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

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Abstract

This paper investigates the hydrological effects of specific land use changes in Malewa catchment through the application of the Soil and Water Assessment Tool (SWAT) as a basis for implementing PES on a daily time step. The model's calibration efficiency is verified by comparing the simulated and observed discharge time series at the outlet of the watershed, where long series of hydrometrical data exist. The model is used to simulate the main components of the hydrologic cycle, in order to study the effects of land use changes. The model was calibrated and validated for the prediction of flow. 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 daily and monthly flows. Water quality parameters (sediment, nitrogen and phosphorous loadings) were not available hence were not calibrated but the model default values were used after calibrating the flow data. At the main gauging station 2GB01; monthly calibration resulted in model prediction average flow within 19% of the measured average flow while the monthly Nash-Sutcliffe (ENS) measure was 0.58. Monthly validation results for 2GC05 and 2GB07 showed the model predicted average flow within 20% of the measured average flow with ENS of 0.58 and 0.61 respectively. Once the model was calibrated for flow, it was used to run scenario analyses for the selected target areas for PES implementation. A criterion was developed based on several parameters to select the target areas for PES implementation. Some of these parameters included annual rainfall, water yield, population density, water conflicts, and pressures on vegetation and water bodies. Based on the mentioned parameters, two areas were identified to be suitable for PES implementation. The two areas are within the upper catchment near GETA and Wanjohi areas. Four land-use scenarios were simulated in the selected headwater sub-basin areas to assess the impact of landuse change on Malewa hydrological regime. The deforestation scenario was the one that resulted in the greatest modification of total monthly runoff.

Key words: Hydrologic models, Soil and Water Assessment Tool, land use changes and PES

1.0 Introduction

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 a 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. This calls for the need of a careful assessment and monitoring of land-water relations for the implementation of 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, e.g., 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. 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).

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

1.2 Overview of the Study Area

Malewa basin lies between the two flanks of the Eastern or Gregory Rift Valley, with the Aberdares Mountains and Kinangop plateau on the east and the Mau Escarpment on the west. The Malewa basin is situated in the central Rift Valley, Naivasha District in Kenya about 100 km northwest from Nairobi (Figure 1). Its geographical position 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.

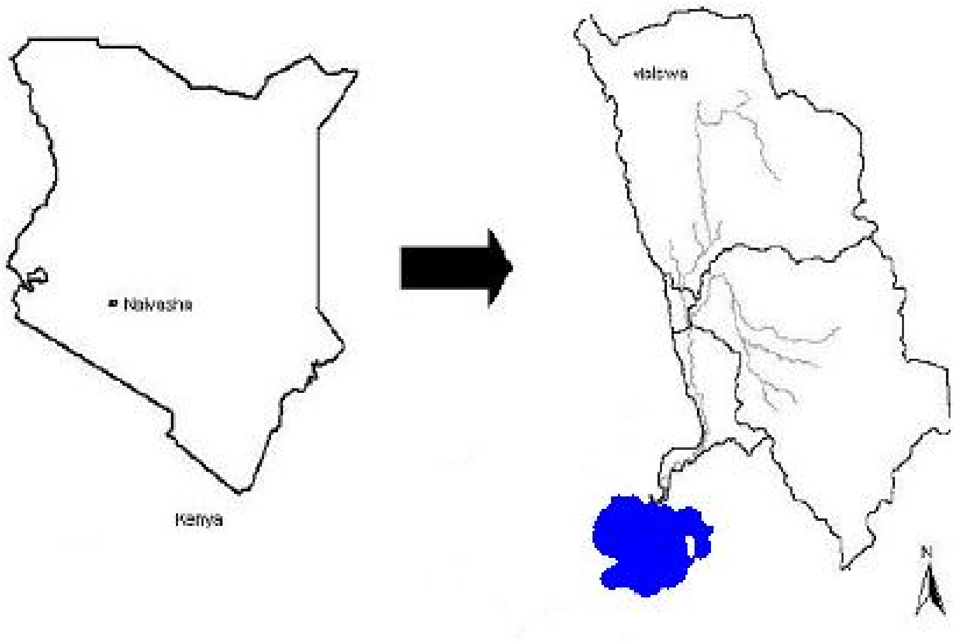
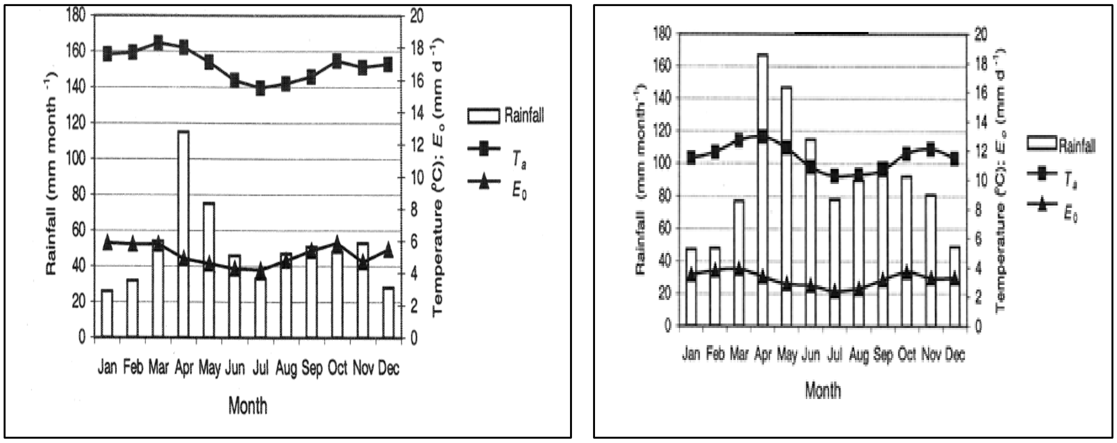


Figure 1: Map of the study area (Lake Naivasha-Malewa basin)

1.2.1 Climate

The Malewa basin belongs to a semi-arid type of climate. The rainfall distribution has a bimodal character (Figure 2). The long term spatial distribution of rain varies from 600mm at Naivasha town to 1700mm at the slopes of the Nyandarua Mountains the Kinangop plateau experiences a yearly rainfall from 1000mm and 1300mm (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 basin humid areas, rainfall exceeds potential evaporation in most parts of the year (Farah, 2001). The annual temperature range is approximately from 8^0C to 30^0C.



(Source: Farah, 2000)

Figure 2: Monthly average rainfall, average daily temperature (1931-1983) and average daily reference E_o (1974-1983) at Naivasha town at altitude 1906 m and at North Kinangop at 2620 m

1.2.2 Vegetation

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

(i) Forest,

(ii) Scrub/Bush-land/native,
(iii) Bare/range brush/moorland,
(iv) Grassland/scrubland, and
(v) 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).

1.2.3 Soils

The soils in Malewa basin can be described as complex due to the influence of extensive relief variation, volcanic activity and underlying bedrocks (Sombroek *et al,* 1980). Based on studies conducted in the area (Sombroek *et al.,* 1980, Siderius, 1998; Atkilt, 2001; and Nagelhout, 2001) soils can be grouped into three (3) groups such as; 1) soils developed from lacustrine deposits; 2) volcanic; and 3) lacustrine-volcanic. These soils are highly susceptible to both erosion and compaction (Kiai and Mailu, 1998). Prominent soil degradations in the area are due to wind and water erosion, sealing and compaction (Nagelhout, 2001). 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 can be classified into 10 different soil categories based on the FAO classification (Figure 3).

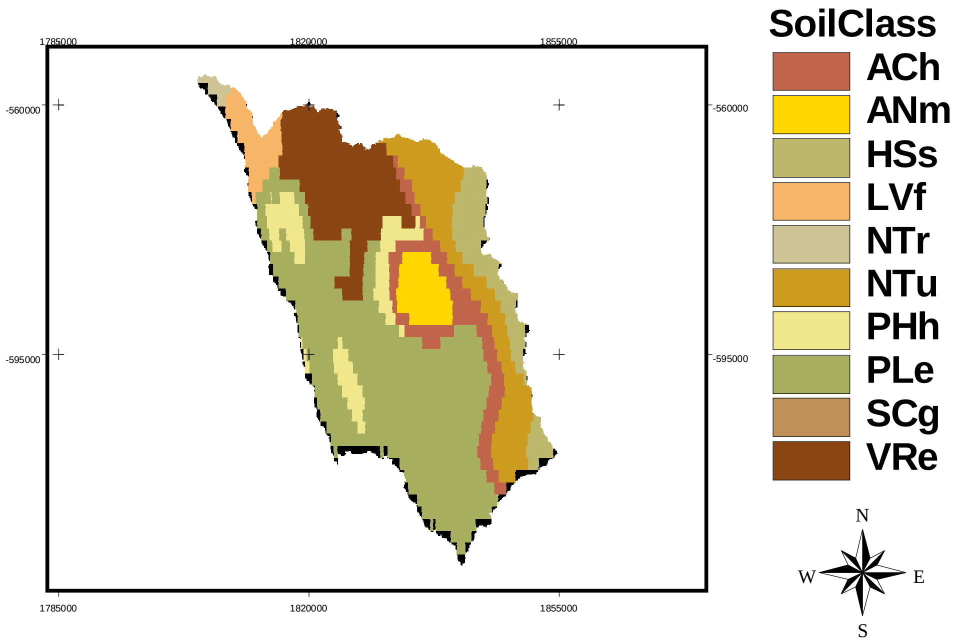


Figure 3: Soil distribution in study area

1.2.4 The Drainage Networks

The Malewa River Basin, including the Turasha 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 starts among the steep forested eastern slopes from the Kinangop plateau (2483m a.m.s.l.) and the Aberdares (3960+m a.m.s.l.) where the average annual rainfall is 1087.5mm (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, develops into four main tributaries namely, Mugutyu, Turasha, Kitiri, and Mukungi. All flow north-south before turning west and joining the River Malewa. River Turasha is the most important tributary and joins the Malewa approximately 8km 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.

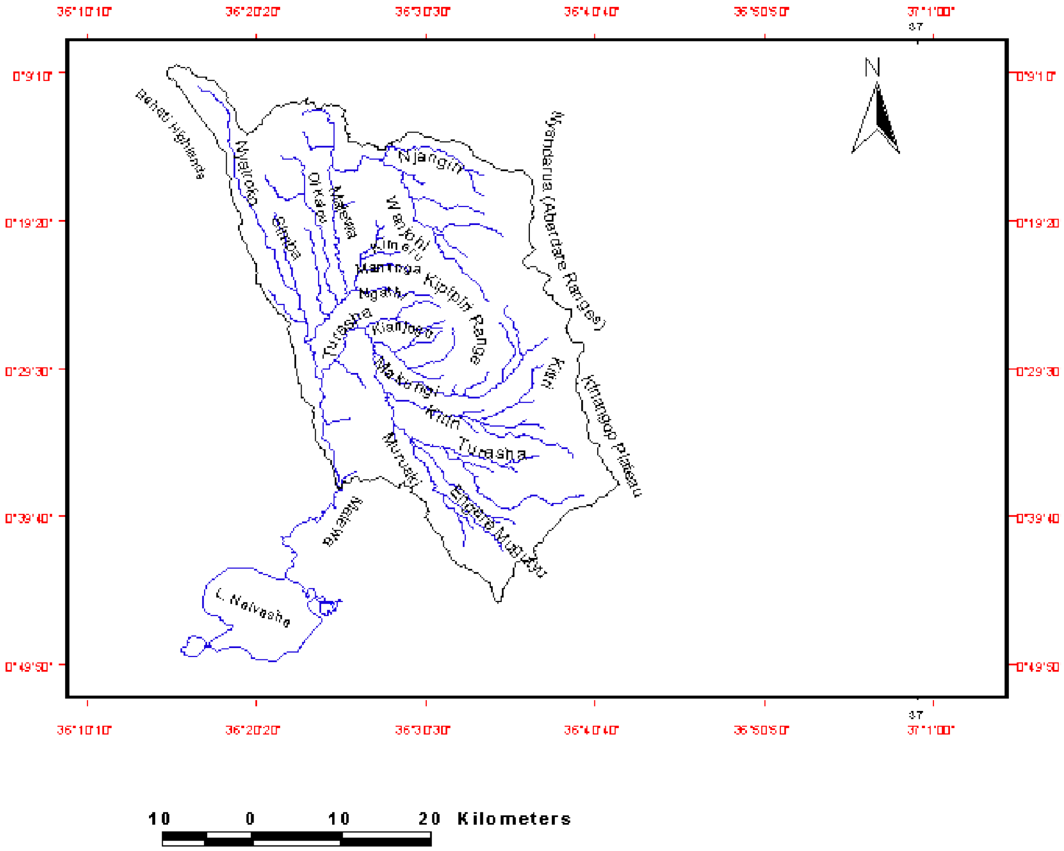


Figure 4: The Drainage Pattern of Malewa Watershed

1.2.5 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 the rift margin and rift floor plain (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. It is abroad 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. Gorges of depths 61 and 122 m have been formed along the northern edge of the area. 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 (Figure 5).

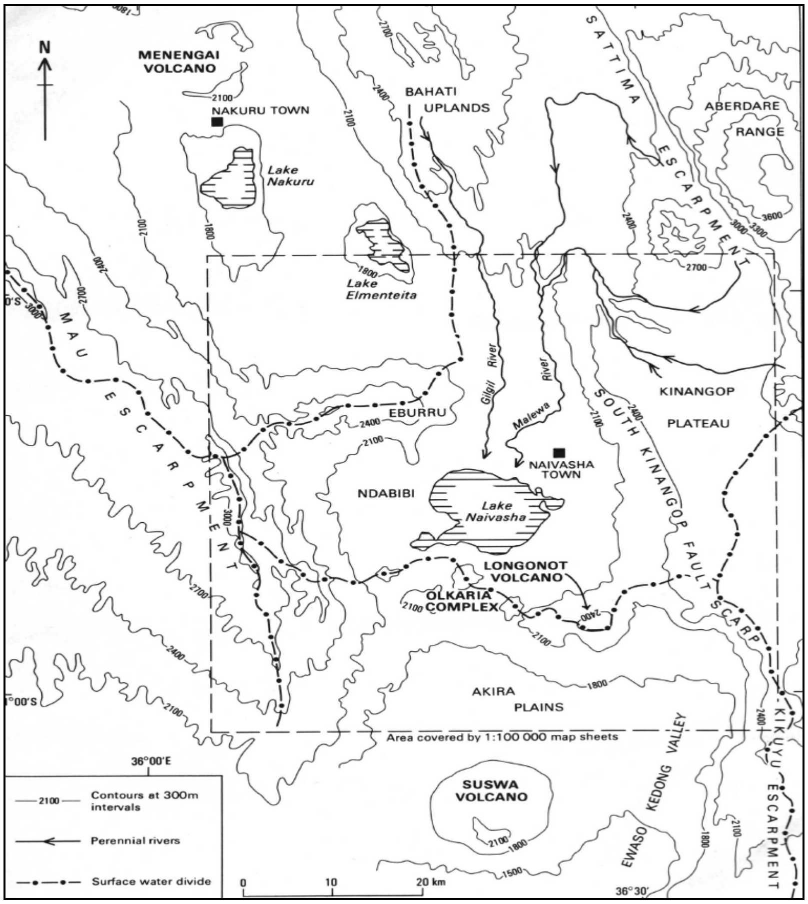


Figure 5: Detailed Physiographic Map of the Lake Naivasha Basin (Adopted after Clarke et al. 1990)

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 Elementaita 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 dominates the Naivasha basin. The lake covers an area of approximately 145 Km^2 and stands at an elevation of 1882.4 m amsl (October 1997). The lake is smooth floored and has a mean depth of 4.7 m (Graham, 1998).

1.2.6 Hydrogeologic Setting

The hydrogeology of Lake Naivasha has been described as complex by Clarke (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.

(i) The Lake Naivasha subsurface seepage and the cold shallow groundwater system.
(ii) The hot highly mineralized deep geothermal systems.

Piezometric plots and isotopic studies 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.

The effect of faulting is to cause groundwater flows from the sides of the rift towards the center to follow longer paths reaching greater depths, and to align flows within the rift along its axis. N-S rift floor faults and fractures control axial groundwater flow through the geothermal system, but this has a shallower influence than the major rift forming faults that provide deep recharge to the geothermal system.

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.

(i) 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.
(ii) The transit zone covers all that area between 2,400 and 2,100 m amsl;
(iii) 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 is underlain by Limuru Trachyte and is thickly forested in the natural state. It provides baseflow generation in streams and rivers and deep percolation to aquifers, almost certainly fault-controlled. Faults are the dominant recharge feature in these areas.

The transit zone lies between the recharge zone (at high elevations) and the discharge zone; this encompasses the areas underlain by step-faults dropping into the basal part of the basin. 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 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. Actual depths and thickness vary across the basal area.

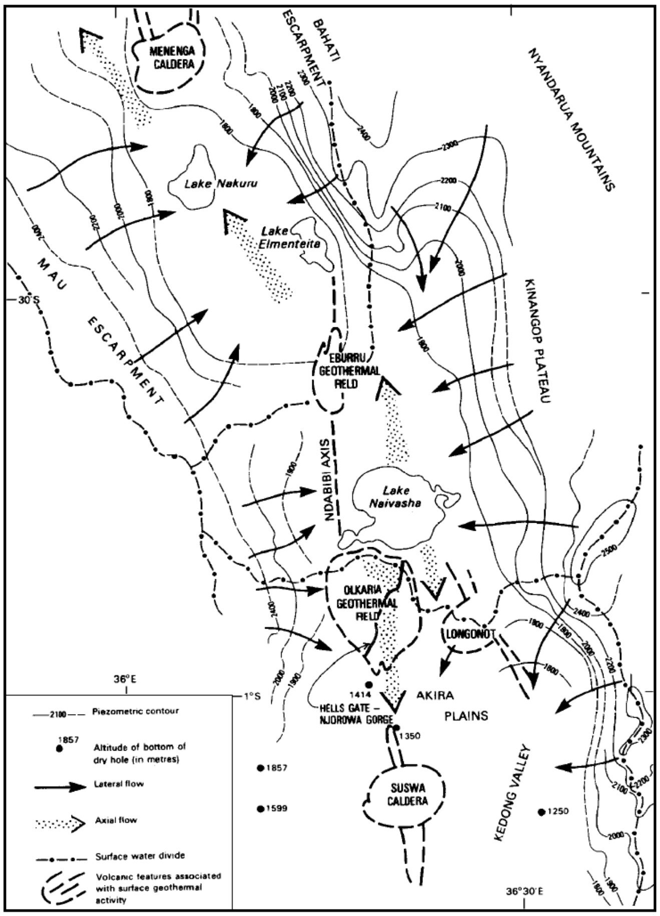


Figure 6: Piezometric Map of Lake Naivasha and Vicinities (Taken from Clarke (1990)

2.0 Methods and Analysis

2.1 Hydrologic Model

The Soil and Water Assessment Tool is a river basin model that was developed for the USDA Agricultural Research Service, by Blackland Research Center in Texas (http://www.brc.tamus.edu/blackland/

The SWAT model is a widely known tool that has been used in several cases world-wide. SWAT has the ability to predict the impact of land management practices on water, sediment yield and agricultural chemical yield in large complex watersheds (Neitsch *et al*., 2002). The present study focuses only on the hydrological component of the model. SWAT is a physical based model. The model takes into account such data as climate, soil properties, topography, land cover and management, and produces outputs with the use of common hydrological equations. Apart from the ability to take into account land use and soil data, SWAT differs from other physical models in its ability to separate the watershed into sub-basins and Hydrologic Response Units (HRUs). The main basin is divided into smaller ones, by selecting points on the stream network that act as outlets. In this way, the model can provide output data, such as discharge, at specific points of the river network. Figure 7 presents a diagram of the SWAT process.

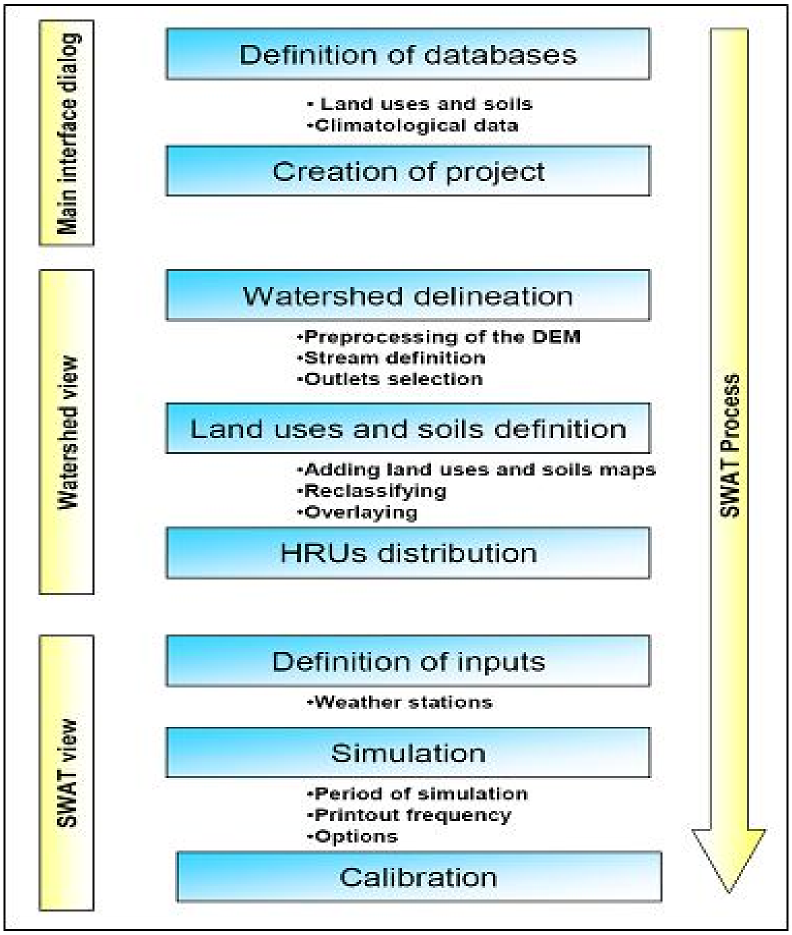


Figure 7: Representation of the SWAT model process

2.2 Input Data

Available data that were used for modeling are depicted in Table 1.

Table 1: 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

2.3 Modeling Process

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 3.2 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 2: 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, i.e., Summary output file; HRU output file; sub-basin output file and main channel/reach output file.

2.3.1 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.

Table 3 show amongst many SWAT parameters that are adjusted during sensitivity analysis process.

Table 3.3: SWAT Parameters

	Parameter	Description	Min	Max	Units	SWAT t 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				

2.3.2 Model Calibration

Calibration of a watershed model is essentially the exercise of adjusting model parameters such that model as described by Beck *et al*. (1997):

(i) Soundness of mathematical representation of processes,
(ii) sufficient correspondence between model outputs and observations, and
(iii) Fulfillment of the designated task.

Model calibration is the exercise of adjusting model parameters manually or automatically for the system of interest until model outputs adequately match the observed data. The credibility of model simulations is further evaluated by investigating whether model predictions are satisfactory on different data sets. Calibration was done through the automatic calibration tool in AVSWAT2005. Procedure provided by (Santhi *et al*., 2001b) was followed. The calibration tool consists of three sub-tools, i.e.,AVSWATX extension; landuse-Land cover splitting tool; SSURGO data Tools; AVSWATX Sens-Auto-Unc; sensitivity analysis and 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.

2.3.3 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.

2.3.4 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:

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

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 are 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).

2.3.5 Criterion for 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.

2.3.6 Scenario Analysis

The following scenarios (Table 4) were adopted on the two selected priority areas:

Table 4: 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. 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 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.

3.0 Results and Discussions

3.1 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 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: 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 8 illustrates the parameters plotted with the least value showing the most sensitivity parameter.

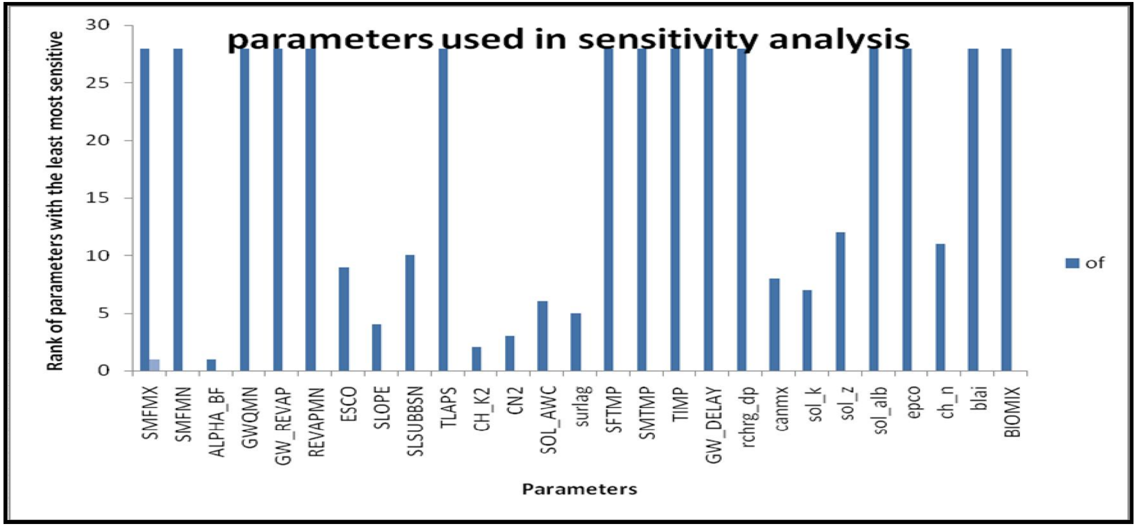


Figure 8: A plot of the SWAT parameters used in sensitivity analysis.

From the sensitivity analysis (Figure 5.8), the following parameters shown in Table 6 were selected for calibration.

Table 6: 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		-50%-50%		2.392

		conductivity (mm/hr)				
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.

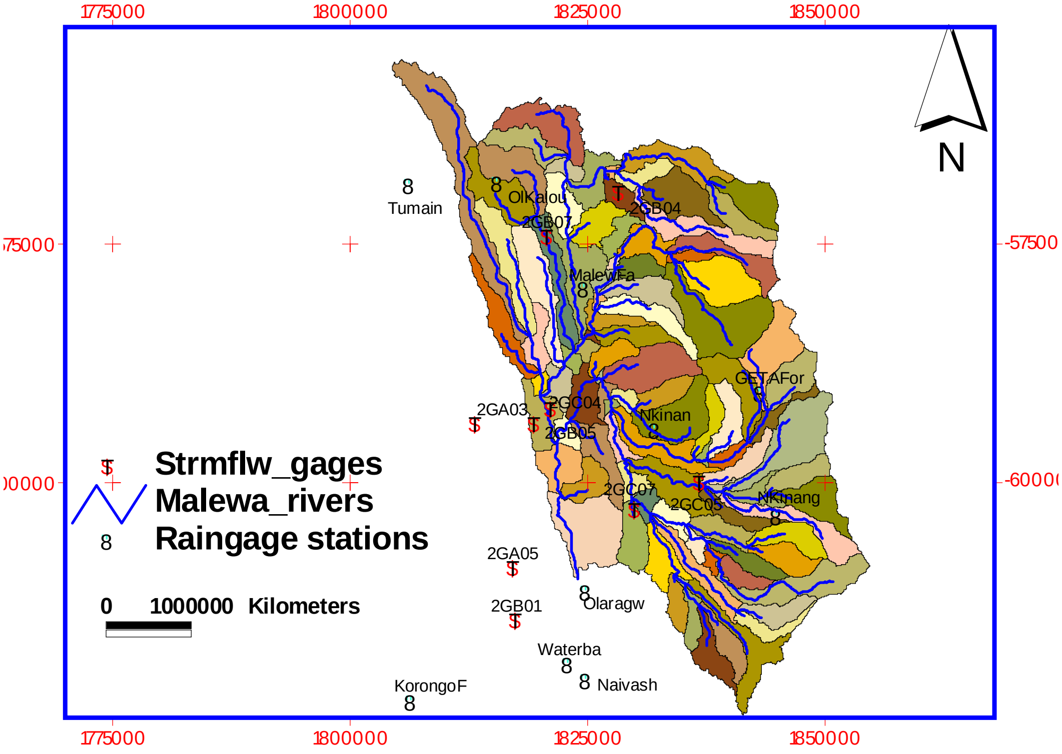


Figure 9: Subbasins and gauging stations of Malewa Watershed

Figure 9: Results of calibration at Kitiri gauging station 2GC05 at sub-basin 72 outlet.

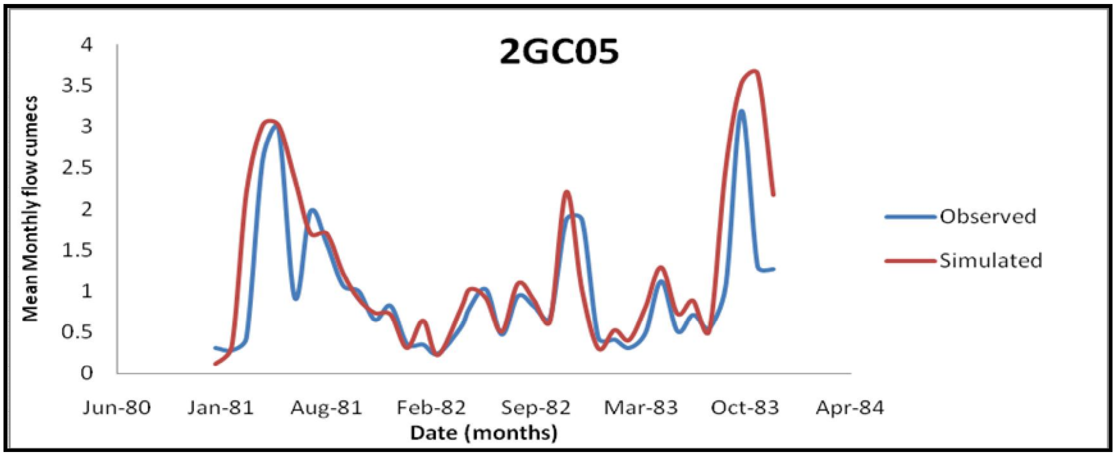


Figure 10: Stream flow calibration results at 2GC05

The next upstream gauging station calibrated was 2GB07. Figure 11 shows the calibration results at Upper Malewa station near Ndemi Bridge (station GB07 near the outlet of sub-basin 15).

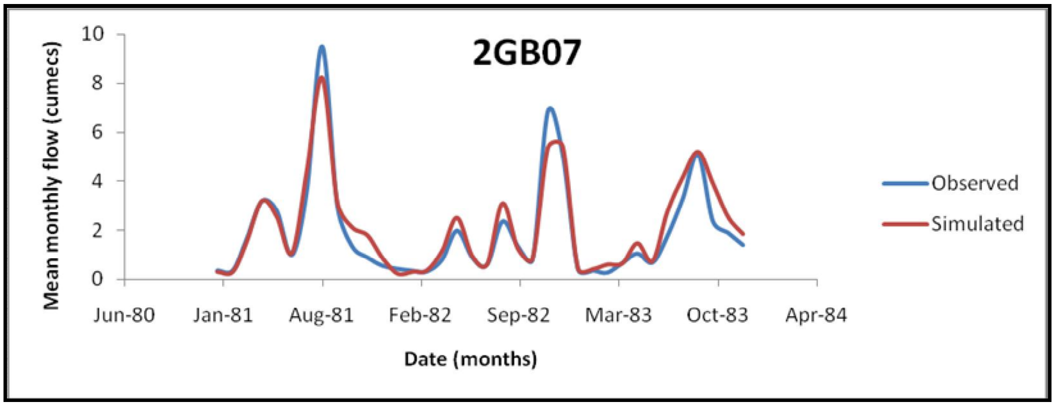


Figure 11: Calibrated streamflow for gage 2GB07

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 12.

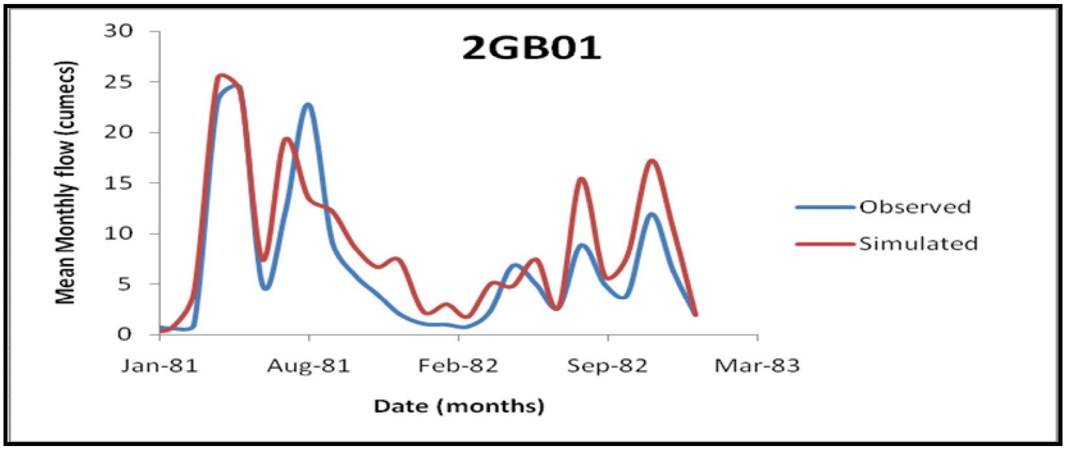


Figure 12: Calibrated streamflow for gage 2GB01

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 12, 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 7).

Table 7: 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

$$SW_t = SW + \sum_{i=1}^{t}[R_t - Q_t - ET_t - P_t - QR_t] \quad \text{……………………………………………………………………(3)}$$

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
    - 15 mm of surface runoff (2.5% of water yield) (Q)
    - 368 mm of lateral flow (61.1% of water yield) (QR)
    - 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.

3.2 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 8 shows the model performance over this period.

Table 8: 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.

3.3 Selection of Priority area for Implementation of PES

3.3.1 Criterion for Priority Area Selection

The priority area for implementing pilot PES was selected based on the following parameters (Table 9):

Table 9: 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.	Rainfall amount	Select areas with highest Rainfall and must be within the upper catchment
2.	Water yield	Select areas with highest water yields and must be within the upper catchment
3.	Groundwater Recharge and discharge zones	Select areas with highest groundwater recharges and low discharge and must be within the upper catchment
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.	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.	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.	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 13). 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.

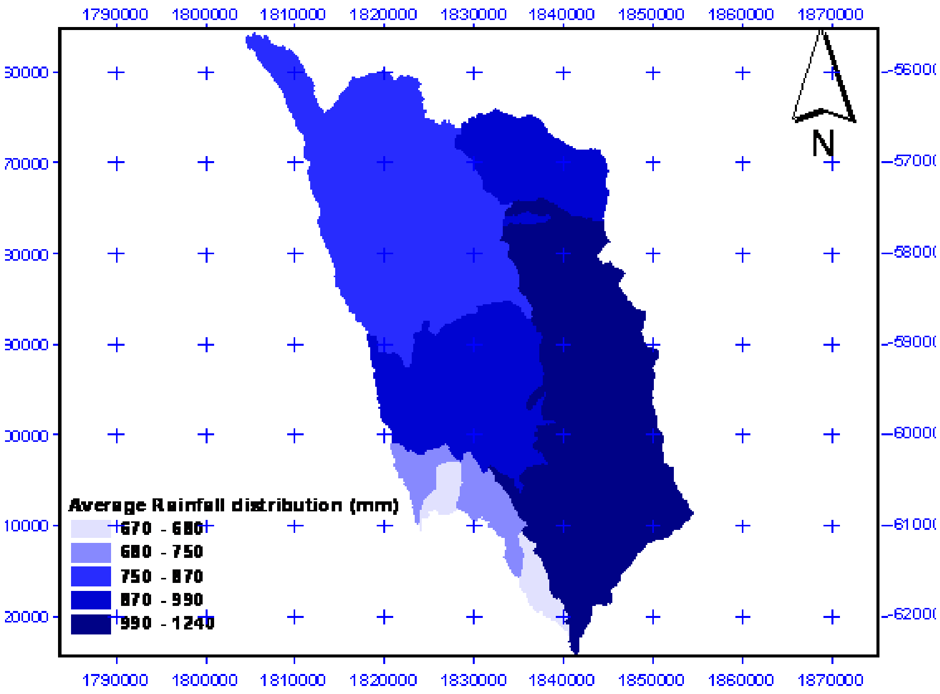


Figure 13: Yearly Rainfall distribution (1972-2003) for Malewa Watershed

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 14).

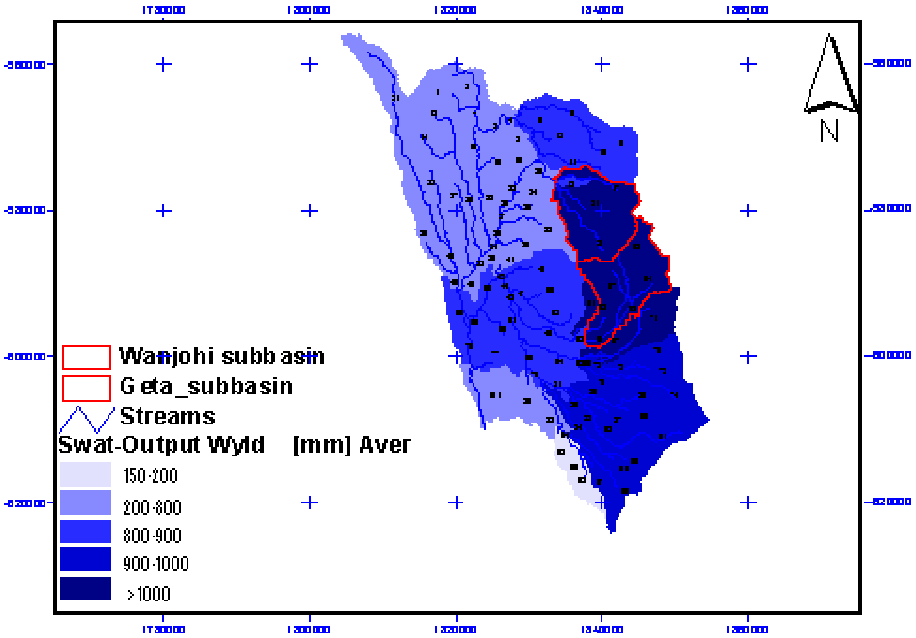


Figure 14: Mean Annual Water yield distribution for Malewa Watershed

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 15, 16 and 17). 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 15) 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 16 and 17) are forced into more and more borderlands lands. Figure 15 shows poverty gap (Percentage gap to bridge for the poor to reach the poverty line) within the Malewa catchment.

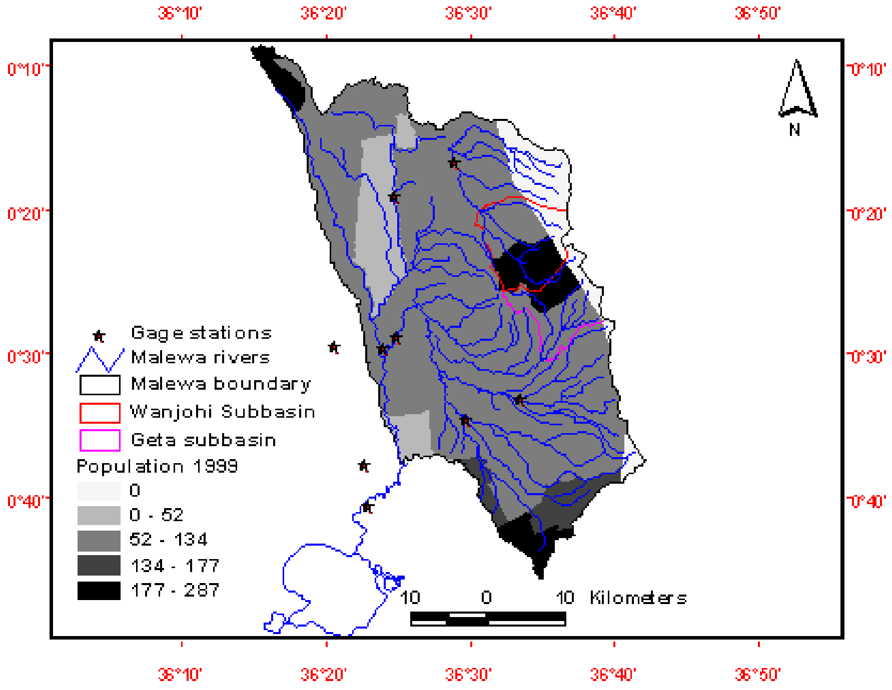


Figure 15: Population density per location (adapted from www ilri.org, 1999)

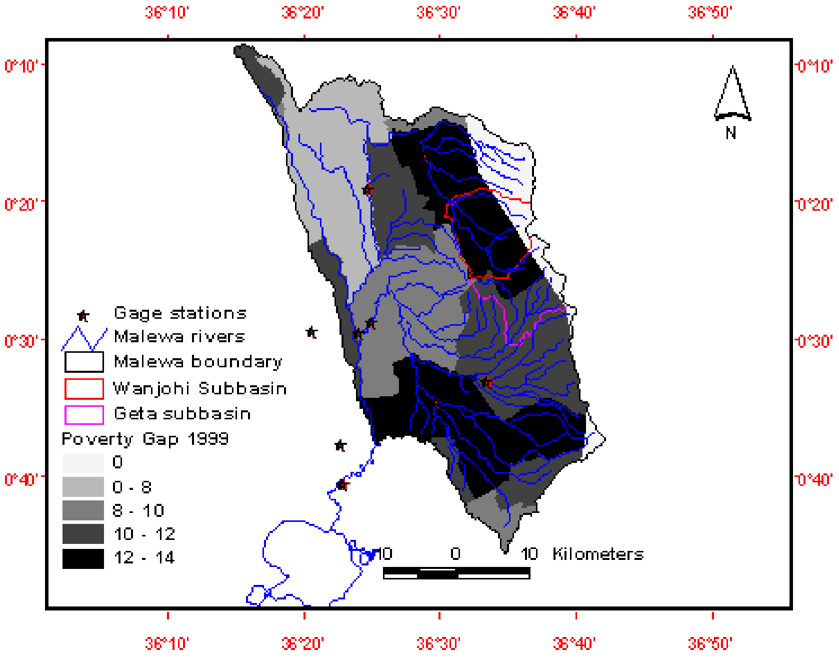


Figure 16: Poverty gap per location (adapted from www ilri.org, 1999)

In river basin headwaters, the poorest (Figure 17) 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.

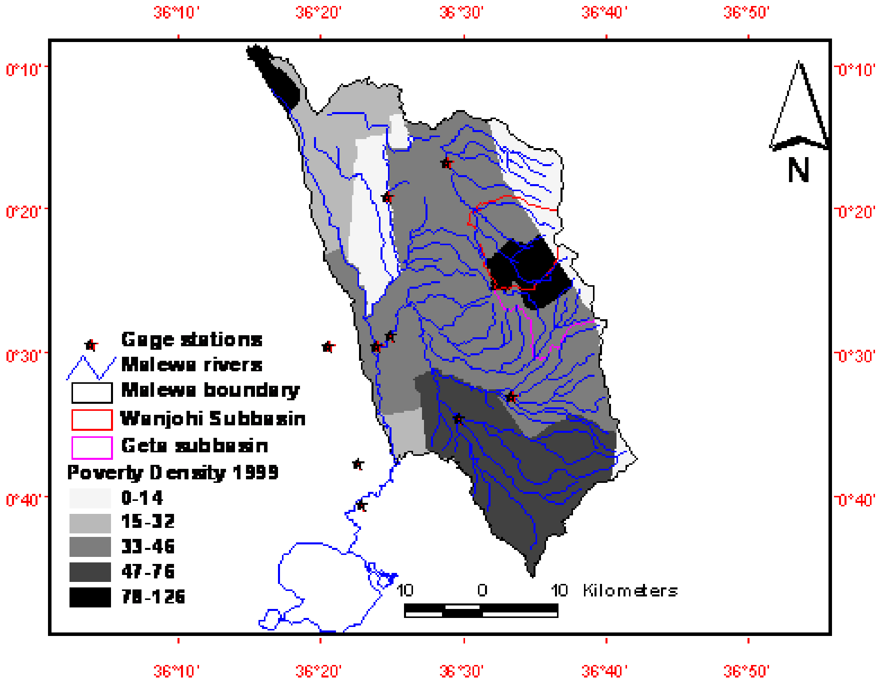


Figure 17: Poverty density per location. (adapted from www.ilri.org 1999)

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 18) and the one *of* pressure on water bodies (Figure 19) indicate that the two pressures are almost complementary.

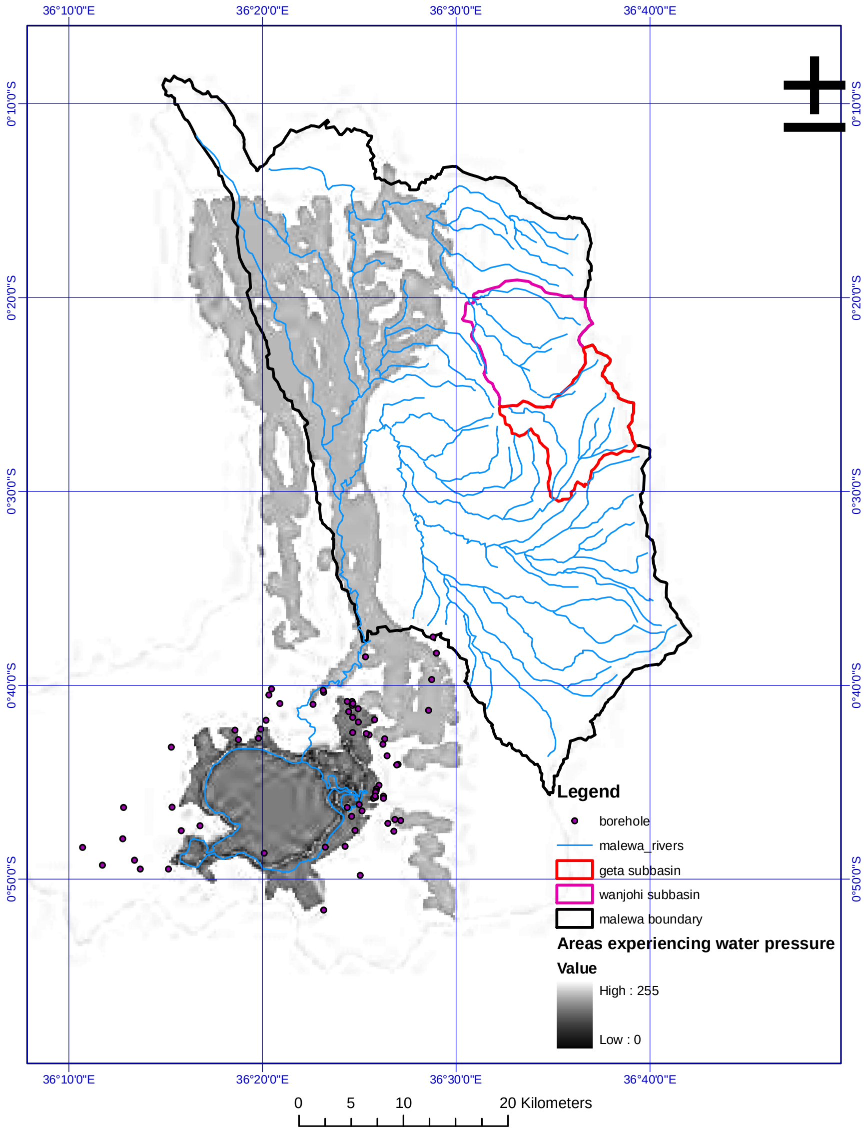


Figure 18: Pressure on Water bodies. (Adapted from Fayos, 2002)

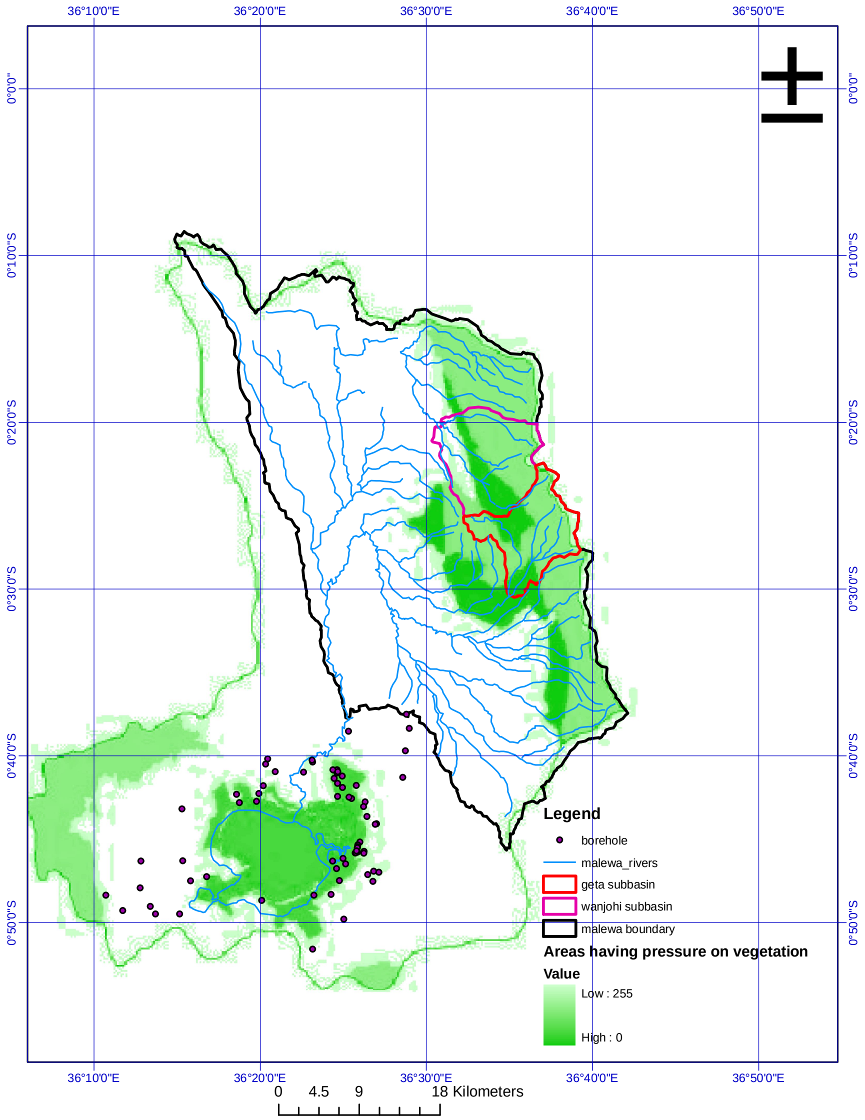


Figure 19: Pressure on Vegetation. (Adapted from Fayos, 2002)

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 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 10) *i.e.* downstream farmers complain about water abstraction from the middle catchment.

Table 10: 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 17). 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 20 shows the conflicts of interest in Table 10.

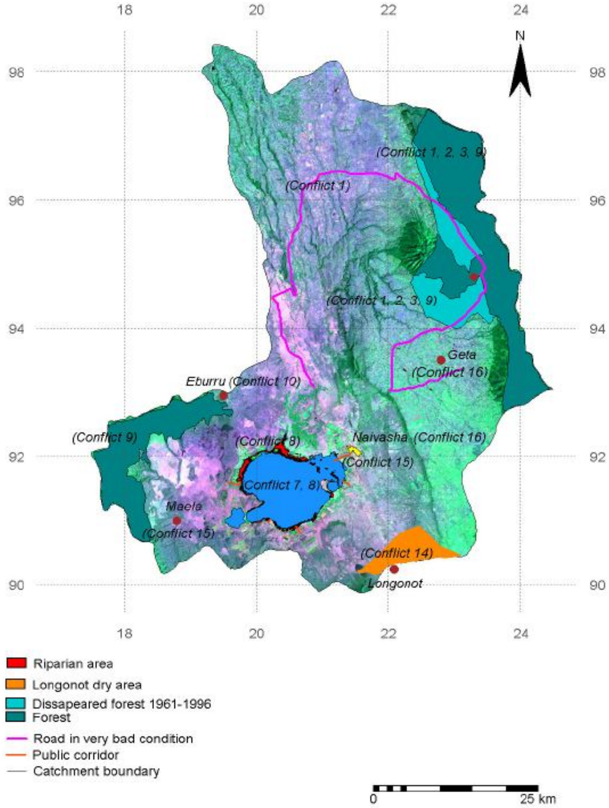


Figure 20: Areas of conflicts indirectly related to water

(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 21 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.

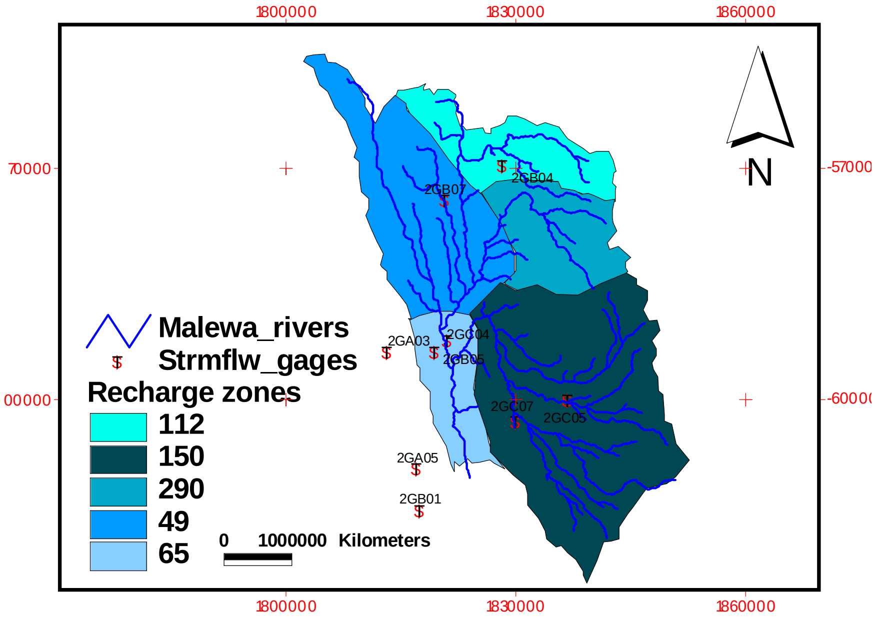


Figure 21: General recharge zonation map in mm/year:(Adapted from Graham, 1998)

The piezometric contours (Figure 22) indicate a development of sink on the North-Eastern side of Lake Naivasha around Three Point Farm and Manera Farms (Nabide, 2002).

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Figure 22: 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 22), 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 23), the resultant selected priority areas for implementing PES are shown in Figure 24.

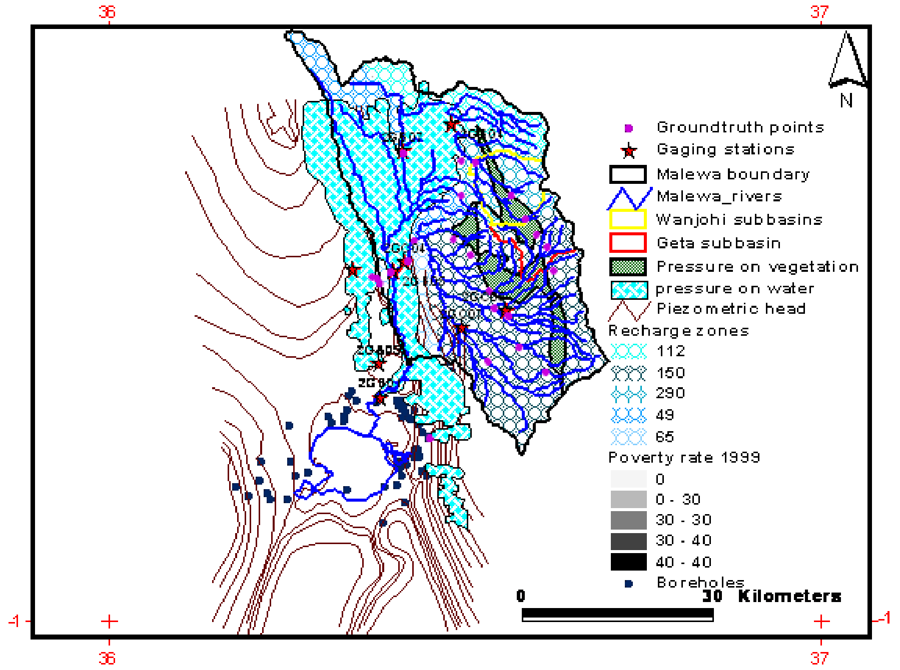

Figure 23: Overlay of parameters to determine the priority area for PES implementation

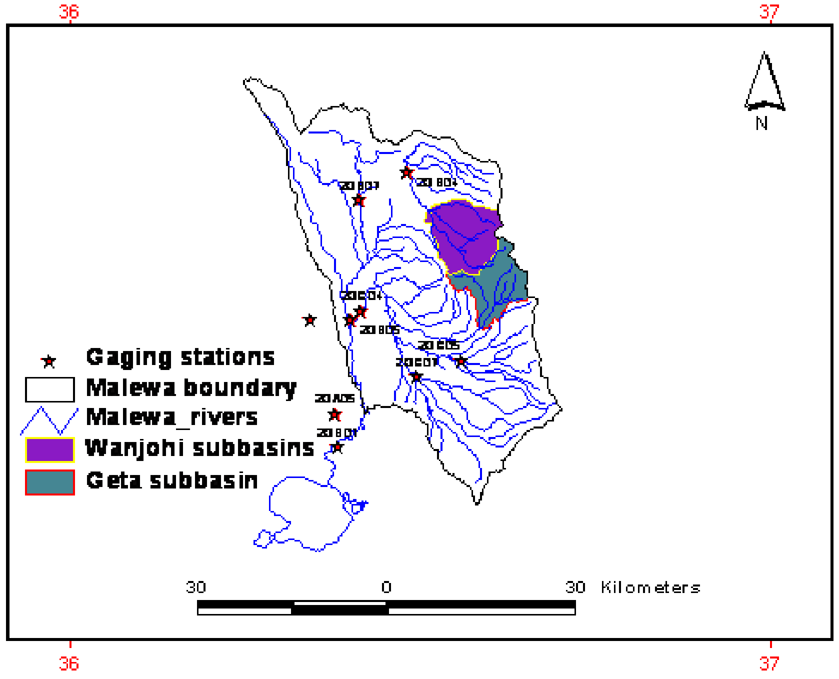

Figure 24: Selected priority areas for PES implementation

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

4.0 Conclusion and Recommendations

4.1 Conclusion

From the demographic data, it can be inferred that accelerated erosion and excessive runoff are connected with development activities and human disturbances; 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 in a given agrarian system, if the population passes a certain threshold, land starts to run short, and soil restoration mechanisms seize up. One speaks of a densely populated degraded area when the population reaches 100inhabitants/km^2.

Two sub-basins were identified to be suitable for PES implementation. The GETA sub-basin covered an area of 121 km^2 and Wanjohi sub-basin covering an area of 112 km^2. The following parameters were used as a criterion for selecting the target sub-basins 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.

The complexity of Malewa watershed makes implementation of PES tricky. The basin does not follow strictly the upstream-downstream user relationship. The over abstraction of water in the middle catchment complicates the relationship and within the same middle catchment, exist rainfall deficiency and this encourages irrigated agriculture practice resulting in overexploitation of groundwater.

4.2 Recommendations

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

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.

Future work ought to include estimation of water abstracted from upper catchments of Malewa River basin for current and future 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 (Three point farm and Manera farms) which is another possible cause of reduction inn water levels of Lake Naivasha. This is vital for balancing water use in various sectors and avoiding conflicts between downstream and upstream water users.

REFERENCES

Atkilt, G. (2001). Soil Survey to Predict Soil Characteristics Relevant to Land Management (Naivasha, Kenya). MSc Thesis. ITC. *Soil Science Division. Enschede*, pp 154.

Beck, M. B., Ravetz, J. R., Mulkey, L. A. and Barnwell, T. O., (1997). On the problem of model validation for predictive exposure assessments, *Stochastic Hydrology and Hydraulics*, **11**(3).

Santhi, C., Arnold, J. G., Williams, J. R., Dugas, W. A., Hauck, L. M. (2001a). Application of a watershed model to evaluate management effects on point and nonpoint pollution. *Transactions of the American Society of Agricultural Engineering*, **44** (66), pp 1559e1770.

Betch, R., and D., Harper. (2002). Towards an understanding of human impact upon the hydrology of Lake Naivasha, *Hhdrobiologia*, **488**, pp 1-11.

Bhandari, A. K., (2005). Study to assess accurate spatial rainfall data in Lake Naivasha basin, Kenya, Enschede, ITC.

Chen, X., (2002). Using remote sensing and GIS to analyze land cover change and its impacts on regional sustainable development. *International Journal of Remote Sensing*, **23**(1), pp 107-124.

Clarke, M. C., G. D. G., Woodhall, D. Allen and G. Darling, (1990). Geological, volcanic and Hydrological Controls on the occurrence of geothermal Activity in the area surrounding Lake Naivasha, Kenya Ministry of Energy, Nairobi.

Congalton, R. G., et al., (1998). Mapping and monitoring agricultural crops and other land cover in the lower Colorado River basin. *American Society for Photogrammetry and Remote Sensing,* **64**(11), pp 1107-1113.

Daniel, J. G., Kulasingam, A. (1975). Problems arising from large scale forest clearing for agricultural use-the Malaysian experience. *Planter, Kuala Lumpur,* **51**, pp 250-257.

Duncan M. (2003). Clarification of the effect of vegetation change on water yield prepared for Environment Canterbury, technical report U03/81.

Farah, H.O., (2001). Estimation of regional evaporation under different weather conditions from satellite and meteorological data: A case study in the Naivasha basin, Kenya. PhD Thesis, Wageningen University, The Netherland.

Graham A., (1998). Groundwater recharge estimation of the Malewa catchment, Naivasha, Kenya, Enschede, ITC.

Hennemann, R. (2001a) Elective on Land Degradation, Assessment, Monitoring and Modelling. Soil Science Division, ITC, Enschede, The Netherlands.Hennemann, R. (2001b) Some Notes About Soil and Land Degrafdation in the Naivasha Rangeland Zone, pp. 3. Soil Science Division, ITC, Enchede, The Netherlands.

Inamdar, S (2004). Assessment of Modeling Tools and Data Needs for Developing the Sediment Portion of the TMDL Plan for a Mixed Watershed. Final Report to the Great Lakes Basin Program. Buffalo, New York, 10-12.

Kamoni, P. T. (1988). Detailed soil survey of a part of quarantine farm-National Husbandry Research Station, Naivasha, Nakuru District, pp. 24. Kenya Soil Survey, Nairobi.

Kiai, S. P. M. and Mailu, G. M. (1998). Wetland classification for agricultural development in Eastern and Southern Africa. FAO, Harare, Zimbabwe.

Motovilov, Y., L.Gottschalk, K.Engeland, A.Rodhe (1999). Validation of a Distributed Hydrological Model against Spatial Observations. *Agricultural and Forest Meteorology* 98-99, 257-277.

Muthuwatta, P. L., (2004). Long term rainfall-runoff-Lake level modeling of the Naivasha Basin, Kenya, Enschede, ITC.

Nagelhout, A. (2001) Performance Analysis of Small Format Aerial Photography (SFAP) in Assessing Current Status and Trends in Wind Erosion: A case study in the Longonot-Kijabe Hill Area, Naivasha District, Kenya. MSc thesis, ITC.

Nash, J. E. and Sutchliffe, J. V. (1970). River flow forecasting through conceptual models, Part I-a discussion of principles, *J.Hydrol.***10**, pp 282-290.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, R. Srinivasan, and Williams, J. R. (2002). Soil and Water Assessment Tool Users Manual: Version 2000. GSWRL Report 02-03, BRC Report 02-07, Published by Texas Water Resources Institute TR-193, College Station, TX.

Ojiambo, B. S., (1992). Hydrogeologic, Hydrochemical and Stable Isotopic Study of Possible Interactions Between Lake Naivasha, Shallow Subsurface and Olkaria Geotherma.

Owor, M. (2000). The Long-term interaction of Groundwater with Lake Naivasha, Kenya : A numerical simulation of the relationship between groundwater and lake allowing for fluctuating lake levels. MSc-Thesis, ITC, Enschede, pp 110.

Pagiola, S., and Platais, G. (2003). Implementing Systems of Payments for Environmental Services: Initial Lessons of Experience. Paper presented at the Workshop on Ecosystem Services in the Tropics: Challenges to Marketing Forest Function, Spring 2003 Meeting of the International Society of Tropical Foresters, Yale University, April 5-6, 2003.

Paruelo, J. M., Burke, I. C., and Lauenroth, W.K., 2001. Land-use impact on ecosystem functioning in eastern Colorado, USA. *Global Change Biology,* **7**, pp 631-639.

Rahim, A. N. (1987). The impact of forest conversion on water yield in Peninsular Malaysia. Paper presented at the workshop on impact of operations in natural and plantation forest on conservation of soil and water resources. Serdang.pp.2326.

Robert, B. and Sarah, H. (2003). Sharing experience and early lessons in GEF and non-GEF lake basin management projects Lake Naivasha brief Prepared for the ILEC foundation of Japan, October 2003.

Rykiel, E. J., (1996). Testing ecological models: the meaning of validation, Ecological Modeling, 90: 229-244.SAF, (2004) Loss of forest land. A position statement of the society of American foresters Retrieved on December 07, 2006, from http://www.safnet.org/policy and press/psst/loss-of-forest-land.cfm

Salah A., (1999). Sustainable use of water among competing sectors: A study in the Naivasha catchment, Rift Valley Province, Kenya, Enschede, ITC.

Siderius, W. (1998). Soils of The Lake Naivasha Environs. In: Contribution to the article in ITC journal, pp. 8. Soil Science Division, ITC, Enshede, The Netherlands.

Sombroek, W. G., Braun, H.M.H. and van der Pouw, B. J. A. (1980). The explanatory soil map and agro-climatic zone map of Kenya. Report No. E.I, Kenya Soil Survey, Nairobi, 56 pp.

Van Liew, M. W., and J. Garbrecht. 2003. Hydrologic simulation of the Little Washita River Experimental Watershed using SWAT. *J. Am. Water Resour. Assoc.*, **39**(2), pp 413-426.

Wischmeier, W. H., and Smith, D. D. (1978). Predicting rainfall erosion loss: A guide to conservation planning. Agricultural handbook 537. U. S. Department of Agriculture, Washington, D.C.