PhD Research Proposal

Quantifying the effect of land use/cover change on its water quantity and quality in Lake Naivasha Basin

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Abstract

Understanding the interactions between terrestrial ecosystems and the atmosphere are fundamental in addressing issues of climate change and environmental degradation. However, quantifying these dynamic interactions both in space and time are compounded by challenges. Specifically, elucidating the impacts of land use and land cover (LULC) at the local to regional scales on surface radiation budgets, surface hydrology, surface energy balance and surface roughness are not straightforward but rather complex to warrant any generalizations. Subsequently, many insights into consequences of LULC on hydrology have been investigated at small spatial, observable scales. However, extrapolating findings from such small scales to larger scales such as river basins is confounded by the diversity of LULC as well as hydrological systems. Not only does the diversity in LULC complicate such a study, but also quantifying the effect of LULC changes of less than 20% have been empirically stated as not discernible from hydrometric measurements alone. The Lake Naivasha Basin qualifies as one such basin where dynamics in LULC changes on hydrology may not be discernible using hydrometric measurements. Hence to investigate this, the present study will adopt three techniques; (1) Statistical methods (2) Hydrological Modeling and (3) Earth observation (EO) techniques. Statistical approaches will be used to analyze time series of hydrological data to identify the time of changes, test the homogeneity of the data, link LULC and catchment characteristics to water quality and reconstruct stream flows. Reconstruction of stream flows is a necessary undertaking in order to pre-determine flows under natural conditions, the output of which will be used to quantify impacts of human induced abstractions against observed stream flows. Hydrological modeling will then be used to quantify the impact of climate variability and LULC changes on the hydrological regime of the catchment. This is important so as to account for the effect of climate signal which masks quantification of LULC effects. The third part of the study will entail the quantification of evapotranspiration (ET) using EO techniques. The spatio-temporal distribution of ET is needed for sustainable management of water resources as well as for a better understanding of water exchange processes between the land surface and the atmosphere. Considering that this work is an integral part of a larger Earth Observation Integrated Assessment (EOIA) project for Lake Naivasha Basin, it will contribute to the existing challenges linking LULC dynamics and catchment hydrology and more specifically unravel the understanding of the interface between LULC/climate and water required to undertake adaptation strategies in Lake Naivasha Basin. Finally, the study outputs will contribute to and/or link with other ongoing components in the EOIA (i.e. Ecology, Limnology, Socio-economic and Water Governance) project.

Table of contents

List of figures

List of tables

List of appendices

Acronyms

AVHRR	Advanced Very High Resolution Radiometer
ET_a	Actual Evapotranspiration
GLDAS	Global Land Data Assimilation System
LULC	Land Use and land Cover
MODIS	Moderate Resolution Imaging Spectroradiometer
MSG	Meteosat Second Generation
N	Nitrogen
P	Phosphorus
SEBS	Surface Energy Balance System
SCOPE	Soil Canopy Observation Photochemistry and Energy
TSS	Total Suspended Solids

1. Introduction

Land use and land cover (LULC) are considered as one of the most important components of the terrestrial environment system (Lin et al., 2009). Changes in LULC mirror the impacts of human activities on the global environment (e.g. Houghton et al., 1999, Schneider and Eugster, 2005). At global scales these changes have been known to have impacts on continental and global atmospheric circulation leading to even larger impacts on regional and continental climate (Lambin and Geist, 2006). Numerous studies have investigated the complex relationships between land surface and other components of the climate at the local to global scales, detailing the differences in magnitude of land surface changes in different geographic localities over the Earth (e.g. Betts et al., 1996, Pielke, 2001, Pielke et al., 1998). Based on these studies, there is evidence that large-scale LULC changes, particularly in the tropics, generate remote climatic effects of global extent far from where the surface has been directly affected by land-cover changes (Franchito and Rao, 1992, McGuffie et al., 1995, Pielke, 2002, Zhang et al., 1996).

At the local to regional scales, the impacts of LULC changes on surface radiation budgets, surface hydrology, surface energy balance and surface roughness are not straightforward but rather complex (Lambin and Geist, 2006) to warrant any generalization. This is because the impacts majorly depend on seasons, climate, and soil conditions (Lambin and Geist, 2006) prevailing at these scales. Schneider and Eugster (2005) also recognized that knowledge about the impact of LULC changes on weather and climate is still limited, especially on the scales that are most relevant for local people, such as a farmers. Subsequently, many insights into consequences of LULC on hydrology and surface energy balance have been elucidated at small spatial, observable scales (DeFries and Eshleman, 2004, Tollan, 2002, Lambin and Geist, 2006, Kiersch, 2001) (See Table 1). Details of such catchment experiment studies date back to the first catchment experiment between 1908-1920's by Bates (1921) at Wagon Wheel Gap in South-western Colorado, US. The objective of the study was to quantitatively evaluate the effects of harvesting on the timing and volume of stream flow, erosion, and sediment (Bates, 1921). Further catchment experiments have been well documented in scholarly articles by a number of researchers (Bosch and Hewlett, 1982, Brown et al., 2005). However, extrapolating findings from such small scales to larger scales such as river basins is confounded by the diversity of LULC as well as hydrological systems (Archer, 2003, Newson et al., 1989, Sivapalan and Kalma, 1995, DeFries and Eshleman, 2004).
The problem of scale has been recognized as fundamental in hydrology (Archer, 2003, Sivapalan and Kalma, 1995). Specifically, discerning the impacts of LULC changes on hydrological signals still remain an unresolved problem (Sivapalan and Kalma, 1995). Archer (2003) argues that land use changes occur as patch works within the catchment and that the reduced rainfall runoff response time in lower or mid catchment may have counteracting effects on a reduced response time in the upper catchment. Lambin and Geist (2006) further augments that dominance of different processes varies

Table 1: **Spatial dimensions of land use effects on the hydrological cycle**

Impact	Basin size (km^2)						
	0.1	1	10	100	1 000	10 000	100 000
Average flow	×	×	×	×	–	–	–
Peak flow	×	×	×	×	–	–	–
Base flow	×	×	×	×	–	–	–
Groundwater recharge	×	×	×	×	–	–	–
Sediment load	×	×	×	×	–	–	–
Nutrients	×	×	×	×	×	–	–
Organic matter	×	×	×	×	–	–	–
Pathogens	×	×	×	–	–	–	–
Salinity	×	×	×	×	×	×	×
Pesticides	×	×	×	×	×	×	×
Heavy metals	×	×	×	×	×	×	×
Thermal regime	×	×	–	–	–	–	–

Legend: **X**: Observable impact; **-**: no observable impact. *Source*: Adapted from Kiersch (2001).

at different scales and that LULC changes in the upper catchment may have a different impact on the hydrology than changes in the lower or mid catchment. In addition, Archer (2003) explains that at small scales, processes such as interception, infiltration and storage dominate whereas channel processes assume a greater role in stream hydrograph as the catchment size increases. Moreover, distinguishing the impact of LULC changes on hydrology from the impact of climatic variability is more difficult at the catchment scale than at the plot scale or small catchment (Archer, 2003, Lambin and Geist, 2006).
While high temporal and spatial variability of hydrologic responses to LULC changes have been well recognized (Andreassian, 2004, Tollan, 2002), nearly all the classical paired catchment experiments have been conducted on catchments with uniform LULC (Costa et al., 2003, Lørup et al., 1998). The LULC changes in the catchment experiments have also been at least more than 20% in areal coverage, the general assumed threshold value that changes in water yield can be detected by hydrometric measurements (Bosch and Hewlett, 1982, Brown et al., 2005, Stednick, 1996, Wang et al., 2009). This complicates investigation of hydrological responses of LULC changes on larger catchments with mixed LULC and with small proportional LULC changes of less than 20%. A fact which has made human-induced LULC changes not be well understood (Bruijnzeel, 2004, Lørup et al., 1998, DeFries and Eshleman, 2004).

In view of the above mentioned research problems, this proposal seeks to investigate the problem of scale and temporal variability at a tropical East African catchment, Lake Naivasha Catchment (~ 3500 km^2), Kenya, which has been undergoing both LULC changes that have been postulated to impact on the hydrology of the Lake (Becht and Harper, 2002). Specifically, the study will quantify the impacts of LULC on water quantity and quality with the aim of elucidating the impacts at a large scale (~ 3500 km^2) which still remains a challenge to hydrologists (Archer, 2003, Newson et al., 1989, Sivapalan and Kalma, 1995, DeFries and Eshleman, 2004). The study shall account for varying climatic conditions and quantify water yield and quality through modeling, remote sensing and statistical techniques for the respective mixed land use/cover within the catchment.

1.1. Problem Statement

Lake Naivasha has been subject to wide fluctuations in water levels over time and is said to have almost dried in the past years (Abiya, 1996, Gaudet, 1977, Verschuren et al., 2000). These natural fluctuations, coupled with consumption by humans, changes in land use/cover over time and climate variability have led to decrease of the water levels which have led to shrinking of the lake (Becht and Harper, 2002, Olaka et al., 2010, Ondimu and Murase, 2007, Otiang'a-Owiti and Oswe, 2007, Trauth et al., 2010). Consequently, the shrinking of the lake has made the lake ecosystem vulnerable and its fragility is a challenge to conservationists and scientists. The lake is a RAMSAR [1] wetland and supports significant economic activities. These include fishing, irrigation, agriculture, geothermal power generation, domestic water supply, sewage effluent disposal and tourism. However, these hydrological benefits could be threatened by land use/cover changes and climate variability. In addition to reduced lake levels, land use/cover changes in the catchment impacting on water quality in streams discharging into the lake has also been a concern to conservationists. Previous study by Tiruneh (2004) in Naivasha catchment has suggested that most of the nutrient loadings into the streams originate from the upper parts of the catchment. These upper parts of the catchment have undergone changes and it is postulated that there is increased inflow of sediments and nutrients mainly caused by the population pressure in the upper catchment. This increased nutrients and sediment loadings coupled with reduced papyrus swamp downstream over the years, acting as a nutrient and sediment sink, has led to increased lake turbidity and eutrophication in the lake. Consequently, the ecosystem services have been compromised. Though a number of studies have highlighted concerns of reduced levels and quality of the lake, there is a clear general lack of quantification of the impact of land use/cover on the hydrology of the catchment. Nonetheless, knowledge of the interface between land use-cover/climate and water required to undertake adaptation strategies is lacking in the area.

1.2. Rationale

Land use/cover and climate are two most important factors influencing hydrological conditions of catchments along with geology and topography. Land use/cover changes have been known to alter the hydrologic cycles and have been reported to cause changes in flood frequency (Brath et al., 2006, Crooks and Davies, 2001, Tollan, 2002), severity (De Roo et al., 2001, Tollan, 2002), base flow (Wang et al., 2006), and annual mean discharge (Costa et al., 2003). On other hand climate variability can change the peak flows, flow routing time and runoff volumes (Changnon and Demissie, 1996, Prowse et al., 2006).

[1] RAMSAR wetlands are a part of an International convention on Wetlands of International Importance. The convention is an intergovernmental treaty for the conservation and sustainable utilization of wetlands. The treaty functions to protect the progressive encroachment and loss of wetlands in the present and future, recognizing the fundamental ecological functions of wetlands and their economic, cultural, scientific, and recreational value. It is named after the Iranian town called RAMSAR where the convention was first institutionalized in 1971. Source: http://www.ramsar.org/

However, ascertaining the combined effect of land use/cover and climate variability due to non-linear relationships, multiple causation, lack of mechanistic understanding of hydrologic response of catchments and lag effects together poses major research challenges to scientists (Allan, 2004, Tollan, 2002). Consequently, distinguishing effects of land use changes from concurrent climate variability poses a particular challenge (Lioubimtseva et al., 2005, Tollan, 2002). To evaluate and distinguish these effects there is need for long term data records for catchments. The availability of long-term records of hydro-meteorological data enables identifying the presence of changes in the river systems and deciphering the possible influencing factors of the detected changes. The detection of changes in the long-term time series of hydro-meteorological data is of scientific and practical importance in the water resource management and is regarded as a permanent exercise with the continuously updated data (Kundzewicz, 2004, Kundzewicz and Robson, 2004). This information is important for land use planning and water resources management to warrant design and implementation of adaptation strategies.

Much of the present understanding of hydrological impacts of land use/cover changes are derived from controlled, experimental manipulations of the land cover, coupled with pre and post-manipulation observations of hydrological processes, commonly precipitation inputs and stream discharge outputs at rather small spatial extent, observable scales of catchment experiments (DeFries and Eshleman, 2004, Tollan, 2002). Identifying and quantifying these hydrological consequences of land use/cover and climate variability at rather larger catchment scales is confounded with challenges in extrapolating or generalizing results from such small catchment experiments.

Moreover, there are tremendous variabilities among basins to realize that no significant knowledge can be acquired without its being based on a large number of observed catchments (Andreassian, 2004). Andreassian (2004) argues that too many misunderstandings have originated in a too hasty generalization of a single point observation. Previous studies have investigated the effects of deforestation and reforestation on watershed hydrology (e.g. Andreassian, 2004, Brown et al., 2005, Jackson et al., 2004, Skaggs et al., 2006, Sun et al., 2001, Swank et al., 2001). Such studies used “paired catchment” approach or analyzed long term hydrologic data for a single catchment that experienced land use/cover changes (DeFries and Eshleman, 2004). Overall, past studies suggest that the magnitude of hydrologic response to land use/cover changes varies with climate, geology, soil, and vegetation growth status (Barlage et al., 2002, Hurd et al., 2004). These findings have suggested that future catchment hydrologic changes due to land conversions are expected to be site specific, and that climate variability is an important factor controlling basin hydrologic processes (Qi et al., 2009).

Though many of these studies have linked land use/cover to water quantity and quality, little have been investigated for tropical East African catchments since the East African catchment experiments (Edwards and Blackie, 1981). The findings of these experiments highlighted the importance of studying and comprehending what happens soonest after land use/cover conversions and before the new land use/cover stabilises (Blackie et al., 1981, Blackie and Robinson, 2007). The overall conclusion of the East African catchment experiments was that changes in land use/cover had no significant effect on the hydrological regime of the catchments where the changes occurred (Blackie and Robinson, 2007, Edwards and Blackie, 1981). The studies further concluded that it was necessary to run a long study in order to detect changes in response to time (Blackie and Robinson, 2007). In line with this suggestion, this present study will use innovative techniques to examine long term changes of land use and land cover on the hydrological regime of Naivasha Basin. In particular, the study will examine the impact of land use/cover on water quantity and quality, taking into account the presence of sub-catchments' characteristics, seasonality and intra-annual variations in order to quantify which land use/cover types drive the water quantity and quality of Lake Naivasha Basin. The need for seasonal and inter-annual analysis is especially important and unique for the Lake considering its levels of fluctuations which are compounded by complex interactions of climate variability and land cover, anthropogenic influence, consequently impacting on water quantity and quality.

1.3. Earth Observation Integrated Assessment (EOIA) Project

The present study falls within an inter-disciplinary approach of the Earth Observation Integrated Assessment (EOIA) project which consists of five components; (1) Hydrology (2) Limnology (3) Ecology (4) Socio-economic and (5) Governance. It is expected that the quantified outputs of the hydrological component will be linked to the other components. Primarily, estimates of water quantity and quality and their seasonal fluctuations, will be used to drive the ecological, limnology and socio-economic components. Estimates of land use and land cover changes will provide input into the socio-economic component to warrant assessment of the major socio-economic driving forces of the land use and land cover changes in Lake Naivasha Basin. Furthermore, estimates of water quality and quantity will also provide benchmark indicators for payment for environmental services (PES). Population changes within the basin that drive land use and land cover dynamics and impact water quality and quantity will be provided by the socio-economic component. On the other hand, the hydrology component will link with limnology studies investigate the spatio-temporal changes of nutrient fluxes in the Lake to elucidate how they compare with nutrient fluxes from upstream of the basin. The hydrology component will also provide water stress indicator maps which can be used for management and monitoring of the Naivasha Basin. These water stress indicator maps may provide a sound basis for water related decision making at policy and water governance levels. Figure 1 illustrates the linkage between hydrology and the other EOIA components.

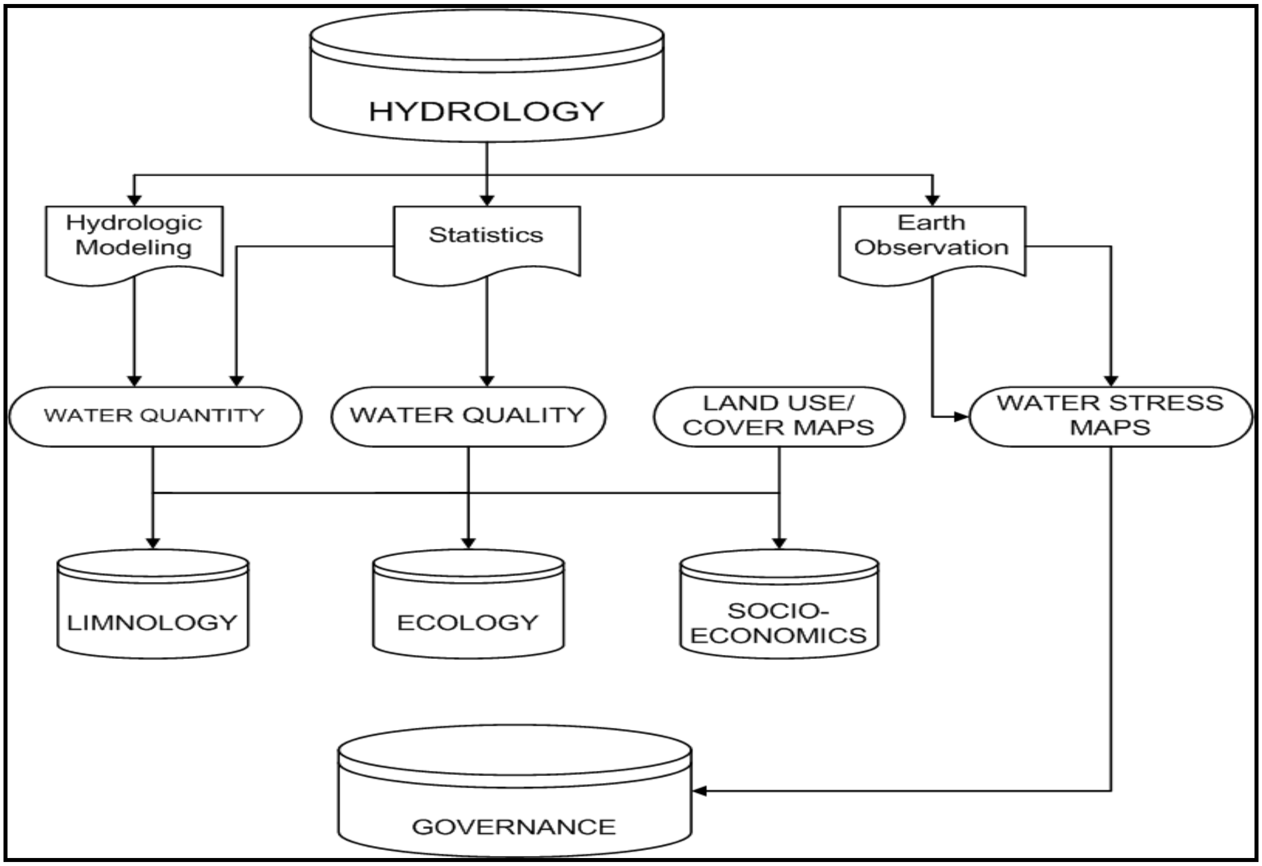

Figure 1: Linkage of hydrology component to EOIA project of Naivasha Basin

1.4. Research Objectives and Questions

1. To investigate the impact of land use/cover change and climate variability on surface hydrology (runoff and evapotranspiration) in the Lake Naivasha catchment

    i. To detect long-term monotonic trends and step/abrupt changes in stream flow and meteorological data resulting from climatic fluctuations and land use/cover changes.

    a) Are there changes in stream flow, precipitation and temperature in Lake Naivasha basin? If there are changes, what are the pattern of the changes i.e. are the changes increasing or decreasing? Are the changes gradual or abrupt? If there are changes, in which months do they occur?

    ii. To investigate the effect of climate variability and human induced abstractions on stream flows and lake levels of Naivasha Basin

    a) What is the effect of climate variability and human induced abstractions on stream flows and lake levels of Naivasha Basin?

    iii. To analyze the long-term water yield of major land use/cover classes.

    a) What is the water yield of the major land use/cover classes in the Naivasha basin?

    b) What is the impact of climate and land use/cover changes on the hydrological regime of the catchment?

    c) How do variations in ET due to climate variability and land use/cover changes affect the hydrological regime of Lake Naivasha catchment? What are the land use/cover effects on evaporative water losses?

    iv. To investigate how land use/cover conversions within the catchment affect surface run-off and lake levels.

    a) How do land use/cover changes affect peak flows, base flow and subsequently lake levels?

2. To investigate the impact of land use/cover on stream water quality under changing climatic conditions in Lake Naivasha catchment.

i. To analyze the influence of spatial and seasonal variability of land use/cover and catchment characteristics on the stream water Nitrates (N), Phosphates (P) and Total suspended sediments (TSS).
    a) Is there seasonality in the spatial pattern of stream water N, P and TSS?
    b) What is the influence of land use/cover and watershed characteristics on stream water N, P and TSS and do the influences vary seasonally?

ii. To quantify which land use/cover types drive chemical loading in the stream water of upper and lower Naivasha catchment.
    a) How does the stream water quality compare between upper and lower parts of the catchment?

2. Background

2.1. Study Area

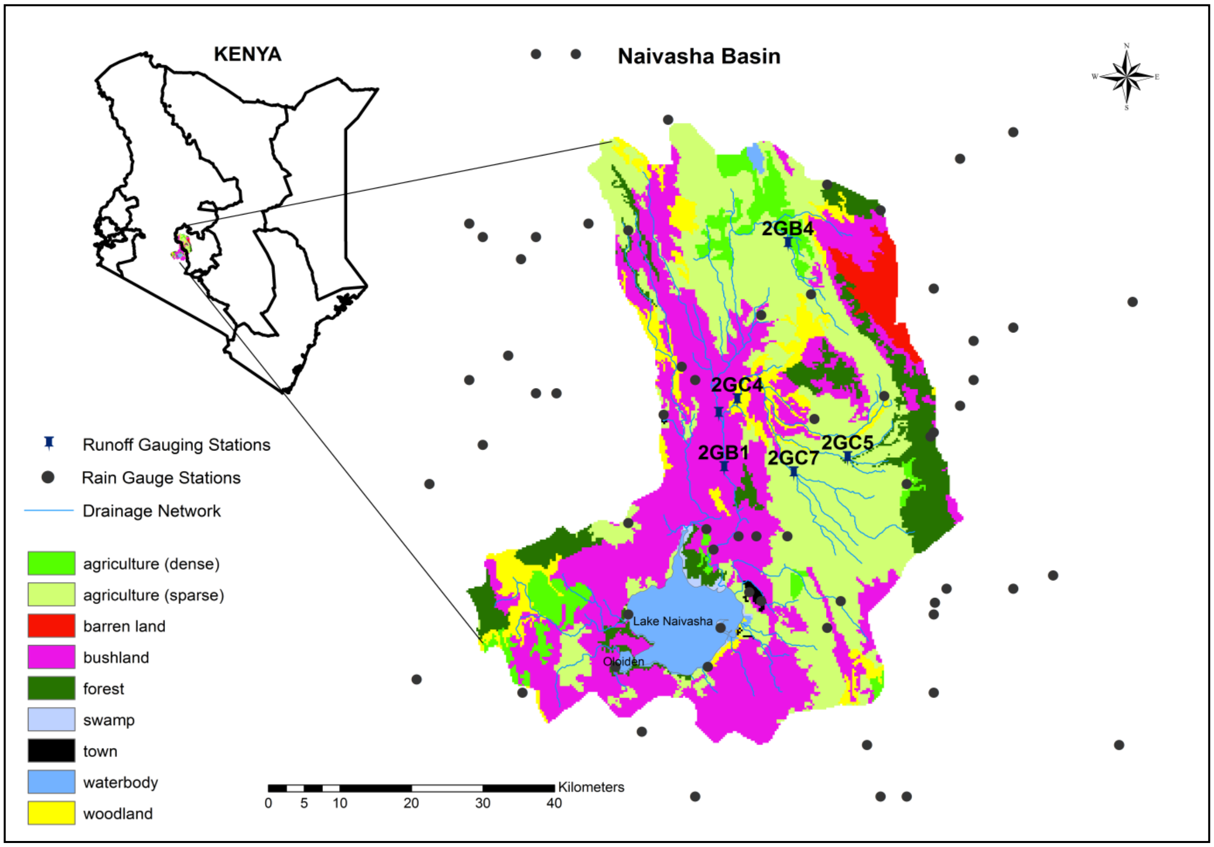

Figure 2: **Land use/cover distribution of 2002 (Source: http://www.africover.org/), Runoff and rainfall gauging stations of Naivasha catchment**

2.2. Location of the Study Area

Lake Naivasha basin is situated approximately 80 km northwest of Nairobi in the Kenyan Rift Valley at a latitude of 0^{o} 09' to 0^{o} 55'S and longitude of 36^{o} 09' to 36^{o} 24'E (Figure 2). The maximum altitude is about 3990 m above mean sea level (a.m.s.l) on the eastern side of the Aberdare Mountain to a minimum altitude of about 1980 m above mean sea level (a.m.s.l). The Aberdare Mountain is one of Kenya's major five water towers. The catchment area is approximately 3500 km^2.

2.3. Geology and Soils

The major soils in the study area are of volcanic origin. The soils found on the mountain and major escarpments of the catchment are developed from olivine basalts and ashes of major older volcanoes. They are generally well drained, very deep (1.2-1.8 m) and vary from dark reddish brown to dark brown, clay loam to loamy soils with thick acid humic topsoil in shallow to moderately deep and rocky places.

2.4. Climate

Climatic conditions in the study area are quite diverse due to considerable differences in the altitude and relief. The annual temperature ranges from 8 ^oC to 30 ^oC (Figure 3). The rainfall regime within the catchment is influenced by local relief with the catchment being in the rain shadow of the Aberdare Mountain to the East and the Mau Escarpment to the West. There are two rainy seasons experienced in this catchment. Long rains occur in the months of March to May and the short rains are experienced between October and November. The Naivasha Basin experiences an average annual rainfall of 600 mm at Naivasha Town and the wettest slopes of the Aberdare Mountain receive as much as 1700 mm a year (Becht and Harper, 2002).

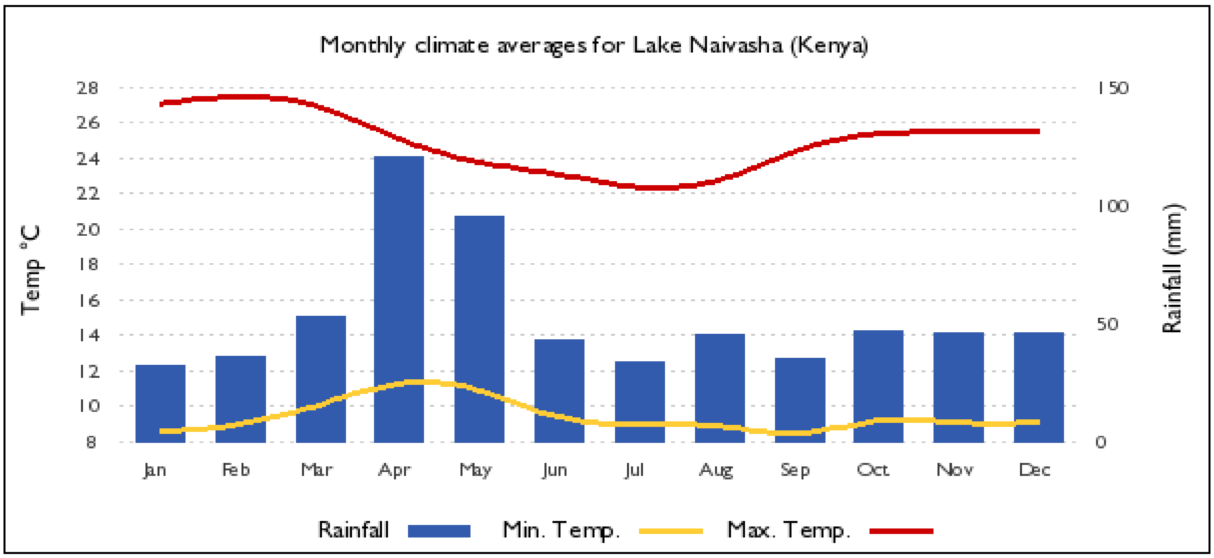

Figure 3: **Monthly climate average distribution of Temperature and Rainfall for Lake Naivasha**

2.5. Overview of existing data and additional data

Hydro-meteorological Data

Hydrological data (i.e. stream flow and lake levels) for the Naivasha Basin have been measured since 1930's for stream flows and 1900's for the lake levels at gauging stations using gauging staff. These have been observed daily using a hired observer. Rainfall data have been measured using rain gauges located at various weather stations located within the basin. See list of Appendices.

Soil database

Soils data for Naivasha exist from the soil and terrain (SOTER) database for Kenya available at http://www.isric.org/isric/. The scale of the data is 1:1M and is compiled by the Kenya Soil Survey (KSS). Parameter estimates are presented by soil unit for fixed depth intervals of 0.2 m to 1 m depth for: organic carbon, total nitrogen, pH, bulk density, content of sand, silt and clay, content of coarse fragments, and available water capacity.

Satellite Data

A number of satellite data, fine and coarse resolution, exist which cover portions of the catchment for different years. This will be collected, corrected, merged, and used in land use/cover classification to monitor previous land use/cover change to present. The images include Landsat MSS, Landsat TM/ETM+, ASTER, Ikonos and Quickbird, Aerial Photographs of 1961.

2.6. Additional data

Required additional data for the study shall include data on surface energy flux measurements for various land use/cover surfaces, wind, temperature, humidity and precipitation, down welling and upwelling long wave and short wave, barometric pressure, sensible heat flux and soil heat flux measurements. These will be measured using an automated flux station to be installed in the basin at the commencement of fieldwork. More existing data will be obtained from existing automatic weather stations previously installed in the catchment. Also collection of present data will form part of additional data requirements to update the existing present data. Meteosat Second Generation (MSG) images will be acquired for retrieval of near-real time precipitation.

3. Methodology

3.1. Effect of climate variability and human induced abstractions on stream flows and lake levels of Naivasha Basin

3.1.1. Trend analysis of hydrological data and climate data

Long-term trends of climate variability, stream flows and lake levels will help discern the inherent mechanism of the hydrological processes in the basin. To do this, homogeneity test of the trends will be first conducted to test for abrupt changes/change points. This will then be followed by examining the long-term term (monotonic) trends in the time series of the data. The following sections detail the method to be adopted. Figure (3) gives an illustration of the methodological framework that will be used in this part of the study.

3.1.2. Test for step/abrupt changes

The hydrological time series and climatic data will first be subjected to homogeneity test. Homogeneity enables identification of possible error sources of gauge station and environmental changes (Biggs and Atkinson, 2010). Homogeneity of the time series records is confirmed when the observed variations in results are due to fluctuations in weather and climate. Since the hydrological and climate time series data of Naivasha are non-normal, the non-parametric Pettitt test (Pettitt, 1979) will be adopted to test the homogeneity of the time series datasets. Pettitt test is a rank-based test for detecting significant changes in the mean of time series data when the exact time of change is unknown. The test is considered robust to changes in distributional form of time series and relatively powerful compared to Wilcoxon-Mann-Whitney test, CUSUM and cumulative deviations (Kundzewicz and Robson, 2004). Furthermore, Pettitt test has been widely adopted to detect changes in climatic and hydrological time series data (Ma et al., 2008, Moraes et al., 1998, Mu et al., 2007, Zhang and Lu, 2009). The test verifies whether two samples $x_1,...,x_t$ and $x_{t+1},..., x_N$ are from the same population or not. The test statistic is shown in Equation (1).

$$U_{t,N} = U_{t,-1,N} + \sum_{j=1}^{N} sgn(x_t - x_j) \text{ for } t = 2, \dots, N \tag{1}$$

The test statistic counts the number of times a member of the first sample exceeds a member of the second sample. The null hypothesis of Pettitt test is the absence of a change point. Its statistic K_t and associated probabilities used in significance testing are given as;

$$K_t = Max_{1 \leq t \geq N} |U_{t,N}| \tag{2}$$

$$p \cong 2\ exp\{-6(K_t)^2/(N^3 + N^2)\}$$

(3)

Where p is the level of significance. When the change point is found significant, the time series is divided into two parts at the location of the change point t.

3.1.3. Monotonic trend test

The non-parametric test based on the Mann-Kendall rank correlation coefficient will be used to detect monotonic changes in both hydrologic and climatic data of the study area. The method has been widely used to assess the significance of trends in hydro-meteorological time-series data (e.g. Bae et al., 2008, Biggs and Atkinson, 2010, Burn et al., 2004, Changnon and Demissie, 1996, Kundzewicz, 2004, Kundzewicz et al., 2005, Kundzewicz and Robson, 2004, Lindström and Bergström, 2004, Ma et al., 2009, Ma et al., 2008, Moraes et al., 1998, Mu et al., 2007, Qi et al., 2009, Radziejewski and Kundzewicz, 2004a, Radziejewski and Kundzewicz, 2004b, Svensson et al., 2005, Swank et al., 2001, Xiong and Guo, 2004, Xu et al., 2007, Xu et al., 2005, Zhang and Lu, 2009). The Mann-Kendall test statistic has been shown to be more robust than parametric tests when dealing with skewed data and outliers in a data series (Onoz and Bayazit, 2003). The Mann-Kendall statistic is given as;

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \tag{4}$$

Where x_j and x_k are sequential data values for the time series data of length n. The test statistic represents the number of positive differences minus the number of negative differences for all the differences between adjacent points in the time series. For $n > 10$, the sampling distribution of S is given in Equation (5) where z follows the standard normal distribution.

$$z = \begin{cases} \dfrac{(S-1)}{\delta_s} & \text{If } S > 0 \\ 0 & \text{If } S = 0 \\ \dfrac{(S+1)}{\delta_s} & \text{If } S < 0 \end{cases} \tag{5}$$

$$\delta_s = \left(\frac{1}{18}\left\{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i\,[(t_i - 1)(2t_i + 5)]\right\}\right)^{1/2} \tag{6}$$

Where t is the extent of any given tie in the data series. $\sum t_i$ denotes the summation over all ties and is only applicable when the data series has tied values. For example, in a data set 4, 4, 6, 7, 9, 9, 9, 10, 10, 13, 17, 17, 17, the t_i values will be as follows: t_1=3 (two untied values (6, 7, 13)), $t_2 = 2$ (two ties of extent two (4, 10)), $t_3 = 2$ (two ties of extent three (9, 17)). Positive values of z indicate an upward trend and negative values indicate a downward trend. The null hypothesis that there is no trend is rejected when the computed z value is greater that $z_{\alpha/2}$ in absolute value.

3.1.4. Double cumulative curves

Double cumulative will be applied to determine the time when human activities began to obviously influence upstream and/or downstream flows. The double cumulative curve between precipitation and total flows from the sub-catchment outlets and the double cumulative curve between the sub-catchment outflows and inflow into the Lake will be used to detect the effects of human activities on upstream and downstream flows respectively. The double cumulative curve is defined as shown in Equation (7).

$$Y(t) = F\big(X(t)\big) \tag{8}$$

For upstream catchments, the double cumulative curve between precipitation and total flow from the sub-catchments is given as,

$$X(t) = \sum_{i=1}^{t} P_{ui,} \;\; Y(t) = \sum_{i=1}^{t} W_{ui} \tag{9}$$

For the inflow into the Lake, the double cumulative curve between total flow from the upstream sub-catchments and inflow into the lake is given as,

$$X(t) = \sum_{i=1}^{t} W_{ui,} \;\; Y(t) = \sum_{i=1}^{t} W_{di} \tag{10}$$

Where P_{ui} (mm) is the annual precipitation is the annual precipitation in the upper catchments region for year *i,* computed using mean precipitation data recorded in stations upstream, $W_{ui,}$ and W_{di} are the total flows from upstream sub-catchments and inflow into the lake respectively for year *i.* For the investigation of upstream flow, $X(t)$ and $Y(t)$ are the cumulative annual precipitation and total flows of the upstream sub-catchments respectively. For the investigation of the inflow into the lake, $X(t)$ and $Y(t)$ are the cumulative total flows of upstream sub-catchments and inflow into the lake respectively.

Under natural conditions, the double cumulative curve produces a straight line. The inflection of the curve is indicative of human-induced abstraction. The difference between the curve and the regression straight line extrapolated to approximate natural conditions gives the cumulative decreased flow due human abstractions and is computed thus,

$$\Delta W_t = Y'(t) - Y(t) \tag{11}$$

Where ΔW_t is the cumulative decreased flow by human abstractions in year t and $Y'(t)$ is the estimated cumulative flow in year *t,* extrapolated by a straight regression line from flow under approximate natural conditions.

3.1.5. Naturalizing stream flows

To better understand and quantify the effect of human induced abstractions on annual upstream and downstream characteristics, reconstructing the stream flow records is necessary to pre-determine flows under natural conditions. Physically based hydrological models have been developed for reconstructing stream flow data in regulated watersheds. However, data requirements of such models may constrain their applicability to sufficiently reproduce naturalized stream flows. Consequently, statistical methods such as auto-regressive moving average (ARMA), Neural Networks (NN) (Abrahart and See, 2000) and multi-regression (MR) (Huang and Zhang, 2004) will be adopted in this part of the study to determine the relationships between climate variability/ natural conditions and streams flows in order to reconstruct upstream and downstream flow data in the absence of human abstractions. The method that yields the most accurate result shall be adopted.

i. **Auto-regression moving average (ARMA)**

This method can be mathematically expressed as,

$$X_t = \emptyset_{p,0} + \emptyset_{p,1}X_{t-1} + \emptyset_{p,2}X_{t-2} + \cdots + \emptyset_{p,p}X_{t-p} + \varepsilon_t \tag{12}$$

Where

$$\emptyset_{p,0} = \left(1 - \emptyset_{p,0} - \emptyset_{p,1} - \cdots - \emptyset_{pp}\right).x \tag{13}$$

Where x is the average value of upstream and downstream flows, $\emptyset_{p,0}$, $\emptyset_{p,1}, \dots, \emptyset_{pp}$ are auto regression coefficient, and ε_t is a random coefficient term.

ii. **Multi-Regression (MR)**

This method can be mathematically expressed as,

$$R_{ru} = \gamma_0 + \gamma_1 P_u + \gamma_2 T_u \tag{14}$$

$$R_{rd} = \beta_0 + \beta_1 P_d + \beta_2 T_d + \beta_3 R_{ou} \tag{15}$$

Where R_{ru} and R_{rd} are the reconstructed annual upstream flows and downstream flows respectively. R_{ou} is the total annual observed upstream flow representative of the upper catchment. The variables P_u (mm) and T_u (^{o}C) are the annual precipitation and mean temperature of the upper catchment respectively. P_d (mm) and T_d (^{o}C) are the precipitation and mean temperature measured of the lower parts of the catchment. The constants $\gamma_0, \gamma_1, \gamma_2$ and $\beta_0, \beta_1, \beta_2$, β_3 are the regression coefficients, respectively for reconstructed upstream flow and downstream flow models, and are obtained using the least-squares method.

The annual stream flow change in the upper and lower catchments induced by human abstraction will then be computed as follows,

$$\Delta R_u = R_{ru} - R_{ou}, \quad \Delta R_d = R_{rd} - R_{od} \qquad (16)$$

Where ΔR_u and ΔR_d are the changes in upstream and downstream annual stream flow induced by human abstraction. R_{od} is the downstream annual stream flow.

Thereafter it follows that, the extent of stream flow response to human abstractions is given as,

$$R_u(\%) = \frac{\Delta R_u}{R_{ru}} \times 100, \quad R_d(\%) = \frac{\Delta R_d}{R_{rd}} \times 100 \qquad (17)$$

And the degree of contribution of human induced abstraction on stream decrease will be computed as follows,

$$C_u(\%) = \frac{\Delta R_u}{R_{iu} - R_{ou}} \times 100, \quad C_d(\%) = \frac{\Delta R_d}{R_{id} - R_{od}} \times 100 \qquad (18)$$

Where $R_u(\%)$ and $R_d(\%)$ are the percent extent of upstream and downstream flow responses to human abstractions respectively. $C_u(\%)$ and $C_d(\%)$ are the percent degree of contribution of human abstractions. R_{iu} and $R_{id}$are the initial annual stream flow of the upstream and downstream catchment respectively.

The results of this part will be;

1. Effect of climate variability and human induced abstractions on upstream flows
2. Effect of upstream flows, climate variability and human induced abstractions on downstream flows and lake levels

3.2. Impact of land use/cover changes on stream flows and lake levels of Naivasha Catchment

Having investigated the influence of human induced abstractions and its impact on the hydrology of the basin, it is also important to investigate of land use/cover changes within the basin and their impacts on the hydrological regime. Considering that climate variability will always be masked in the analysis, its quantification and isolation from that of land use/cover effect is paramount. Hence, to evaluate the effect of land use/cover changes and climate variability on the hydrology of Naivasha Basin, two approaches will be employed. Figure 4 highlights the methodological framework to be adopted in this part of the study.

The first of this will use a rainfall-runoff model which will be calibrated and validated for the 'before' change period and used together with observed rainfall to reconstitute catchment yield 'after' change period as if no change had occurred in the catchment between the two periods. The Soil Water Assessment Tool (SWAT) previously tested and validated for Naivasha basin by Muthuwatta (2004) and Muthuwatta and Becht (2006) will be adopted as the Rainfall-Runoff Model to investigate the 'before' and 'after' change effects. The 'before' and 'after' change periods will be determined using the double cumulative curves and pettit's test statistics as explained in Sections 3.1.2 and 3.1.4. Based on these periods, Land use/cover will be reconstructed using imagery acquired in those periods. The effects due land use/cover changes will then be estimated by comparing simulated and observed flow discharges in the catchment. The same procedure will then be reversed by calibrating and validating the model with 'after' change period data and reconstituting catchment yield for the 'before' change period as if change had occurred during that period. Consequently, four scenarios will be generated:

- Scenario 1: "Before" change Land use/cover and "Before" change climate
- Scenario 2: "After" change Land use/cover and "Before" change climate
- Scenario 3: "Before" change Land use/cover and "After" change climate
- Scenario 4: "After" change Land use/cover and "After" change climate

The difference between Scenario 1 and 2 represents the effect of land use/cover change between the two periods. The difference between Scenario 1 and 3 will give an indication of the influence of climate variation. Scenario 1 and 4 is representative of the combined effect of land use/cover change and climate variability at the respective times. This approach employs the use of one factor at a time while holding others constant. This technique has been widely used to study the effects of land use/cover changes on catchment hydrology in many parts of the world (Dunn and Mackay, 1995, Huang and Zhang, 2004, Li et al., 2009, Ma et al., 2008, Siriwardena et al., 2006, Wang et al., 2006, Wang et al., 2009) and has proven effective in quantifying and disassociating the contribution of climate variability from that due to land use/cover changes.

The second part of the study will use regression analysis to eliminate the effect of climate from that of water-related human activities. A simple annual water balance model (Equation 7) based on standard hyperbolic function of rainfall-runoff relationship (Grayson, 1996, Siriwardena et al., 2006) will be used in this part of the study;

$$Q = (P - L) - F\, tanh \frac{(P - L)}{F} \qquad (7)$$

Where Q is runoff (mm), P is precipitation (mm), L is notional loss (annual precipitation below which no runoff is generated) (mm), F is the shape parameter estimated by least squares method. Recorded rainfall and runoff for the "before" change period will fitted in the equation and used to estimate runoff for the "After" change period. The reverse approach will then be done with the "After" change period, rainfall and runoff, being fitted into the equation and used to estimate runoff for the "Before" change period. This technique is chosen because it is able to suppress the effect of precipitation spatial variability.

The result of this part of the study will be;

1. The quantification of the impact of land use/cover changes on the magnitude of change resulting from modeled runoff, base flow and lake levels. This is an important undertaking considering that, detecting such changes in larger basins are difficult to discern (Kiersch, 2001, Siriwardena et al., 2006).

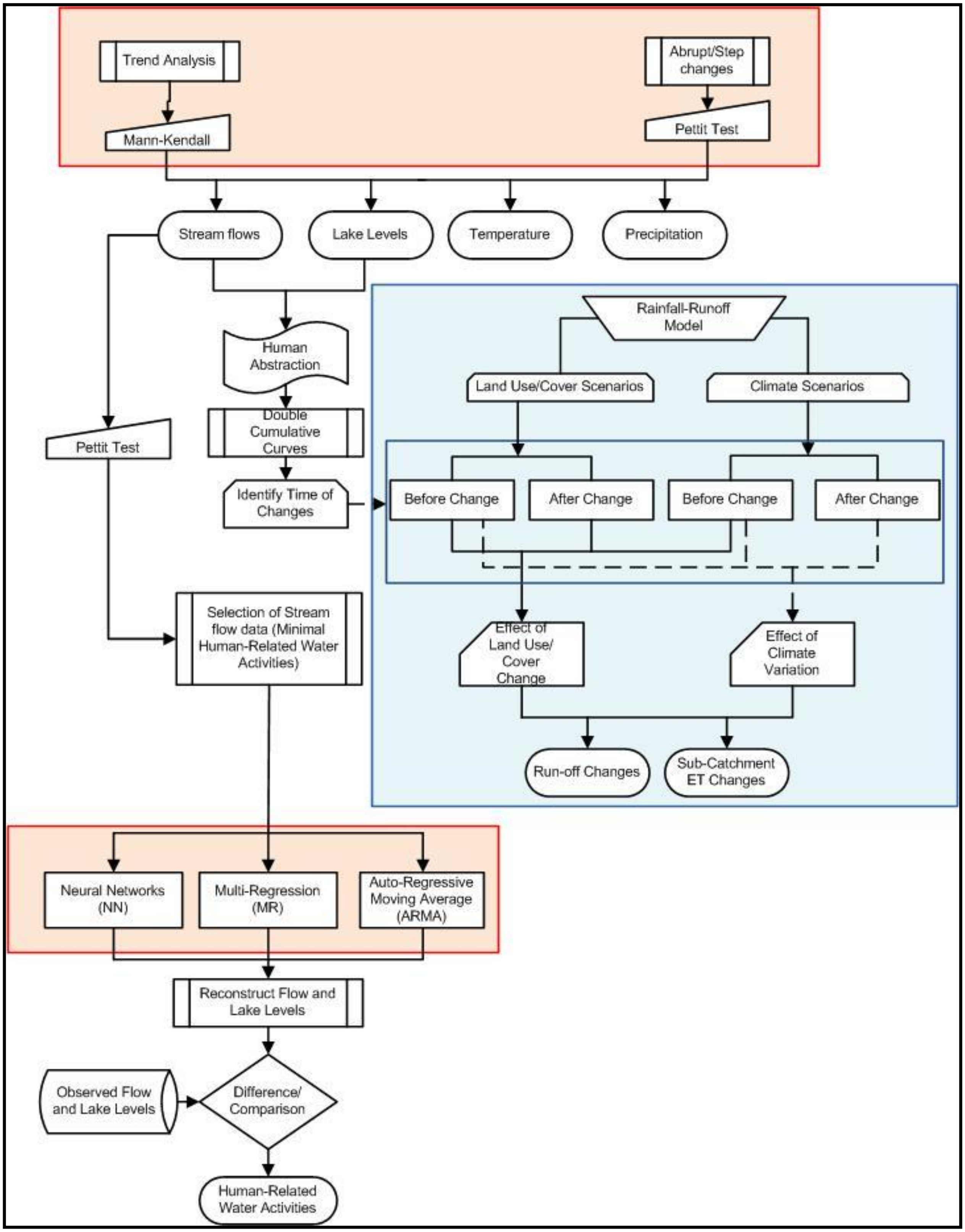

Figure 4: Methodological framework for the statistical and hydrological modeling approach

3.3. Impact of Evapotranspiration changes on water resources of Lake Naivasha Basin

Evapotranspiration (ET) plays an important role in water balance and it is vital that ET is accurately estimated when quantifying the availability of water resources (Jin et al., 2009). In order to investigate the impact of ET on the hydrology of Lake Naivasha Basin, two approaches will be adopted. The first approach will use the rainfall-runoff model described in Section 3.4 to evaluate the effects of climate and land/cover changes on the lumped ET regime of the Basin at sub-catchment level. The method described in Section 3.4 will be adopted to examine 'before' and 'after' change to account for the impact of climate and land use/cover. Finally, to investigate how the differences in changes affect the hydrology of the catchment, the following statistics will be extracted from the results to provide a measure of the change in model predictions: peak-over-threshold (POT), percentage runoff of the catchment, flow duration at the outlet and number of peaks. The second approach will use remotely sensed ET to quantify the water consumption of individual land use/cover within the basin.

3.3.1. Quantification of the water consumption of various land use/cover in the Naivasha Basin

To compliment the use of ET outputs from the Rainfall Runoff model, spatial distribution of ET changes from individual land use/cover changes will be accomplished using a remotely sensed surface energy balance model. It is proposed to use AVHRR and MODIS images to investigate the long-term changes in ET of the catchment. The use of remotely sensed ET will enable spatial identification of ET changes linked to individual land use/cover within the catchment (Schuurmans et al., 2003). In this study the quantification of total water consumption of the various land use/cover will be accomplished by use of the Surface Energy Balance System (SEBS) model (Su, 2002). The choice of the SEBS model is based on the fact that it is the only model that incorporates the formulation of roughness height for heat transfer (Su et al., 2010) and does not require calibration (e.g. Bastiaanssen et al., 1997) when computing actual evapotranspiration (Et_a) (Equation (8)). Details on the formulation of SEBS algorithm are provided in Su (2002).

$$E_{daily} = \frac{86400\ \Lambda\ (R_{n24} - G_{24})}{\lambda} \tag{8}$$

Where E_{daily} is the daily 24 hour actual evapotranspiration, $\Lambda = \lambda E/(\lambda E + H)$ is the evaporative fraction, 86400 is a constant for time scale conversion, R_{n24} is the daily averaged net radiation and G_{24} is the daily averaged soil heat flux.

In order to run SEBS, three sets of input data will be required: (1) Products derived from remote sensing data: albedo, emissivity, temperature and local surface roughness parameters. In this study, these remote sensing products will be derived from existing MSG, MODIS, AATSR/MERIS, Landsat TM and ASTER data; (2) Meteorological parameters collected at a reference height (air pressure, temperature, relative humidity, wind speed); (3) Radiation data (downward solar radiation, downward long wave radiation). Inputs data (2) and (3) will be obtained from an automated flux station which will be installed in the catchment during the period of study. The flux station is equipped with 3D sonic anemometer for wind speed measurements, Soil heat flux plates, Humidity sensors, Radiation sensors for measuring the down welling and upwelling short and long wave radiation, Scintillometer and Bowen Ratio.

Simulated daily spatial ET based on ground measurements of ET (herein referred as ET $_{\text{FLUX STATION}}$) and SEBS ET will also be generated using Equation (9) for days with no satellite overpass.

$$ET_{SEBS\_Daily}(x_i, y_i, t_{i+1}) = [ET_{SEBS}(x_i, y_i, t_{24})].\left[\frac{ET_{SEBS}(x_i, y_i, t_i)}{ET_{FLUX\ STATION}(x_i, y_i, t_i)}\right]_j .ET_{FLUX\ STATION}(x_i, y_i, t_{i+1}) \quad (9)$$

Where $ET_{SEBS\_Daily}(x_i, y_i, t_{i+1})$ is the simulated remotely sensed daily ET on day t_{i+1} , $[ET_{SEBS}(x_i, y_i, t_{24})]$ is the daily remotely sensed ET on day i, $ET_{FLUX\ STATION}(x_i, y_i, t_i)$ and $ET_{SEBS}(x_i, y_i, t_i)$ are the ET from flux station and satellite based ET on day i at the instantaneous time of satellite overpass j. $ET_{FLUX\ STATION}(x_i, y_i, t_{i+1})$ is the daily flux station ET measurement for any other day $i + 1$ when there are no satellite overpass. This procedure is similar to that used by Jin et al. (2009) though the researchers used ET estimates from an evaporation pan in their simulation of $ET_{SEBS\_Daily}(x_i, y_i, t_{i+1})$.

Considering that variation in meteorological variables such as wind speed, cloud effect and temperature may vary over a given time span, say within or over months, care will be taken in the determination of the ratio $[ET_{SEBS}(x_i, y_i, t_i)/ET_{FLUX\ STATION}(x_i, y_i, t_i)]$ across space. Having simulated the daily remotely sensed ET [$ET_{SEBS\_daily}(x_i, y_i, t_{i+1})$] for whole basin, the ratio will be assumed to compensate for heterogeneity of land use/cover to warrant inter-comparison of the aggregated ET per land class cover type. Moreover, this technique will compensate for the effective utilization of sparse meteorological data in the basin. The aggregated ET will be compared to daily and monthly ET estimates from the Rainfall-Runoff model at a sub-catchment scale. The aggregated simulated ET will also provide the possibility to test on the accuracy of predicting runoff using the Rainfall-Runoff model at the outlet of the sub-catchments using data assimilation techniques.

3.3.2. Validation of water consumption of the various land use/cover in the Naivasha Basin

Having quantified the water consumption of the land use/cover using SEBS model, validation of the outputs will then be carried out. This will be achieved by ground measurements conducted simultaneously at sensor overpass of surface energy fluxes using the flux station to be installed in the catchment and also existing Pan Evaporation data. The flux station will provide Large Aperture Scintillometer (LAS) and Bowen Ratio measurements necessary to compute the energy fluxes. Scintillometry calculates the sensible heat flux by measuring the refractive index of the air over a specified distance (De Bruin, 2002). The LAS technique is robust in that it measures areally-averaged sensible heat flux up to scales of 3000m. By measuring the soil heat flux and net radiation, latent heat flux can then be calculated as the remaining term of the energy balance as shown in Equation (10).

$$\lambda ET = R_n - G - H \tag{10}$$

Where R_n is the net incoming radiation flux density (Wm^{-2}), G is the ground heat flux density (Wm^{-2}), H is the sensible heat flux density (Wm^{-2}), λET is the latent heat flux density, and λ is the latent heat of vaporization of water (Jkg^{-1}).

The Bowen ratio method partitions energy into sensible heat and latent heat (Pauwels and Samson, 2006, Su et al., 2010). The ratio of these two components is the Bowen ratio and it is controlled by the difference in air temperature and humidity at two heights in the air above the canopy. Three major land use/cover classes namely; (1) Agriculture (2) Grassland and (3) Woodland will be used to evaluate the accuracy of the SEBS output. The first phase will monitor energy fluxes downstream of the catchment using the flux station. A reconnaissance survey will be done in combination with negotiation with the land owners to identify suitable location for installing the equipment bearing in mind security of the equipment. The second phase will entail monitoring the energy fluxes in the upstream part of the catchment. The monitoring of these flux measurements will be conducted for the duration of the growing cycle to capture the influence of seasonality.

Other methods of validation such as the simple water balance and Canopy Observation Photochemistry and Energy Fluxes (SCOPE) model (Van Der Tol et al., 2009) will also be used as independent checks of remotely sensed ET. Water balance will be computed for the basin by subtracting the mean annual evapotranspiration from mean annual precipitation for each water year. This will be done for the time periods under investigation considering that the Lake Naivasha recharge is entirely dependent on the precipitation and evapotranspiration alone and hence treating the water storage component as the closing factor of the water balance (Bastiaanssen and Chandrapala, 2003). SCOPE is a soil vegetation atmosphere transfer (SVAT) model that uses meteorological forcing data to simultaneously estimate vertical distribution of the within-canopy heat flux and aerodynamic resistances (Van Der Tol et al., 2009). The advantages of this model are that it is able to interpolate between satellite overpasses and can be used as a remote sensing product simulator by providing measurements even under cloudy days (Su et al., 2010). More detailed explanation of the SCOPE model can be found in Van Der Tol et al. (2009).

3.3.3. GLDAS ET product for evaluation of water use consumption of Land use/cover

The Global Land Data Assimilation System ((GLDAS) has been generating land surface states e.g. soil moisture and surface temperature and energy fluxes e.g. evapotranspiration and sensible heat flux products simulated by four land surface models (Community Land Mode (CLM), Mosaic, Noah and Variable Infiltration Capacity (VIC)) (Fang et al., 2007). These products are generated using huge amounts of observed data reproduced at a spatial resolution of 0.25^{o} to 1^{o} and temporal resolution of 3-hours (Kumar et al., 2006). The course resolution renders them inadequate in investigating the water use changes of the land use/cover occurring at local scales such as Naivasha Basin. However, their temporal resolution of 3-hourly provides a high temporal resolution to investigate changes at local scales. This study intends to exploit information available from GLDAS data, specifically Evapotranspiration data, at these high temporal resolutions by using down scaling techniques to within local scales of individual land use/cover classes. But in order to test their usability at local scales e.g. the size of Naivasha Basin, validation of the GLDAS ET product is important.

Validation of GLDAS will be achieved by performing an up-scaling procedure of the SEBS simulated ET of high resolution maps by pixel aggregation to the GLDAS pixel size. Up-scaling refers to the aggregation of coarse resolution imagery to fine resolution imagery (Hong et al., 2009). A number of up-scaling approaches for evaluation of coarse resolution imagery exist. In the proposed study, two techniques, simple averaging and nearest neighbor (Hong et al., 2009), will be used. Simple averaging entails calculating by resampling over *n*x*n* window since a pixel value is considered an integral value over corresponding surface on the ground. Nearest neighbor uses the value of the input pixel closest to the centre of the output pixel. To carry out the two techniques, the following procedures will followed; The first procedure will entail applying SEBS model first on the high resolution imagery (e.g. Landsat in this case) and then aggregating the output variable (daily ET) to the coarser resolution of GLDAS. The aggregated output will then be compared with the GLDAS ET product. The second approach will entail aggregating the Landsat pixels of input variable (radiance) to obtain pixels at the GLDAS scale before running SEBS model. The aggregated radiance pixels will then be input into the SEBS model and the output compared with the GLDAS ET product. Figure 5 illustrates the two up-scaling procedures that will be used to validate the GLDAS ET product.

This part of the study is important in that it will provide an opportunity to test the consistency of SEBS model performance under very coarse resolution offered by GLDAS ET product. If the model is insensitive to an input parameter, aggregating the value with increasing scale will have little influence on model predictions. However, when the model is not operating linearly, the change in data aggregation could increase or decrease model performance (Liang, 2004).

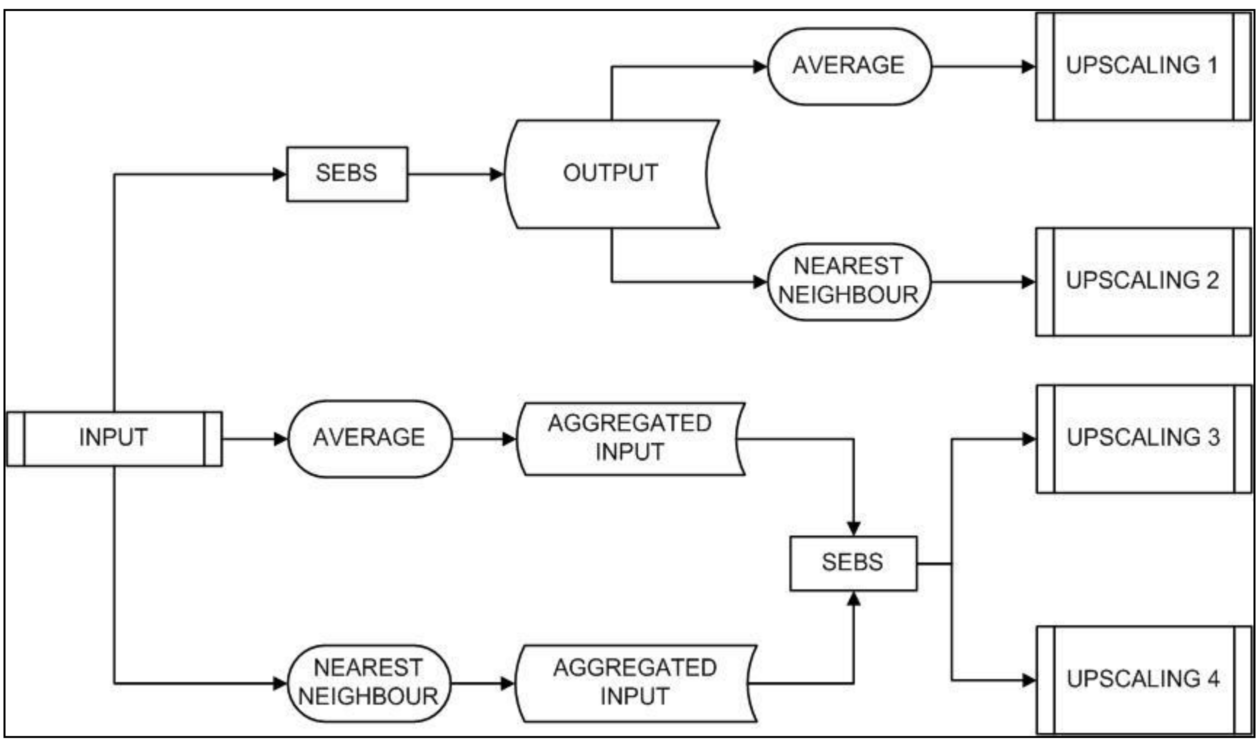

Figure 5: Simple average and Nearest neighbour up-scaling techniques

3.3.4. Development of a downscaling approach to exploit the use of GLDAS data products to evaluate water use consumption

Down-scaling sometimes referred to as disaggregation is the use of information taken at larger scales to derive processes at smaller scales (Anderson et al., 2004, Kustas et al., 2003, Vazifedoust, 2007). The main technique of down-scaling that will be adopted here is the output down-scaling where ‘high resolution’ evapotranspiration output from SEBS model is first ran and then disaggregation of the GLDAS evapotranspiration is effected. Figure (6a) and (6b) illustrate two types of downscaling approaches that will be adopted in the study.

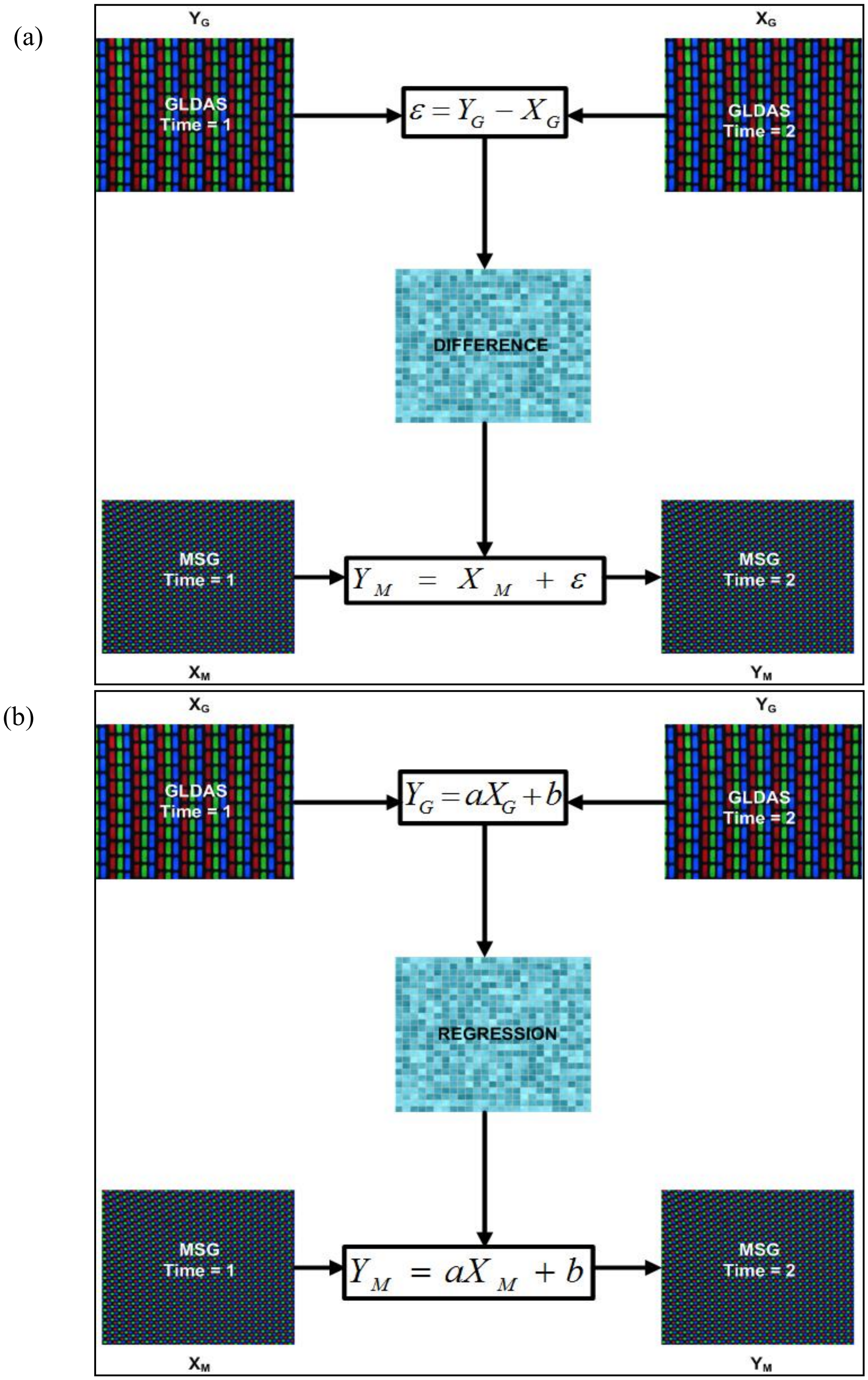

Figure 6: Down-scaling coarse GLDAS to finer resolution using (a) Subtraction and (b) Regression technique to predict fluxes at finer resolution

The subtraction method disaggregates imagery by applying the distribution of pixel by pixel difference between two coarse resolution images (in this case GLDAS) to a previous fine resolution imagery (which can be MSG or Landsat) covering the same area. On the other hand, the regression method applies a 1st

order linear regression between two coarse resolution imagery and then the regression is applied to prior fine resolution imagery. The assumption here is that the linear relationship between coarse resolution images is valid between fine resolution imagery and that fine scale variability of the area of interest changes linearly during the time interval between two satellite estimated maps.

Other approaches for down scaling that will be tested are the weighted ratio approach (Vazifedoust, 2007) as given in Equations (11) and (12).

$$ET_{downscaled}(x_i, y_i, t_{i+1}) = \left[\frac{ET_{landsat}(x_i, y_i, t_i)}{ET_{GLDAS}(x_i, y_i, t_i)}\right] . ET_{GLDAS}(x_i, y_i, t_{i+1}) \quad (11)$$

$$ET_{downscaled}(x_i, y_i, t_{i+1}) = \left[\frac{ET_{landsat}(x_i, y_i, t_i)}{\overline{ET_{GLDAS}(x_i, y_i, t_i)}}\right] . \overline{ET_{GLDAS}(x_i, y_i, t_{i+1})} \quad (12)$$

Where $ET_{downscaled}(x_i, y_i, t_{i+1})$ is the disaggregated ET map on day t_{i+1}, $ET_{GLDAS}(x_i, y_i, t_i)$ is the GLDAS ET map on day t_i, $ET_{landsat}(x_i, y_i, t_i)$ is the SEBS ET map produced on day t_i, $ET_{GLDAS}(x_i, y_i, t_i)$ and $ET_{GLDAS}(x_i, y_i, t_{i+1})$ are the global average ET obtained from GLDAS data covering the Landsat scene. The advantage of Equations (11) and (12) is that it will be possible to simulate and produce ET maps during periods when high resolution imagery are not available. Furthermore, the technique will allow for simulation of ET even under cloudy weather conditions. However, the major assumption in the ratio technique is that the quotient of Landsat/GLDAS ET is assumed to vary linearly. The downscaled GLDAS ET once validated are better placed to provide high resolution and high temporal ET input into a Rain-Runoff Model which is postulated to improve hydrological modeling of the catchment.

The modeled ET maps together with Meteosat (MSG) precipitation products and measured runoff at the outlets of the sub-catchments will provide a sound basis for analyzing the water balance of individual sub-catchments. Furthermore, these shall be used to produce water performance indices maps at sub-catchments' level (Chemin et al., 2004, Molden, 1997). Examples of these water performance indices are the depletion fraction of gross inflow, depletion of net inflow or depleted fraction of available water. These indices provide indications on the pre-existing water use patterns and are useful in water management in identifying areas where there are water savings or need improvement in water savings (Chemin et al., 2004). Figure 7 illustrates an example of determining the depleted fraction of gross inflow.

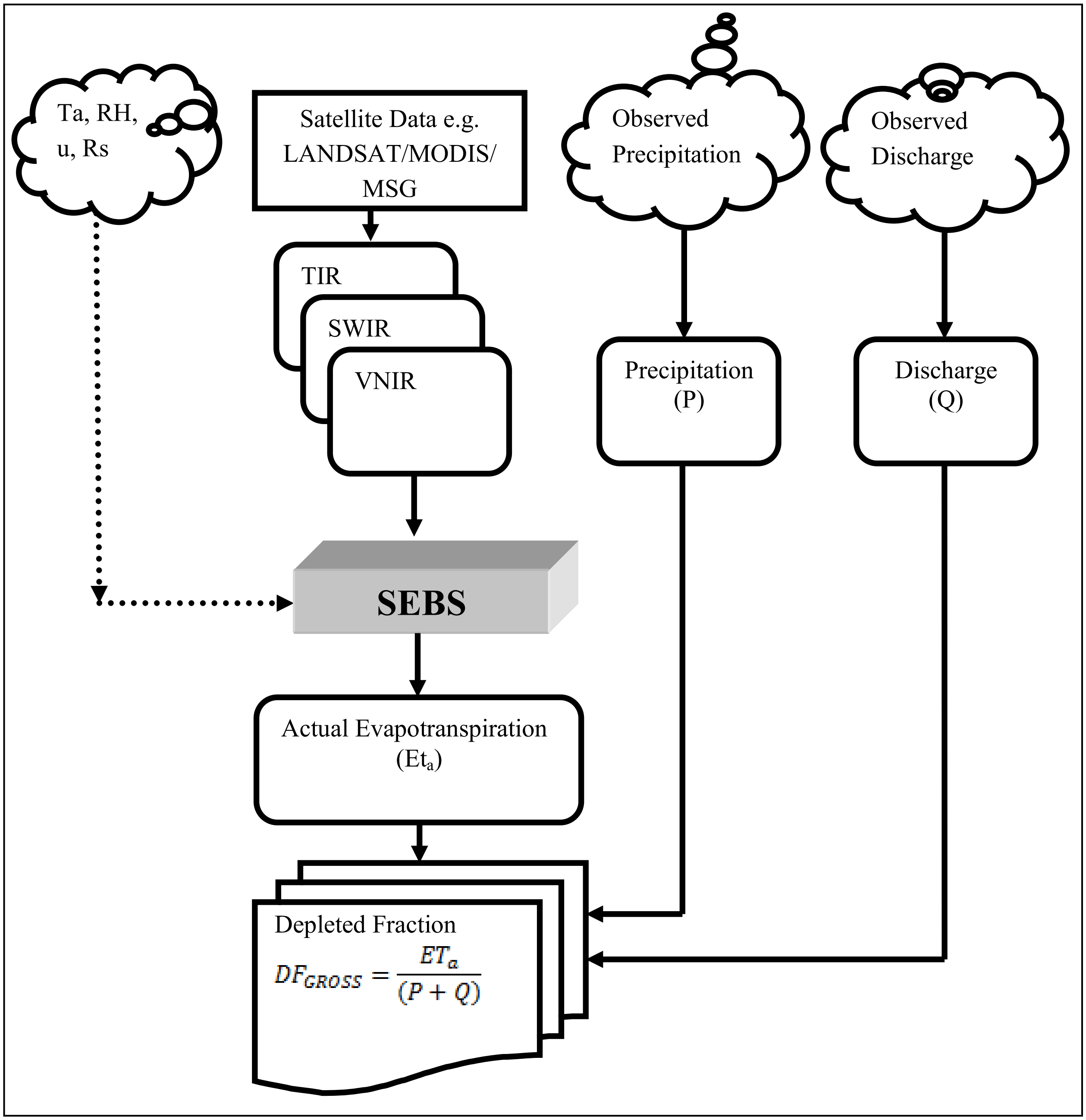

Figure 7: Generating depleted fraction of gross Inflow

The result of this part of the study will be;

1. Quantifying the impact of variations in ET as brought about by climate variability and land use/cover changes and how it affects the hydrological regime of Lake Naivasha basin. Specifically, the results will answer the question: What are the land use/cover and climate effects on evaporative water losses and how do these effects impact on the hydrological regime?

2. High Resolution and high temporal downscaled GLDAS ET outputs which can be used to improve hydrological modeling.

3. Generation of water depletion indices to identify water use patterns within the basin.

4. Evaluation of SEBS consistency in validating coarse resolution GLDAS ET products by up-scaling techniques.

3.4. Land use/ cover influence on water quality of Lake Naivasha Basin

3.4.1. Stream water sampling and analysis

Grab samples will be collected in 500ml high density polyethylene (HDPE) bottles from respective river gauging stations (Appendix 1) at approximately mid-depth of the river. For each station N, P, and TSS shall be analyzed in the laboratory. This will be conducted on a seasonal basis by mounting a two field campaigns to capture variability of the constituents during low and high flow seasons. Estimated daily discharges for each sub-catchment will then be multiplied linearly by each constituent concentration of N, P and TSS. Resultant constituents for each sub-catchment shall then be summed by year and/or season and inflowing constituents from above contributing sub-catchments subtracted. This shall then be divided by the sub-catchment area to determine the spatial distribution of the constituents per respective sub-catchment. Further evidence on the use of fertilizer within the catchment will be collated for inference in the analysis.

The data structure of the constituents collected over the two seasons is a longitudinal, cross-sectional survey of N, P and TSS fluxes repeated yearly for sub-catchments. In order to account for co-dependence introduced by repeated measurements on the experimental units (sub-catchments) linear mixed effects (LME) (Equation 8) modeling (Pinheiro and Bates, 2000) will be adopted to examine the relationship between land use/cover and water quality constituents.

Linear mixed effects modeling employs regression techniques (Pinheiro and Bates, 2000) well suited to water quality and other environmental research, where researchers repeatedly sample a set of locations to determine if a water quality or other environmental parameters are associated with one or more land use patterns, climate measurements, geomorphological attributes, or other such independent factors operating at the plot, field, or catchment scale (Ahearn, 2005, Ragosta et al., 2010). The results of the model (coefficients, P-values, 95% confidence intervals) are adjusted for the amount of correlation within the dataset induced by repeated sampling of a set of sites (Ragosta et al., 2010). In essence, mixed-effects modeling allow for robust and simultaneous evaluation of associations between response variables and environmental factors while at the same time compensating for the repeated measures embedded in the data structure (Ahearn, 2005, Tate et al., 2003). The resulting regression equations will then provide for evaluation of the influence of different land use/cover types on water quality dynamics within the catchment under different seasons and water year scenarios.

Mixed-effects modeling have a distinct approach of representing a family of curves as random variations around the population average curve (Omuto et al., 2010). For the case of land use/cover effect on water quality, this can be accomplished by simultaneous modeling of the average population of water quality-land use/cover relationship and the same relationship for the individual land use/cover types. In the process, it accommodates unique characteristics of different land use/cover types in the landscape. Its statistical formulation for water quality-land use/cover relationship can generally be written as shown in Equation (9).

$$
\begin{aligned}
&y_i = f_i(x, \varphi) + e_i \\
&\varphi_i = D\beta + Bb_i \\
&b_i \sim N(0, \psi),\ e_i \sim N(0, \sigma^2) \quad i = 1, 2, \ldots, m
\end{aligned} \tag{9}
$$

Where $\boldsymbol{y}$ is the vector of water quality parameter (i.e. N, P or TSS) to be estimated, $\boldsymbol{x}$ is the vector of land use/cover types and any other catchment characteristics that may influence water quality, $\boldsymbol{\varphi}$ is a vector of the fitting parameters in the function $\boldsymbol{f}$ linking water quality parameters and land use/cover, $\boldsymbol{e}$ is a vector of the residuals between actual and predicted water quality parameters, $\boldsymbol{\sigma}$ is the residual standard error, $\boldsymbol{m}$ is the number of land use/cover types/classes in the study area, $\boldsymbol{\beta}$ is a vector of population average parameters for the water quality-land use/cover relationship (they are also known as fixed-effects), $\boldsymbol{b}$ is a vector of random variations of the fitting parameters for the land use/cover types in the study area (they are also known as random-effects), $\boldsymbol{D}$ and $\boldsymbol{B}$ are design matrices for solving Equation (8), and $\boldsymbol{\psi}$ is a variance-covariance matrix for the random-effects (Laird and Ware, 1982). The random-effects are associated with different land use/cover types/classes in a study area and so provide a statistical opportunity for including their influence into the modeling of water quality-land use/cover relationship.

The result of this part of the study will be;

1. Quantification of the influence of land use/cover and watershed characteristics on stream water N, P and TSS and how this influence varies seasonally. Further, the modeling approach will provide the relative contribution from both upper and lower parts of the basin.

4. Timeline

No.	ACTIVITY	2010				2011				2012				2013				2014			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1	PROPOSAL PREPARATION		■	■																	
2	LITERATURE REVIEW		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
3	STAKE-HOLDERS MEETING				■																
4	FIELD WORK :				■	■															
	1. Land use/cover data				■	■	■	■	■	■	■	■	■								
	2. Hydro-meteorological Data				■	■	■	■	■	■	■	■	■								
	3. Water Quality Data collection				■	■	■	■	■	■	■	■	■								
5	ANALYSIS AND WRITE UP																				
	1. CLIMATE vs HUMAN ABSTRACTIONS ON HYDROLOGY					■	■														
	2. CLIMATE vs LAND USE/COVER ON HYDROLOGY							■	■	■											
	3. EVAPOTRANSPIRATION CHANGES ON HYDROLOGY										■	■	■								
	4. LAND USE/COVER vs WATER QUALITY													■	■						
6	CONFERENCE PROCEEDINGS AND JOURNAL PUBLICATIONS																				
	1. CLIMATE vs HUMAN ABSTRACTIONS ON HYDROLOGY							■													
	2. CLIMATE vs LAND USE/COVER ON HYDROLOGY									■											
	3. EVAPOTRANSPIRATION CHANGES ON HYDROLOGY												■								
	4. LAND USE/COVER vs WATER QUALITY															■					
7	THESIS PREPARATION AND SUBMISSION															■	■				

Key

■ The timeline is divided into activities to be undertaken and corresponding start period. An individual year is divided into quarters with each quarter being equal to 3 months.

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6. Appendices

Appendix 1: Discharge data

No.	Name of RGS	Code	Data record available	Remarks
1.	MALEWA-GILGIL	2GB01	JULY/31 - AUG/85	* START-97
2.	MALEWA-GILGIL	2GB02	XX	CLOSED
3.	MALEWA	2GB03	SEP/50 - DEC/92	
4.	WANJOHI	2GB04	JAN/61 - JUN/94	*63 - 73 NO RECORD
5.	MALEWA	2GB05	DEC/58 - JUN/88	
6.	MALEWA	2GB07	JAN/60 - JUL/94	
7.	TURASHA	2GC04	AUG/50 - DEC/92	
8.	NANDARASI	2GC05	JULY/58 - MAR/94	
9.	TURASHA	2GC07	SEP/50 - NOV/93	
11.	GILGIL	2GA03	DEC/58 - DEC/94	
12.	GILGIL	2GA05	DEC/59- FEB/88	* CLOSED
13.	LITTLE GILGIL	2GA06	JAN/68 - NOV/92	
15.	KARATI	2GD07	JAN/62 - OCT/90	

Appendix 2: Rainfall data

STATION NAME	STATION ID	X_COORD	Y_COORD	PERIOD	years
NAIVASHA D.O.	9036002	214500	9920200	1935-2000	64
KEDONG VALLEY, MAAI MAHIU	9036011	232895.8	9891262.9	1926-1972	27
N. KINANGOP FOREST STATION	9036025	236545.6	9935511.5	1937-2000	44
GILGIL RAILWAY STATION.	9036034	202500	9945300	1957-1998	42
KANGARI FARM , NAIVASHA	9036059	219843.2	9928092.2	1957-1974	18
KIRITA FOREST STATION	9036061	236570.6	9891265.5	1957-1998	42
NAIVASHA KONGONI FARM	9036062	195794.8	9909601.7	1967-1991	25
NAIVASHA NANGA GERRI	9036065	225418.9	9915152.1	1957-1981	24
MWEIGA ESTATE	9036072	268163.1	9961292.3	1957-1998	39
NAIVASHA K.C.C. LTD.	9036073	209500	9926205.7	1957-1992	36
TECHNOLOGY FARM, NAKURU	9036076	167914.4	9966798.7	1957-1998	42
NAIVASHA VET.EXPT. STATION	9036081	213000	9928088.5	1957-1998	42
KARAMENO SHOPPING CENTRE N/MORU	9036085	251455.9	9985289.6	1957-1998	30
NAIVASHA MARULA ESTATE	9036109	208500	9929100	1957-1998	42
CHOKEREREIA F.C. SOCIETY	9036129	205018.6	9952093.3	1957-1977	19
ELEMENTAITA,SOYSAMBU ESTATE	9036147	187500	9948325.1	1957-1998	42
GILGIL, KIKOPEY RANCH	9036150	184633.5	9948323.6	1957-1990	34
SUBUKIA PYRETHRUM NURSERY	9036151	184623.1	9996348.4	1957-1998	40
S.KINANGOP NJABINI F.T.C.	9036152	240500	9918700	1957-1998	40
KIJABE RAILWAY STATION	9036162	230997.6	9898562.4	1957-1996	39
S. KINANGOP FOREST STATION	9036164	242120.7	9920692	1957-1998	42
ABERDARE PARK FORT JERUSALEM	9036174	240329.2	9942813.5	1967-1978	12
NAIVASHA KORONGO FARM	9036179	197572.2	9917016.2	1957-1985	29
NAIVASHA KARATI SCHEME	9036183	227310	9918914.3	1957-1975	14
KINANGOP SASUMUA DAM	9036188	240340.8	9917040.8	1957-1996	40
NEW GAKOE FARM (NAKURU)	9036198	184626.5	9970454.8	1957-1975	19
NAIVASHA LONGONOT FARM	9036214	208715.8	9909610.3	1957-1984	26
ELEMENTAITA NDERIT RANGER POST	9036227	180743.3	9953655.1	1957-1997	38
NAKURU LANET POLICE POST	9036236	182533.3	9967302.7	1957-1994	34
GETA FOREST STATION	9036241	233394	9947946	1958-2000	40
DUNDORI FOREST STATION	9036243	191979.1	9972337.6	1958-1998	41
KIENI FOREST STATION	9036244	240347.1	9905979.6	1958-1997	40
MENENGAI FOREST STATION	9036252	175267	9972333.9	1960-1998	39
THOME FARMERS NO.2	9036253	197564.8	9929961.6	1960-1989	28
AVONDALE ESTATE SUBUKIA	9036256	190193.7	9996348.5	1962-1998	37
GATARE FOREST STATION	9036259	251474.6	9920696.6	1963-1998	35
NAKURU METEOROLOGICAL STATION	9036261	177161.6	9970453.1	1964-1998	35
OLARAGWAI FARM NAIVASHA	9036262	215500	9928090.4	1964-1998	35
N. KINANGOP MAWINGO SCHEME	9036264	223622.8	9944687.8	1964-1998	32
MUTUBIO GATE (A.N.PARK)	9036272	239876	9942226	1965-1998	29
MAGURA RIVER	9036277	244002.9	9946575.6	1966-1985	16
RIUNGE HILL	9036278	245893.2	9955756.7	1967-1985	16
CULVERT CAMP	9036279	251460.8	9957638.5	1968-1991	18
CHANIA RIVER,ABERD. NAT. PARK	9036280	245894.9	9950226.3	1969-1985	15
NAIVASHA W.D.D.	9036281	216172.6	9918908.1	1965-2000	36

LONGONOT AKIRA RANCH	9036285	206946.9	9891243.3	1967-1975	9
WANJOHI CHIEF'S CAMP	9036289	223136	9962352	1969-2000	29
MALEWA FARMER'COOP. SOC.	9036290	216155.3	9959398.7	1969-1994	24
NGECHA NEW FARMERS CO-OP.	9036294	206913	9950213.1	1969-1986	10
KURASE HILL ABERDARE PARK	9036296	240323	9963166.1	1970-1985	14
KANGUI SECONDARY SCHOOL	9036307	203117.1	9987055.1	1971-1992	18
NGETHU WATER SUPPLY	9036308	266295.5	9898584.6	1971-1998	27
MITI MINGI FARM	9036309	177172	9941016.9	1972-1985	9
KAMIRITHU FANCY FARM	9036310	169698.8	9961265.8	1972-1998	21
CHAMATA GATE	9036312	225396.1	9977875.4	1973-1998	26
CHEBUSWA HILL	9036313	232858.9	9974226.1	1973-1989	12
SAKUTIEK C.C. OUTPOST	9036317	182763.8	9905940.9	1973-1992	10
MUGUNDA PRIMARY SCHOOL	9036319	243994.9	9981528.2	1974-1994	19
NAISHI RANGER'S POST	9036320	175273.9	9950201.1	1979-1997	16
CRESCENT ISLAND	9036322	210500	9915137.6	1973-1998	21
KIANGANYE FARM ICHICHI	9036323	257041.3	9922579.5	1975-1998	24
OLCHORO AGRI. OFFICE	9036331	167944.8	9907811.1	1980-1997	18
TUMAINI N.Y.S. CAMP	9036336	197549.7	9971400	1981-1998	18
SURURU FOREST STATION	9036337	169709.7	9935479.8	1984-1998	15
OLKARIA GEOTHERMAL STATION	9036343	199477.2	9900420.8	1984-1998	15
Total	65 stations				1833

Appendix 3: List of Instruments contained in the Automatic Flux Station

Instrument Name	Quantity
Soil moisture temperature sensors Decagon 5ET	4
Decagon devices Data logger EM50	1
RH/T sensors Rotronic MP100A	2
Leaf wetness sensor Decagon LWS-L	1
Pressure sensor Setra 276	1
Radiation balance sensor Hukseflux NR01	1
Windmaster 3D anemometer Gill instrument	1
Tipping bucket raingauge 7852M	1
Datalogger Campbell scientific CR3000	1
Relay multiplexer AM16/32B	1
compact flash module CFM100 with 2Gb flash card	1
GSM modem CS-GPRS	1
Soil heatfluxplate HFP01SC	1
Infrared temperature sensor IR100	1
temperature sensors SD-1K-STE-10000-S-05	10
Scintillometer Scintec BLS450	1