 20 meters), and deep aquifer (more than 20 meters). Flow, sediment, nutrient, and pesticide loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

HRUs within each subbasin are defined by first selecting land uses whose percentages (based on area) are greater than the user-defined land use threshold percentage and within those selected land uses, by selecting the soils whose percentages are greater than user-defined soil threshold percentage (Neitsch *et al.*, 2002). SWAT model operates on a daily time step and is designed to evaluate the impacts of different management conditions (point and nonpoint sources) on water quality in large ungauged basins. Major components of the model include hydrology, weather, erosion, soil temperature, crop growth, nutrients, pesticides, and agricultural management. A complete description of all components can be found in Arnold *et al.*, (1998) and Neitsch *et al.,* (2002).

Three options exist in SWAT for estimating surface runoff from HRUs – combinations of daily or sub-hourly rainfall and the Natural Resources Conservation Service Curve Number (CN) method (Mockus, 1969) or the Green and Ampt method (Green and Ampt, 1911) and for the study the CN method was chosen. This option was chosen because there were no hourly or sub-hourly rainfall for first option and no infiltration records were taken for Green-Ampt method. Three methods for estimating potential evapotranspiration are also provided: Priestly-Taylor (Priestly and Taylor, 1972), Penman-Monteith (Monteith, 1965), and Hargreaves (Hargreaves *et al.,* 1985). Sediment yield was calculated with the Modified Universal Soil Loss Equation (MUSLE) developed by Williams and Berndt, (1977). Neitsch *et al.,* (2001) provide further details on input options. Additional information and the latest model updates can be found at http://www.brc.tamus.edu/swat/

Once the land use and soil data have been reclassified, converted to raster and overlaid, the hydrologic response units are created by the combination of soil and land use. The SWAT view was then activated and it allows the input of other data such as climatological data. Concerning rainfall, temperature, solar radiation, wind speed or relative humidity, the daily inputs can be either simulated or defined by dbase tables. In this project, the weather stations used are the daily values defined by the temperature (minimum and maximum), the rainfall and the wind speed. Because of the lack of temperature data in the study area, a relation between altitude and monthly temperature has been used in this study (see Appendix 5). The relation between altitude and temperature has been quoted from a report by the Ministry of Agriculture and Livestock Development. According to the report, the relations are based on data from 160 stations in Kenya. Data on absolute and mean, maximum and minimum, monthly and annual temperatures for the 160 stations are given in a publication of the East African Meteorological Department (EAMD 1970). Also the EAMD publication gives the equations relating the temperatures in Celsius (^{o}C) to the altitude in meters (m). Appendix 5 which was extracted from the report shows the equations for the different months and for the average, minimum, and maximum temperature. The monthly data were then extrapolated to get the mean daily values.

Humidity, solar and wind data were not available hence simulation of SWAT was used. In the case where all inputs have been successfully entered, simulation proceeded. The period of simulation, the printout frequency and some options such as the channel water routing method and the water quality processes have to be chosen to run SWAT. In this study, a yearly/monthly and daily printout on the period 1972 – 2003 was used. From the 1st Precipitation of January 1972, to the 31st Precipitation of December 2003, the outputs were then fully simulated. The outputs of SWAT are in different types: grids, shape files and tables. The results are presented in four main tables:

- Summary output file
- HRU output file
- Sub-basin output file
- Main channel/reach output file

4.4.2 Sensitivity Analysis

Large complex watershed models contain hundreds of parameters that represent hydrologic and water quality processes in watersheds. Model predictions are more sensitive to perturbation of some input parameters than others, even though the insensitive parameters may bear a larger uncertain range. Thereby, adjustment of all model parameters for a given study area not only is cumbersome, but is not essential. Sensitivity analysis was done through the SWAT model sensitivity analysis tool. The AVSWATX sens-Auto-Unc was loaded and sensitivity analysis selected. The dialog window allows the selection of scenario and simulation target. The output variables selected was flow with usage of observed flow data. The observed flow data used was at the basin outlet 2GB01.

4.4.3 Model calibration

Calibration was done through the automatic calibration tool in AVSWAT2005. Procedure (Appendix 2) provided by (Santhi *et al.*, 2001b) was followed.

The calibration tool consists of three sub-tools i.e.

- AVSWATX Extension
    - ~~2.0~~ Landuse-Land cover splitting tool
    - ~~2.1~~ SSURGO Data Tools
    - ~~2.2~~ AVSWATX Sens-Auto-Unc
- Sensitivity Analysis
- Auto-Calibration and Uncertainty

The land-land cover splitting tool was used to split the Agriculture close into onion, potato, carrot and cabbage during scenario development for the selected target areas for implementing PES.

Simulation runs were conducted on a daily/monthly basis to compare the modeling output with the corresponding observed discharge. The calibration considered fourteen model parameters that can be summarized in three groups: (1) Parameters that govern surface water processes, including curve number (CN), soil evaporation compensation factor (ESCO), plant uptake compensation factor (EPCO), and available water capacity of the soil layer (SOL_AWC; (2) Parameters that control subsurface water processes, including capillary coefficient from groundwater (GW_REVAP), groundwater delay (GW_DELAY), and deep aquifer percolation fraction (RCHRG_DP); And (3) parameters that influence routing processes, including Manning's roughness coefficient in main channel routing (CH_N(2)) (Neitsch *et al.*, 2002). One parameter was adjusted while others were kept unchanged.

4.4.4 Model validation

Data for a period of twenty-one years from January 1st, 1981 to December 31st, 1995 was used for validating the SWAT model for the Malewa River Basin.

4.4.5 Model Evaluation Criteria

The accuracy of SWAT simulation results was determined by examination of the coefficient of determination (R^2) and the Nash and Sutcliffe model efficiency coefficient (E_{NS}) (Nash and Sutcliffe, 1970). The R^2 value indicates the strength of the linear relationship between the observed and simulated values. The E_{NS} simulation coefficient indicates how well the plot of observed verse simulated values fits the 1:1 line. The E_{NS} can range from 2:1 to 1:1, with 1 being a perfect agreement between the model and real data (Santhi *et al.*, 2001). E_{NS} is defined as:

$$\mathbf{E_{NS} = 1 -} \left[\left\{\sum_{i=1}^{n}(Measured_i - simulated_i)^2\right\} / \sum \left(measured_i - \frac{1}{n}\sum_{i=1}^{n} measured_i\right)^2\right] \quad \textbf{Equation 1}$$

E_{NS} values range from 1.0 (best) to negative infinity. E_{NS} is a more stringent test of performance than R^2 and is never larger than r^2. E_{NS} measures how well the simulated results predict the measured data relative to simply predicting the quantity of interest by using the average of the measured data over the period of comparison. A value of 0.0 for E_{NS} means that the model prediction are just as accurate as using the measured data average to predict the measured data. E_{NS} value less than 0.0 indicate the measured data average is better predictor of the measured data than the model predictions while a value greater than 0.0 indicates the model is a better predictor of the measured data than the measured data average. The simulation results were considered to be good if $E_{NS} \geq 0.75$, and satisfactory if $0.36 \leq E_{NS} \leq 0.75$ (Van Liew and Garbrecht, 2003).

4.4.6 Target sub-basin Area Selection

The following parameters were considered in selecting the principal target areas for pilot PES implementation:

- Water yield (model output)
- Sediment yield (model output)
- Nutrient load/pollution load (Phosphorous and Nitrates)
- Water conflicts (based on literature review of previous studies)
- Population density (based on 1999 census)
- Landcover/landuse activity
- Water abstraction points
- Availability of historical data (streamflow)
- Rainfall amount (input)
- Recharge and Discharge zones.

4.4.7 Scenario Analysis

The following scenarios (Table 4.7) were adopted on the two selected priority areas:

Table 4.7: Scenario Analysis

N	Scenario	Description
1	Base Scenario (Business as usual)	This is the status quo condition i.e. Business as usual
2	Horticultural scenario	This scenario consisted of various horticultural crops in equal proportions making 100% i.e. 25% cabbage,25% carrot 25% onion and25% potatoes i.e. an horticultural scenario (see sample output in Appendix3)
3	100% High Density Residential	This consisted 100% residential which are highly dense
4	53% Forest and 47% range brush	The scenario consisted with only two types of vegetation i.e. Forest at 53% and Range brush at 47%
5	100% Forest	This scenario was 100% Forest. The whole area was put under forest wholly
6	Best Management practice	This scenario involved implementing two BMP. ~~1.6~~a) Filter strip (0, 1, 5, 10 m edge). This scenario involved altering the filter width from no filter width 0m to 1, and running the scenario, then 1m, 5m, and 10m respectively. Each scenario was compared with base scenario 0m ~~2~~b. Contours (P=0.1, P=0.65, and P=1). This scenario involved implementing contouring practices. In order to achieve this, the P in the support practice factor in USLE equation was modified from base condition 1 with no erosion control to erosion controlled structure with USLE-P value of 0.1, and 0.65 respectively.

CHAPTER V

5.0 RESULTS AND DISCUSSIONS

5.1 Introduction

Land cover change plays a pivotal role in regional socioeconomic development and global environment changes (Chen, 2002). In arid environment, where fragile ecosystems are dominant, the land cover change often reflects the most significant impact on the environment due to excessive human activities. Macleod and Congalton, (1998) list four aspects of change detection that are important when monitoring natural resources:

1. Detecting changes that have occurred,
2. Identifying the nature of the change,
3. Measuring the areal extent of the change,
4. Assessing the spatial pattern of the change.

This study evaluated the changes in land use/cover that have occurred in Malewa Watershed over a monitoring timeframe of 30 years and their effect on the watershed hydrologic system.

5.2 Land use

The major land use units in the Malewa catchment can be categorized as agriculture, forest, natural vegetation (scrubs and range brush land), rangeland, pasture, settlement and water body. Most of the agriculture in the catchment is small scale mixed farming mainly in the upper catchment while in the lower catchment, large-scale mixed farming and intensive livestock farming are predominant. Maize is the main staple crop grown by almost all farmers in the catchment (Table 5.1, and Figure 5.1).

Table5.1: Current land use patterns along Malewa catchment

Catchment Name	Land use
Malewa Lower catchment	Large scale mixed farming Very intensive livestock farming
Upper catchment of Malewa	Both small scale and large scale farming of wheat Arable small scale farming of vegetables, maize Very intensive livestock grazing
Ol Kalou	Small scale mixed farming and very intensive grazing
Aberdares range	Large scale farms growing onions and vegetables
Kipipiri range	Small scale mixed farming
Turasha Sub-basin	Small scale mixed farming, very intensive livestock grazing
Kinangop plateau	Small scale mixed farming, Intensive livestock grazing
Wanjohi river	Small scale mixed farming mainly vegetables Intensive livestock grazing
Aberdares range (along Turasha sub-basin)	Small scale mixed farming mainly vegetables

The main vegetables grown in the catchment are sweet potatoes, kales, carrots and cabbages. Considerable land is allocated for pasture in Turasha and Malewa river sub-basins. Small-scale and large scale farmers also grow pyrethrum on the Kipipiri range and wheat in Turasha and upper Malewa basin. There is intensive farming of onions in the Aberdares range. Extensive or range livestock production is mainly practiced in the drier parts of the catchment (Kitaka, 2000).

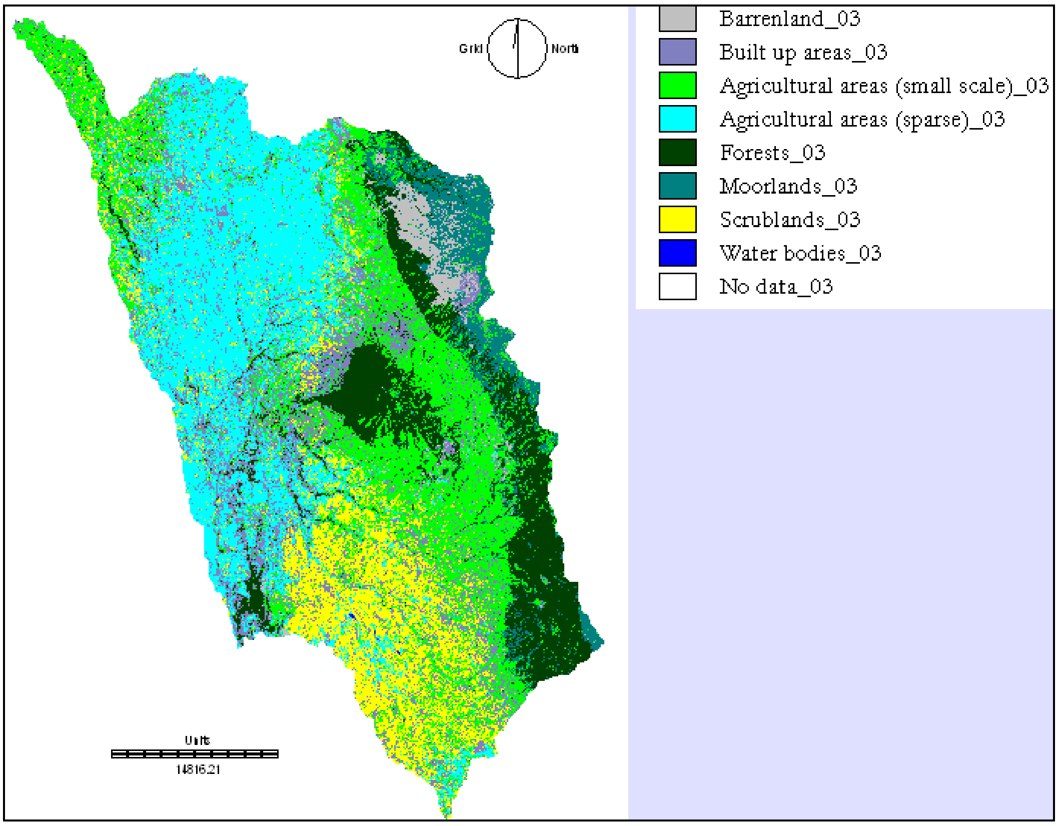


Figure 5.1: The 2003 Landuse/cover map for Malewa watershed developed from the 2003 ETM Landsat image .

5.2.1 Classification of Land-use and accuracy assessment

Using the developed land cover classification scheme, the multi-temporal images were classified into eight classes: 'barren land' which includes lands having no vegetation and lands consisting of outcrops, 'built-up areas', 'water body', 'agricultural areas (intensive small scale)', 'sparse agricultural areas', 'scrubland', 'moorland', and 'forests'. The classification accuracy was assessed using the common 'confusion matrix' method, showing an overall accuracy of 65.9% with a Kappa coefficient of 0.66-0.78 (see Appendix 5) for 2003 Landsat image. The details are shown in Table 5.2.

Table 5.2: Error matrix Analysis of test cluster map (column: truth) against land cover map (rows: mapped)

Landuse Category	Barren Land	Built-up areas	Agric Areas (small scale	Agric Areas (sparse)	Forest	Moor Lands	Scrub Lands	Water bodies	Young Forest	**Total**	**User Accuracy (%)**
Barren land (includes bare lands)	**11**	2	0	0	0	0	0	0	0	**13**	**84.6**
Built up areas	3	**20**	0	0	0	0	0	0	0	**23**	**87.0**
Agricultural areas (small scale)	2	1	**25**	3	2	0	1	0	3	**37**	**67.6**
Agricultural areas (sparse)	3	1	5	**13**	3	0	0	0	0	**25**	**52.0**
Forests	0	2	9	2	**23**	0	3	0	8	**47**	**48.9**
Moorlands	2	0	0	0	0	**10**	0	0	0	**12**	**83.3**
Scrublands	1	0	2	2	1	0	**12**	0	1	**19**	**63.2**
Water bodies	0	0	0	0	0	0	0	**10**	0	**10**	**100.0**
Young Forest	0	0	3	1	5	0	0	0	**13**	**22**	**59.1**
Total	22	26	44	21	34	10	16	10	25	**208**	
Producer accuracy (%)	50.0	76.9	56.8	61.9	67.6	100.0	75.0	100.0	52.0	**65.9**	

Note: Producers accuracy indicates how well the training sets pixels of a given cover types are classified and user accuracy is a measure of commission error and indicates the probability that a pixel classified into a given category actually represents that category on ground.The overall classification accuracy is the percentage of correctly classified pixels among total randomly selected reference pixels. The total classified pixels in this case are 208 while the sum of correctly classified pixels is 137. Therefore the overall accuracy would be 137/208 = 65.9%. This error matrix is based on training data. A value less than 50% indicates uncertainty in classification and one way to rectify this is by field measurements and re-classification. The implication of error matrix analysis is that if the results are good, then it indicates that the training samples are spectrally separable and the classification works well in the training areas.

5.3 Land use/Land cover change in Malewa catchment between 1973 and 2003

The three-date 1973, 1987 and 2003 classified images were integrated to GIS database. The area statistics of land use classes are depicted in attribute table (Table 5.3). The study area covered a total area of 1605.4 km^2 .Each area per land-use category was calculated for each image used i.e. 2003, 1987 and 1973 images and the surface area extent expressed in both square kilometer and as a percentage of the total area as depicted in Table 5.3

Table 5.3: Actual and % area contribution per landuse/cover in 1973, 1987 and 2003.

Land use Category	Area in km²	% Area 2003	Area in km²	% Area 1987	Area in km²	% Area 1973
Barren land (includes bare lands and outcrops)	273.22	17.02	202.23	12.60	264.45	16.47
Built up areas	590.67	36.79	407.89	25.40	338.51	21.08
Agricultural areas (small scale)	188.66	11.75	251.67	15.68	210.67	13.12
Agricultural areas (sparse)	66.09	4.12	168.64	10.50	217.66	13.56
Forests	211.16	13.15	261.75	16.30	192.95	12.02
Moorlands	62.13	3.87	90.51	5.64	149.26	9.30
Scrublands	187.81	11.70	222.28	13.85	172.90	10.77
Water bodies	0.474	0.03	0.504	0.03	59.18	3.69
Young Forest (re-growth)	25.23	1.57	-		-	
Totals	**1605.4**	**100**	**1605.5**	**100**	**1605.6**	**100**

The area statistics for the Malewa catchment for the 1973-2003 are shown in Table 5.4. Some major changes of land use can be observed in the past 30 years. The area under small-scale agriculture decreased from 13% in 1973 to 11% in 2003. For scrubland, the area increased from 11% in 1973 to 14% in 1987 and back to the levels of 1973 in 2003 (11%). The area under sparse agricultural farming decreased from 14% to 4% during the same period.

Table 5.4: Areas statistics (Areal extent of change for different land use in Malewa)

Land use Category	% Area 2003	% Area 1987	1987-2003 %change	% Area 1973	1973-2003 %change
Barren land (includes bare lands and outcrops)	17.02	12.60	-4.42	16.47	-0.55
Built up areas	36.79	25.40	-11.39	21.08	-15.71
Agricultural areas (small scale)	11.75	15.68	3.93	13.12	1.37
Agricultural areas (sparse)	4.12	10.50	6.38	13.56	9.44
Forests	13.15	16.30	3.15	12.02	-1.13
Moor lands	3.87	5.64	1.77	9.3	5.43
Scrublands	11.70	13.85	2.15	10.77	-0.93
Water bodies	0.03	0.03	0	3.69	3.66
Young Forest (re-growth)	1.57	N/A	N/A	N/A	N/A

Water body accounted for 3.69% in 1973, 0.03% in 1987, and 0.025% in 2003. The moorlands decreased from 9% to 4% between 1973 and 2003. The area under forest only changed marginally between 1973 and 2003 being 12% in 1973, 16% in 1987 and 13% in 2003. Built-up areas have shown marked increase from 21% in 1973 to 37% in 2003. This increase can be attributed to the ever increasing population pressure on Malewa river basin borderlands. The area under barren/bare land which includes lands having no vegetation and lands consisting of outcrops such as rocks has remained virtually unchanged between 1973 and 2003 at 16% and 17% respectively. However, the proportion of bare/barren land was low compared to the other two images in 1987 at 12.6%. This change can be attributed to either bare land during land preparation for planting or early stages of crop growth where most of the land cover is minimally covered with vegetation or bare. The spatial distribution pattern of land use over the study period is shown in Figure 5.2.

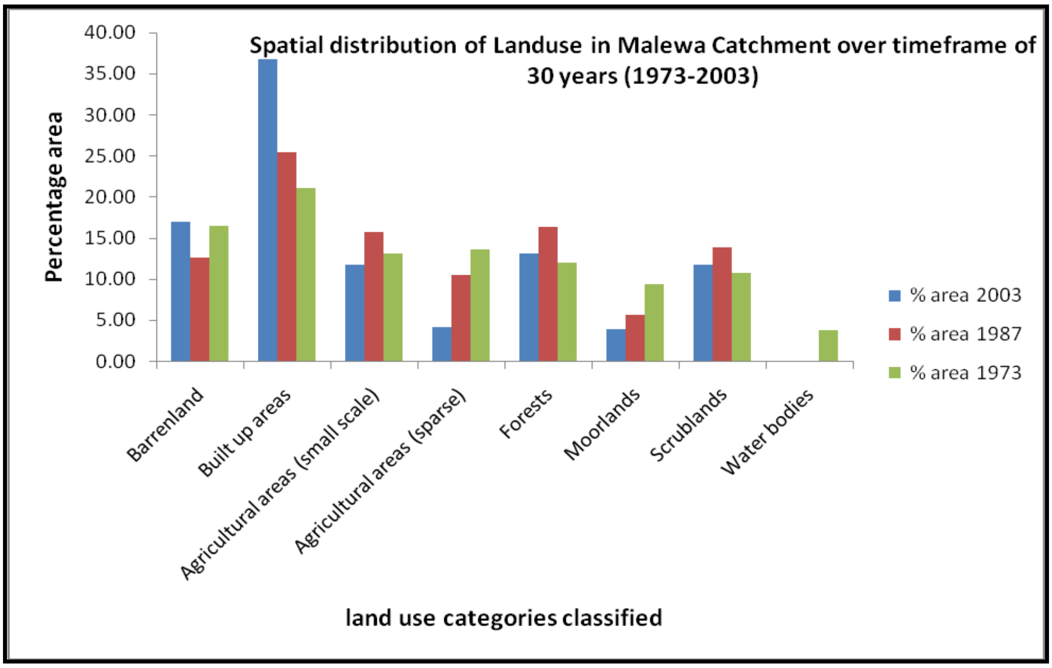


Figure 5.2: Spatial distribution of different landuse/cover categories in Malewa Catchment

Figure 5.2 indicates increasing pressure on land bordering forest, grasslands and water bodies from ever expanding population within the catchment. Forests, scrublands and any open space are being converted to agricultural lands and settlement. The agricultural lands are experiencing reduced fertility as evidenced by increased use of organic and inorganic manures due to over use and poor farm practices. As a result there is reduced farm yield and increased use of both organic and inorganic fertilizers with organic fertilizers particularly livestock manure becoming highly valued and used by smallholder farmers due to increasing cost of mineral fertilizer (Lekasi, 2001). There is also increasing land fragmentation (especially in Geta) with current land area per family being a quarter acre.

Land-use change in Malewa River Basin can be said to be driven by synergetic factor combinations of resource scarcity leading to an increase in the pressure of production on resources, changing opportunities created by markets, outside policy intervention, loss of adaptive capacity, and changes in social organization and attitudes. In short, these land use changes can be summarized as functions of various parameters such as pressure, opportunities, policies, vulnerability and social organization. Figure 5.3 displays the spatial distribution of land use over a timeframe of 30 years from 1973 to 2003.

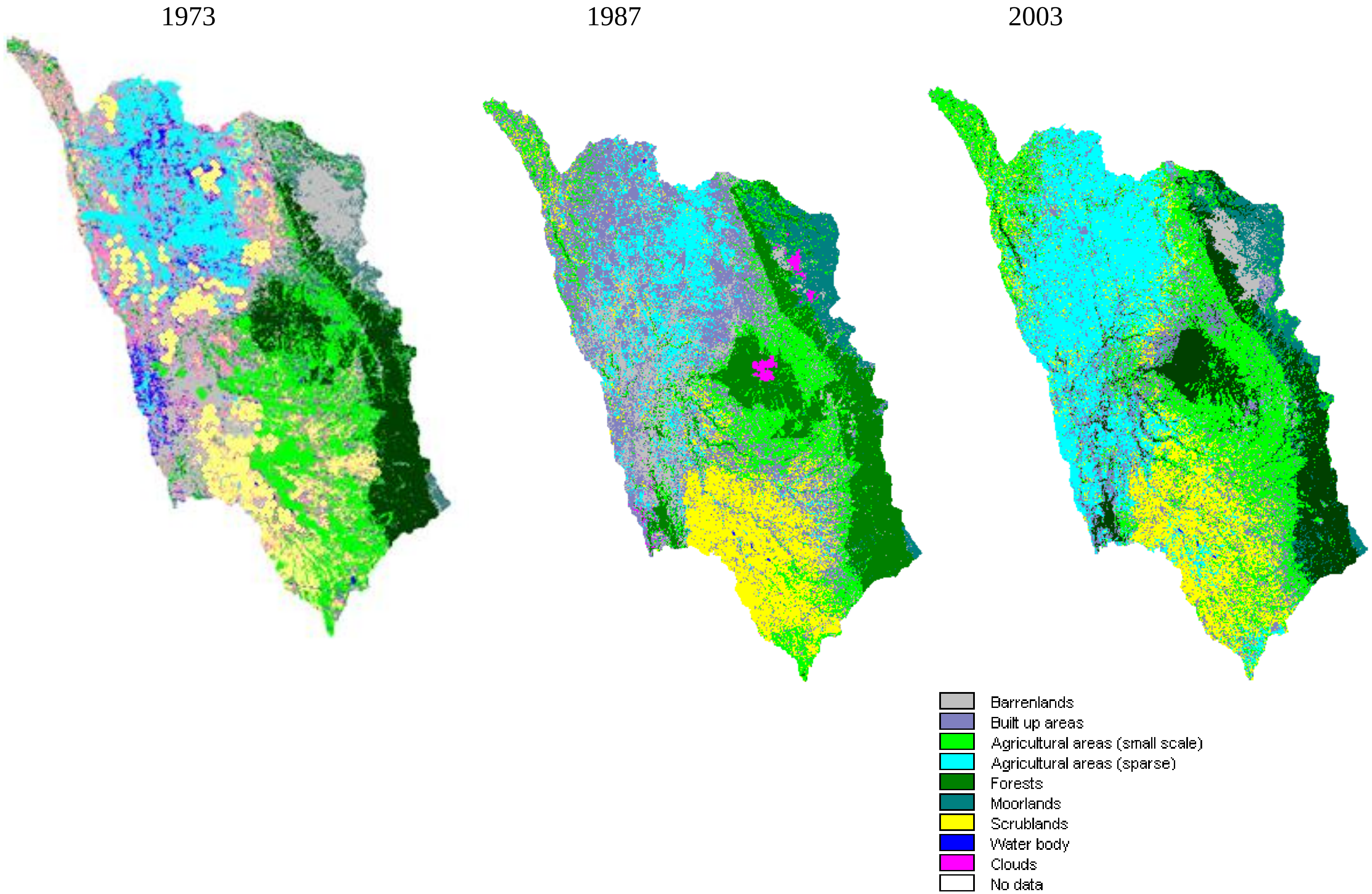


Figure 5.3: Land Use Maps of Malewa catchment for 1973, 1987 and 2003

5.4 Water Quality

The water quality parameters evaluated were PO_4, NO_3 and sediment load. These parameters were selected due to their sources and consequently their impacts on water quality. Primary agricultural pollutants are sediment, nutrients, pesticides, salts, and pathogens. Sediment clog roadside ditches and irrigation canals, block navigation channels, and increase dredging costs. Nutrients, chiefly nitrogen, potassium, and phosphorus, promote plant growth. Of the three nutrients, nitrogen and phosphorus causes quality problems when they enter water systems. Nitrogen and phosphorus from agriculture accelerate algal production in receiving surface water, resulting in a variety of problems, including clogged pipelines, fish kills, and reduced recreational opportunities (EPA, 2004). Besides harming aquatic ecosystems, nitrate is also a potential human health threat. EPA has established a maximum contaminant level (MCL), a legal maximum long-term exposure) in drinking water of 10 mg/liter. The detailed analytical procedures adopted are presented in Appendix 1

5.4.1 Results of the Water Quality Analysis

The results of water quality for the three parameters measured on 21st November 2006 are shown in Figure 5.4 and Table 5.5. These are grab sample and do not represent long term data for the catchment.

Table 5.5: Grab Water Quality Results

RIVER	LAT	LON	TSS (mg/l)	Phosphorous levels (mg/l)	Nitrate levels (mg/l)
Turasha (Downstream)	-0.56739	36.49169	0.014	0.078	0.210
Wanjohi (Upstream)	-0.48683	36.51325	0.112	0.295	0.210
Mkungi (Downstream)	-0.52228	36.53414	0.129	0.092	0.094
Malewa (Downstream)	-0.66867	36.38683	0.110	0.085	0.500
Nanadarashi Upstream	-0.48411	36.61981	0.004	0.001	0.080
Kitiri Downstream	-0.54547	36.54039	0.029	0.019	0.400
Muruaki	-0.62779	36.52260	0.051	0.188	0.280
Turasha (Upstream)	-0.60228	36.57983	0.008	0.000	0.063
Mkungi (Upstream)	-0.47214	36.61250	0.035	0.082	0.370
Malewa (Downstream)	-0.66861	36.38683	0.144	0.035	0.080

Note: Statistical analyses were not done to determine the differences in water quality parameters.

Table 5.5 indicate that there was an increase in nitrate, total and soluble phosphorous and suspended sediment where steep slopes and erodible soils have been disturbed (upstream of Wanjohi,) (see the digital elevation model in Figure 5.4 and land use in Figure 5.3 for the steep slopes and disturbed areas in landuse map). The following are considered as disturbed areas includes places where settlement has taken place or areas where forest/pasture lands have been opened up for cultivation, settlement or grazing. Many steep, erodible slopes (see plates in Appendix 8) have been disturbed by road development, settlement, agricultural activities such as cultivation, and manure/fertilizer applications around the basin. More erodible soils are found in the drier areas of the catchment mainly in the mid and lower parts of the Malewa catchment. These results indicate that with continued sustained pressure and human activity, the water quality will continue to deteriorate if no intervention measures are taken.

Disturbance of soil associated with agriculture generates runoff polluted with sediment, a major nonpoint source pollutant. Nutrients mainly nitrogen, phosphorous, and potassium which are applied during the growing season are assumed to be leaching into ground water or flow in surface water to stream corridors, either dissolved or adsorbed to soil particles. Applied aerially, these same chemicals can drift into the stream corridor. Improper storage and application of animal waste from concentrated animal production facilities are potential sources of chemical and bacterial contaminants to stream corridors. These results imply that water quality solely depends upon the anthropogenic activities carried out in the upstream and rivers offshore.

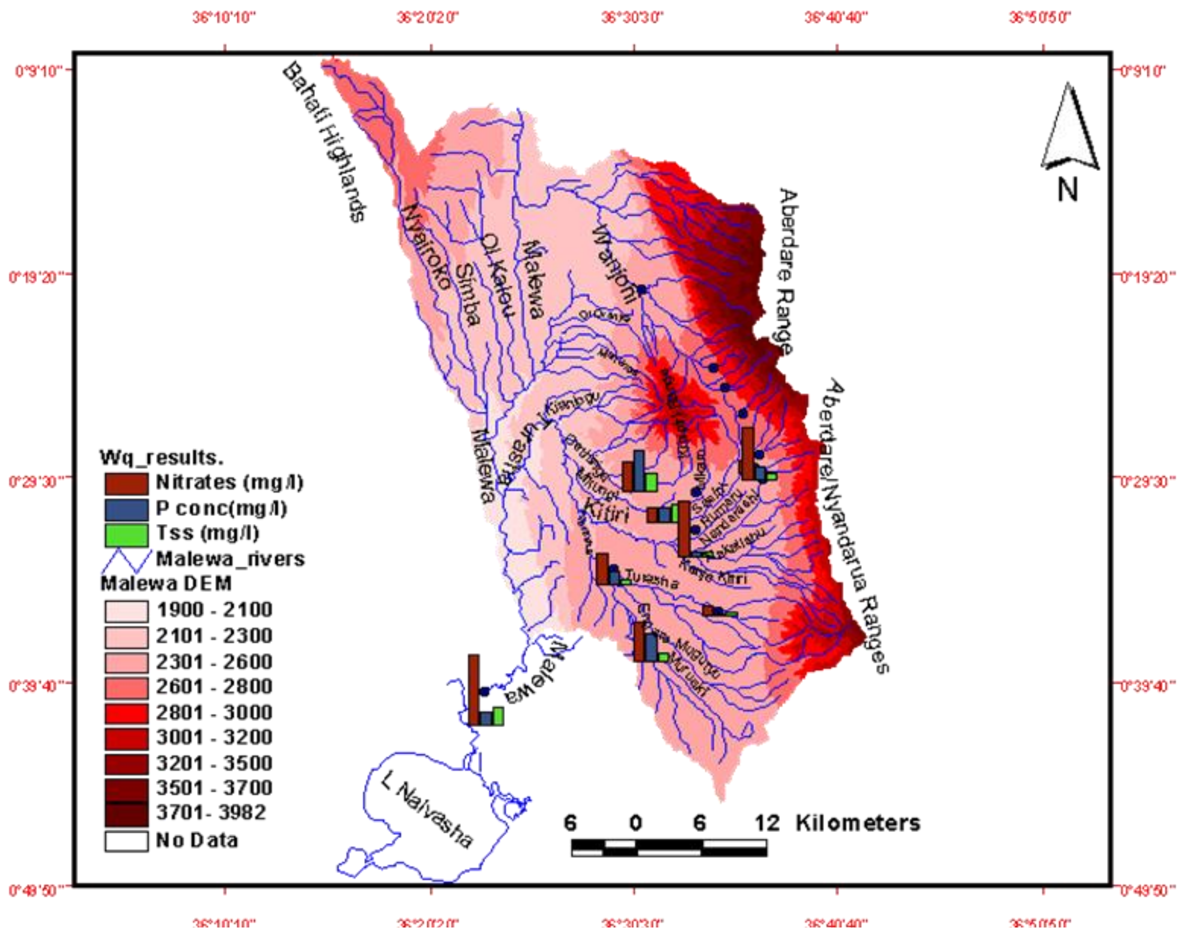


Figure 5.4: Water Quality Results: (Test done on 21st November 2006. NB: Attribute table for values are in Table 5.5)

5.4.2 Nutrient Analysis

A study conducted by Berihun, (2004) on modeling water quality using SWAT in Lake Naivasha Basin concluded that there is a variation of nutrient inputs into streams from different land uses as shown in Table 5.6. There is some concurrence from the grab sample collected and analyzed, (Figure 5.4) and results of Berihun (Table 5.6). Both results indicate that the nutrient pollution is mainly from agricultural fields (Figure 5.3). The concentrations are also seen to increase downstream.

Table 5.6: Trends in water quality for N and P between 2003 and 2006

RIVER	TSS (mg/l) (grab)	Phosphorous levels (mg/l) (grab)	P Levels by Berihun (2004)	Nitrate levels (mg/l) (grab)	NO_2-N (mg/l) Levels by Berihun (2004)	NO_3-N (mg/l) Levels by Berihun (2004)
Turasha (Downstream)	0.014	0.078	0.12	0.21	0.02	5
Wanjohi (Upstream)	0.112	0.295	0.1	0.21	0.004	4.3
Mkungi (Downstream)	0.129	0.092	0.79	0.094	0.004	4.6
Malewa (Downstream)	0.11	0.085		0.5		
Nanadarashi Upstream	0.004	0.001	0.27	0.08	0.005	4.8
Kitiri Downstream	0.029	0.019	0.14	0.4	0.004	6.8
Muruaki	0.051	0.188		0.28		
Turasha (Upstream)	0.008	0		0.063		
Mkungi (Upstream)	0.035	0.082		0.37		2.2
Malewa (Downstream)	0.144	0.035		0.08		

Note: Statistical analyses was not done to determine the difference in nutrient levels between upstream and downstream nutrient levels

From results in Table 5.5, Table 5.6 and Figure 5.4 it can be noted that runoff that passes through areas of intensive anthropogenic activities such as forest clearing, tillage operations, on farm manure application, fertilizer application, grazing, etc; especially in small-scale farming areas are rich in nutrients concentration compared to undisturbed areas such as the Mkungi and Turasha up streams. The relative differences in concentration of nutrients between upstream and downstream for example in Mkungi is 12% and in Turasha is 100% for phosphorous levels The surface runoff flowing from the Aberdares range where small scale and medium farming are dominant (croplands) (see Plates in Appendix 8) contributes considerable amount of nutrient input load to the Mukungi River compared to areas with natural ground cover such as forest. This can be attributed to fertilizer applications on onion, vegetable and maize farms and intensive livestock grazing. The nutrients concentration from the grab samples (Table 5.7 and Figure 5.4) confirms that agricultural activities are the major contributors to nutrient pollution loading in the catchment.

Table 5.7: Results of water quality by Berihun done in 2003 (Source : Berihun, 2004)

Sample ID SR (surface-runoff)	Source	NH_3-N (Mg/l)	NH_3 (Mg/l)	NH_4+ (Mg/l)	NO_3-N (Mg/l)	NO_3- (Mg/l)	NO_2-N (Mg/l)	NO_2- (Mg/l)	NaNO 2 (Mg/l)	PO43- (Mg/l)	P (Mg/l)	P_2O_5 (Mg/l)	X-Cord	Y-Cord
SR1	Aberdare	0.59	0.72	0.76	2.2	9.5	0.004	0.012	0.019	0.17	0.06	0.13	234431	9947088
SR2	Aberdare	1.58	1.93	2.04	6.2	27.6	0.005	0.015	0.023	0.2	0.06	0.15	234759	9949588
SR3	Aberdare	1.48	1.79	1.9	6.2	27.6	0.005	0.017	0.026	0.28	0.09	0.21	234769	9949590
SR4	Mkungi	0.58	0.7	0.74	3.6	16.1	0.008	0.03	0.045	0.11	0.04	0.08	234398	9949936
SR5		1.03	1.25	1.32	4.3	18.9	0.004	0.014	0.022	0.31	0.1	0.23	233126	9951460
SR6		0.49	0.6	0.63	4.8	21.1	0.005	0.017	0.025	0.82	0.27	0.61	229926	9940940
SR7		0.89	1.08	1.14	4.1	18	0.005	0.015	0.023	0.35	0.12	0.27	228489	9938850
SR8		0.81	0.99	1.05	2.7	12.1	0.004	0.013	0.02	0.56	0.18	0.41	220555	9934502
SR9	Turasha	1.91	2.33	2.46	6.8	29.9	0.004	0.014	0.021	0.43	0.14	0.32	226312	9939634
SR10		0.66	0.81	0.86	5	22.2	0.02	0.065	0.098	0.38	0.12	0.28	220844	9937152
SR11	Kipipiri	1.38	1.68	1.78	4.6	20.2	0.004	0.012	0.018	2.42	0.79	1.81	223417	9945356

Note: SR refers to surface runoff

The Turasha tributary drains from small-scale farms of peas, beans, and maize as well as from grassland areas. These areas are rich in nutrient input loads as a result of manure and fertilizer applications. In southern parts of Kipipiri range, there is intensive maize farming as a result of which the Phosphorous concentration of the samples collected in this area was high in comparison with samples collected elsewhere. This can be attributed to the intensive small-scale farming, mainly maize and livestock grazing, and medium scale farming practiced around the Kipipiri range.

A low concentration of phosphorous (P) was observed in forested and pasturelands in the Mkungi River. This can be attributed to the fact that the land is well covered with forest in the upper catchment and pasturelands in the nearby areas. Surface runoff is the major carrier of phosphorous out of most catchments and when surface runoff is reduced, phosphorous load is also reduced.

5.4.3 Suspended solids

Sediment and nutrient yield from a watershed have important implications for water quality and water resources. Offsite effects of soil erosion are the degradation of water quality in streams and water storages. Water quality issues often arise because sediments serve as carriers for various pollutants such as nutrients, pathogens, and toxic substances. Surface water quality is important not only for protection of fish and aquatic life, but it is often used as an indicator of the environmental health of a watershed. Increased sediment load to a watershed can be detrimental to an entire ecosystem.

The absence of long-term records of sediment yield generally precludes detailed analysis of the effects of a documented history of land use change on the records of sediment yield. Continuous records of monitoring data for sediment and nutrients were not available for this watershed. Therefore, only data from grab samples obtained for some points within the Malewa river watershed are presented. Consequently, rigorous calibration of sediment and nutrients could not be performed due to limited sampling data.

The natural sources of sediment within the Malewa watershed are primarily upland areas, agricultural lands and steep slopes, including hillslope where sheet and rill erosion are expected to be predominant due to high rainfall hence overland flow dominates. This trend can be seen in Figure 5.4 and Table 5.5, though the concentrations are not alarming. Human activities lead to creation of important sources of sediments and nutrient. Among these activities, agricultural tillage has the strongest influence especially cultivation upstream along the Malewa tributaries riverbanks and steep slopes of Aberdares and Kipipiri ranges (See plates in Appendix 8). Rural roads construction, timber cutting within and without the forests and riverbanks, quarrying along the Ndunyu Njeru area, urbanization, land development for recreational use and domestic animals and wildlife grazing within the upstream of the watershed and within the forests may also contribute to sediment yields in varying degrees.

Large channels within the watershed not only serve as the avenue for movement of contaminant-laden sediments, but may also act as a source because of erosion from streambeds or banks (see plates on Appendix 8). On the other hand, depending on the main channel geometry, sediment particles could be deposited in the main channel. There is hence a significant difference between sediment and nutrient loads generated from upland areas such as Turasha upstream with source in Aberdares (0.008mg/l), (Table 5.6) and the ones measured at the outlet of the watershed i.e. at station 2GB01(0.144mg/l) (Table 5.6). Considering this phenomenon, implementation of sediment and nutrient reduction plans will be highly affected by the control processes within the watershed. For example, in a transport-limited watershed, the transport capacity of the watershed stream network is less than the sediment generated in upland areas (Keller *et al.*, 1997). Various studies points out that Malewa basin is considered as a transport limited watershed. For example Rupasingha, (2002) reported that the sediment input in Lake Naivasha in the period 1957 – 2001 was 19.0 million m^3 of sediment, which, if spread evenly over the depositional area of lake bottom (89.23 km^2 at 1884 m a.m.s.l.) would give an average thickness of 0.21 m. The total mass of sediment accumulated in the lake was estimated at $7.07 x 10^6$ tons for the 44 year period from 1957-2001. Out of this, 5.75 $x10^6$ tons was determined as inorganic mineral matter and 1.32 $x10^6$ tons of organic matter. A comparison of the lake sedimentation with suspended sediment fluxes of Malewa and Gilgil rivers reveals that the Malewa river wash load contributes to 35% of the lake sedimentation. This implies that 65% of the sediment mass is transported either as bed load, a fraction also by the much smaller Gilgil river, or by another active sediment source.

5.5 Hydrologic Modeling Results

5.5.1 Sensitivity analysis

The main objective of sensitivity analysis was to explore the most sensitive parameters to facilitate model calibration procedure. The SWAT model outputs depend on many input parameters related to the soil, land use, management, weather, channels, aquifer, and reservoirs. Table 5.8 summarizes the 27 SWAT parameters selected out of for sensitivity analysis in this study. These parameters were chosen based on the results of auto-sensitivity analysis run.

Table 5.8: Parameters used in sensitivity analysis

	Objective Function			Objective Function	
Parameters	**OF**	**OUT**	**Parameters**	**OF**	**OUT**
SMFMX	1	1	**SOL_AWC**	6	5
SMFMN	28	28	**Surlag**	5	10
ALPHA_BF	28	28	**SFTMP**	28	28
GWQMN	1	2	**SMTMP**	28	28
GW_REVAP	28	11	**TIMP**	28	28
REVAPMN	28	28	**GW_DELAY**	28	16
ESCO	28	28	**rchrg_dp**	28	13
SLOPE	9	8	**Canmx**	8	9
SLSUBBSN	4	3	**sol_k**	7	4
TLAPS	10	14	**sol_z**	12	7
CH_K2	28	28	**sol_alb**	28	28
CN2	2	6	**Epco**	28	15
CN2	3	1	**ch_n**	11	12

The **OF** refers to "objective function' thus the error function compared to observations. If you have observations, this line will give the most valuable information selecting the parameters for a calibration in which case, the first line labeled **OF** (Objective Function) was used to select the parameters for auto calibration. **OUT** refers to the model output (default, the average output). The second line is the output using the observed data set. Figure 5.5 illustrates the parameters plotted with the least value showing the most sensitivity parameter.

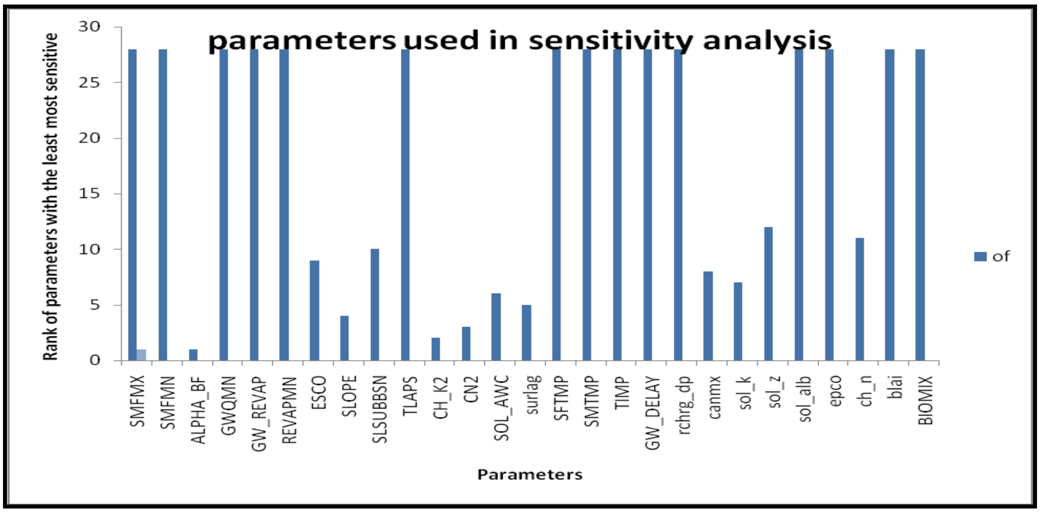


Figure 5.5: A plot of the SWAT parameters used in sensitivity analysis.

From the sensitivity analysis (Figure 5.8), the following parameters shown in Table 5.9 were selected for calibration.

Table 5.9:Initial and finally adjusted parameter values of flow calibration.

No	Parameter	*Description*	*Effect on simulation when parameter values increase*	*Range*	Initial Value	Adjusted Value
1	CN2	Initial SCS CN II value	Increase surface runoff	35-98	Default	37.438
2	GWQMN	Threshold water depth in shallow aquifer for flow (mm H_2O)	Decrease baseflow	0-5000	1000	2279.3
3	ESCO	Soil evaporation compensation n factor	Decrease evaporation	0-1	1	0.55
4	SLOPE	Average slope steepness (m/m)	Increase the lateral flow	0-0.6	Default	0.493
5	RCHRG_DP	Deep aquifer percolation fraction	Increase deep aquifer recharge	0-1	0.05	0.107
6	GW_REVAP	Groundwater "revap" coefficient	Decrease baseflow by increasing water transfer from shallow aquifers to root zone	0.02-0.2	0.02	0.042
7	GW_DELAY	Groundwater delay (days)	Increase the time between water exits the soil profile and enters the shallow aquifer	0-500	31	36.979
8	SLSUBBSN	Average slope length (m)			60.967	108.4
9	SOL_K	Saturated hydraulic conductivity (mm/hr)		-50%-50%		2.392
10	REVAPMIN	Minimum shallow aquifer depth for return flow to occur (mm H_2O)	Increased so that groundwater return flow occurs before 'revap' (transfer of groundwater to upper soil layers)		0.5	316.6
11	SURLAG	Surface runoff lag time (hours)	Reduced so that some portion of surface runoff is lagged one day before reaching the channel			1.446
12	ALPHA_BF	Baseflow alpha factor (days)	Increased to simulate steeper hydrograph recession	0.001-1	1	0.837
13	EPCO	Plant uptake compensation factor		0-1		0.444
14	SOL_AWC	Soil available water capacity (mmH2O/mm soil)	Increased base value by 70% for layer 1 inputs & 30% for all other layers for soil to hold more water	0-1	0.15	0.645

Stream flow calibration was performed for the period from 1981 through 1983 and validation period was from 1972 to1987. Calibration was performed for annual and monthly-simulated flows using observed flows from the Ministry of Water and Irrigation (MWI) gauging stations shown in Figure 5.6 and Appendix 8.

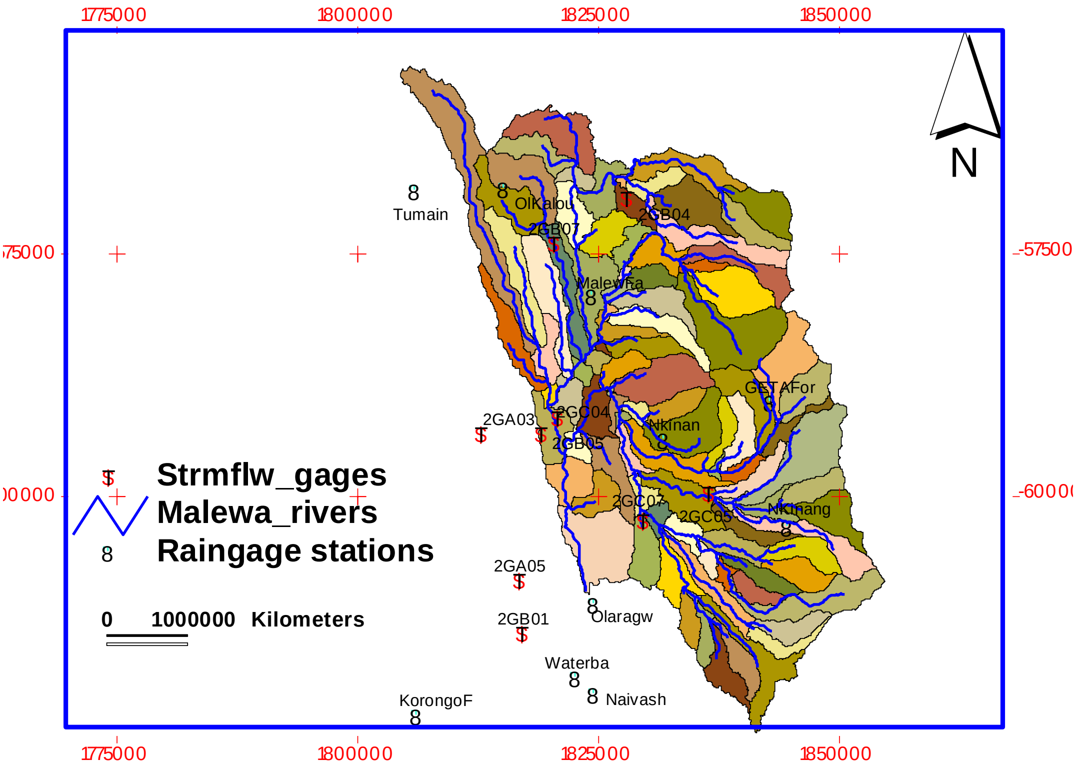


Figure 5.6: Subbasins and gauging stations of Malewa Watershed

Figure 5.7 Results of calibration at Kitiri gauging station 2GC05 at sub-basin 72 outlets.

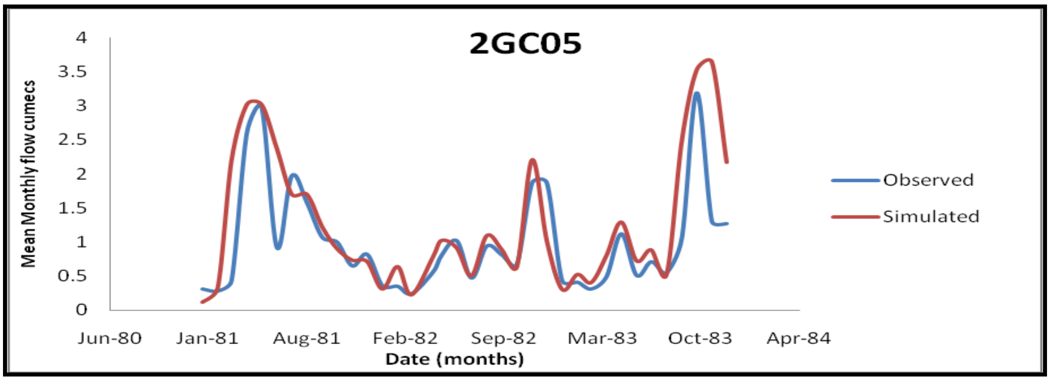


Figure 5.7: Stream flow calibration results at 2GC05.

The next upstream gauging station calibrated was 2GB07. Figure 5.8 shows the calibration results at Upper Malewa station near Ndemi Bridge (station GB07 near the outlet of sub-basin 15).

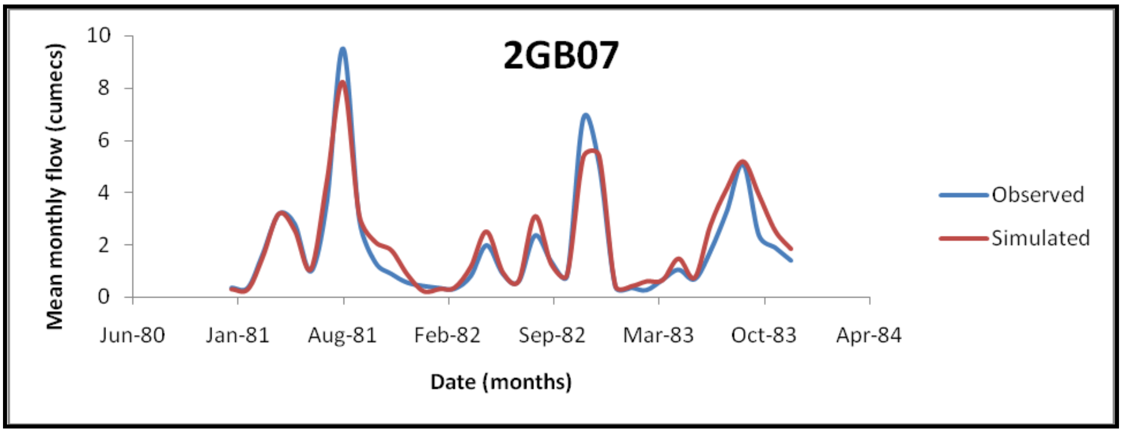


Figure 5.8: Calibrated streamflow for gage 2GB07

The other gauging station calibrated was the main Malewa watershed outlet gauging station at Naivasha (Station 2GB01 near the outlet of subbasin 101 main outlet for the entire basin). The calibration results are presented in Figure 5.9.

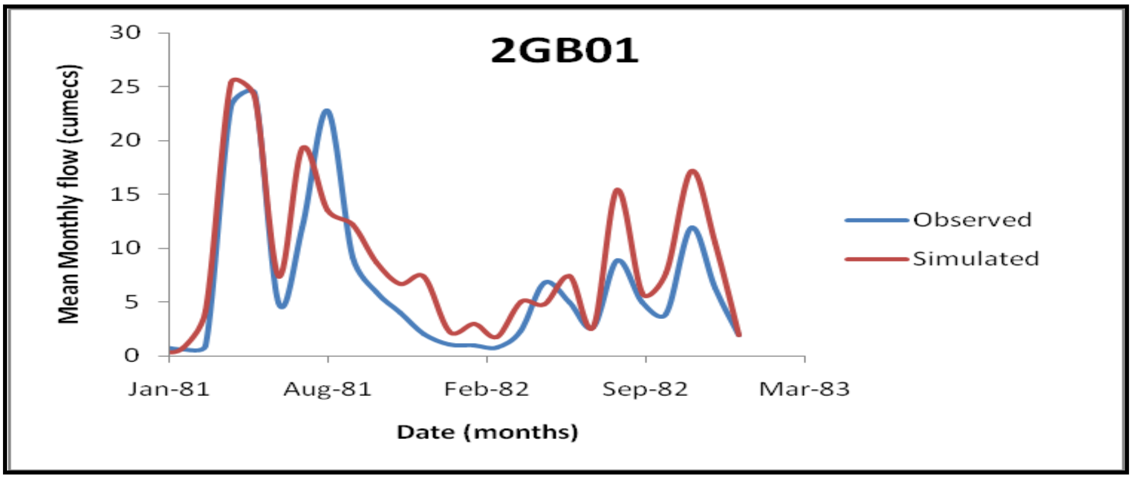


Figure 5.9: Calibrated streamflow for gage 2GB01

The calibration process consisted of ensuring (a) the simulated flow match the observed flow at Upper Malewa (GB07), Kitiri (GC05) and Naivasha (GB01) and (b) proper split (proportioning) of the simulated flow between surface runoff and base flow.

Surface runoff and base flow were calibrated simultaneously. Calibration parameters adjusted for surface runoff were mainly curve number (CN) and Manning's n. The parameters adjusted for base flow proportioning were groundwater revap coefficient, plant uptake compensation factor, and soil evaporation compensation factor and threshold depth of water in shallow aquifer. These parameters were adjusted within the reported ranges. The calibration for surface runoff was continued until average observed and simulated surface runoff was within 15% and R^2, and E_{NS} above 0.5, as possible. The calibration for base flow was continued until the simulated base flow was within 15% of the observed base value. Surface runoff was continually verified as the base flow calibration variables also affect surface runoff. Detailed calibration procedures for SWAT model and the definitions of various calibration parameters are described by Neitsch *et al.,* (2002) and Santhi *et al.*, (2001a) and reproduced in Appendix 2.

As can be seen from Figure 5.9, the calibration result for the main watershed outlet 2GB01 with R^2 of 0.80 and E_{NS} of`0.72 were not good compared to the other two gauging stations used. Beyond January 1983, there was a lot of divergence between simulated and observed hence R^2 and E_{NS} calculation was done between January 1981 and December 1982 in the case of 2GB01. This was attributed to the unreliable flow data. The unreliability of the data was attributed to inaccuracies in measured flow rates, complex relationships between water levels and flow rates in the Malewa streams, transformation of stream cross sections, and change in water surface profiles due to continuous sedimentation and stream bed scouring, etc. Another reason was due to temperature data used. Due to lack of temperature data in the study area, a relation between altitude and monthly temperature was used in this study. The equations (refer to Appendix 5) used were derived from long term data by meteorological department and gives mean monthly temperature for different altitudes in Kenya. Deriving mean daily temperatures from these equations results in over-simplicity and only one year data could be calculated and then replicated for the entire period of model run. By extrapolating the mean monthly data to daily data, unavoidable errors were bound to be introduced in subsequent calculations. Becht and Harper, (2002) stated that the Malewa basin flow data is considered unreliable after the mid 1970's. The possible causes of unreliable streamflow data are as follows; disagreement of observed water levels between gauges and streams, inaccurate results of measured flow rates, complex relationships between water levels and flow rates in streams, transformation of stream cross sections, change in water surface profiles due to continuous sedimentation and stream bed scouring, missing values, wrong value entries, error due to the accuracy of the instruments being used, error due to timing (approximation uncertainty), and hysteresis in the stage-discharge relationship.

Several statistics including the mean, coefficient of determination (R^2), and Nash-Sutcliffe prediction efficiency (E_{NS}) were used to evaluate the model predictions against the observed values (Table 5.10).

Table 5.10: Calibration Table

Gage ID	R^2	E_{NS}	Days of measured data	Mean measured data (m^3)	Mean simulated flow (m^3)	Difference between measured and simulated (m^3)
2GC05	0.77	0.76	1/1/1981-31/12/1983	2.125	1.922	0.203
2GB07	0.79	0.77	1/1/1981-31/12/1983	0.998	0.963	0.035
2GB01	0.80	0.72	1/1/1981-31/12/1982	6.723	8.062	-1.339

The R^2 value is an indicator of strength of relationship between the observed and simulated values. The Nash-Suttcliffe simulation efficiency (Nash and Suttcliffe, 1970) indicates how well the plot of observed versus simulated value fits the 1:1 line. The prediction efficiency indicates the ability of the model to describe the probability distribution of the observed results. If the R^2 and E_{NS} values are less than or very close to 0.0, the model prediction is considered 'unacceptable or poor'. If the values are 1.0, then the model prediction is 'perfect'. Previous studies indicate that E_{NS} values ranging from 0 – 0.33 are considered to indicate poor model performance, 0.33 – 0.75 are acceptable values, and 0.75 – 1.0 are considered good (Motovilov *et al.*, 1999; Inamdar, 2004). The threshold value of acceptance was taken as 0.5 for R^2 and $E_{NS.}$ A value greater than 0.5 for these variables was considered acceptable, which was the criteria used by Santhi *et al.*, (2001b). In overall assessment, the model calibration was within acceptable ranges hence the model can be said to predict the flow well and can be used for prediction of flow.

As a check of the calibration results, a water balance was performed for the study area. SWAT model is based on the water balance equation

$$SW_t = SW + \sum_{i=1}^{t}[R_t - Q_t - ET_t - P_t - QR_t]$$

equation 3

Where SW is the soil water content minus the 15-bar water content, t is the time in days, and R, Q, ET, P, and QR are the daily amounts of precipitation, runoff, evapotranspiration, percolation, and return flow, respectively; all the units are in mm. Over the calibration period, the simulated basin wide water balance components on annual average basis were as follows:

- 965 mm of precipitation (R)
- 136 mm of evapotranspiration (ET)
- 668 mm of water yield (i.e. streamflow leaving the basin) partly made of

- ~~1.0~~o 15 mm of surface runoff (2.5% of water yield) (Q)
- ~~1.1~~o 368 mm of lateral flow (61.1% of water yield) (QR)
- ~~1.2~~o 219 mm of groundwater flow (36.4% of water yield) (P)

Not included in the above-simulated balance are the very minimal losses of water to deep aquifers, percolation and channel transmissions, which total less than 1% of the annual precipitation. Transmission losses are losses of surface flow via leaching through the streambed. Water losses from the channel are a function of channel width and length and flow duration and deep, confined aquifer losses which contributes return flow to streams outside the watershed.

5.5.2 Validation of the SWAT model in streamflow prediction

Application of simulation modeling in research and decision-making requires establishing credibility, for model simulations (Rykiel, 1996). The model was validated for the period 1972-1987. This involved running the calibrated model without changing any parameter and then comparing the simulated and observed streamflow. Table 5.11 shows the model performance over this period.

Table 5.11: Validation Table results

Gage ID	R^2	E_{NS}	Days of measured data	Mean measured data (m^3)	Mean simulated flow (m^3)	Difference between measured and simulated
2GC07	0.61	0.55	1/1/1981-31/12/1991	0.236	0.922	-0.686
2GB07	0.69	0.61	1/1/1981-31/12/1991	1.288	2.456	-1.168
2GB01	0.63	0.56	1/1/1981-31/12/1991	4.975	6.893	-1.918

The validation statistics in Table 5.11 shows that the simulated flow has a good correlation with the gauged flow. The E_{NS} was found to range from 0.55 to 0.61, which is relatively small but still acceptable as this value is more than 0.5 and R^2 ranged between 0.61 and 0.69 which is above 05 and was considered as acceptable. However, the overall flow trend is well simulated by the model. These results showed that the model is able to describe the hydrologic processes of the watershed.

5.6 Selection of priority area for implementation of PES

5.6.1 Criterion for priority area selection

The priority area for implementing pilot PES was selected based on the following parameters (Table 5.12):

Table 5.12: Criterion used for selecting target areas for pilot PES implementation

#	Parameters	Condition that must be met for the area to be selected pilot PES area
~~1)~~1.	**Rainfall amount**	Select areas with highest Rainfall and must be within the upper catchment
~~2)~~2.	**Water yield**	Select areas with highest water yields and must be within the upper catchment
~~3)~~3.	**Groundwater Recharge and discharge zones**	Select areas with highest groundwater recharges and low discharge and must be within the upper catchment
~~4)~~4.	**Water conflicts**	Select areas facing water conflicts between downstream users and upstream land owners, also areas having human-animal conflict and must be within the upper catchment
~~5)~~5.	**Population pressures i.e. population density, poverty gap and poverty rate**	Select areas with highest population density (>100 inhabitants per km^2), poverty rate and poverty gap and must be within the upper catchment
~~6)~~6.	**Land-cover/land-use activity (anthropogenic activities)**	Select areas with highest anthropogenic activities and areas facing high pressure from human activities and are considered as fragile ecosystem. These includes steep slopes >10%, undisturbed lands such as virgin forest, protected areas, range brush, and highly erodible soils and must be within the upper catchment
~~7)~~7.	**Hydrogeology of the Malewa basin.**	Select areas where the drainage pattern is concentrated and are the source of the streams within the upper catchment. Also considered here are the recharge, transit and discharge zones. Piezometric heads were also considered

Initially, the focal area selection was based on the areal rainfall distribution. Since rainfall is the prime driving force in hydrologic processes, it was ranked first. The areas with the highest annual rainfall (over 1000 mm/year) were selected (Figure 5.10). Another consideration was based on the drainage network formation within the study area. The drainage network defines the sub-watershed boundaries and points for monitoring and evaluating the discharge and other water quality parameters.

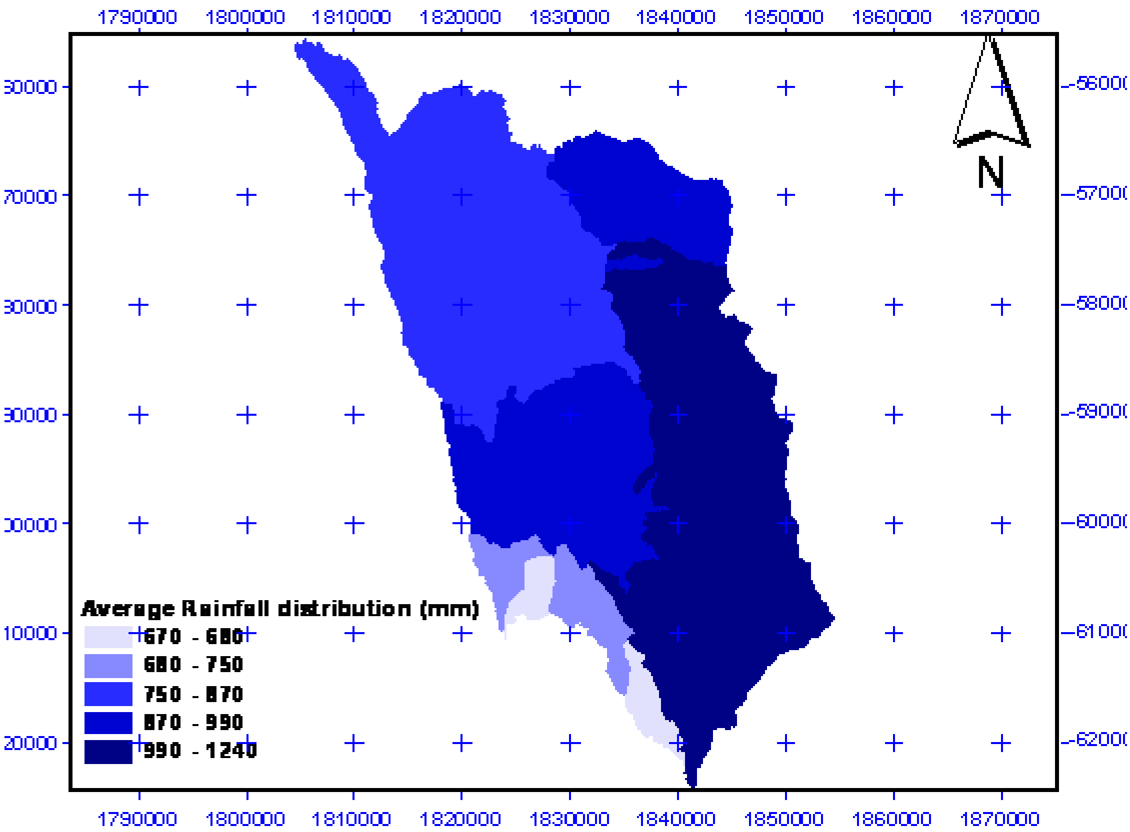


Figure 5.10: Yearly Rainfall distribution (1972-2003) for Malewa Watershed.

The second parameter considered was water yield, recharge and discharge zones. Since the amount of water yield in a given area is a function of the rainfall amount, topographical aspects, soil and geological properties, groundwater withdrawal and watershed storage, it was considered an important parameter in priority area selection. Areas having water yield greater than 1000mm of water yield per annum were selected (Figure 5.11).

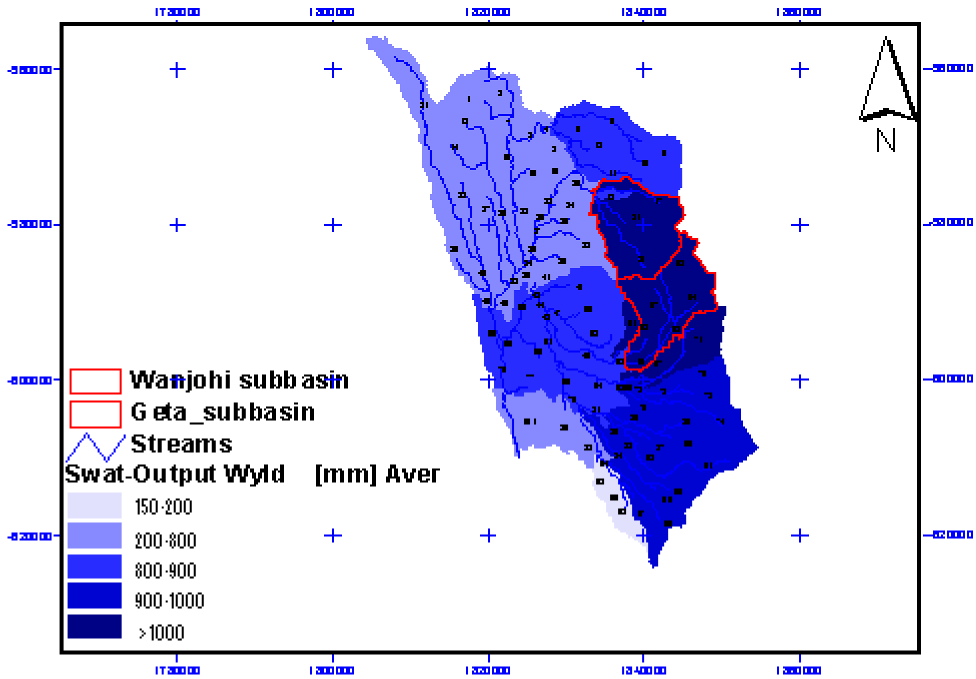


Figure 5.11: Mean Annual Water yield distribution for Malewa Watershed

The third parameter considered in selection of priority conservation areas was population factors such as poverty rate, poverty gap (the difference between the rich and the poor), and poverty density (Figures 5.12, 5.13 and 5.14). Geta, Wanjohi and North Kinangop sub catchments were selected in this category. These are the areas vulnerable to high poverty, lie within the upper catchment, and are dissected by the major Turasha tributaries (Kitiri, Nandarashi and Mukungi rivers). Human population plays a vital role in any water catchment. Accelerated erosion and excessive runoff are connected with development activities and human disturbances, e.g. clearance of fragile zones, denudation and compaction of soil through overgrazing, exhaustion of soil through intensive cropping. Erosion increases as a function of population density (Figure 5.12) in a given agrarian system. If the population passes a certain threshold, land starts to run short, and soil restoration mechanisms begins to fail (Pieri, 1989). One speaks of a densely populated degraded area when the population reaches 100 inhabitants per km^2 (FAO, 1996).

As populations and pressures on land grow, the poorest of the poor (Figure 5.13 and 5.14) are forced into more and more borderlands lands. Figure 5.12 shows poverty gap (Percentage gap to bridge for the poor to reach the poverty line) within the Malewa catchment.

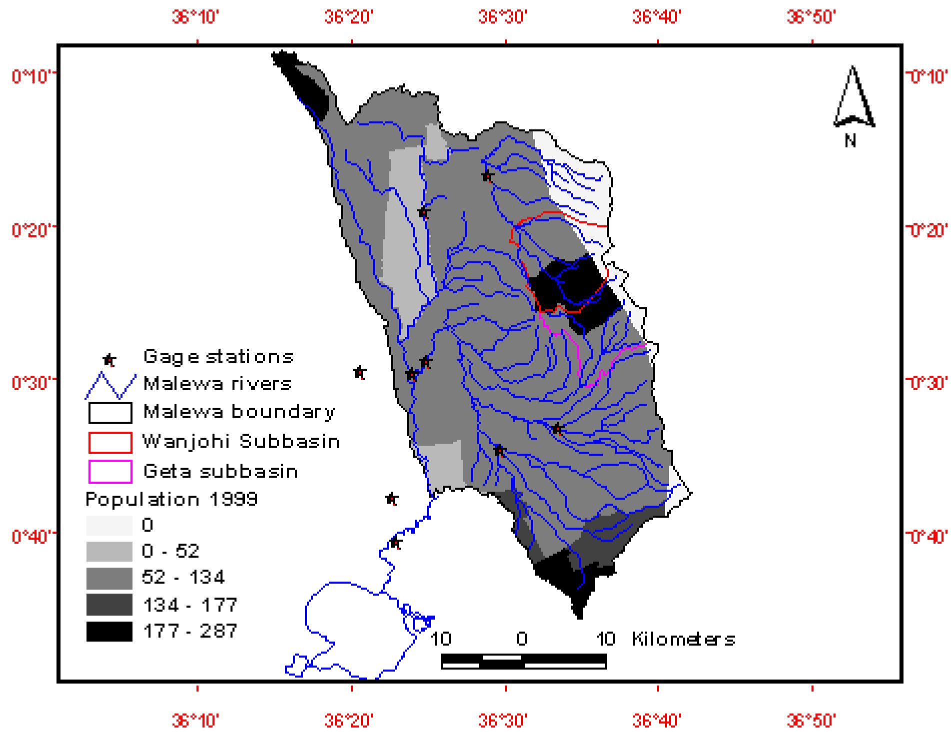


Figure 5.12: Population density per location (adapted from www ilri.org, 1999)

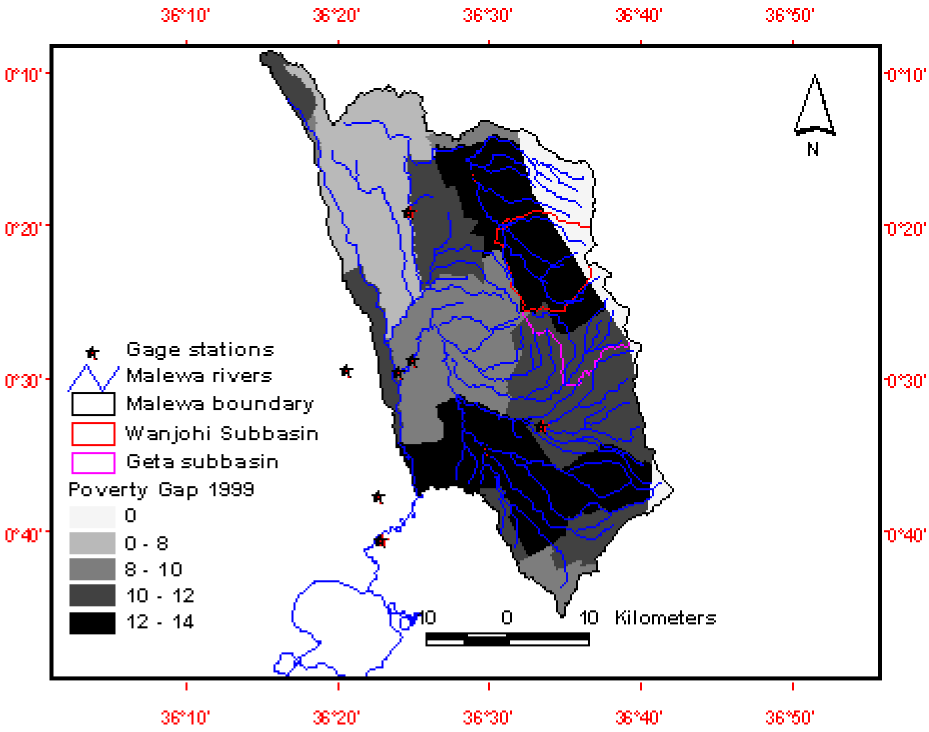


Figure 5.13: Poverty gap per location (adapted from www ilri.org, 1999)

In river basin headwaters, the poorest (Figure 5.14) settle on the most vulnerable uplands, often with high incidences of poverty rate, high slopes and thin soils. Forests are cut down, and slopes are cultivated. Soils are eroded, resulting in minimal crop yields and unsustainable livelihoods. More dangerously (insidiously) groundwater recharge is reduced, river flows become flashier and downstream flood and drought impacts can be greatly enhanced.

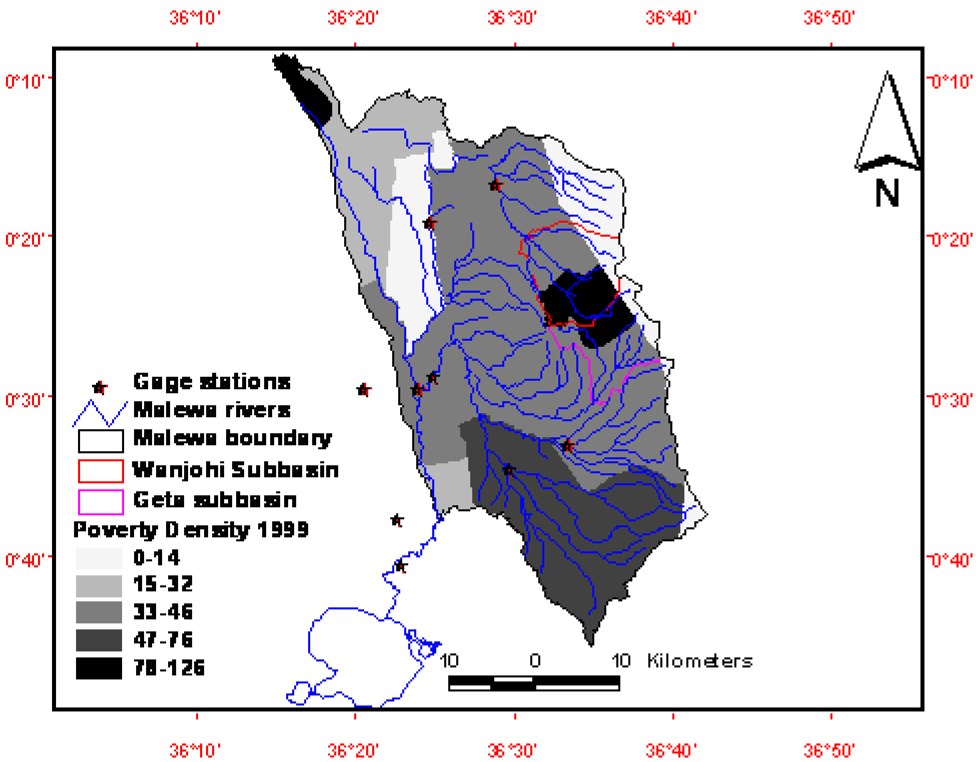


Figure 5.14: Poverty density per location. (adapted from www.ilri.org 1999)

Poverty also creates disincentives to manage long-term resource values, as they create the need for immediate economic returns from forestland. Population pressure such as population density, poverty rate and consequently poverty gap within the catchment has resulted in extended periods of land over-use with the consequent shortening of fallow periods, deforestation, and cultivation and grazing on marginal lands such as steep slopes greater than 15%. This lowers productivity and the vicious poverty cycle is repeated. Dispute over land and the myriad challenges relating to land use, environmental sustainability and fragmentation of plots, tend to become more frequent and more challenging when population density increases.

The next process involved previous studies mainly focusing on water conflicts (see Appendix 6), pressure on water, and pressure on vegetation. The map of pressure on vegetation (Figure 5.15) and the one *of* pressure on water bodies (Figure 5.16) indicate that the two pressures are almost complementary.

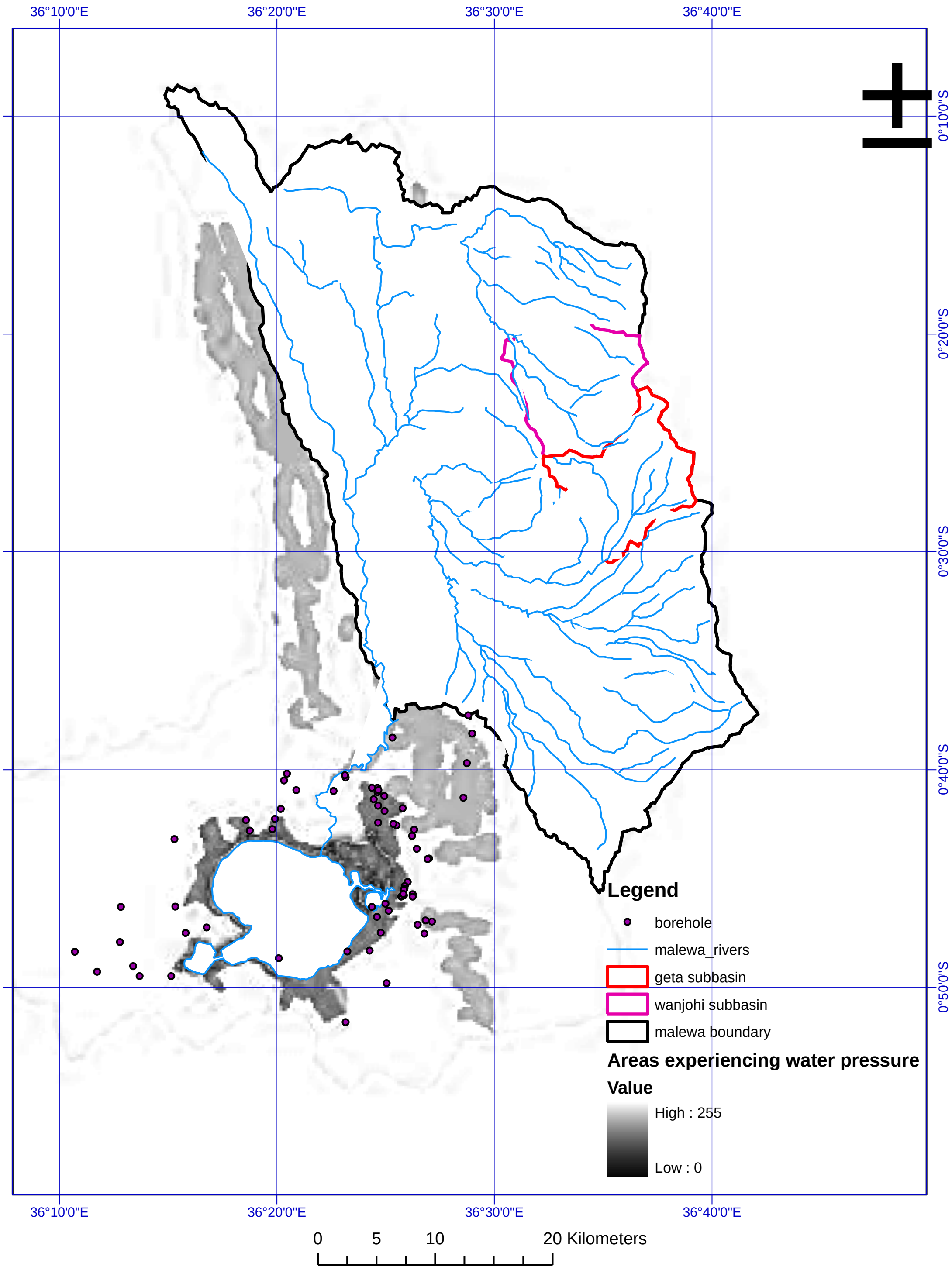


Figure 5.15: Pressure on Water bodies. (Adapted from Fayos, 2002)

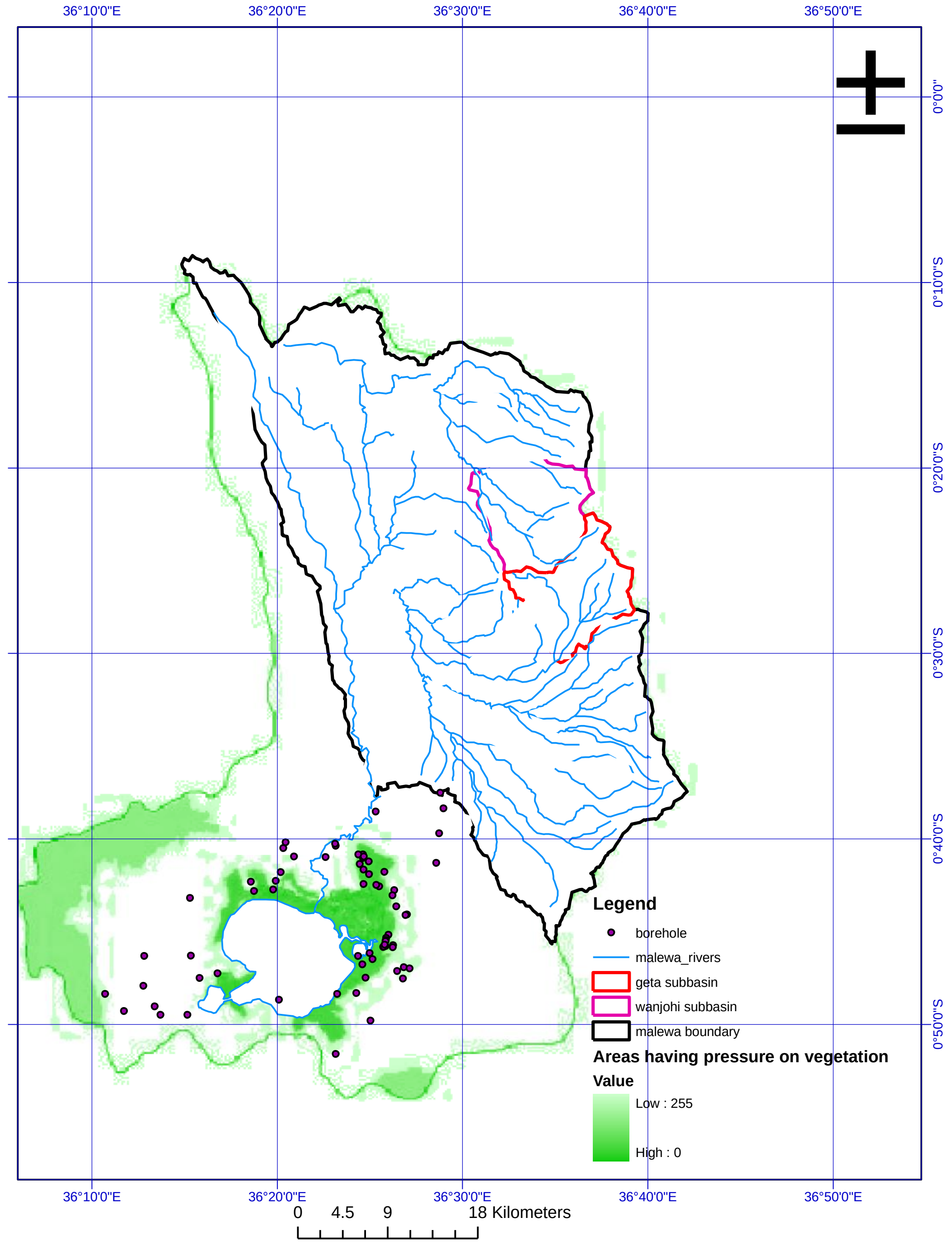


Figure 5.16: Pressure on Vegetation. (Adapted from Fayos, 2002)

This means that high-medium pressure on water bodies correspond with low-medium pressure on vegetation and vice versa, of course with some exceptions. However this general pattern is logical in the case of the Naivasha catchment because closeness to forest and to watercourses does not always coincide. Where the pressure is on the water body, these places have low rainfall which is usually less than evaporation. Such areas tend to be either arid or semi-arid with low population density. However, forests usually occupy the cooler zones of the catchment where rainfall exceeds evaporation, hence no pressure on water bodies.

High population densities are found in upper Malewa catchment (near the forest) and coincidently there is high fragmentation of land while places with low population density experiences pressure on the water resources. The drier zones of the catchment are also occupied by large farms practicing irrigation compounding further the problem of water utilization. Furthermore, Figure 5.20 shows that the high and medium pressure areas appear distributed mainly in two areas:

- Around the Malewa river and
- Around Lake Naivasha

The two areas overlap very well with the densest areas of drainage where at the same time agriculture practices that are not completely rainfed are practiced. The rainfall distribution (Figure 5.10) also shows an area of less rainfall along the middle catchment of Malewa where irrigation needs are likely to be high. The middle catchment is also where there is the conflict of *Small Malewa farmers versus the big farms downstream (Fayos, 2002)* (Table 5.12) *i.e.* downstream farmers complain about water abstraction from the middle catchment.

Table 5.12: Water conflicts within upper and middle Malewa catchment.(Source: adapted from Fayos, 2002)

Conflict number	Conflicts	Components of the conflicts	Spatial indictor of the component and source
1	North Kinangop farmers vs. farmers middle catchment	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
		Bad infrastructure	Roads in bad condition
2	South Kinangop farmers vs. small Malewa farmers	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
3	North/South Kinangop farmers vs. big farmers downstream	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
		Water Pollution of the rivers	Malewa and Gilgil rivers and main subsidiaries (Drainage map of the ITC Naivasha data base and sampling for river pollution from Munoz Villers,2002)
		Bad infrastructure	Roads in bad condition
4	Small Malewa farmers versus big farmers downstream	Water extraction from the rivers	Malewa and Gilgil rivers and main subsidiaries (Drainage map of the ITC Naivasha data base Fayos, B.C.,2002)
		Water Pollution of the rivers	Sampling points for river pollution Munoz Villers (2002)
5	Mixed cattle/agriculture versus large commercial farms	Land utilization	Water consumption by farmers (Pereira, 2002)
6	Farmers versus Fishermen	Water pollution of the lake	Point pollution sources from Munoz Villers (2002) and area of non point source pollution (information from Mulot Villers Fayos, B.C., 2002)
		Water Extraction from the lake	Water consumption by farmers (Pereira, 2002)
12	Water supply GETA project	Water supply GETA project	GETA settlement (own elaboration)
13	Nakuru water project	Nakuru water project	Nakuru settlement (own elaboration)
16	Water supply Naivasha	Water supply Naivasha	Naivasha town (Mena, 2002)
	GETA project	GETA project	GETA settlement (own elaboration)

Higher pressure on vegetation is distributed mainly in the areas surrounding the Aberdares (Geta and North and South Kinangop), and Kipipiri forests (Figure 5.14). Population growth is also causing tremendous pressure on natural vegetation such as forest and rangelands. The areas marked as high pressure are where the forest has disappeared in the last 40 years. These areas were established as high density settlements and coupled with the bad access roads; the areas have seen reduction in the competitiveness in marketing agricultural products hence forcing the inhabitants to use the forest as an alternative economic source which is seen as the most economical venture. With people living closer to the forested areas, a pressure is created on production resources with the following practice such as timber logging, forest grazing, *shamba* systems and forest encroachment, leading to change in opportunities created by markets, an outside policy intervention, loss of adaptive capacity, and changes in social organization and attitudes. Consequently, the anthropogenic activities lead to further siltation as a result of increased sediment yield. Activities including tillage, manure application, cutting down of forests and intensive livestock grazing affect water quality and quantity within the Turasha and Kitiri catchment tributaries of the Malewa River Basin. Figure 5.17 shows the conflicts of interest in Table 5.12.

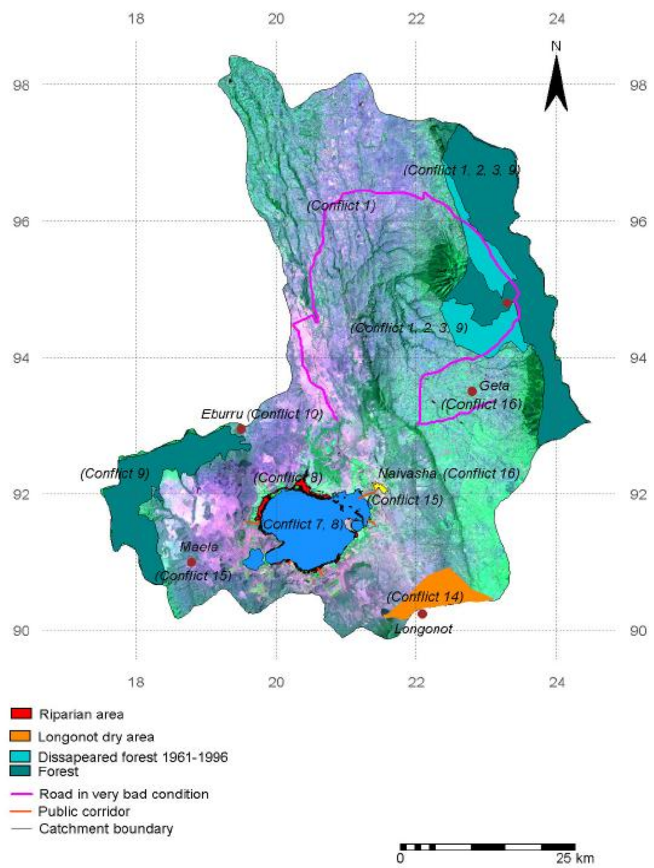


Figure 5.17: Areas of conflicts indirectly related to water.

(In the back a False Color Composite TN 96 Bands 3, 4, 5, green areas correspond to vegetation).
Source: Fayos, 2002

The other parameter considered in selection of priority area was the hydrogeology. The hydrogeology of the Naivasha Basin is simple in concept but complex in detail. The complexity is due to the rift valley geometry and tectonic activities (Clarke *et al*, 1990). At its simplest, the hydrogeology system can be regarded as having three main zones: the recharge, transit and discharge zones. Figure 5.18 shows the general recharge zones within the catchment. The recharge zones are those at the periphery of the basin; in the east the highlands of the Nyandarua Mountains and Kipipiri ranges. The transit zone covers all that area between ≈ 2,400 and ≈ 2,100 m. a.m.s.l. The discharge zone covers the basal part of the basin, culminating in the Lake itself. This is the most complex part of the basin in hydrogeological terms as the lake lies in the bottom of the rift valley.

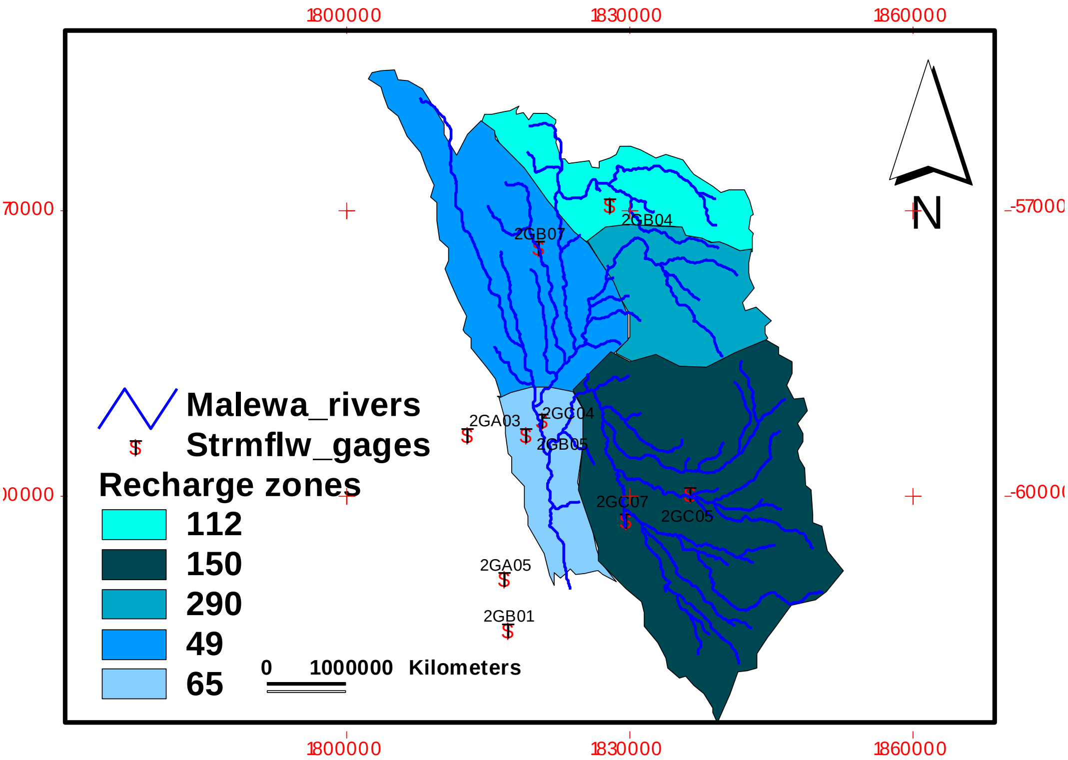


Figure 5.18: General recharge zonation map in mm/year:(Adapted from Graham, 1998)

The piezometric contours (Figure 5.19) indicate a development of sink on the North-Eastern side of Lake Naivasha around Three Point Farm and Manera Farms (Nabide, 2002).

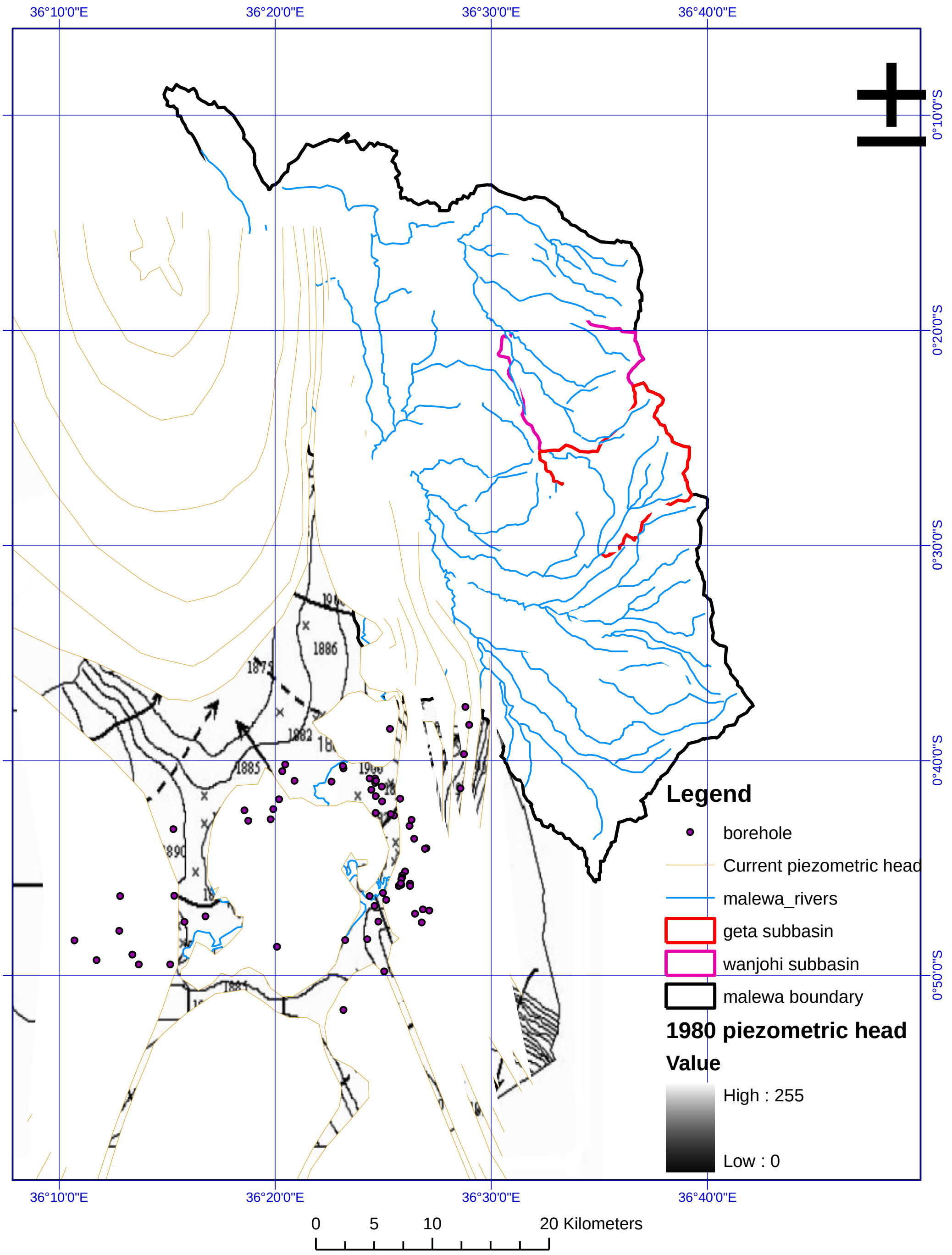


Figure 5.19: Current and 1980 Piezometric Head Contours. W indicates the depression due to extraction from the well field: (Adapted from Nabide, 2002).

There has not been a major change in the flow pattern since early 1980s to the present according to the 1980 piezometric contour map. There has been a fall in the piezometric heads in the North-Western part area around Three Point Farm and Manera Farm (point W in Figure 5.19), where over-abstraction of groundwater occurs (Owor, 2000) resulting into a cone of depression and hence back flow of groundwater from the lake itself. The piezometric head indicates that the middle catchment is where the problem is but since the main concern was to identify headwater as a priority area its significance is downplayed in the criterion for selection.

Two priority areas were selected based on the in-depth analysis of the indicated parameters. Overlaying the parameter (Figure 5.20), the resultant selected priority areas for implementing PES are shown in Figure 5.21.

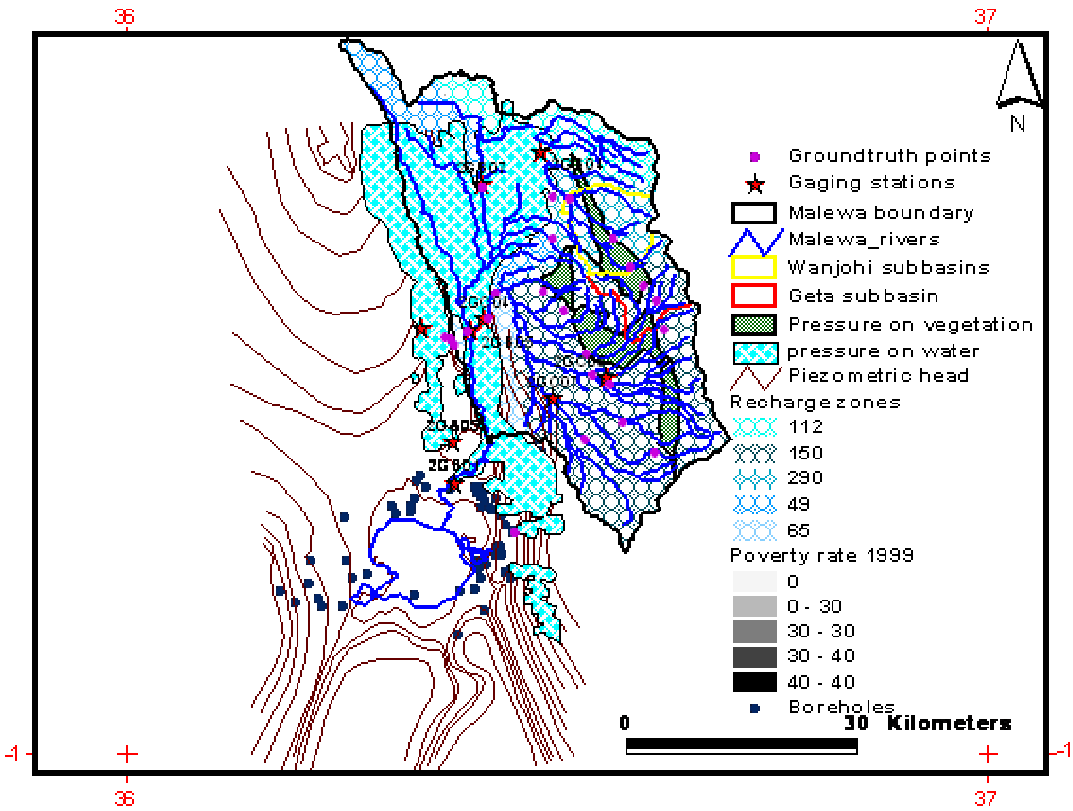


Figure 5.20: Overlay of parameters to determine the priority area for PES implementation.

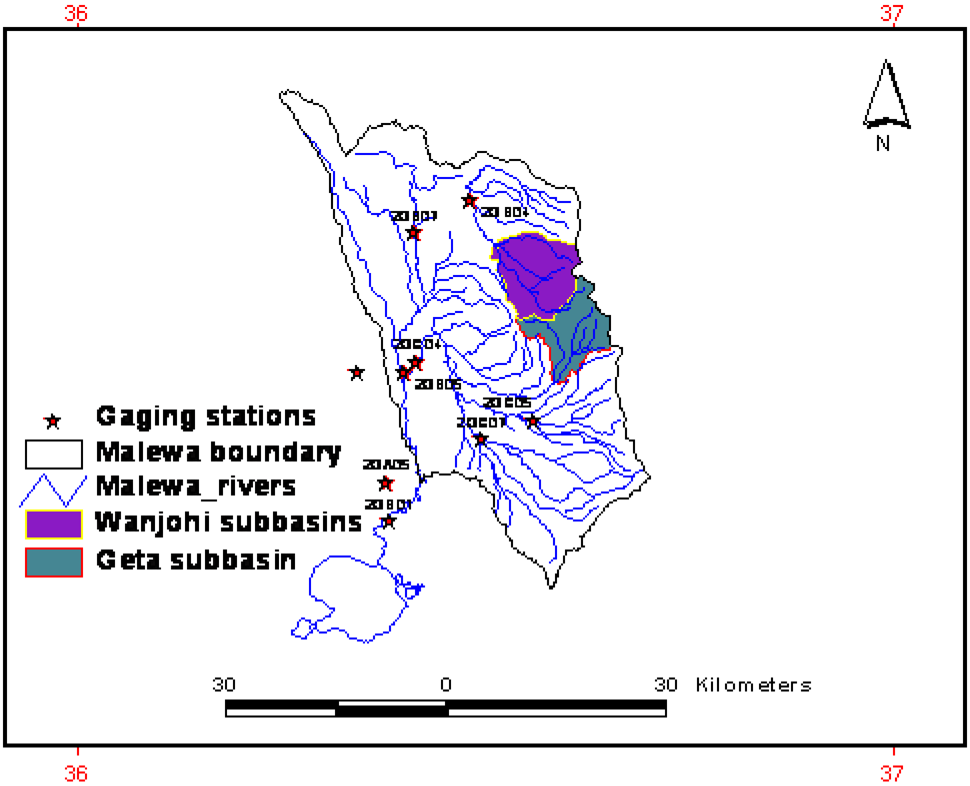


Figure 5.21: Selected priority areas for PES implementation:

GETA sub-basin (Area1) =121km^2 and Wanjohi sub-basin (Area2) =112 km^2

5.7 Scenario development

Paying for environmental services (PES) requires the establishment of cause-effect relations between the land use - upstream - and the water resource conditions downstream in the watershed. In this study, the environmental services were water services.

Many different human activities are carried out in the selected sub-basins. They include small intensive mixed farming, intensive zero grazing, deforestation, land acquisition for agriculture, and land fragmentation. These activities have brought about the land degradation, increased pressure on forested land and myriad problems resulting from high population densities. To analyse the effect of these activities and their consequences on water quantity and quality in relation to land use changes and management practices, the following scenarios were developed for the priority areas (Table 5.13 and Table 5.14 respectively).

Table 5.13: Land use scenarios adapted for studying Impacts of Land-use change on MalewaWatershed

Alternative	Case 0	Case 1	Case 2	Case 3	Case 4
Description	Current land use (Base scenario){ 26% Mixed forest,37% Range brush and 37% Agricultural Dense}	Alteration of Base scenario to 57% mixed forest and 47% Range brush	Alteration of base scenario to 100% Mixed Forest	Alteration of Base scenario to 100% Dense Agriculture	In-corporation of Base scenario (no conservation measures)with Conservation measures (filter width and contour terracing)

Table 5.14: Best Management Practices (BMPs) scenarios adapted for studying Impacts of Land-use change on MalewaWatershed.

BMP parameter	**Base Scenario**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Filter strip	Base Filter width (0 m)	Filter width 1 m	Filter width 5 m	Filter width 10 m	Filter width (0 m)	Filter width (0 m)
Contour farming	Base USLE_P P=1	USLE_P P=1	USLE_P P=1	USLE_P P=1	USLE_P P=0.1	USLE_P P=0.65

Note: P is the support practice factor in USLE equation. Numerical values of *P-USLE* for these practices (Support practices include contour tillage, strip cropping on the contour and terrace systems) are given in Wischmeier and Smith, (1978) and reiterated by Neitsch *et al.*, (2002) as used in the SWAT.

5.8 Hydrological Impacts of Land-use/cover changes

5.8.1 Effects of land use change on streamflow

Four land-use scenarios were simulated in the selected priority areas to assess whether they can be used as instruments for PES implementation. These land-uses are indicated in Table 5.15

Table 5.15: Land-use scenarios used to study impacts of land-use change in Malewa basin

Scenario	*Agricultural dense (AGRC) (%)*	*Mixed Forest (FRSE) (%)*	*Range brush (RNGB) (%)*
Base	37	26	37
Scenario1	100	-	-
Scenario 2	-	100	-
Scenario 3	-	53	47

The results of land-use change on streamflow scenario analysis for Wanjohi sub-basin are presented in Figure 5.22.

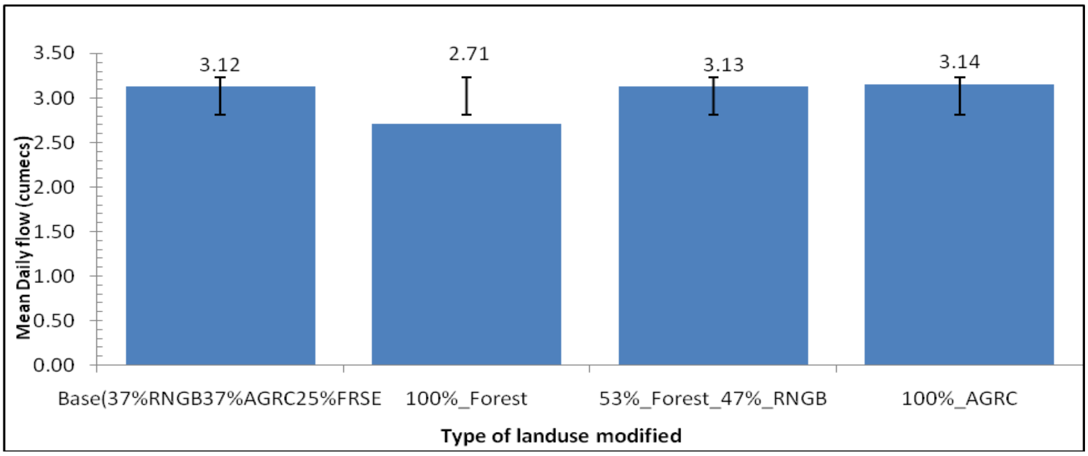


Figure 5.22: Impacts of landuse change on streamflow (Error bars with standard deviation)

The results in Figure 5.22 indicate that all the land use scenarios adopted except the 100% forest have little impact on stream flow. Infact the impact of these scenarions was not different from the base case scenario of 37% range brush, 37% agriculture and 26% forest. When the selected priority areas were put under 100% agriculture close (closely grown crops i.e. onions, carrots, sweet potatoes and cabbages), there was only a marginal increase in stream flow compared to base scenario. This could be due to same density of cover between the two scenarios resulting into near similar moisture flux also the variegated ground cover makes analysis inconclusive. Rooting depth was not a major factor here. When the land use was modified to 100% forest, there was a significant decrease in streamflow from 3.12 m^3/s to 2.71 m^3/s when compared to the base scenario. This was attributed to increased moisture fluxes (different evapotranspiration rates) than those of the base scenario. Tree covered catchments have higher aerodynamic roughness than scrub or grass-covered catchments. Given a sufficient period without rain, all vegetation types will exhaust the supply of soil moisture within their root zone. Rooting depth generally increases with the height of the vegetation. Rain reaching the ground during a rainstorm will first fill the soil storage before any runoff can occur. The greater the rooting depth of the vegetation, the greater the loss of soil moisture, and the more rainfall will be needed to replenish the soil moisture store before runoff is generated. Also, because of the higher interception capacity of tall vegetation, less water will be delivered to the soil under trees than under short vegetation such as grassland. The combination of interception capacity and rooting depth for trees will result in reduced runoff from areas covered in tall vegetation. When the land use was converted to 53% forest and 47% range brush the change in stream flow was very minimal compared to base scenario. This can be ascribed to similar growing dynamics for agricultural crops grown, range brush and forest (rooting depth is not a limiting factor, climatic conditions being the same).

Finally, it is increasingly becoming recognized that land use and land cover management in the uplands affects water cycling through the Earth's natural systems. The conversion from native vegetation to another is manifested in biophysical effects that influence energy and water cycling. Seasonality, albedo, leaf area index, surface roughness, and moisture fluxes are altered with conversion to new vegetation type e.g. conversion of native grassland to cropland.

Growing season dynamics are changed with conversion to agriculture. With deciduous forest featuring a mixture of cool- and warm-season trees, photosynthesis occurs during the entire growing season and peak biomass occurs in early summer (Paruelo *et al*., 2001). In contrast, croplands have one dominant plant with dramatically different growing seasons and peak biomass, with dryland and irrigated crops peaking earlier and later than short-grass, respectively (Paruelo *et al*., 2001). From these results, any land cover that enhances percolation, less evapotranspiration and reduced surface runoff will be encouraged.

5.8.2 Effects of land use change on water yield

Vegetation affects water yield by removing water from the catchment that would otherwise contribute to stream flow. The main features that distinguish different vegetation types from a water yield point of view are the combined characteristics of spatial coverage, interception capacity, rooting depth and aerodynamic roughness (Duncan, 2003). The results of water yield as affected by the different simulated scenarios in the priority sub-basins are presented in Figure 5.23.

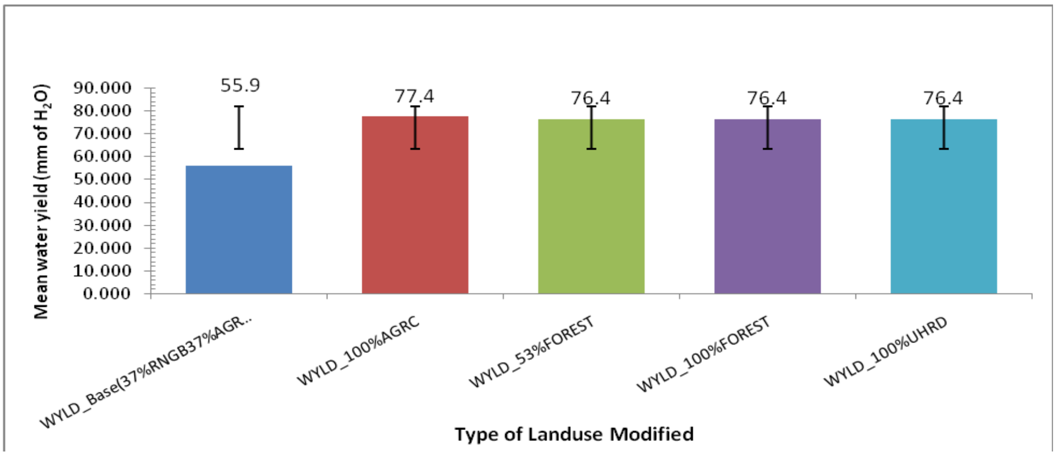


Figure 5.23: Impacts of landuse change on water yield (Error bars with standard deviation)

The results show that when land-use is modified to 100% agriculture, there is a significant increase in water yield from 56 mm to 77 mm when compared to the base scenario. This can be attributed to the increase in infiltration and reduced overland flow. When land use was changed to 100% forest, and 53% forest 47% range brush, there was an increase in water yield from mean annual of 56 mm to 77 mm, 76 mm, and 76 mm respectively. The increase from 100% forest is expected as forests do have influence on infiltration and lateral flow. Since the rooting depth is not a limiting factor, more water is trapped by the debris of the forest slowing down the runoff and hence increasing infiltrated water. There is also an increased interception by the increased coverage area of the forest leading to, increased recharge (infiltration), and increased through fall. This can be said of the other scenarios. Any mechanism that slows runoff will eventually increase the amount of water percolated into the soil resulting into increased groundwater yield.

The results from the scenario studies do not indicate a clear distinction between the various impacts of land-use change on the hydrologic regime. This can be attributed to the large area selected (>100km^2 (112 km^2 and 121 km^2)). The complex nature of the terrain, varied geological conditions in the catchment, and different human activities which are taking place within the catchment also affects the hydrologic regime of Malewa watershed. Mixed vegetative nature in the selected areas are difficult to simulate and interpret the combined effects compared to single pure strand vegetation used for simulation.

Results of the effect of land use changes on hydrology from small catchments (< 1 km^2) studies have been fairly consistent while those from large catchments (>1000 km^2) have been contradictory (Daniel and Kulasingam, 1974; Rahim, 1987; and SAF, 2004). This is probably because large catchments vary widely in properties and characteristics. Small scale catchment studies may give consistent results due to their homogeneity as compared to large scale catchments as was the case of the study area. The Malewa catchment is influenced by diversity of land use types, vegetation types in various growth stages and different human activities which normally occur concurrently. This is expected since different types of vegetation at various growth stages consume water differently. It is also likely that, soil conditions and properties will always vary in different sections of large catchments. This determines soil moisture which in turn influences evapotranspiration. Rainfall patterns and amounts vary depending on the nature of a catchment. The rainfall range in the study area was from 600mm to 1200mm p.a. For instance where there is wide variation in topography, erosion is likely to be more pronounced. The overall effect is change in soil moisture storage which in turn influences evapotranspiration rate of the trees.

~~0~~5.9 Impacts of best management practices on Water Quantity and Quality

5.9.1 Effects of BMPs on Streamflow

The effect of implementing the best management practices (BMPs) on runoff volume and streamflow at the outlets of the two selected target areas are presented in Figures 5.24 for Wanjohi sub-basin and Figure 5.30 for Geta sub-basin respectively. USLE_P was modified to represent parrallel terrace/contouring with P value set at 0.1 and 0.65, filter strip was represented in the model by modifying filter width to 1 m, 5 m and 10 m. In the study area there are neither installed BMPs nor existing ones nor any data for analysis, hence it necessitated the use of SWAT model for simulating the impacts of implementing the BMPs on the selected priority sub-basins.

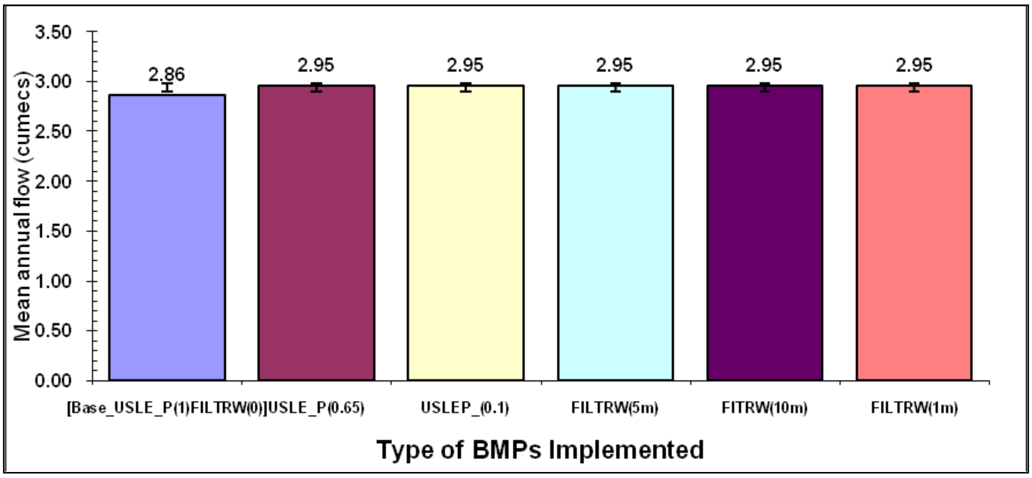


Figure 5.24: Impacts of BMPs on Streamflow at Wanjohi area (Error bars with standard deviation)

The results shows that with the installation of BMPs in the Wanjohi catchment, streamflow increased from a mean of 2.86 cumecs in base scenario to 2.95 cumecs with all the BMPs installed in Wanjohi sub-basin. The results from Geta catchment (Figure 5.25) are however completely the opposite. The implementation of BMPs resulted in a reduction of streamflow though marginally compared to base scenario i.e. from 3.1 to 3.0 cumecs.

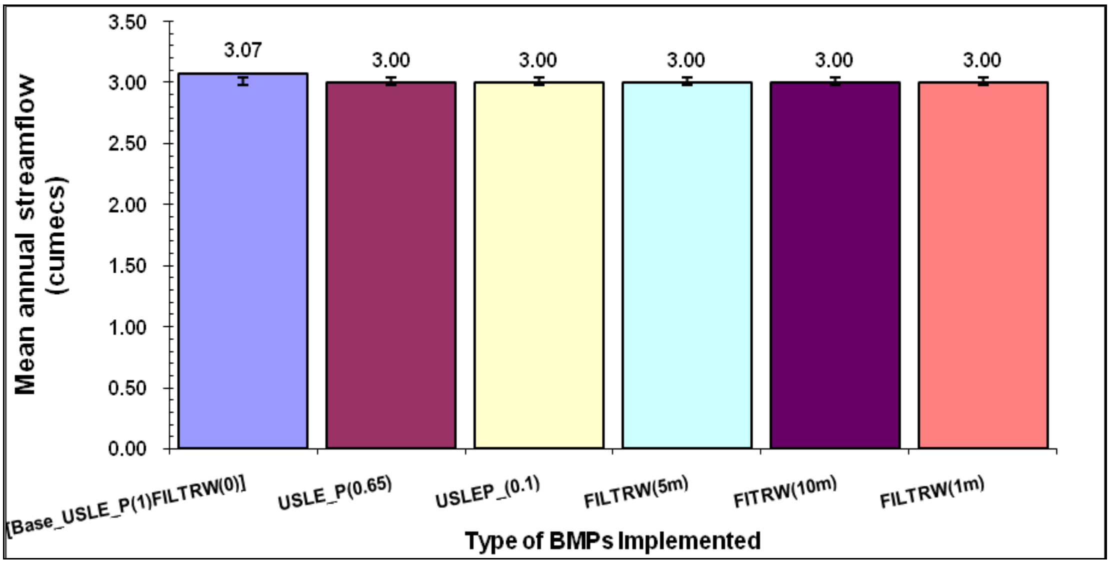


Figure 5.25: Impacts of BMPs on Streamflow at GETA area (Error bars with standard deviation)

These difference in results for Geta subbasin can be attributed to varying land slopes. In Geta, there are more steep slopes (>10%) compared to Wanjohi area. When the slopes exceed 10%, the effectiveness of filter strips and contour farming (contour tillage, strip cropping on the contour and terrace systems) are drastically reduced. This calls for introduction of more advanced conservation measures such as grade stabilization or bench terraces since contour farming practice applies on sloping land where crops are grown and is most effective on slopes between 2 and 10 percent.

Implementation of Best Management Practices (BMPs) is a conventional approach for controlling nonpoint sources of sediments and nutrients. However, implementation of BMPs is rarely followed by a good long-term data monitoring program in place to study how effective they have been in meeting their original goals. Long-term data on flow and water quality within watersheds, before and after placement of BMPs, is not generally available. Therefore, evaluation of BMPs (especially new ones that have had little or no history of use) must be necessarily conducted through watershed models.

5.9.2 Effects of BMPs on Sediment Yield

The simulated effect of filter strip and contour terrace on sediment output at the outlets of the two selcted areas are depicted in Figure 5.26 for Wanjohi sub-basin and Figure 5.27 for Geta Sub-basin respectively.

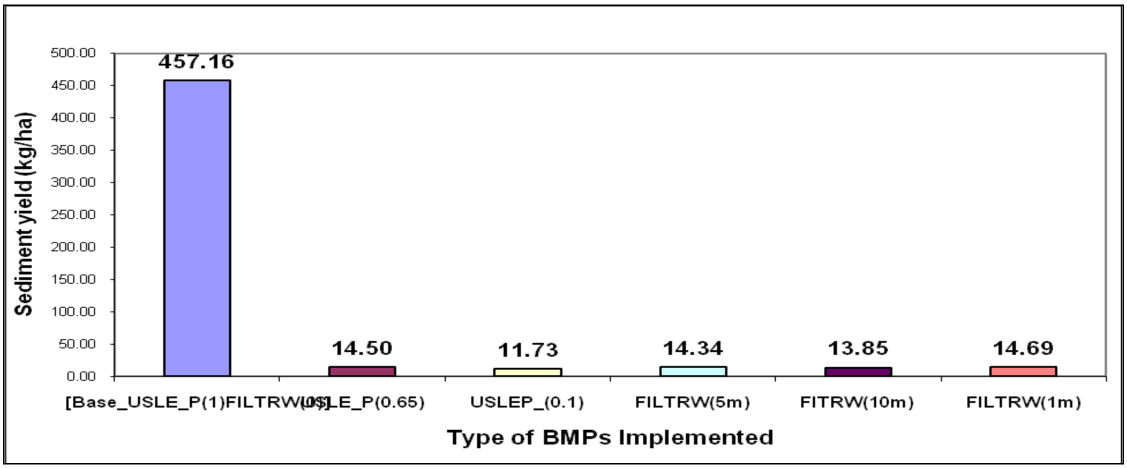


Figure 5.26: Impacts of BMPs on Sediments at Wanjohi area

The results show that the BMPs decreased the average monthly sediment yield at Wanjohi sub-basin outlet from 457.16 kg/ha (without BMPs) to 11.73 kg/ha for the best BMP (USLE_P=0.1 which is equivalent to contour terrace). Other BMPs had similar reductions ranging from 14.69 kg/ha for filter width of 1 m , 13.85 kg/ha for filter width of 10 m, 14.34 kg/ha for filter width of 5 m and 14.5 kg/ha for contour terrace with USLE_P value of 0.5. The introduction of filter strip had a significant effect in sediment yield reduction. Changing the filter strip from 5 m width to 10 m width had very little change on sediment yield reduction.

When BMPs are implemented in Geta, there is a substantial decrease in sediment yield from 424.56 kg/ha with no BMPs to 18.9 kg/ha with contour terrace in place (USLE_P value of 0.50, 15.52 k/ha for contour terrace with USLE_P value of 0.1, 15.52 kg/ha, 18.74kg/ha and 19.08 kg/ha for filter widths of 5m, 10m and 1m respectively. The results show that sediment trapping efficiency improves with increasing buffer width.

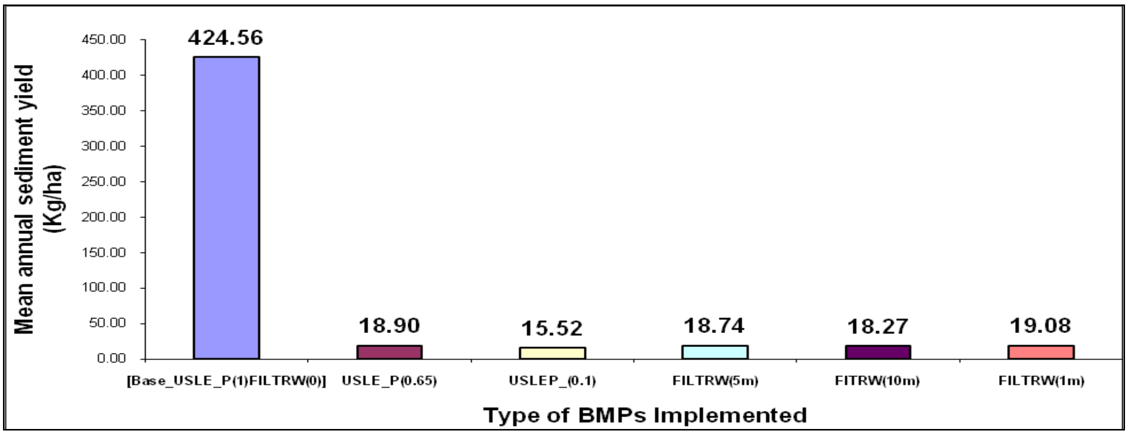


Figure 5.27: Impacts of BMPs on Sediments at GETA area

Further analysis was done to see the efficiency of the implemented BMPs. An overall evaluation was made by estimating BMP efficacy in terms of percentage reduction of the parameter (Equation 4):

$$\text{Reduction (\%)} = \frac{\text{Model output (Without BMPs)} - \text{Model output (With BMPs)}}{\text{Model output (Without BMPs)}}$$

Equation 4

The efficacy of the BMPs for abating sediment yield in the selected areas calculated using equation 3 is given in Table 5.16.

Table 5.16: The efficacy of BMPs simulated in the study sub-basin areas.

		% Reductions				
Sub-basin	**Measured output parameters for BMPs**	**Contour terrace (USLE_P=0.65)**	**Contour terrace (USLE_P=0.1)**	**Filter width 5m**	**Filter width10m**	**Filter width 1m**
Wanjohi	FLOW_OUT	-0.43	-3.31	-3.32	-3.32	-3.32
	SED_OUT	96.83	97.43	96.86	96.97	96.79
	ORGN_OUT	97.33	99.25	98.3	98.86	97.37
	ORGP_OUT	96.86	99.1	98.03	98.68	96.95
	NO3_OUT	91.9	91.84	92.29	92.68	92.05
Geta	FLOW_OUT	2.52	2.52	2.51	2.51	2.51
	SED_OUT	95.55	96.34	95.59	95.7	95.51
	ORGN_OUT	-21.87	64.63	24.04	49.17	-17.74
	ORGP_OUT	60.56	88.54	75.43	83.56	61.92
	NO3_OUT	99.07	99.06	99.18	99.28	99.11

Table 5.16 presents the efficacy results of implementing BMPS as percentage reductions in average annual sediment, total nitrogen (organic and mineral nitrogen) and total phosphorus (organic and mineral phosphorus) loadings at Geta and Wanjohi sub-basins outlets. The results indicate a significant reduction in sediment, total N and total P with implementation of BMPs. The decrease could be due to lesser sheet erosion from upland areas.

5.9.3 Effects of BMPs on Nutrient Yield

The results of the effects of BMPs on nutrient yield are presented as percentage reductions in average annual total nitrogen (organic and mineral nitrogen) and total phosphorus (organic and mineral phosphorus) loadings at the selected subbasins (Geta and Wanjohi). Loadings generated in the pre-BMP conditions were used as the base to estimate the percentage load reductions. Figure 5.28 and Figure 5.29 presents the results of the simulated total organic N yields at the Wanjohi and Geta outlets respectively.

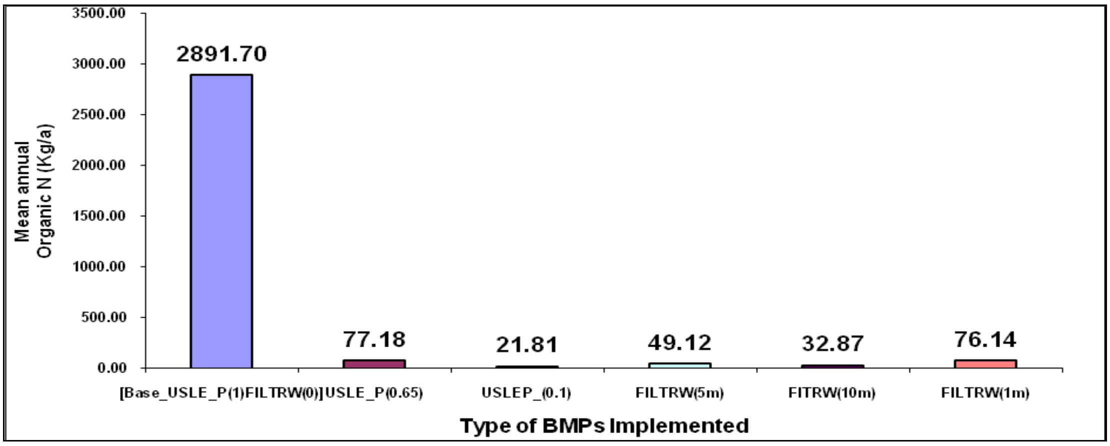


Figure 5.28: Impacts of BMPs on Organic N at Wanjohi area

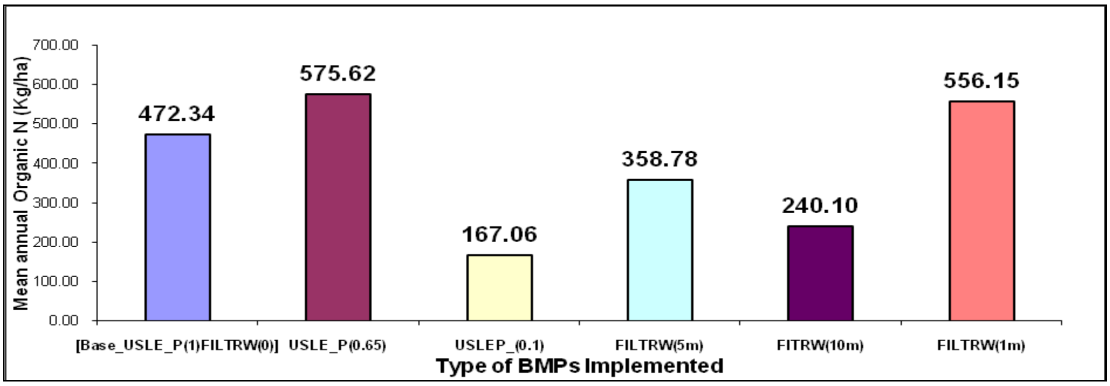


Figure 5.29: Impacts of BMPs on Organic N at Geta area

The results of installing BMPs in the watersheds indicates that without BMPs, total organic N yield predicted by the SWAT were 2891 Kg/ha for Wanjohi and 472 Kg/ha for Geta. After the implementation of the BMPs, there was a significant decrease in organic N in both sub-basins. The decrease for Wanjohi sub-basin was from 2891 kg/ha to 77.18, 21.81, 49.12, 32.87 and 76.14 kg/ha for contour terrace (USLE_P=0.5), contour terrace (USLE_P=0.1), and filter widths of 5m, 10, and 1m respectively. The decrease for Geta was from 472.34 kg/ha to 167.06 kg/ha for contour terrace (USLE_P=0.1) and 358.78kg/ha and 240.1kg/ha for filter width of 5m and 10m respectively. Contour terrace having USLE_P value of 0.5 and filter width of 1m were not effective in Geta sub-basin. The organic N increased from

472.34 in base conditions to 575.62 for USLE_P=0.5 and to 556.15kg/ha for filter width of 1m respectively. Filter strips are based on the filter strip's ability to trap sediment and nutrients based on the strip's width. The shorter the width, the lower the trapping efficiency is. In Geta sub-basin, the slopes are steep hence the ineffectiveness of the 1m width filter strip.

The results of the total P predictions of the model results for selected priority sub-basins with BMPs implemented are presented in Figure 5.30 for Wanjohi and Figure 5.31 for Geta.

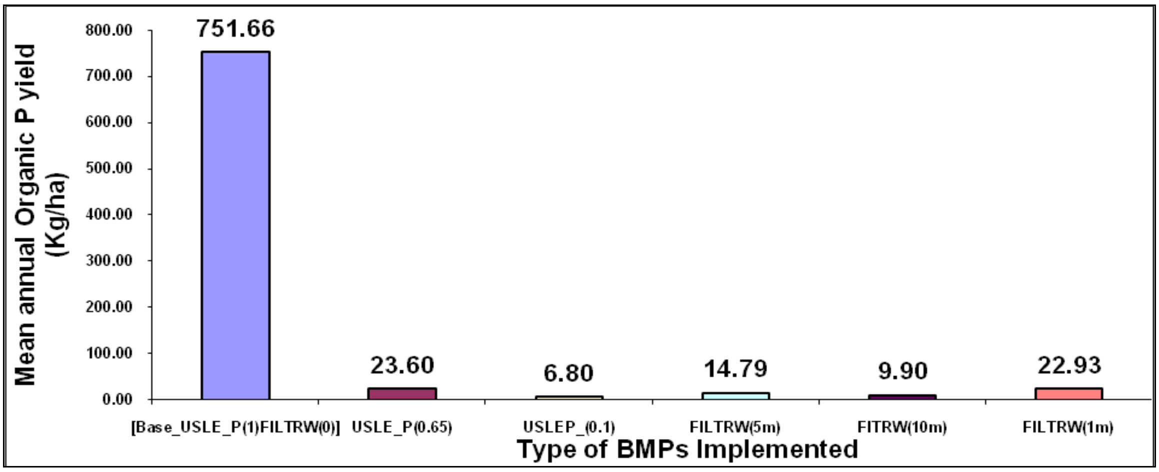


Figure 5.30: Impacts of BMPs on Organic P at Wanjohi outlet

The installed BMPs reduced the total P output from the sub- basins. For Wanjohi area, total P was reduced from 751.86 kg/ha to 23.6 kg/ha with contour terrace of USLE_P value 0.5and 6.8 kg/ha for contour terrace of USLE_P value of 0.1. The total phosphorous P values were also reduced with filter width put in-place. These reductions were as 14.79 kg/ha, 9.90kg/ha, and 22.93 kg/ha for filter widths of 5 m, 10 m and 1 m respectively.

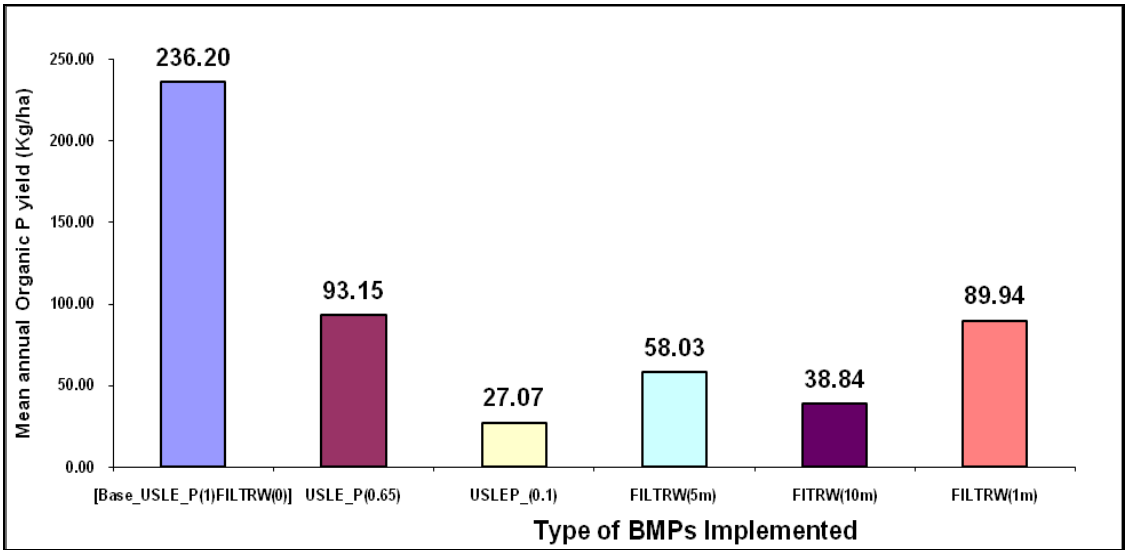


Figure 5.31: Impacts of BMPs on Organic P at Geta area

Figure 5.31 shows the results of impacts BMPs on organic P at Geta sub-basin outlet. The reductions were from 236.2kg/ha to 93.15kg/ha and 27.07kg/ha for contour terraces having USLE_P values of 0.5 and 0.1 respectively. The reduction of organic P achieved with filter widths of 5m, 10m, and 1m were as follows, 58.03kg.ha, 30.84kg/ha and 89.94 kg/ha respectively. The installed BMPs were estimated to effectively reduce N and P yields between 99-24% and 99-51% respectively (Table 5.14) for the two selected areas. It's worth noting that field border strip of 1 m and USLE_P of 0.5 were not effective in the Geta area. This is due to steep slopes found within the Geta sub-basin.

Most of the nutrients (total P, and total N) are introduced into the main channel and transported downstream through surface runoff and lateral subsurface flow. Major phosphorous sources are from mineral soil which include organic phosphorus available in humus, mineral phosphorus that is not soluble, and plant available phosphorus. Phosphorus may be added to the soil from agricultural lands in the form of fertilizer, manure, and residue application. Surface runoff is the major carrier of phosphorous out of most catchments (Sharpley and Syers, 1979). Major nitrogen sources in mineral soil include organic nitrogen available in humus, mineral nitrogen in soil colloids, and mineral nitrogen in solution. Nitrogen may be added to the soil from agricultural lands in the form of fertilizer, manure, or residue application. Plant uptake, denitrification, and volatilization, leaching, and soil erosion are the major mechanisms of nitrogen removal from a field. In the study area, soil erosion and leaching can be said to be the major mechanisms of nitrogen removal.

From the results of implementing BMPs, it can be noted that the reduction in total P load was consistent with the reduction of sediment yield at the outlet of the watersheds (Figure5.26, Figure 5.27, Figure5.30 and Figures5.31). This was anticipated for two reasons. First, in relatively small watersheds like Wanjohi and Geta, the role of in-stream nutrient processes that are simulated by SWAT, such as algal decay on phosphorus yield, is negligible compared to soil loss from upland areas and secondly due to channel erosion. In such watersheds, it can be claimed that sediment and nutrient yields are correlated. Moreover, the BMPs installed in the study watersheds were basically sediment control structures. The impact of the BMPs on nutrient loads was as a consequence of reduction of sediment yield. With installation of conservation structures such as filter strips, contour farming e.g. contour tillage, strip cropping on the contour and terrace systems, etc will enhance water quality coming from the upland areas of the catchment.

In summary, upstream land use practices have important impacts on water resources such as good water quality, less sediments, or more regular water flow for downstream users. However, much controversy exists about the direction and magnitude of such impacts. Payment for environmental services by downstream users to upstream users depends much on perceived and agreed upon mechanism for sharing of resulting benefits and costs by all recourse users in a watershed context. The study has focused on few management systems e.g. filter strips and contour farming systems that could be adopted in the study area in order to improve on the water quality and water flowing downstream. These management systems can be incorporated into the PES system which is a promising mechanism of improving the conditions of water resources in watersheds. For specific case of PES schemes in watersheds, the service usually relates to the maintenance of the availability and/or quality of water. The providers are upstream land users, whose land use is to be modified or conserved to render the service, and the users are downstream consumers – companies or individuals – of the water resources. For PES to have the desired effects they must reach land users in a way that motivates them to change their land use practices to more sustainable ones and for starting, the two management systems i.e. contour farming and 5m width filter strip will provide a beginning for implementation. The contour farming and 5m filter strip has the effect of improving water quality when managed well by upstream land owners.

CHAPTER VI

6.0 CONCLUSIONS

6.1 Conclusions

The most significant part of the study was the assessment of the impact that land use changes have on discharge, in terms of quantifying the results from pre-specified scenarios. The process of building a scenario is the creation of a new digital map of land uses, based on the one that depicts the present state of land cover in the watershed.

- Over the last 30 years that's from 1973 to 2003, there has been spatio-temporal change in landuse within Malewa watershed. These alterations of land-use exert influence on the ecosystem as a whole as they affect water cycle, biodiversity, radiation budgets and many other processes. The categorized landuse consisted of 13.5% forestry, 50.4% agricultural, 0.03% water-bodies, 5.7% moorland, scrubland/rangelands 13.8%, built-up areas, and 2.8% bare lands based on the 2003 Landsat image.
- From the area statistics some major changes of landuse were observed over the study time frame (1973 to 2003). Agricultural areas (small scale intensive farming) area increased from 13.1% on the 1973 MSS image to 23.7% on the 2003 ETM image. Scrubland area increased from 10.8% on early MSS to 13.8% on later TM and ETM images. Agricultural areas (sparse farming) increased from 13.6% on the MSS to 26.7% on the 2003 ETM image. Water body accounted for 3.7% on the MSS 1973, 0.03% on the TM 1987, and 0.03

on the ETM 2003 image. The moorlands decreased from 9.3% in the early MSS image to 5.7% on the later TM and ETM images. Forests slightly changed in the three images 12.0% in 1987, 15.9% in 1987 and 13.5% in 2003 ETM image. Built-up areas markedly increased from 21.1% in the MSS 1973 image to 36.8% in the ETM 2003 image.

~~2~~• Two sub-basins namely Geta and Wanjohi were identified to be suitable for pilot payment for environmental services (PES) implementation. The Geta sub-basin covered an area of 120.6 km^2 and Wanjohi sub-basin covering an area of 111.8 km^2. These subbasins were selected based on the following parameters namely mean annual water yield, mean annual rainfall, population density, poverty density, sediment yield, water conflicts pressures on vegetation and water bodies and recharge/discharge zones.

~~3~~• A key strength of SWAT is its flexible framework that allows the simulation of a wide variety of conservation practices and other BMPs, such as filter strips, conservation tillage, irrigation management, flood prevention structures, grassed waterways, and wetlands. The majority of conservation practices can be simulated in SWAT with straightforward parameter changes. However, assessments of targeted filter strip placements within a watershed are limited, due to the lack of HRU spatial definition in SWAT. For this study, SWAT was found to be adequate in hydrological analysis to simulate different landuse changes and their impacts on the river hydrology.

~~4~~• The best management practices (BMPs) that were simulated in the selected sub-basins were represented in the model by altering corresponding model parameters. Model simulations were performed at various watershed subdivision levels. Comparisons of sediment and nutrient predictions with and without implementation of the BMPs were used to determine the efficiency of the BMPs at each watershed subdivision level. USLE support practice factor (USLE_P) accounts for the impacts of specific support practice on soil loss from a field. Support practices such as contour tillage, strip cropping on the contour, and terrace systems the default value for USLE_P is unity, this value was altered to 0.1, and 0.65 for the HRUs to implement the contour practice. The result shows that Filter strip and contours are effective in reducing the nutrient and sediment pollutant loads. Of the two best management practices simulated, filter strip offers the best alternative for reducing pollutant loads and should be encouraged for adoption by the upper catchment farmers.

5• Filter strips were found to have varying effectiveness at reducing overland flow, sedimentation, and removing nutrients. The hydrologic benefit of riparian buffers increases with width.

In summary, hydrological processes are extremely complex and sometimes counterintuitive. Careful analysis is required if hydrological services are to be properly defined and marketed. Such analysis may yield more specific means of providing hydrological services than an undifferentiated prescription of forest protection or reforestation. For instance, it may be that replanting of denuded slopes can be 'fine-tuned' to maximize water yield while reducing sedimentation, or that maintenance of forest cover near streams has a much higher sediment-reducing effect than in other areas.

~~b.~~6.2 Recommendations & Future Direction

Based on the lessons learned in this study some recommendations including proposed future work are listed below.

~~6~~a) More climatological and hydrological monitoring stations need to be established in Malewa river basin especially in the upstream end for better results in hydrological studies. This is necessary since ground truthing is always needed even with estimations of satellite based rainfall data.

~~7~~b) Future work ought to include estimation of water abstracted from upper catchments of Malewa River basin for the proposed projects. Although this was not part of the study it was noted that many sectors are competing for the limited amount of water available in Malewa River basin. Apparently potentials of such planned abstractions are not known. Agriculture being the main user (expansion of irrigated agriculture) can perhaps be one of the causes of reduced flows downstream with previous research showing a cone of depression in the middle catchment, this is vital for balancing water use in various sectors and avoiding conflicts between downstream and upstream water users.

~~8~~c) There is a need to develop regulations and monitoring points for the Total Maximum Daily Load (TMDL) program and to identify impaired water bodies within the Malewa watershed, and develop abatement strategies for the impairment(s) of concern. Implementation of TMDL program is pivotal in securing the nation's water quality goals and should be the target of management and decision making in watershed systems.

~~9~~d) The implementation of filter strip of minimum width 5m or more planted with fodder shrubs such as calliandra will go a long way in reducing water quality problems within the upper catchment. It is one of the most viable options for quick adoption as best management practices. Steeper slopes of the catchment calls for combined implementation of contour farming and buffer filter strips.

~~10~~e) Successful development of the Total Maximum Daily Load program will depend to a large extent on the ability of managers and analysts to understand the transport and fate of contaminants within watersheds, and to evaluate the outcome (s) of a certain management action on water quality of the system. Modeling proves to be a useful tool for such purposes. Simulation models not only facilitate contemplating the future of a given system under various management scenarios, but can also be used to examine whether a certain future state is attainable for the system.

CHAPTER VII

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APPENDICES

2 APPENDIX 1: Water Quality Procedures

Total Suspended Solids Dried At 103-105^{0}c

The principle of total suspended solids is as follows. A well mixed sample is filtered through a weighed standard glass-fiber filter and the residue retained on the filter is dried to a constant weight at 103-105^{0}C. Increase in weight of the filter represents the total suspended solids. If the suspended material clogs the filter and prolongs filtration, the difference between the total solids and the total dissolved solids may provide an estimate of the total suspended solids. Exclude large floating particles or submerged agglomerates of non homogeneous materials from the sample if it is determined that their inclusion is not desired in the final result. The following apparatus are needed for total suspended solids; Aluminum weighing dishes, Suction filtering apparatus 103-105^{0}C drying oven.

Procedure for carrying total suspended solids is as follows.

1. Put a glass-fiber filter paper in an aluminum dish and put in the oven to dry (103-105^{0}C) for 1 hour.
2. Cool in a desiccator to balance temperature and weigh.
3. Assemble the filtering apparatus and filter paper.
4. Shake the sample and take an appropriate volume of sample, about 200 ml.
5. Put in the filtering apparatus and begin suction. Allow complete drainage of the water.
6. Carefully remove filter from filtration apparatus and transfer to an aluminum weighing dish as a support.

7. Put the filter paper and the dish in the oven and dry for 24 hours at 103-105^{0}C to achieve a constant weight. Cool in a desiccator to balance temperature and weigh.

Calculation was performed as described below.

$$Mg/_L\,(total\ suspended\ solids) = \frac{(A-B)*1000}{Sample\ volume\ (ml)} \qquad \text{Equation 5}$$

Where:

A = weight of filter + dried residue, mg

B = weight of filter, mg.

Nitrates

Reagents needed were, Palintest nitratest powder, Palintest nitrate tablet, and Palintest nitricol tablet. The apparatus included Photometer, and Test tubes. Operating instructions for the photometer were as follows: Select the required wavelength. Place blank tube in the test chamber, Press ON button, Keep depressed until display reads 100%T, Release ON button, Remove blank tube, Place sample tube in test chamber, Note displayed %T reading, and Compare reading against appropriate calibration chart.

The following Procedures were adopted.

a) Put 20 ml of sample into a test tube.

b) Add a spoon pack of palintest nitratest powder.

c) Add 1 palintest nitrate tablet.

d) Shake for a minute and leave to stand.

e) Decant 10 ml into a test tube.

f) Add 1 tablet of palintest nitricol tablet.

g) Crush and mix to dissolve.

h) Leave to stand for 10 minutes.

i) Take the test reading from the photometer at 570nm.

Total Phosphorus: Ascorbic Acid method

Principle:

Ammonium molybdate solution and potassium antimonyl tatrate solution react in acid medium with orthophosphate to form a heteropoly acid-phosphomolybdic acid-that is reduced to intensely colored molybdenum blue by ascorbic acid.

Apparatus:

a) Spectrophotometer with infrared phototube for use at 880nm, providing a light path of 2.5cm or longer.

b) Beakers

Reagents:

a) Sulphuric acid H_2SO_4, 5N:

Dilute 70 ml conc. H_2SO_4 to 500ml with distilled water.

b) Potassium antimonyl tatrate solution:

Dissolve 1.3715g K (SbO) $C_4H_4O_6.\frac{1}{2}H_2O$ in 400 ml distilled water in 500 ml volumetric flask and dilute to volume.

Store in a glass stoppered bottle.

c) Ammonium molybdate solution:

Dissolve 20g $(NH_4)_6Mo_7O_{24}.4H_2O$ in 500 ml distilled water.

Store in a glass stoppered bottle.

d) Ascorbic acid, 0.1M:

Dissolve 1.76g Ascorbic acid in 100 ml distilled water.

The solution is stable for about 1 week at 4^0C.

e) Combined reagent:

Mix the above reagents in the following proportions for 100 ml of the combined reagent:

-50 ml 5N H_2SO_4

~~1.~~a) 5 ml potassium antimonyl tatrate solution

~~2.~~b)15 ml ammonium molybdate solution

~~3.~~c) 30 ml Ascorbic acid solution.

Mix after addition of each reagent. Let all reagents reach room temperature before they are mixed. Mix in the order given

f) Stock phosphate solution:

Dissolve in distilled water 219.5 mg anhydrous KH_2PO_4 and dilute to 1000 ml;

1.0ml= 50µg PO_4^{3-} P.

g) Standard phosphate solution:

Dilute 50.0 ml stock phosphate solution to 1000 ml with distilled water.

1.0ml = 2.5µg P.

Procedure

a) Treatment of sample

Pipette 50.0 ml sample into a clean dry test tube or 125-ml Erlenmeyer flask. Add 0.5 ml (1 drop) phenolphthalein indicator. If a red colour develops, add 5N H_2SO_4 solution drop wise to discharge the colour.

Add 8.0 ml combined reagent and mix thoroughly.

After at least 10 minutes and not later than 30 minutes, measure absorbance of each sample at 880nm, using reagent blank (distilled water) as the reference solution.

b) Correction for turbidity or interfering color:: Natural colour of water generally does not interfere at the high wavelength used. For highly colored or turbid waters, prepare a blank by adding all reagents except ascorbic acid and potassium antimonyl tatrate to the sample.

Subtract blank absorbance from absorbance of each sample.

c) Preparation of calibration curve: Prepare individual calibration curves from a series of four standards within the phosphate ranges shown in the table below:

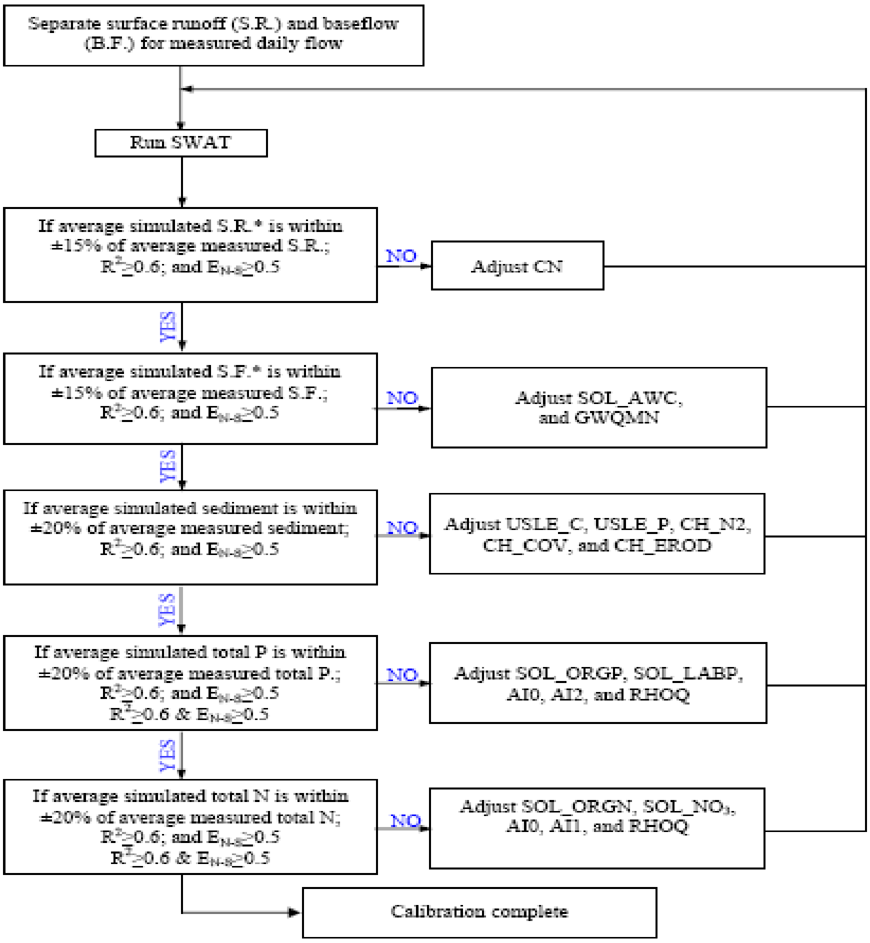
Standard Phosphate solution (ml)	Concentration (mg P)
1/50	2.5
5/50	12.5
10/50	25.0
20/50	50.0

Use a distilled water blank with the combined reagent to make photometric readings for the calibration curve. A plot of absorbance versus Phosphate concentration was done to give a straight line passing through the origin. Test at least one Phosphate standard with each set of samples.

Calculation:

$$\frac{mgP}{L} = \frac{mg\ P\,(in\ approximately\ 58\ ml\ final\ volume) * 1000}{ml\ Sample}$$ **Equation 6**

~~15~~43 APPENDIX 2: Calibration Flowchart



- S.R.: surface runoff, S.F.: streamflow, and B.F,; baseflow

Calibration Flowchart (Adapted from Santhi *et al.*, 2001b)

~~1.~~4 APPENDIX 3: Detailed LANDUSE/SOIL distribution

SWAT model class for scenario1 (25% cabbage, carrot, onions and potatoes**)**

	Area [ha]	**Area [acres]**	
Watershed	162481	401498.6	
LANDUSE	**Area [ha]**	**Area [acres]**	**%Wat.Area**
Cabbage --> CABG			
Range-Brush --> RNGB	19075.42	47136.32	11.74
Range-Grasses --> RNGE	13872.35	34279.28	8.54
Commercial --> UCOM	323.6278	799.7005	0.2
Forest-Evergreen --> FRSE	378.716	935.8261	0.23
Potato --> POTA	21561.7	53280.05	13.27
Forest-Mixed --> FRST	19075.42	47136.32	11.74
Agricultural Land-Row Crops --> AGRR	3208.832	7929.184	1.97
Carrot --> CRRT	46834.03	115729.2	28.82
Onion --> ONIO	19075.42	47136.32	11.74
	19075.42	47136.32	11.74
SOIL			
Ach			
HSs	13104.74	32382.47	8.07
PLe	12109.26	29922.6	7.45
VRe	66522.7	164380.9	40.94
SCg	25813.54	63786.56	15.89
NTr	109.7141	271.109	0.07
NTu	1284.183	3173.28	0.79
ANm	20542.4	50761.29	12.64
PHh	6342.119	15671.69	3.9
LVf	10532.01	26025.11	6.48
	6120.282	15123.52	3.77

~~2.~~5 APPENDIX 4: Available streamflow data

Station ID	Name	Data Available	Missing data	Totat data	%Missing
2GB01	Malewa-gilgil	1/1/1932-12/31/1985	1359	19721	6.89
2GC04	Turasha	1/2/1981-5/31/1999	941	6724	13.99
2GB05	MalewaI	1/1/1981-12/31/1987	231	2556	9.04
2GB03	Malewa	9/5/1959-12/31/1992	1183	12172	9.72
2GB04	Wanjohi	9/3/1961-1/3/1994	2393	12017	19.91
2GB07	MalewaI	5/20/1959--7/30/1994	1014	12856	7.89
2GA03		1/1/1981-12/31/1998	1103	6421	17.18
2GA05	Gilgil		204	2535	8.05
2GA06	Little Gilgil	1/1/1981-12/31/1990	568	3652	15.55
2GC05	Nandarashi	1/1/1981-8/31/2000	558	7183	7.77
2GC07		1/1/1981-8/31/2000	876	7183	12.20
2GA02	TurashaI				

~~3.~~6 APPENDIX 5: Temperature equations

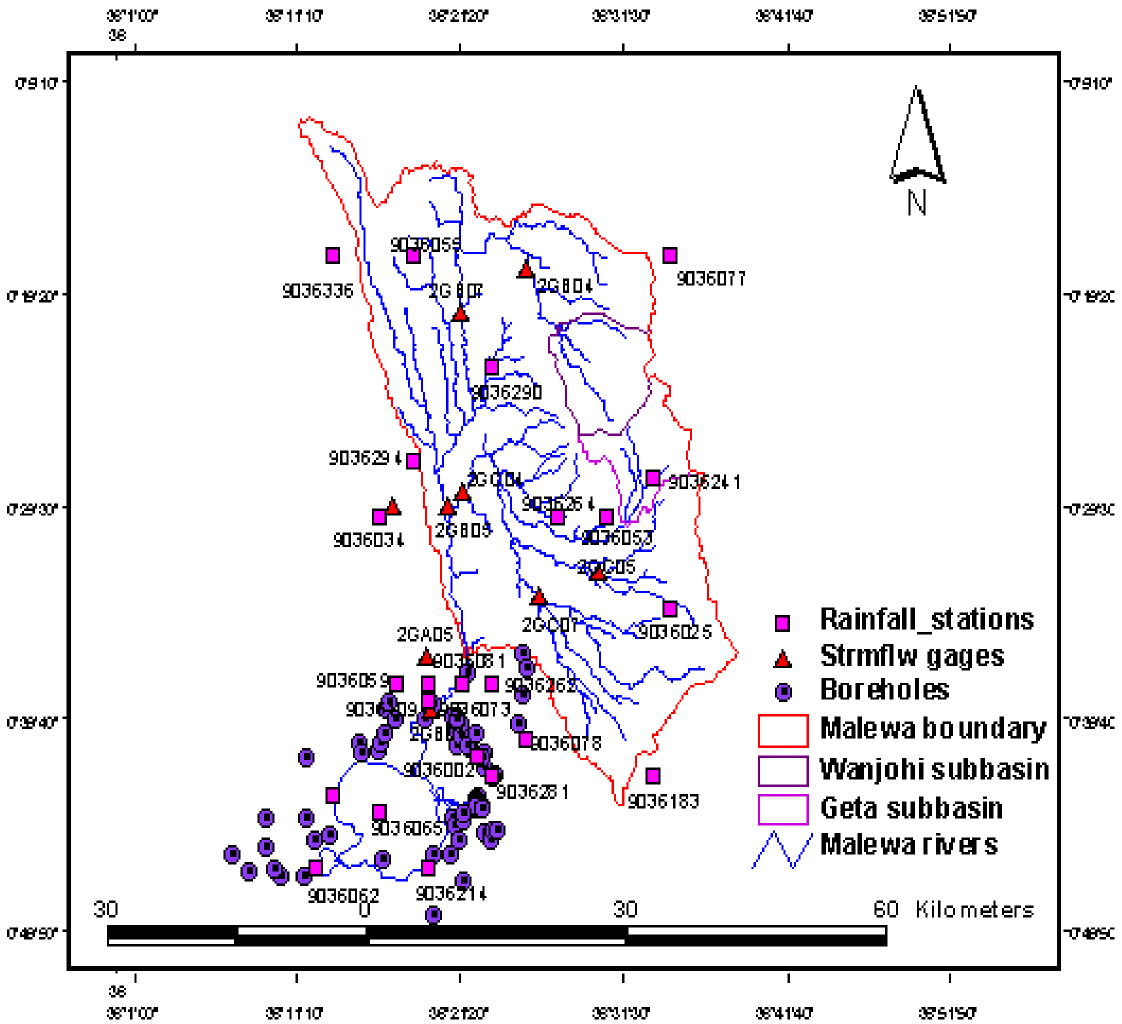
Regression equation for estimating the monthly mean, maximum, minimum and average temperature in (^{0}C) from the altitude in meters (m).

	Mean Maximum	Mean Minimum	Average
Jan	36.7-0.00571X	25.0-0.00745X	30.8-0.00659X
Feb	37.4-0.00577X	25.8-0.00761X	31.6-0.00669X
Mar	37.6-0.00577X	26.3-0.00755X	31.9-0.00666X
Apr	35.8-0.00574X	26.1-0.00705X	30.9-0.00643X
May	34.6-0.00587X	25.1-0.00682X	29.9-0.00633X
Jun	33.9-0.00584X	23.8-0.00666X	28.9-0.00627X
Jul	33.5-0.00600X	22.8-0.00636X	28.2-0.00617X
Aug	33.7-0.00610X	23.8-0.00646X	28.5-0.00627X
Sep	35.4-0.00604X	24.1-0.00705X	29.7-0.00653X
Oct	36.4-0.00614X	24.8-0.00712X	30.6-0.00663X
Nov	36.2-0.00643X	25.2-0.00709X	30.7-0.00676X
Dec	35.5-0.00594X	25.1-0.00725X	30.3-0.00656X

~~4.~~7 APPENDIX 6: Decomposition of conflicts into components and indicators used to spatially present the components. (Source Fayos, B.C., 2002)

Conflict number	Conflicts	Components of the conflicts according to the interviews	Spatial indictor of the component and source
1	North Kinangop farmers vs. farmers middle catchment	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
		Bad infrastructure	Roads in bad condition
2	South Kinangop farmers vs. small Malewa farmers	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
3	North/South Kinangop farmers vs.. big farmers downstream	Upper catchment destruction (Kinangop)	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
		Water Pollution of the rivers	Malewa and Gilgil rivers and main subsidiaries (Drainage map of the ITC Naivasha data base and sampling for river pollution from Munoz Villers,2002)
		Bad infrastructure	Roads in bad condition
4	Small Malewa farmers versus big farmers downstream	Water extraction from the rivers	Malewa and Gilgil rivers and main subsidiaries (Drainage map of the ITC Naivasha data base Fayos, B.C.,2002)
		Water Pollution of the rivers	Sampling points for river pollution Munoz Villers (2002)
5	Mixed cattle/agriculture versus large commercial farms	Land utilization	Water consumption by farmers (Pereira, 2002)
6	Farmers versus Fishermen	Water pollution of the lake	Point pollution sources from Munoz Villers (2002) and area of non point source pollution (information from Mulot Villers Fayos, B.C., 2002)
		Water Extraction from the lake	Water consumption by farmers (Pereira, 2002)
7	Fishermen department Versus Poachers	Fishing methods	Lake map (Fayos, B.C., 2002 elaboration from water bodies map from ITC Naivasha data base)
		Economic alternatives for fishermen	
8	Fisheries Department versus Poachers	Illegal fisheries	Lake map (Fayos, B.C., 2002 elaboration from water bodies map from ITC Naivasha data base)
		Cutting papyearus	Area of *Cyperus papyearus* 2001 from Mena (2002)
		Fishing methods	Lake map (Fayos, B.C., 2002 elaboration from water bodies map from ITC Naivasha data base)
9	Friends of Eburru Forest versus Eburru Forest users	Destruction of Eburru forest	Forest disappeared after 1961 (forest cover according to Carey Jones, 1965 and Fayos Boix, 2002)
10	KPC vs. Eburru settlement	Water supply Eburru	Eburru settlement (elaboration by Fayos, B.C., 2002)
11	IBECA versus LNRA	Water pollution of the lake	Point pollution sources from Munoz Villers (2002) and area of non point source pollution (information from Mulot Villers Fayos, B.C., 2002)
12	Water supply GETA project	Water supply GETA project	GETA settlement (own elaboration)
13	Nakuru water project	Nakuru water project	Nakuru settlement (own elaboration)
14	Longonot dry area	Longonot dry areas	Longonot dry areas (elaboration of Rainfall and land cover map of ITC Naivasha database by Fayos, B.C., 2002)
15	Water supply Kongoni-Maela project	Water supply Kongoni-Maela	Maela settlement (elaboration by Fayos, B.C., 2002)
	Water quality	Water Quality	
	Maasai water access	Maasai water access	Public corridors (Mena, 2002)
16	Water supply Naivasha	Water supply Naivasha	Naivasha town (Mena, 2002)
	Sewage system	Sewage system	Point pollution sources from Munoz Villers (2002)
	GETA project	GETA project	GETA settlement (own elaboration)

~~5.~~8 APPENDIX 7: Location of Streamflow gages and Rainfall station gages



~~6.~~9 Appendix 8: Photograph gallery from the study area

Aerial photo of part of settled forest areas near Kipipiri

Cultivation on steep slopes (GETA)

Mixed small scale Intensive farm (GETA)

Small intensive farming (carrot)

Burnt vegetation

Mutarakwa Forest station

Small intensive farming (N Kinangop)

Small intensive farming (N Kinangop)

Non working weather station (Naivasha water bailiff) Turasha

Vandalized automatic gauging station


Turasha treatment works (Downstream)


Turasha intake point (Upstream of Turasha River)


Turasha intake point


Turasha Treatment works


Turasha gauging station


Malewa gauging station


Upper Malewa Treatment works


Upper Malewa River Intake point


Pasture land (Game North)


Small intensive farming (onions) Kangogo Centre