QUANTIFYING ECOLOGICAL PRODUCTIVITY AND VALUE OF WATERSHED ECOSYSTEM SERVICES IN CHANIA RIVER BASIN, KENYA

JAMES KIPTANUI RONOH

MASTER OF SCIENCE

(Civil Engineering)

JOMO KENYATTA UNIVERSITY OF

AGRICULTURE AND TECHNOLOGY

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Quantifying Ecological Productivity and Value of Watershed Ecosystem Services in Chania River Basin, Kenya

James Kiptanui Ronoh

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D E C L A R A T I O N

This thesis is my original work and has not been submitted for a degree in any university.

Signature…………………………………….. Date …………………………………

James Kiptanui Ronoh

This thesis has been submitted for examination with our approval as university supervisors.

Signature…………………………………….. Date …………………………………

Dr. Eng. Jeremiah K. Kiptala, PhD

JKUAT, Kenya

Signature…………………………………….. Date …………………………………

Dr. John .K. Mwangi, PhD

JKUAT, Kenya

DEDICATION

Dedicated to my grandmother – Siakwei Chepkieng'. Your relentless push to your grandchild's pursuance for further learning has brought me this far. I pray that God gives you more years on earth that you may keep the challenge alive.

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ABBREVIATIONS AND ACRONYMS

AET	Actual Evapotranspiration
AGB	Above Ground Biomass
CICES	Common International Classification of Ecosystem Services
DEM	Digital Elevation Model
DRO	Direct Runoff
EPIC	Environmental Policy Integrated Climate
ET	Evapotranspiration
GIS	Geographical Information System
GIT	Geographical Information Technologies
GPS	Geographical Positioning System
HRU	Hydraulic Response Units
ILRI	International Livestock Research Institute
IWRM	Integrated Water Resources Management
LAI	Leaf Area Index
LCSCMP	Lower Chania Sub-Catchment Management Plan
MA	Millennium Ecosystem Assessment
MAES	Mapping and Assessment of Ecosystem Services
MU	Management Units
NDVI	Normalized Difference Vegetation Index
NIR	Near-infrared
P	Precipitation
P3DM	Participatory 3-Dimentional Mapping
PGIS	Participatory Geographical Information System

PET	Potential Evapotranspiration
RGS	River Gauging Station
RO	Runoff
ROI	Regions of Interest
RP	Revealed Preference
RUE	Radiation Use Efficiency
SEEA	UN Systems of Environmental-Economic Accounts
SDG	Sustainable Development Goals
SWIR	Shortwave Infrared
SMF	Snow Melt Fraction
SP	Stated Preference
SR	Simple Ratio
STC	Soil-Moisture Storage Capacity
STW	Soil-Moisture Storage Withdrawal
SVIs	Spectral Vegetation Indices
SWAT	Soil and Water Assessment Tool
TEEB	The Economics of Ecosystems and Biodiversity
TEV	Total Economic Value
UNEP	United Nations Environment Programme
UMRW	Upper Mississippi River Watershed
UPRW	Upper Pearl River Watershed
USGS	United States Geologic Survey
WTA	Willingness to Accept
WTP	Willingness to Pay

WRMA	Water Resource Management Authority
WRUA	Water Resources Users Association

A B S T R A C T

The Millennium Ecosystem Assessment indicates that most ecosystems and the services associated are declining globally. This has triggered a wide range of research on innovative ways to characterise, quantify, and value –these ecosystem services across a range of scales for better and sustainable management. Ecosystem services are often related to biophysical features of a catchment or watershed (Precipitation, evapotranspiration, topography, soil, biomass productivity). According to Global Water Partnership, the biophysical provisioning ecosystem services either at watershed, continental, sub global or global scale is constrained by data availability. This study was carried out in the Chania River catchment in Kenya with the objective to quantify the watershed ecosystem services and their related values. Geographic Information System (GIS) and Remote Sensing (RS) technology were used to quantify biomass at spatial-temporal scales using 30-m resolution Landsat images. Normalized Difference Vegetation Index (NDVI) was used as a proxy for determining above ground biomass (AGB) while Thornthwaite model was used to determine actual water use (ET_a). Predictive equations relating NDVI and AGB provided good correlations with R^2 values ranging between 0.66 and 0.90. The estimated AGB compared well with measured AGB, with 62% of the validation points giving deviations of less than 15%, and maximum deviations of below 31%. Forests and wetlands had the highest annual ET_a values of 921.8mm and 919mm, while coffee and mixed crops had the lowest values of 819.5 and 801. 9mm.Young forests, mature forests and tea had the highest value of biomass water productivity 0.085, 0.025, 0.018 kg/m3 and shrub and maize had the lowest at 0.002 kg/m3. The results revealed a substantive decline of forest cover by 7.78% in 11 years with a steep increase in built up areas, areas under tea, coffee and maize. The precipitation in the catchment showed a negative trend which was attributed the reduced forest cover.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Ecosystem services are the benefits that human beings derive from the natural environment. Millennium Ecosystem Assessment (MEA) of 2005 grouped the ecosystem services into five broad groups; Provisioning, regulating, cultural and supporting services. The Economics of Ecosystem and Biodiversity (TEEB, 2011) and the Common International Classification of Ecosystems Services (Haines-Young, 2013) further refined the categories of ecosystem services and goods. All of them maintained provisioning services as the key category of ecosystem services. The examples of the ecosystem services given are biomass (food, raw materials, medicinal resources and ornamental resources), water for drinking and water for non-drinking purposes.

Liu *et al*. (2012) recognises watersheds as sources of ecosystem services listed in the paragraph above. It is however a challenge to achieve effective and sustainable balance between human and ecological needs for freshwater in these watersheds as noted by Poff *et al.* (2003). The population growth and climate change has in addition imposed constraints on both spatial and temporal distribution of water resulting in increased competition for declining water resources (UNEP, 2012).

According to Global Water Partnership (2012), the biophysical provision of ecosystem services at continental, sub global or global scale is in general constrained by data availability. An attempt to produce a global map of ecosystem services was presented by Naidoo *et al*. (2008) who succeeded in mapping four proxies: carbon storage and sequestration, grassland production for livestock and fresh water provision. MEA, (2005), and its follow-up projects such as 'The Economics of Ecosystems and Biodiversity (TEEB, 2010) raised awareness of ecosystem services in the scientific community, its stakeholders and decision-maker circles. In the context of planning and decision support however, geographical mapping of services has been one of the challenges. United States Geological Survey and Esri (USGS &

Esri, 2014) published the global ecological land unit map. However, these maps provide limited information on the ecosystem services provided in each individual watershed, having in mind that watersheds have been recognised as the source of the services.

In Kenyan context, the World Resources Institute, the Department of Resource Surveys and Remote Sensing, Ministry of Environment and Natural Resources, the Central Bureau of Statistics, Ministry of Planning and National Development, Kenya, and the International Livestock Research Institute (ILRI) produced the atlas of Ecosystems and Human well-being for Kenya, in May 2007 based on MEA (2005). The atlas focused to integrating spatial data on poverty and ecosystems in Kenya. The parameters mapped were spatial patterns of poverty and human well-being, water, food biodiversity, tourism and wood. All these parameters were mapped at national level without elaboration of the ecosystem services that affect human well-being at the local/watershed level. ILRI (2011) did a valuation and mapping exercise. However, their mapping was confined to the Ewaso Ngiro watershed biased on livestock and the arid and semi-arid lands only.

Chania River has not been exempted from the challenges of inefficient and unsustainable use of ecosystem services. The Lower Chania Sub-Catchment Management Plan of 2010 has listed water scarcity, pollution, deforestation, siltation, over abstraction, water unfriendly vegetation, inadequate water infrastructure, water related conflicts among other problems in the watershed. Several studies have been done in the catchment in an effort to counter these challenge. Most of these studies however have focused on pollution. These studies have been done by (Karuri *et al.*, 2003; Mwangi *et al.*, 2013). The two studies indicated that there was pollution in the river system, however they did not capture the available water and how this pollution would impact on the availability of water as a provisioning service. In order therefore to clearly understand the distribution, capacity, constraints and value of ecosystem services it is necessary to carry out a study to quantify and value ecosystem services and present them spatially in temporal and spatial form. This research therefore focused on the distribution, quantities and values of ecosystem services and goods on a landscape in temporal and spatial scale in the Chania river basin. It has also evaluated how ‘natural infrastructure’ (e.g., wetlands, floodplains, forests) and built water infrastructure (e.g., dams, levees, irrigation channels) interact in the Chania ecosystem and contribute to poverty reduction, water-energy-food security, biodiversity conservation, and climate resilience at a watershed scale. This will provide information to the user on the capacity of the watershed to provide ecosystem services. In addition, it will provide information to policy makers and enforcers on the areas to give attention in order to allow the watershed provide the ecosystem services sustainably.

1.2 Problem statement

According to the Lower Chania Sub-Catchment Management Plan (SCMP, 2010), the hydrology of the sub catchment is greatly influenced by climate variability, topography, land use among other ecosystem functions which have impacted the resource quality and quantity.

The plan reveals that Lower Chania River and its tributaries have about 103 known abstractors drawing nearly 444,417m^3/day for domestic, irrigation and commercial purposes. There is also a significant number of illegal water abstractors in the sub-catchment which has led to over abstraction by the abstractors upstream without taking consideration of the water users downstream. The SCMP indicates that the available water resource within Lower Chania sub catchment currently does not adequately meet demand due to increasing population with diminishing water resource quantity especially during dry period. There are occasional conflicting water uses such as domestic, livestock, irrigation, environment, commercial among others. In addition to the aforementioned problems, there is also no water allocation plan in place which has resulted in water-related conflicts. All these uses therefore need to be reconciled in order to proportionately address the demands for every use.

Pollution also occurs at different points. The main point sources of pollution within the Sub-catchment includes pollution from agro-based industries like coffee factories and car washing. Quarrying near the River banks is a factor that has a potential negative impact on the quality of the catchment’s water resource as well. Most springs within the sub-catchment are also not developed nor protected additionally lowering the water quality. Sewage in the catchment area is not treated adequately before discharge leading to further deterioration of water quality. These challenges that affect water quality further reduces the quantity of water that is available for use.

According to Lower Chania Sub-catchment management plan, there is severe data gap in the catchment essential for sustainable water resource management. This is a serious challenge since data is essential in exploiting the highest benefits of ecosystem services within a catchment while ensuring that the catchment ecosystem is conserved.

These problems have had an impact in the sustainable production and utilization of ecosystem services and goods. By quantifying the ecosystem services and goods both in spatial and temporal scales, there will be enhanced understanding of how availability of these services change over time. It will also contribute to understanding the potential of the ecosystem to provide certain goods and services. Quantification of ecosystem goods and services will form the basis of deriving their value.

Evaluating how built and natural infrastructure affect the provision ecosystem services will ensure that they bear no negative impacts on the water resources.

1.3 Objectives

1.3.1. Overall objective

The main objective was to quantify the watershed ecosystem services of the Chania river system and their related socio-economic values.

1.3.2. Specific objectives

i. To identify and differentiate by gender the most important watershed ecosystem services of the Chania river system
ii. To spatially quantify the ecological production and related ecosystem services generated by the river system
iii. To value the spatial biophysical productivity of the Chania river system

iv. To evaluate the impacts of built infrastructure on the natural ecosystem provisioning services

1.4 Research questions

i. What are the main services produced by the watershed ecosystem?
ii. What is the spatial productivity of the various ecosystem services generated in the catchment?
iii. What is the value of the ecosystem services?
iv. What is the impact of built infrastructure on the ecosystem services provided by the catchment?

1.5 Justification

Mapping of ecosystem services helps in conceptualizing the ecosystem services in a landscape. One of the goals of the conceptualization of ecosystem services is to make more visible the key role that biodiversity and ecosystem functions play to support multiple human benefits, such as nutrition or safety. Understanding the linkages between the natural and socio-economic systems can lead to appreciation and, consequently, to improved protection and management of ecosystems (Alahuhta *et al.*, 2013).

The understanding on how different ecosystem functions link to the ecosystem services while taking into account other ecosystems functions that affect the services such as topography, land use, climate variability, hydropower, fishing etc. will result into fair allocation based on facts.

Mapping will also increase the understanding of the watershed by filling the data gaps that have been clearly stated by the catchment management plan as an impediment to sustainable water resource management in the catchment. Without these maps users, policy makers and other stakeholders in the catchment may not visualize the degree and rate of catchment degradation nor the potential of the catchment to provide crucial ecosystem services that improve human well-being.

1.6 Scope and limitations

The research was carried out in the Chania river basin. Participatory GIS mapping was carried out in three areas; one upstream, another one mid-stream and the last one downstream. The research only focused on watershed provisioning ecosystem services that are of importance in different agro-ecological zones. Using indicators from literature these goods and services were quantified and valued. An evaluation on the influence of built and natural infrastructure on this goods and services was also done.

One limitation which affected the methodology of this study is that the daily data that was available had severe gaps as well and the latest data was not available. Monthly data was therefore used in water balance analysis.

CHAPTER TWO

LITERATURE REVIEW

2.1 General theory of ecosystem services

2.1.1 Ecosystem services

MA, 2005 defines ecosystem services as the benefits people obtain from ecosystems. TEEB, 2010 defines ecosystem services as direct and indirect contributions of ecosystems to human well-being.

There are 3 classification systems available to classify ecosystem services: MA (2005); TEEB (2010); CICES (2013).

MA (2005) classified the ecosystem services into four broad categories:

- Provisioning services – These are products obtained directly from ecosystems, such as food, fresh water, fuel, wood, fibre, and medicine.
- Regulating services – These are benefits obtained by regulating ecosystem processes, such as climate, floods, disease, and water quality.
- Cultural services – Material and non-material benefits derived from ecosystems, such as aesthetic, spiritual, educational, and recreational.
- Supportive services – Species life cycle maintenance, genetic diversity.

MA, 2005 was the first large scale ecosystem service assessment. It created the framework which was adopted and refined by the TEEB and CICES.
Following the MA classification, TEEB (2010) proposed four main categories of 22 typologies of ecosystem services:

- Provisioning services
- Regulating services
- Habitat services
- Cultural and amenity services

TEEB did not include supporting services, which it considers as a subset of ecological processes. In its place, habitat services have been identified as a separate category. This was done to emphasize the importance of ecosystems to provide habitat for migratory species (e.g. as nurseries) and gene-pool “protectors” (e.g. natural habitats allowing natural selection processes to maintain the vitality of the gene pool).

The CICES (2013) offers a structure that links with the framework of the UN System of Environmental-Economic Accounts (SEEA). It builds on MA (2005) and TEEB (2010) classifications but focusses on the ecosystem service dimension. In the CICES system services are either provided by living organisms (biota) or by a combination of living organisms and abiotic processes. Abiotic outputs and services, e.g. provision of minerals by mining or the capture of wind energy, can affect ecosystem services but they do not rely on living organisms for delivery.

CICES (2013), in page iii, clearly shows biomass as one common indicators to quantify a number of ecosystem services.

2.2. Spatial indicators for ecosystem services

Maes *et al.* (2013) collected spatially explicit indicators for 13 ecosystem services. For each service they identified indicators for service capacities and service flows, benefits derived from each service, biodiversity components that are essential to sustain the generation of this services and the contributing land cover classes using CORINE land cover data.

Provisioning services supplying food, fibre and water are summarised in the table below.

Table 2.1: Definition and indicators expressing the capacity, flow and benefits of timber, crop production, livestock production and water provision

Capacity	Flow	Benefits	Biodiversity
Timber			
Forest capacity to produce timber Timber stock (ha, m^2)	Timber increment Average dry matter productivity in the forests (m^2 $year^{-1}$)	Production for fuel production and paper Round wood production (m^2 $year^{-1}$)	Forest connectivity Conservation status of forest Tree species diversity
Crops			
Potential production agro – ecosystems Total area of crop land (ha) Agricultural limits for soil (ha)	Realised crop production (ton ha^{-1} $year^{-1}$)	Realised crop production (ton ha^{-1} $year^{-1}$)	Genetic diversity in crops and wild crops diversity
Livestock			
Potential livestock production The total area of grasslands suitable for grazers The density of grazing livestock	Total livestock production derived from grazing on (unimproved) grassland (ton ha^{-1} $year^{-1}$)	Livestock production of grazers (ton ha^{-1} $year^{-1}$)	Genetic diversity in livestock species
Water Provision			
Excess of precipitation of a landscape which will constitute flow of blue water downstream	Water balance (mm)	Total annual freshwater consumption per sector	

Source:, Maes *et al.* (2013)

2.3 Water related ecosystem services

MEA, TEEB and the MAES have covered a lot in regard to the assessment of ecosystem services. In mapping Chania watershed, the interest of this thesis are ecosystem services that are related to water and aquatic ecosystem services. Brauman *et al*. (2007) discussed the 'hydrologic ecosystem services' defined as the ecosystem services that "encompass the benefits to people produced by terrestrial ecosystem effects on freshwater" and Maes *et al.* (2013) analysed the 'ecosystem services by typology of the ecosystems' with a consideration to the services delivered by lakes, rivers, groundwater and wetlands in the freshwater pilot study, and those provided by transitional waters, coastal waters, shelf waters and open ocean in the marine pilot study. Brauman *et al.* (2007) characterized hydrological ecosystems by hydrological attributes such as quality, quantity, spatial and temporal distribution. Before Maes *et al.* (2014), Kreeler *et al.* (2012) had earlier described in detail the water-quality related ecosystems.

Water related ecosystem services were more generally addressed by Guswa *et al.* (2014). The link between the hydraulic modelling and ecosystem services related to water was discussed in Guswa et al's study.

2.4 Participatory Geographical Information System (GIS) mapping

Participants in the Mapping for Change International Conference (PGIS'05) which took place in Nairobi, Kenya in September 2005, defined Participatory GIS (PGIS) as an emergent practice in its own right; developing out of participatory approaches to planning and spatial information and communication management. PGIS resulted from the merger of Participatory Learning and Action (PLA) methods with Geographic Information Technologies (GIT). PGIS uses a combination of geo-spatial information management tools and methods such as sketch maps, Participatory 3D Models, aerial photographs, satellite imagery, Global Positioning Systems (GPS) and Geographic Information Systems (GIS) to represent peoples' spatial knowledge in the forms of virtual or physical, two- or three-dimensional maps used as interactive vehicles for spatial learning, discussion, information exchange, analysis, decision making and advocacy.

Participatory GIS implies making GIT available to disadvantaged groups in society in order to enhance their capacity in generating, managing, analysing and communicating spatial information.

PGIS practice results in empowerment of the community through user-friendly and integrated applications of geo-spatial technologies which target their demands. The practice integrates several tools and methods whilst often relying on the combination of ‘expert’ skills with socially differentiated local knowledge. It promotes interactive participation of stakeholders in generating and managing spatial information and it uses information about specific landscapes to facilitate broadly-based decision making processes that support effective communication and community advocacy.

According to McCall 2004, there are more than 500 published examples of applying P-mapping or P-GIS in rural local resource situations, and hundreds more examples of urban community implementation. These applications are mainly in natural resource identification and management (especially forests), or for instance, environmental hazard mapping. P-GIS has also been used for legitimising customary land and resource claims, e.g. Canada, USA, Australia, New Zealand, Philippines, Indonesia, South Africa, Brazil and Peru. In the Philippines, community GIS resulted in strengthening Ifugao community groups when preparing for negotiations with provincial & municipality authorities ancestral lands (Gonzalez, 2000). P3DM (participatory 3-dimensional mapping) has been used in the Philippines for conflict analysis and resolution between indigenous groups, which should reduce possibilities of inter-group warfare over land resources. In Cameroon, P-mapping and P-GIS applied to the regularisation of communities’ customary entitlements to forest land - 2 phases from the Tinto case (Minang & McCall, 2003)

In these studies however there are limited information and specifically in Kenya where PGIS has been used to map ecosystem services.

2.5 Land use and land cover maps

Land Use and Land Cover (LULC) mapping has over the years been used to describe various categories of land use activities on the earth surface to aid water resources management in various watershed. FAO (1999) describes Land use as the arrangements, activities and inputs people undertake in a certain land cover type to produce change or maintain it. Contemporary methods of developing LULC maps usually utilize remotely sensed data usually space-borne platforms and recently aerial platforms. A selection criterion for the platform to be used is usually dependent on data availability and usage. The spatial and temporal resolution of the data used in the land use will determine the extent of detail and quality of the LULC and will be dependent on the intended usage. For example, LULC used for agricultural land management will have higher resolution than used in climate studies.

Satellite platforms are the commonly used platforms as compared to the aerial platforms due their availability, temporal resolution and less restriction in acquisition. In selecting the best satellite platform to use for LULC generation, there are aspects considered which in the end determine quality of the Land Use Land Cover generated. These are; -

Spatial resolution is the ability to distinguish between two closely spaced objects on an image. It is the minimum distance between two objects at which the images of the objects appear distinct and separate. Objects spaced together more closely than the resolution limit will appear as a single unit on the image (Sabins, 1987). In a more specific way, spatial resolution can be said to be the limit on how small an object on the earth's surface can be and still be "seen" by a sensor as being separate from its surroundings i.e. how well a sensor can record spatial detail. Examples are MODIS 250-m, Landsat 30-m, SPOT images 10-m, Sentinel (ESA) 10-20m.

Radiometric resolution is the ability to discriminate very slight differences in electromagnetic radiation energy. The finer the radiometric resolution of a sensor, the more sensitive it is to detecting small differences in reflected or emitted energy.

Temporal resolution is the revisit period of a satellite to image the same portion of the earth within a given period. This is usually important while choosing the best satellite platform especially when carrying out change detection of a specific theme such as a natural resource.

Temporal resolution is crucial especially where particular study seeks to investigate change detection within a given duration on the same area of study. Bearing this in mind this study thus sought to use the best platform with regard to cost and time constraints

To determine the various LULC types in the watershed from the satellite ground training data is needed. The training data is dependent on the vegetation growth and cropping calendar of various LULC types.

2.6 Net biomass production of yield

The net biomass production of yield of crops is defined as the total plant dry matter and the dry matter of economically useful portion respectively that can be produced by healthy crops when adequately supplied with water and nutrients. These useful portions are the goods that can then be said to be derivatives of the ecosystem. According to the three classification systems, biomass provides provisioning ecosystem services in form of nutrition, material and energy.Net biomass production of yield is therefore a good indicator to measure provisioning services that are linked to biomass.

The procedure for calculating the net biomass production and yield of crops, uses information on the climatic factors of radiation and temperatures within the growing periods together with the photosynthesis capacity of crops and the fraction of the net biomass which crops convert into economically useful yield.

To the extent that the upper agronomic limit of crop performance can be computed for a given area, the estimated values also reflect the present agronomic potential of the constraint-free climatic resources under consideration.

Although the upper limit of crop performance is set by the climatic characteristics of radiation and temperature, the extent to which it can be reached is determined by the quality of the genetic resources of the crop in question.

2.7 Gross and net biomass production

In order to calculate the net biomass production (B_n) of a crop, an estimation of the gross biomass production (B_g) and respiration loss (R) is required (Equation 2.1):

$$B_n = B_g - R \quad \text{...} \quad (2.1)$$

The equation relating the rate of net biomass production (b_n) to the rate of gross biomass production (b_g) and the respiration rate (r) is (Equation 2.2):

$$b_n = b_g - r \quad \text{...} \quad (2.2)$$

The maximum rate of net biomass production (b_{nm}) is obtained when the crop fully covers the ground surface. The period of maximum net crop growth, i.e., the point in time when maximum net biomass increments occur, is indicated by the inflection point of the cumulative growth curve. When the first derivative of net biomass growth is plotted against time the resulting graph resembles a normal distribution curve. The model assumes that the average rate of net production (b_{na}) over the entire growth cycle is half the maximum growth rate, i.e., $b_{na} = 0.5b_{nm}$. The net biomass production for a crop of N days (B_n) is then (Equation 2.3):

$$B_n = 0.5b_{nm}xN \text{..} \quad (2.3)$$

The maximum rate of gross biomass production (b_{gm}) is related to the maximum net rate of CO_2 exchange of leaves (P_m) which is dependent on temperature, the photosynthesis pathway of the crop, and the level of atmospheric CO2 concentration.

For a standard crop, i.e., a crop in adaptability group I (FAO, 1999) with P_m = 20 kg ha $^{-1}$ hr $^{-1}$ and a leaf area index of LAI = 5, the rate of gross biomass production b_{gm} is calculated from the Equation 2.4:

$$b_{gm} = Fxb_o + (1 - F)\, b_c \text{...} (2.4)$$

Where:

F = the fraction of the daytime the sky is clouded,

$F = \frac{(A_c - 0.5R_g)}{0.8\,A_c}$, where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal cm-2 day-1).

b_o = gross dry matter production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965).

b_c = gross dry matter production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg ha^{-1} day^{-1}) (de Wit, 1965).

When P_m is greater than 20 kg ha^{-1} hr^{-1}, b_{gm} is given by Equation 2.5:

$$b_{gm}=F(0.8 + 0.01P_m)b_o+ (1 - F)(0.5 +0.025\,P_m)b_c \quad ....(2.5)$$

When P_m is less than 20 kg ha^{-1} hr^{-1}, b_{gm} is calculated according to Equation 2.6:

$$b_{gm} = F(0.5+0.025P_m)\,b_o + (1 - F)\,(0.05\,P_m)\,b_c \quad ....(2.6)$$

To calculate the maximum rate of net biomass production (b_{nm}), the maximum rate of gross biomass production (b_{gm}) and the rate of respiration are required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate (r_m) is (Equation 2.7):

$$r_m = kb_{gm} + cB_m \quad ....(2.7)$$

Where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non-legume crops k equals 0.28. However, c is temperature dependent and differs for the two crop groups. At 30 °C, factor c30 for a legume crop equals 0.0283 and for a non-legume crop 0.0108. The temperature dependence of ct for both crop groups is modelled with a quadratic function (Equation 2.8):

$$c_t = c_{30}\,(0.0044+0.0019T+0.0010T^2) \quad \text{......} \quad (2.8)$$

It is assumed that the cumulative net biomass B_m of the crop (i.e., biomass at the inflection point of the cumulative growth curve) equals half the net biomass that would be accumulated at the end of the crop's growth cycle. Therefore, we set B_m = 0.5 B_n , and using (3), B_m for a crop of N days is determined according to Equation 2.9:

$$B_m = 0.25b_{nm} \text{ x } N \quad \text{......} \quad (2.9)$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (b_{nm}) or the rate of net dry matter production at full cover for a crop of N days becomes (Equation 2.10):

$$b_{nm} = \frac{0.72bgm}{1 + 0.25\,ctN} \text{......} (2.10)$$

Finally, the net biomass production (B_n) for a crop of N days, where $0.5b_{nm}$ is the seasonal average rate of net biomass production, can be derived as in Equation 11:

$$B_n = \frac{(0.36bgmxL)}{(1/N + 0.25c_t)} \quad \text{......} \quad (2.11)$$

Where:

b_{gm} = maximum rate of gross biomass production at leaf area index (LAI) of 5

L = growth ratio, equal to the ratio of bgm at actual LAI to bgm at LAI of 5

N = length of normal growth cycle

c_t = maintenance respiration, dependent on both crop and temperature according to Equation (2.8)

2.8 Crop yield

Potential yield (Y_p) is estimated from net biomass

(B_n) using Equation 2.12:

$$Y_p = H_i x B_n \quad (2.12)$$

Where:

H_i =harvest index, i.e., proportion of the net biomass of a crop that is economically useful.

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over the crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis P_m, (c) length of growth cycle (from emergence to physiological maturity), (d) length of yield formation period, (e) leaf area index at maximum growth rate, and (f) harvest index.

Biologically crops consume water for evapotranspiration (ET), and the rest of supplied water does not participate in the yield formation. In order to assess the productivity of ET, Equation 2.13 is used (Abdullaev *et al*., 2004):

$$W_p = \frac{Crop\ Yield}{ET} \quad (2.13)$$

2.9 Use of remote sensing in estimating biomass

Remote sensing techniques have become prevalent in the recent years in estimating Above Ground Biomass (AGB) (Nelson *et al.*, 2009). The complexity of vegetation structures results in highly variable standing stocks of AGB and an even more variable rate of AGB accumulation following a deforestation event.

Different approaches, based on (1) field measurement (Brown *et al.*, 1989; Brown & Iverson, 1992; Houghton *et al.*, 2001; Brown, 2002), (2) remote sensing (*Nelson et al.*, 2009) and (3) GIS (Brown & Gaston, 1995) have been applied for AGB estimation. Traditional techniques based on field measurement are the most accurate ways for collecting biomass data. A sufficient number of field measurements is a prerequisite for developing AGB estimation models and for evaluating the AGB estimation results. However, these approaches are often time consuming, labour intensive, and difficult to implement, especially in remote areas; also, they cannot provide the spatial distribution of biomass in large areas. GIS-based methods using ancillary data are also difficult because of problems in obtaining good quality ancillary data, indirect relationships between AGB and ancillary data, and the comprehensive impacts of environmental conditions on AGB accumulation. Hence, GIS-based approaches have not applied extensively for AGB estimation. The advantages of remotely sensed data, such as in repetitively of data collection, a synoptic view, a digital format that allows fast processing of large quantities of data, and the high correlations between spectral bands and vegetation parameters, make it the primary source for large area AGB

The possibility of estimating biomass and LAI by satellite remote sensing has been investigated in several studies at various spatial scales and environments (Brown *et al.,* 2000; Brown 2001; Chen *et al.,* 2002). The most frequently used remote sensing data continue to be from the optical moderate resolution sensors, like Landsat Enhanced Thematic Mapper Plus (ETM+).

In general, Spectral Vegetation Indices (SVIs) attempt to enhance the spectral contribution of vegetation while minimising that of the background. SVIs using some combination of red and near-infrared (NIR) reflectance, like the simple ratio (SR) and the normalised difference vegetation index (NDVI) have been particularly popular. However, the empirical relationships are affected by various factors, including canopy closure, understory vegetation and background reflectance A set of soil-adjusted vegetation indices have been developed to reduce the effects of the soil background reflectance (Major *et al.,* 1990; Qi *et al.,* 1994; Rondeaux *et al.,* 1996). Furthermore, some studies have stated that the inclusion of the shortwave infrared (SWIR) into the SVIs would unify different cover types and reduce the background effects (Nemani *et al.,* 1993; Brown *et al.,* 2000). It is obvious that the effect of the background reflectance is pronounced in the treeline, where canopy closure varies considerably (Brown, 2000).

Table 2.2: Spectral Vegetation Indices and related formulas

SVI	Equation	Reference
DVI	$NIR - Red$	Tucker (1979)
SR	$\frac{NIR}{Red}$	Birth and McVey (1968)
NDVI	$\frac{NIR - Red}{NIR + Red}$	Rouse *et al.* (1973)
RDVI	$\sqrt{NDVI * DVI}$	Roujean and Breon (1995)
GEMI	$\eta(1 - 0.25\eta)\frac{Red - 0.125}{1 - Red}$; $\eta = \frac{2(NIR^2 - Red^2) + 1.5 * NIR + 0.5 * Red}{NIR + Red + 0.5}$	Pinty and Verstraete (1992)
MSI	$\frac{SWIR}{NIR}$	Rock *et al.* (1986)
$NDVI_c$	$\frac{NIR - Red}{NIR + Red}\left(1 - \frac{SWIR - SWIR_{min}}{SWIR_{max} - SWIR_{min}}\right)$; $SWIR_{min}$ and $SWIR_{max}$ are the minimum and maximum reflectances observed in the field plots.	Nemani *et al.* (1993)
RSR	$\frac{NIR}{Red}\left(1 - \frac{SWIR - SWIR_{min}}{SWIR_{max} - SWIR_{min}}\right)$; $SWIR_{min}$ and $SWIR_{max}$ are defined as in $NDVI_c$	Brown *et al.* (2000)
SAVI	$(1 + L)\frac{NIR - Red}{NIR + Red + L}$; L was set to 0.5	Huete (1988)
OSAVI	$(1 + L)\frac{NIR - Red}{NIR + Red + L}$; L was set to 0.16	Rondeaux *et al.* (1996)
SAVI2	$\frac{NIR}{Red + b/a}$; b was set to 0.025 and a to 1.25	Major *et al.* (1990)
MSAVI2	$NIR + 0.5 - \sqrt{(NIR + 0.5)^2 - 2(NIR - Red)}$	Qi *et al.* (1994)

Source: Heiskainen, (2005)

2.10 Water balance for different agro-ecological zones

The source of water in any ecological zone is the hydrological process that is driven by temperature, precipitation and evapotranspiration. The water that enters the ecological system can be retained as storage or flow as runoff. In principle the water that enters the system must equate the water that is stored in the system and the water that flows as runoff. The interaction of these parameters in a hydrologic system is known as the water balance.

Equation 2.14 is the general water balance equation:

$P = RO + ET + \Delta S$ .... (2.14) *Or*

$P\text{-}ET = (RO + \Delta S) =$ *Water yield* .... (2.15)

Where P is precipitation, RO is runoff, ET is evapotranspiration, ΔS is the change in storage (in soil or the bedrock)

Equation 15 uses the principles of conservation of mass in a closed system, whereby any water entering a system (via precipitation), must be transferred into either evaporation, surface runoff (eventually reaching the channel and leaving in the form of river discharge), or stored in the ground. This equation requires the system to be closed, and where it isn't (for example when surface runoff contributes to a different basin), this must be taken into account.

Gregory and Steven (2007) represented these in the Thornthwaite Monthly Water-Balance model

A water balance can be used to help manage water supply and predict where there may be water shortages. It is also used in irrigation, runoff assessment, flood control and pollution control. Further it is used in the design of subsurface drainage systems which may be *horizontal* (i.e. using pipes, tile drains or ditches) or *vertical* (drainage by wells).To estimate the drainage requirement, the use of an hydrogeological water balance and a groundwater model may be instrumental.

The water balance can be illustrated using a water balance graph which plots levels of precipitation and evapotranspiration often on a monthly scale.

The ET values are often different in every agro-ecological zone. Several monthly water balance models had been developed for several conditions and purposes.

2.11. Water balance Toolbox (v.2) for ArcGIS

A water balance (or budget) explores the interactive relationship between energy and moisture at a place, by modelling moisture demand (potential evapotranspiration) and supply (precipitation and soil moisture storage). The ArcGIS toolbox computes a complete monthly water balance for each pixel within a digital elevation model, using readily-available data layers.

The water balance tool computes potential evapotranspiration using the Turc method.

$$PET = 0.013 \{T/ (T+15\} \{R_S+50\}$$

Where PET= monthly potential evapotranspiration in mm, T= normal monthly temperature in ^oC, and R_s= monthly global radiation received at the earth's surface, in Cal cm^{-2}.

The toolbox then computes soil moisture storage, actual evapotranspiration, soil moisture deficit, and soil moisture surplus for every grid cell within a DEM, using the Thornthwaite-Mather approach.

2.11.1. Water balance toolbox data requirements

Data requirements for performing a water balance using GIS are few: a digital elevation model (DEM), soil available water capacity (AWC), and monthly temperature, precipitation, and solar radiation.

2.12. Valuation of ecosystem services

The value is "the contribution of an action or object to user-specified goals, objectives, or conditions" (MA, 2005). Valuation is the process of attributing a value. The value of ecosystem services is the relative contribution of ecosystem to the goal of supporting sustainable human wellbeing. Any decision involving trade-offs of ecosystem service implies valuation.

The concept of value should not be merely restricted to monetary value but a larger range of values. If restricting the value of ecosystem services to economic value, we risk to fail accounting all value dimensions and environmental components (trade-offs) of policy decision (Kreeler *et al.*, 2012). The non-monetary values of nature, such as inherent, fundamental values, can be neglected in the assumption that the natural capital can be substituted by other capital. Other valuation methods (non-monetary) should be adopted to account for values other than instrumental values.

These values are considered in a Total Economic Value (TEV) framework, which takes into account both the use and non-use values individuals and society gain or lose from marginal changes in ecosystem services.

Figure 2.1 illustrates some of the complex interactions between services and their economic endpoints in a wetland context. For example, an ecosystem service provided by wetlands is filtration of water, which improves water quality; a resulting benefit to society that can be valued is cleaner drinking water. An economic analysis is the last stage of an often detailed qualitative and quantitative impact assessment.

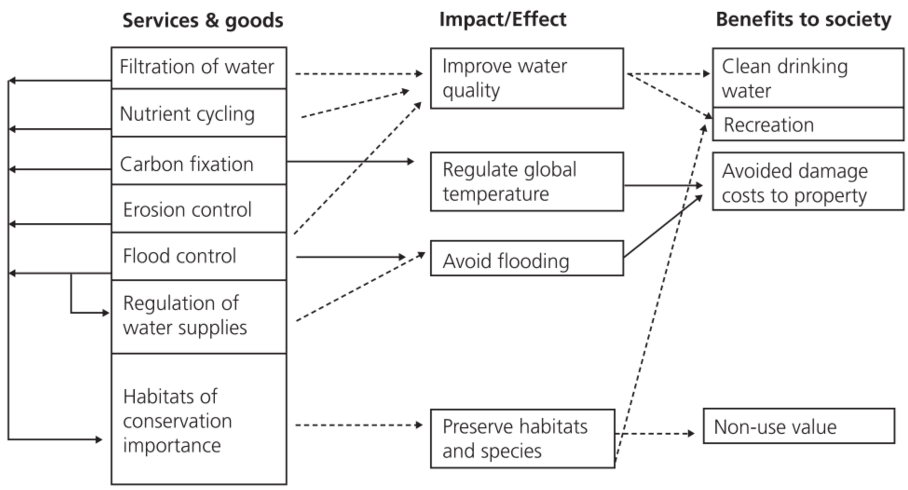

Figure 2.1: Wetland functions interactions

Source: R. Price (2007)

The value of natural resources is often considered within the framework of Total Economic Value (TEV), and this framework can be used to value ecosystem services.

TEV comprises use and non-use values. TEV refers to the total gain in well-being from a policy measured by the net sum of the willingness to pay (WTP) or willingness to accept (WTA).

Use value includes direct use, indirect use and option value:

Direct use value**:** where individuals make actual or planned use of an ecosystem service.

This can be in the form of consumptive use which refers to the use of resources extracted from the ecosystem (e.g. food, timber) and non-consumptive use, which is the use of the services without extracting any elements from the ecosystem (e.g. recreation, landscape amenity). These activities can be traded on a market (e.g. timber) or can be non-marketable i.e. there is no formal market on which they are traded (e.g. recreation or the inspiration people find in directly experiencing nature).

Indirect use value: where individuals benefit from ecosystem services supported by a resource rather than directly using it. These ecosystem services are often not noticed by people until they are damaged or lost, yet they are very important. These services include key global life-support functions, such as the regulation of the chemical composition of the atmosphere and oceans, and climate regulation; water regulation; pollution filtering; soil retention and provision; nutrient cycling; waste decomposition; and pollination.

2.13.1. Methods of eliciting values

Valuation methods fall broadly into two main types: economic and non-economic valuation approaches.

Economic valuation attempts to elicit public preferences for changes in the state of the environment in monetary terms. The main types of economic valuation methods available for estimating public preferences for changes in ecosystem services are Revealed Preference (RP) and Stated Preference (SP) methods.

Revealed preference (RP) methods rely on data regarding individuals' preferences for a marketable good which includes environmental attributes. These techniques rely on actual markets. Included in this approach are: market prices, averting behaviour, hedonic pricing, and travel cost method, and random utility modelling. Market prices and averting behaviour can also be classified under-pricing techniques.

Stated preference (SP) methods use carefully structured questionnaires to elicit individuals' preferences for a given change in a natural resource or environmental attribute. In principle,

SP methods can be applied in a wide range of contexts and are the only methods that can estimate non-use values which can be a significant component of overall TEV for some natural resources.

In each case of ecosystem services quantified, consideration needs to be given to the appropriate valuation method.

For certain ecosystem services, only some valuation methods may be applicable. In addition, not all methods capture all elements of TEV. These points are summarised in the introductory guide to valuing ecosystem services by Department for Environment, Food and Rural Affairs, London, 2007.

Some valuation methods may be more suited to capturing the values of particular ecosystem services than others. For example, market prices are often used for valuing provisioning services, while stated preference studies are well suited to capturing non-use values (e.g. existence value of a rare species). In many valuation contexts, more than one technique is likely to be employed (for example, the direct-use values of cultural services may be captured by revealed preference methods such as travel cost, while stated preference methods will capture the non-use values associated with cultural services).

A conservative estimate of the economic value of an ecosystem service can be defined as:

$$EV = S_i P_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \quad (2.16)$$

Where S_i is the supply and P_i the market price, gate price or shadow price of an ecosystem service i. Consequently, the total economic value (TEV) of ecosystem services can be calculated as;

$$TEV = \sum_{i=1}^{n} SiPi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (2.17)$$

Where n is the total number of services considered in the study. When ecosystem services are tradable commodities they have a market price that can be used to indicate their value, assuming that the market is well-functioning. Typically, the provisioning services (e.g., food and timber) are proper market commodities and thus market price information can be used to calculate their values.

Deliberative or participatory approaches tend to explore how opinions are formed or preferences expressed in units other than money. The choice is not a case of either economic or non-economic valuation methods but of using a combination of both.

These deliberative or participatory methods obviously have a part to play in understanding people's preferences and the process of decision-making and may therefore influence policy choices. They do not, in general, easily fit into the more formal process of economic appraisal that aims to capture the TEV of ecosystem services.

2.14. Ecosystem drivers

2.14.1. General theory of ecosystem drivers

Fresh water and the hydrological cycle also sustain inland water ecosystems, including rivers, lakes, and wetlands. These ecosystems provide cultural, regulating, and supporting services that contribute directly and indirectly to human well-being through recreation, scenic values, and maintenance of fisheries. The infrastructure that contribute directly to human well-being are known as the direct drivers while the indirect ones are termed as the indirect drivers. Fresh water also plays a role in sustaining freshwater-dependent ecosystems such as mangroves, inter-tidal zones, and estuaries, which provide another set of services to local communities and tourists alike.

2.14.2. Direct drivers

In its natural state, fresh water varies considerably in terms of its availability in time and space. Water resources development activities such as the construction of dams and irrigation channels, the construction of river embankments to improve navigation, drainage of wetlands for flood control, and the establishment of inter-basin connections and water transfers has the aim of re-regulating the natural hydrograph to meet human needs. This has resulted in the replacement of naturally occurring and functioning systems with highly regulated and modified human engineered systems. These ‘‘developed’’ systems have typically been designed solely for the satisfaction of the major human consumptive uses (irrigation or municipal and industrial use) or non-consumptive use (hydropower and navigation).

These structural and capital-intensive responses—particularly large dams—have greatly augmented the natural availability of freshwater provisioning services. In the last 20 years alone, more than 2.4 billion people have gained access to water supply and more than 600 million have gained access to sanitation. At the same time, these supply responses have themselves become direct drivers of ecosystem degradation.

The impacts of water resource development are two-fold: less water remains in the ecosystem and the distribution and availability of the remaining water often has a different pattern from that present under natural conditions. It is estimated that the amount of water withdrawn from inland water systems has increased by at least 15 times over the past two centuries. (MA, 2005. Current State and Trends, Chapter 7.) As a result, humans now control and use more than half of the continental runoff to which they have access. The impact of withdrawals, though, is not evenly spread and it is estimated that about 80% of the global population is living downstream of only 50% of earth’s renewable water supplies.

Due to this demand there has also been alteration of the natural ecosystem through diversions, draining of wetlands, deforestation, land use and release of polluted effluent. There are however limited published information of this indicators in the Kenyan catchments.

2.14.3. Indirect drivers

Most water-related problems, although caused by direct drivers such as water abstraction and pollution, are ultimately a product of indirect drivers. The development of water resources over the past century has been largely a result of the need to supply expanding populations with food, energy, and domestic and industrial water supplies and to facilitate opportunities for transport.

Economic growth has further served to enhance the demand and consumption of freshwater services.

However, given the public as well as private good characteristics of fresh water, most water-related problems are ultimately a product of indirect drivers associated with the economic nature of fresh water in all its guises—and the manner in which this nature is accommodated or not by the institutional arrangements that govern the production, allocation, distribution, and consumption of freshwater services. The economic characteristics of fresh water, when combined with the dynamic nature of the hydrological cycle, present special challenges in the case of fresh water.

The potential for fresh water or ecosystems to have multiple uses, some of which will be private goods and others of which will either be perfect public goods or variations such as common pool or toll goods, creates this management challenge, as each type lends itself to a different management regime. The market failure associated with public good characteristics suggests a need for mechanisms of social coordination in the form of institutional arrangements that can define, and adaptively manage, the level of provision and allocation of these goods and services that is desired by society.

Governance and the role of economic incentives are therefore critical indirect drivers with respect to balancing competing demands for freshwater. The inadequate governance associated with water resource development, particularly a single-minded, engineering-economic approach to the ecosystems services that inland water systems provide, has led to significant social and environmental impact that have disproportionately affected the rural poor that rely on the natural functioning of inland water ecosystems.

CHAPTER THREE

METHODOLOGY

3.1. Study area

The study watershed lies between longitudes $36^0 32'59''$ E to $37^0 3'1''$ E and latitude $0^0 37'09''$S to $0^0 62'10''$S. The watershed is generally hilly with elevation ranging between 2100m ASL in the upstream to 1500m ASL downstream areas. The watershed straddles across Mang'u, Chania, Kariara, Gatanga, Thamuru, South Kinangop and Thika Municipality Divisions. It is drained by River Chania which enters the watershed at Ragia location in Nyandarua County and flows downstream to the confluence of Thika and Chania rivers near Blue Post Hotel covering a distance of 50km and an area of 531km^2. Lower Chania sub catchment has an estimated human population of 144,258 persons

The main economic activities in the watershed are cash crop and subsistence farming, quarrying, fish farming, livestock keeping, cottage industries, horticulture agro-forestry and business enterprises. The watershed experiences two rain seasons, long rains from March to May (Masika Season) and short rains from October to December (Vuli Season) and receives an average of 1200-1600mm per annum of rainfall. The hydrology of the watershed is influenced greatly by climate variability, topography and land use among other factors which have impacted on the resource quality and quantity.

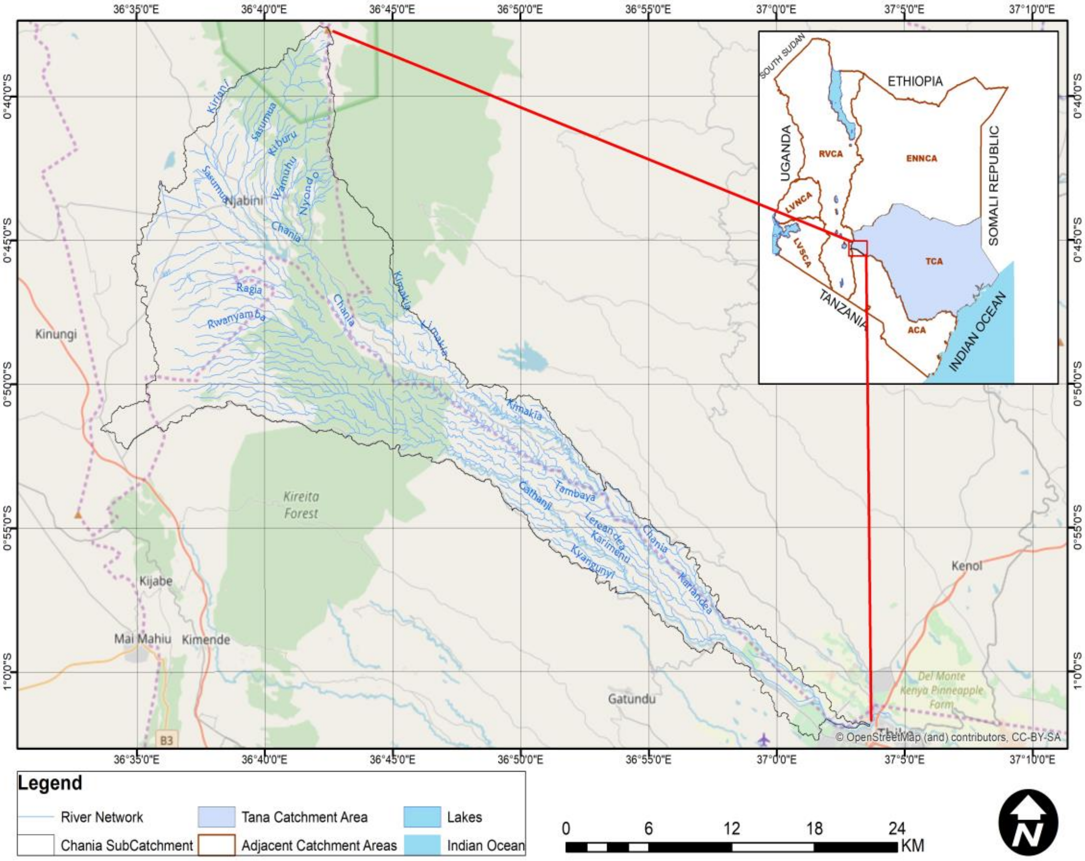

Figure 3.1: Location map of the Chania river system

Chania River is served by; Kariminu, Nyakibai, Mataara and Kimakia, as the main tributaries all forming a dendritic drainage pattern. Besides the tributaries the sub catchment has several streams, springs, wetlands, boreholes, Dams etc.

A number of stakeholders from the public and private sectors are involved in the use and management of water resources within the Sub-catchment. In this Sub-catchment stakeholders include: Riparian land owners, People who use water directly at the source, Legal water abstractors, Non –consumptive and Observer members.

3.2 Important watershed ecosystem services differentiated by gender

The methodology that was used is described below under the wider topic of community level mapping

3.2.1. Community level mapping

Community level mapping was carried out in three areas of the catchment. One upstream (Karangi), another one midstream (Mbugiti) and the last one downstream (Gatunyu).

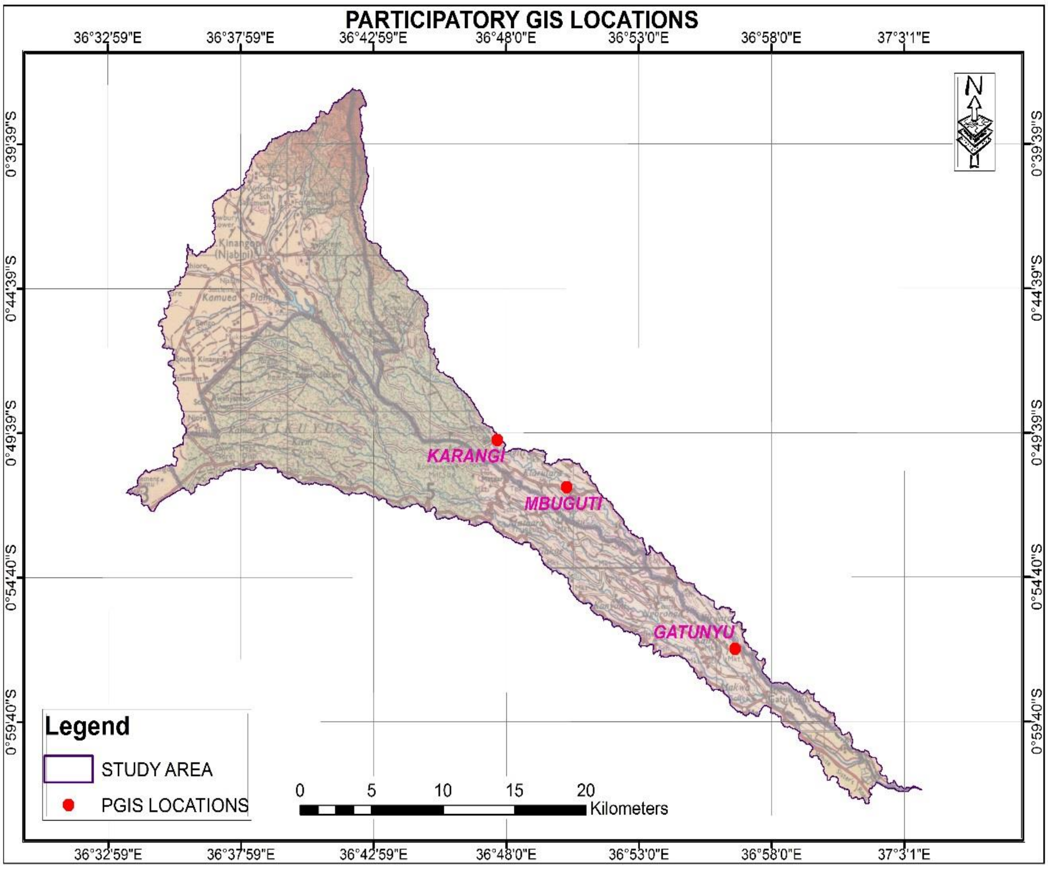

Figure 3.2: Locations where Participatory GIS was carried out

It was carried out using two broad techniques; knowledge based community mapping and expert based community level mapping.

In this method two-dimensional printed flat maps as well as finer resolution maps and satellite images of the instrumented catchment were used. Participants marked where they live and carry out activities.

They were guided through a series of focused questions (Appendix 1) and asked to identify location of resources on the maps corresponding to places on the landscape that pertain to their lives and activities they undertake.

To develop the Participatory GIS survey tools, a survey toolkit was generated with a focus on ecosystem services. The toolkit comprised a series of qualitative questions with supporting two-dimensional maps and satellite images that were used by participants during survey implementation to indicate where they obtain resources on the landscape. Local partners and collaborators, such as water resource user associations (WRUAs) and other local government water related agencies, were used during identification of participants to point out the stakeholders within and around the instrumented catchment sites for focused mapping work.

One of the assumptions of this study was that women are disproportionately impacted by climate change thus the research sought ways to integrate gender aspects of ecosystem, services. Women utilize landscapes differently from men due to their engagement in separate types of livelihood activities and as a consequence may have different set of ecosystem services priorities. A gender differentiated approach to the PGIS survey was utilized.

As part of the participant selection process, effort was undertaken to ensure gender differentiated participation opportunities, allowing females and males who live within the same household or community to carry out separate surveys. To take care of the interest of households missing either a man or woman, equal number of female and male who are widows and widowers was taken for PGIS to represent the opinions of single parent families.

On completion, these products were assessed collectively as well as differentiated by gender to ensure the range of ecosystem services valued across genders was captured. The outputs that were realized from the community mapping activities included a list and description of locally relevant ecosystem services and users, ecosystem services maps of the catchment. Finally benefit functions that illustrate the value of different aspects of the specific ecosystems services as well as their relative value in ecosystem services delivery.

Expert based mapping was utilized in form of remote sensed satellite images of the catchment which were used to trace the ecosystem services. Another part of expert based mapping in this context was carried out during the digitization of this map. ArcGIS and QGIS was used. The list was aligned to the classification by the CICES V 4.3. (Haines-Young and Potschin 2013). To validate the digitised maps, the participants were involved in reviewing the outputs.

3.3. Spatial quantification of ecological production of ecosystem services in the river system

3.3.1 Spatial quantification and mapping

After the relevant ecosystem services were deduced they were quantified in order to determine the capacity and potential of the ecosystem to provide the ecosystem services. Hotspots of ecosystem were identified in the basin and used as nodes where changes in services delivery could be quantified under different land use and climate change scenarios. Due to the catchment size and resources constraints, it was not feasible to carry out PGIS type activities throughout the catchment. To facilitate identifying critical nodes throughout each of the sub catchment, remote sensing methods were used.

The identification of the indicators corresponding to each ecosystem service were derived from the indicators of the Maes (2014). The report highlights the indicators of the following ecosystem services in provisioning, regulating and cultural section of ecosystem services; forest ecosystems, agro-ecosystems, freshwater ecosystems and marine ecosystems

<u>Land use maps</u> formed the baseline for the quantification of the ecosystem services by giving descriptions and information pertaining to land use management practices. Using these maps, detailed analyses of the <u>water balance</u> and <u>biomass</u> for each land use was developed. Following the CICES v4.3 classifications, biomass is a key indicator for provisioning ecosystem services (nutrition, material and energy)

Table 3.1: Provisioning ecosystem services

	Ecosystem services terminology proposed by MARS	Examples	Ecosystem services from CICES
Provisioning	Fisheries and aquaculture	e.g. fish catch	Food-Biomass
	Water for drinking	e.g. provision of water for domestic uses	Drinking water
	Raw (biotic)materials	e.g. algae as fertilizers, vegetal compounds for cosmetics	Materials-Biomass
	Water for non-drinking purposes	e.g. provisioning of water for industrial or agricultural uses	Non-drinking water
	Raw materials for energy	e.g. wood	Energy - Biomass

3.3.2. Land use map for Chania Watershed

Normalised Difference Vegetation Index (NDVI) was used as a proxy for estimating biomass productivity in this study. Before relating NDVI with the actual biomass however, classification had to be carried out in order to generate boundary conditions for each land use type for the biomass productivity analysis

Landsat 8 (Operation Land Imager) imagery for 12th March 2016 with 30m resolution was downloaded from USGS website. Lidar data would have offered the best resolution of 1-5 m with 3D analysis capabailies. However, the cost was prohibitive.

The decision to use Landsat 8 satellite imageries was based on the following considerations.

a) Spatial resolution
b) Revisit time
c) Radiometric resolution
d) Availability and
e) Cost of acquiring the imageries

Landsat 8 imageries were readily available at no cost, and the spatial resolution is relatively good for the study since the images are multi spectral imageries.

Since the data collection for training data and ground truthing was done in March 2016, the imagery adopted was for the month of March. However, a small section had cloud and cloud shadow. Supervised classification system using the maximum likelihood algorithm and parallelepiped was used to classify the land use types.

The following tools were used to generate this data:

GPS Receiver- GPS data was necessary in the study for generating the training sites and ground truthing that would aid in assessing classification accuracy. Garmin Etrex 20 and Garmin 62S were used for these task.

Camera- Photographs taken during training data collection were later used during processing of the land use classes developed so as to ascertain that classes collected were the same classes pre-processed prior to performing land use classification. In order to achieve this, unique photo numbers were recorded alongside GPS waypoint numbers.

Notebooks- These were crucial especially in recording training data classes adopted alongside their consequent waypoint numbers and their unique photo numbers.

The image analysis and classification is undertaken using computer software. Several software are available. The most used include ERDAS Imagine, QGIS, ArcGIS, and ENVI

The software utilized by the research were ArcGIS version 10.2, ENVI version 5.1 (classic), Google Earth PRO and Global Mapper V15.0. The choice of these software was informed by availability and suitability. The software had different strength at different stages of the classification process, thus they were combined in order to get the best classification possible.

ArcGIS was key in performing GIS analysis that would later on be used in discussing results achieved within chapter four of this research. **ENVI** is remote sensing software that was utilized by the study to perform classification. Classification was an integral part of this study as quantification of ecosystem services generated by each land use was obtained using a formulae derived by considering the area for each class. **Google Earth** was utilized in conducting visual analysis of training data through an overlay after the training data shape file were converted into KML (Keyhole Mark-up Language) format readable by Google Earth. Google Earth was also key in performing a "pre-ground truthing" reconnaissance activity using already classified data as ENVI contains a plug in that prompts Google Earth to open a region identified in Envi's classified image. **Global Mapper** was used in converting KML to shape file format and vice versa. This was later used in the "pre-ground truthing" reconnaissance activity prior to the actual ground truthing activity.

The following stages were followed in order to achieve proper and accurate land use and land cover map: -.

Stage 1: Image pre-processing

Prior to downloading of the imageries, it necessary to know the path and row within which study area lies. This is because USGS website recognizes path and rows as the unique identifiers of every part of the Earth surface. This study required only one scene. The entire study area fell under path 168 and row 61. Cleaning and rectification of the imageries was also carried out in this stage in order to reduce the bulkiness in order to achieve quick processing by the software. This was achieved by removing unnecessary information.

a) Converting raw digital number (DN) values to reflectance

This stage was necessary since Landsat 8 data downloaded from USGS site was obtained in its raw state. Converting the data to reflectance was thus key. This was achieved by loading the metadata file into Envi software. Radiometric calibration was then ran to perform the conversion.

b) Layer sub setting against study area shape file

This step was necessary in order to reduce bulkiness of the data as satellite imageries, reduce area of focus to only study the area of interest and image enhancement that aided in classification since the processed DN values were stretched.

c) **Band combination**

Satellite platforms are calibrated in a way that they have detectors each being sensitive to certain portions of the electromagnetic spectrum (EMS). For this reason, Landsat platforms utilize bands that are sensitive to certain portions of the EMS, Landsat 8 has eleven bands but this research sought to utilize three bands to develop LULC map for the whole region. Bands utilized were from Band 5, which is the Near Infrared (NIR), Band 4 which is Red and Band 3 which is Green, all sensitive to their respective portions of the EMS. The reason for this was because NIR is very crucial in discriminating water portions against dry land areas on the Earth surface. NIR is also crucial is discriminating between various vegetation cover and also vegetation cover against bare ground. By using the band combination above therefore, vegetation areas were depicted by red colour, water areas depicted by dark blue colour with bare ground being depicted by grey colour.

Envi software was used to carry out band combination with the input being the product of the pre-processed images as explained in the above stages. The screenshot in Figure A.7.2 illustrates a step of sub setting procedure. The area of study shape file is symbolized with a yellow outline. White portions within the imagery indicate cloud portions. Adjacent to the white portions, are black portions which indicate cloud shadow. This are the parts that necessitated cloud cover and shadow removal in order to improve results LULC generation.

d) Cloud cover and shadow removal

Cloud cover and shadow within an imagery is brought about by the interference of electromagnetic transmission by the clouds within the atmosphere. Cloud removal was achieved by replacing portions of the imagery affected by cloud cover with portions of another image of 24th February 2017 from the same path and row using the Seamless Mosaic tool within ENVI. According to Helmer and Ruefenacht (2005), histogram matching based on image overlap areas permits seamless mosaicking of scenes that have undergone cloud removal with regression tree prediction. Other studies have also found image mosaicking as an appropriate way of removing cloud cover from images (Suming et al 2013).

Cloud removal was then carried out using the Seamless Mosaic tool within ENVI to ensure that the area of study had no cloud portions (Suming et al 2013). Both images underwent the same pre-processing procedure. Figure A.7.3 illustrates the image obtained after cloud removal.

Stage 2: Image classification

Prior to performing supervised classification, the study carried out an unsupervised classification. A total of eleven (11) classes were generated. With unsupervised classification the software generated land use classes by assigning unique signatures to a pre-processed imagery giving special regard to the number of classes that the user commands or inputs into the software. There was no use of training data in unsupervised classification. The study utilized unsupervised classification workflow within ENVI Software environment. This was because workflow is usually a quick and easy way of operationalization in performing analysis within ENVI. It was not however very easy to interpret classes given the mixed nature of classes in the area. Knowing that the algorithm may mistakenly separate pixels with slightly different spectral values and assign them to a unique cluster when they, in fact, represent a spectral continuum of a group of similar objects the risk of false classification was high. It was therefore inevitable to carry out supervised classification.

This study utilized two types of supervised classification techniques; maximum likelihood and parallelepiped. The results between the two methods were then compared against each other and the best result adopted.

Parallelepiped classification uses a simple decision rule to classify multispectral data. The dimensions of the parallelepiped classification are defined based upon a standard deviation threshold from the mean of each selected class. If a pixel value lies above the low threshold and below the high threshold for all bands being classified, it is assigned to that class. If the pixel value falls in multiple classes, ENVI assigns the pixel to the first class matched. Areas that do not fall within any of the parallelepiped classes are designated as unclassified.

Maximum likelihood classification assumes that the statistics for each class in each band are normally distributed and calculates the probability that a given pixel belongs to a specific class. Unless you select a probability threshold, all pixels are classified. Each pixel is assigned to the class that has the highest probability. If the highest probability specified is smaller than a threshold the pixel assigned to the unclassified class.

Prior to performing supervised classification with any of the two methods, regions of interest were first generated using the training data for the classification. The ROIs created were later on used to perform both Parallelepiped and Maximum likelihood this was done to ensure that the same input parameters were observed so as to highlight for differences with the two outputs generated.

Since the same ROI was used for the two methods, the output files obtained the same symbology thus this was easy in comparing the results generated for the two land use maps.

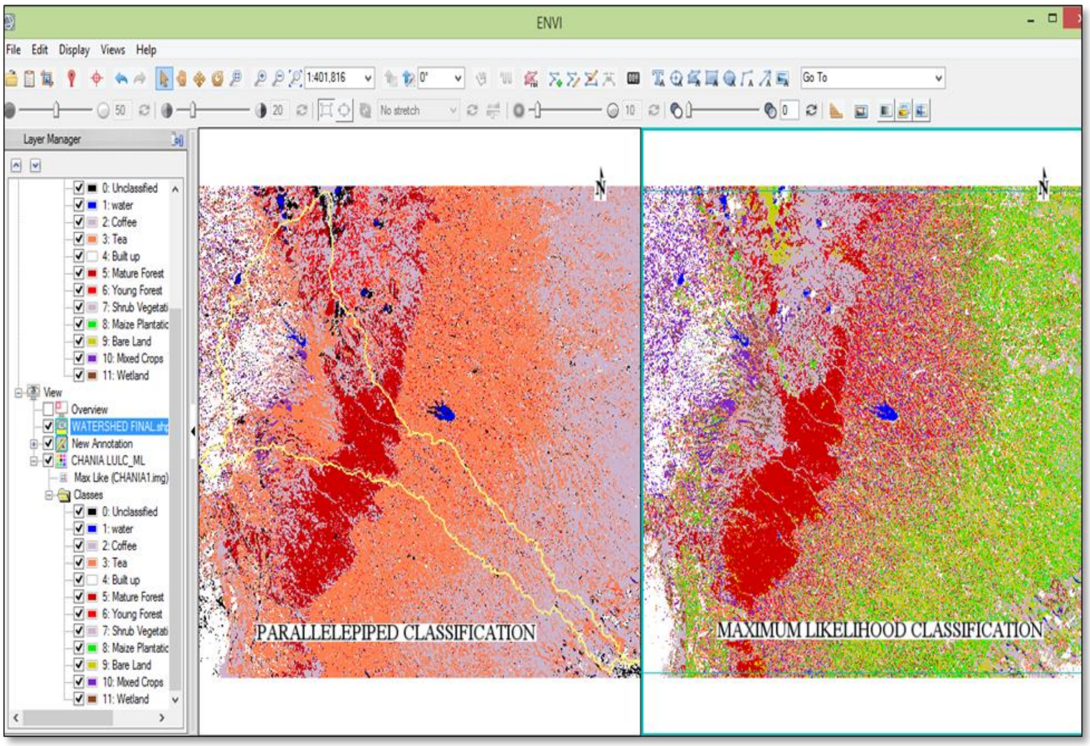

Figure 3.3: A screenshot of parallelepiped and maximum likelihood classification

From Figure 3.3, maize plantation symbolized as green is only distinct and visible through Maximum Likelihood method. Though parallelepiped may be the most objective with respect to ROIs generated, it usually tends to generate lots of unclassified data depicted as black portions.

Stage 3: Ground truthing

This stage was crucial in validating the image classification method to utilise (either Maximum likelihood classification or Parallelepiped classification method). Based on literature either of which can be used and it was important to establish the best method in this studies context. Owing to this, ground truth ROIs were created in

ENVI software from ground truth data that had been collected during training data collection exercise.

Figure 3.4 is a map of the of the ground truth points.

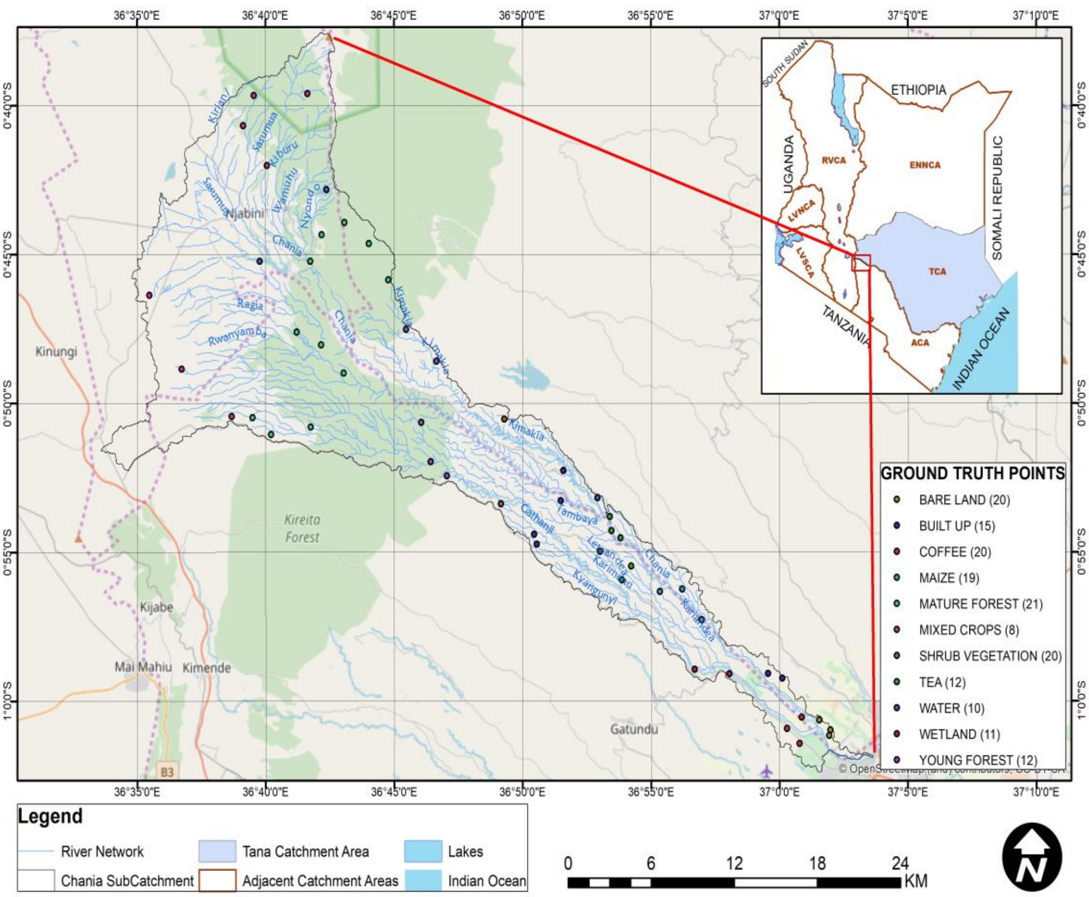

Figure 3.4: Ground truthing points

Stage 4. Accuracy assessment

In order to better understand the differences between Parallelepiped and Maximum Likelihood the study generated a confusion matrix (also referred to as contingency matrix). Table 3.2 below illustrates most important parts that highlighted the differences. The most crucial parameters being the overall accuracy and the Kappa coefficient. The rest of information indicates percentage accuracy for each and every class generated both for producer and user accuracies.

Table 3.2: Contingency Matrix obtained through Maximum Likelihood Classification

Overall Accuracy = (2980/3041)	***97.9941%***			
Kappa Coefficient = 0.9698				
Class	***Producer Accuracy (%)***	***User Accuracy (%)***	***Producer Accuracy (Pixels)***	***User Accuracy (Pixels)***
Water	99.88	99.77	855/856	855/857
Coffee	94.61	100.00	228/241	228/228
Tea	80.00	77.78	8/10	7/9
Built up	100.00	100.00	165/165	165/165
Mature Forest	98.88	100.00	1497/1514	1497/1497
Young Forest	95.65	97.78	132/138	132/135
Shrub Vegetation	81.48	82.22	22/27	37/45
Maize Plantation	81.81	81.81	9/11	9/11
Bare Land	71.42	75.00	5/7	15/20
Mixed Crops	88.14	94.55	52/59	52/55
Wetland	92.31	84.21	12/13	16/19

Table 3.3: Contingency Matrix obtained through Parallelepiped Classification

Overall Accuracy = (2791/3041)	***91.7790%***			
Kappa Coefficient = 0.8773				
Class	***Producer Accuracy (%)***	***User Accuracy (%)***	***Producer Accuracy (Pixels)***	***User Accuracy (Pixels)***
Water	99.07	99.88	848/856	848/849
Coffee	100.00	96.02	241/241	241/251
Tea	100.00	5.18	10/10	10/193
Built up	99.39	100.00	164/165	164/164
Mature Forest	97.29	100.00	1473/1514	1473/1473
Young Forest	3.62	55.56	5/138	5/9
Shrub Vegetation	40.74	36.67	11/27	11/30
Maize Plantation	0.00	0.00	0/11	0/0
Bare Land	0.00	0.00	0/7	0/0
Mixed Crops	66.10	100.00	39/59	39/39
Wetland	0.00	0.00	0/13	0/0

Maximum Likelihood classification method produced more accurate results following an overall accuracy of 98.0% versus 91.8% produced from the output classes for Parallelepiped classification. Another indication on accuracy while performing image classification is the Kappa coefficients that range between 0.0 – 1.0 with values closer to 1.0 indicating high level accuracy of image classification. Therefore, from the contingency matrix generated by the study, the Kappa coefficients obtained from parallelepiped classification was 0.87 with maximum likelihood classification method having a Kappa coefficient of 0.96.

Following the above comparison, the study sought utilize out generated from Maximum likelihood classification. Ground trothing was carried out in order to ascertain the accuracy of Maximum likelihood classification.

Stage 5: Vectorization of the output

The final stage after LULC generation was vectorization of the output so as to establish the areas of each land use and land cover classification in square metres.

3.3.3. Water balance

Water provisioning serves the same classes ecosystem services (nutrition, material and energy). Establishing the direct interaction between the river system and various ecosystem services relied on establishing actual evapotranspiration from the different land use types and then estimating the precipitation deficit, which is an indication of the amount of water exchanged between the river system and an ecosystem.

The significance of the evapotranspiration can be seen in the equation below.

Water yield in a catchment = Precipitation – actual evapotranspiration (Equation 15). The expression derived is derived from Equation 14 which relates the change of soil storage (ΔS) to Precipitation (P), Runoff (RO) and Evapotranspiration.

Water balance within a catchment is mainly influenced by the dynamics of hydrological cycle. With this regard; factors such as Precipitation, Evapotranspiration, overland flow and change in ground water storage are very essential in modelling for water balance within a watershed. This study utilized Thornthwaite Monthly Water Balance Model (Gregory and Steven, 2007). The reason for using this model is because it is pre-calibrated and takes localised data to generate the required outputs. The model is a monthly model which is ideal for the data that was available. The data that was available was monthly data (Appendix 4).

The input parameters for the model were run off factor, latitude of location, soil moisture storage capacity and direct run off factor. It also employed two sets of hydro-met data; monthly mean temperature and monthly precipitation. These two sets of hydro-met data were fed into Thornthwaite Monthly Water Balance software in ASCII format so as to generate; Total Runoff (RO), Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET). The hydromet data that was utilized was data taken from Thika Meteorological Station and were acquired from Kenya Meteorological Department (Appendix 3). These factors were highly dependent on Land use as each Land use would in turn dictate the parameters to utilize. A table was hence developed with Run off and Soil Moisture Storage Capacity parameters per Land Use developed by the study.

Table 3.4: Percentage runoff factors and soil moisture stage capacities of different land uses

Land use type	Runoff Factor (%)	Crop Type	Soil Moisture Storage Capacity (mm)	Soil Type	Source Station for Hydro-met
Tea	50	Deep-rooted	250	Silt Loam	Kimakia
Coffee	50	Deep-rooted	250	Silt Loam	Thika Agro-Met
Maize	50	Moderately deep-rooted	200	Silt Loam	Kimakia
Shrub Vegetation	50	Deep rooted	250	Silt Loam	Kimakia
Young Forest	40	Orchards	300	Silt Loam	Kimakia
Mature Forest	30	Closed mature forest	400	Silt Loam	Kimakia
Wetland	00	Moderately deep rooted	400	Clay	Kimakia
Mixed Crops	50	Orchards	300	Silt Loam	Thika

The study designed the table in accordance to the one developed by (Thornthwaite & Mather, 1957) for Soil Moisture Holding Capacity while Run off factor was designed with regard to one developed by. McCuen, 2004 on Hydrologic Design and Analysis. Latitude of location input parameter was a constant input of -1 since the area of study was located within South of Equator at a Latitude range -0.6 and -1.0.

Hydro-met data inadequacy prompted the study to utilize 2013 to 2014 Monthly precipitation and Mean monthly temperature. The assumption was that since the land use generated was developed from Landsat imageries obtained within the year 2016 and bearing the fact that climate change is generally considered after a duration of 35years (Rood, 2015) 2013 and 2014 weather data would cause less or no deviance in results generated from Thornthwaite Monthly Water Balance.

The water yield was then calculated from the water balance formulae (Equation 14 and 15) as the difference between precipitation and evapotranspiration. To validate the results, the sum of run off and change in storage (which also give water yield) was calculated and the two compared against each other.

The units for all parameter in the water balance table was in millimetres.

The water balance for each LULC is presented in the next chapter

3.3.4. Biomass production

Apart from water all other provisioning ecosystem services (food/nutrition, material and energy) are often linked to biomass production, which can also be determined from remote sensing images (Bastiaanssen & Ali, 2003). As stated in section 3.3.2, NDVI was used as a proxy for measuring above ground biomass (AGB). In order to estimate the AGB for the entire catchment, actual AGB for few selected sites were measured and their relationship with NDVI established. The relationship in the form of regression expression would be used to establish the AGB for the entire catchment.

Remote sensing was used to estimate biomass. Regression models that utilized spectral Vegetation Indices (SVI) to estimate biomass were generated. Examples of the spectral SVI that can be utilized and derived from Red and Near Infrared (NIR) bands are; Normalized Difference Vegetation index (NDVI, Difference Vegetation Index (DVI), enhanced vegetation index (EVI), soil adjusted vegetation index (SAVI) and modified soil adjusted vegetation index (MSAVI). Based on many studies NDVI has been identified as the best SVI to estimate biomass. Examples of these studies are; '*Relationships of NDVI, Biomass, and Leaf Area 2 Index (LAI) for six key plant species in Barrow, 3 Alaska*'(Goswami *et al.*, 2015) and '*Remote Sensing-Based Biomass Estimation and its Spatio-Temporal Variations in Temperate Grassland, Northern China*' (Jin *et al.*, 2015). In addition, ArcGIS and ENVI have the ability to process Landsat remote sensing images to spatially represented NDVI values. It is for these reasons that NDVI was used to estimate biomass. The equation to determine NDVI is given below.

$$NDVI = \frac{NIR - Red}{NIR + Red} \ldots\ldots\ldots\ldots\ldots.. \quad (18)$$

Where NIR is the Near-infrared irradiance and RED is the Red irradiance.

3.3.4.1. Generating the NDVI for the entire catchment

The study utilized the already pre-processed Landsat imagery used for land use land cover generation within the previous stage. This was because the imagery had already been corrected for interferences such as cloud cover.

The generation of the NDVI for the whole of the study area was achieved by inputting the required bands which were bands 1, 2 and 3 achieved after layer stacking that were Near Infrared, Red and Green respectively. Figure 3.5 illustrates the output generated by running NDVI in ENVI.

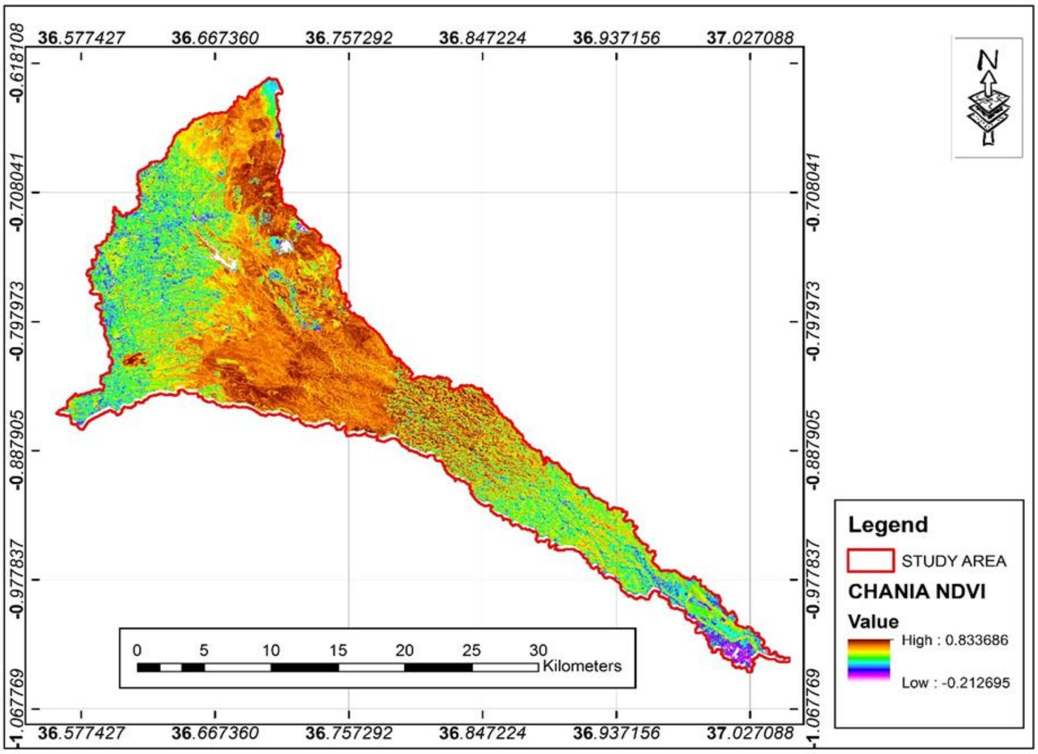

Figure 3.5: Chania catchment NDVI values

NDVI range usually vary between -1 to 1, with values closer to 1 representing the healthiest or green vegetation while values closer to -1 indicates features captured that do not depict vegetation and in other cases unhealthy vegetation is indicated by values that lie closer to -1. NDVI values obtained within the area of study ranged between -0.21 to 0.83.

3.3.4.2. Generation of the NDVI map for each LULC class

The NDVI values for each class were obtained by clipping the NDVI map using the shape files of the classes that had been generated during the LULC classification. The field samples were obtained at defined intervals of the NDVI range. The extracted classes were only the ones that contained vegetation as these were the ones that would later on be evaluated against their biomass. The NDVI created for the whole of study area were hence clipped against their corresponding LULC class shape files.

10 equal intervals of NDVI classes for each Land use class was generated for symbolization. It is from these NDVI class intervals that points were randomly selected, this formed a base for selection criteria from which field samples for biomass estimation were carried out. Biomass calculated was all carried out within an area of 1 metre by 1 metre for all land use classes under study.

Two methods for biomass estimation were utilized depending on the land use type under study, allometric methods and "harvest methods" which is considered by many as destructive. Allometric models were applied for young trees and mature trees which could not allow for physical measurements. For the vegetation that could allow physical measurements (Tea, Coffee, Maize, Wetland and Shrub Vegetation) "harvest methods" of biomass estimation was used.

Application of "harvest method" was made possible through sample selection criteria whereby the selected samples were dependent on NDVI Range values within each class as discussed earlier. NDVI ranges were represented via a distinct colour scheme whereby the colour scheme comprised pixel based unique values. It is from these pixels that the coordinates were selected to form sampling area of 1metre by 1metre.

Reason why the pixel method was adequate to form the sample area of 1metre by 1 metre is that Landsat pixel represents an area of 30 metre by 30 metre on the ground.

The sample size formed quadrats whereby the corners of these sample sizes were marked with a flagging tape after confirming the homogeneity of the sample within each land use type. Harvested biomass was sorted then weighed using an Ohaus field test scale with accuracy of 0.01g. Samples were then oven dried and weighed several times until no further loss in weight was recorded. The mean biomass for each land use was then recorded against the corresponding NDVI. The results were then plotted and the regression expression to predict biomass for each class determined. These regression equations are summarised in Table 3.16.

The process of generating the equations and utilization of the same to predict biomass for the individual LULC class is outlined below.

A. Estimation of above ground biomass for tea

From the NDVI ran for tea, the 10 categories were developed as follows and the random field samples taken at the coordinates indicated in Table 3.5.

Table 3.5: Tea NDVI-Coordinates

TEA NDVI COORDINATES					
LONGITUDE	**LATITUDE**	**NDVI_RANGE**	**MIN NDVI**	**MAX NDVI**	**MEDIAN NDVI**
36.715	-0.743	0.08 - 0.15	0.08	0.15	0.12
36.729	-0.732	0.15 - 0.23	0.15	0.23	0.19
36.998	-1.0183	0.23 - 0.31	0.23	0.31	0.27
36.995	-0.983	0.31 - 0.38	0.31	0.38	0.34
36.995	-0.983	0.38 - 0.46	0.38	0.46	0.42
36.997	-0.984	0.46 - 0.54	0.46	0.54	0.50
36.996	-0.983	0.54 - 0.61	0.54	0.61	0.57
37.002	-0.989	0.61 - 0.69	0.61	0.69	0.65
36.984	-0.983	0.69 - 0.77	0.69	0.77	0.73
36.845	-0.889	0.77 - 0.84	0.77	0.84	0.80

The above ground biomass of tea was measured to constant dry mass from the coordinates within each NDVI range. The weight in kg/m^2 was then tabulated.

Table 3.6: NDVI and corresponding measured above ground biomass for tea

MEDIAN NDVI	0.12	0.19	0.27	0.34	0.42	0.50	0.57	0.65	0.73	0.80
BIOMASS (10^3 g/ m^2)	1.50	1.90	2.45	3.30	4.40	6.15	8.10	11.35	15.80	18.50

When these variables were plotted on a graph the output produced befitted an exponential regression as indicated from Figure 3.6

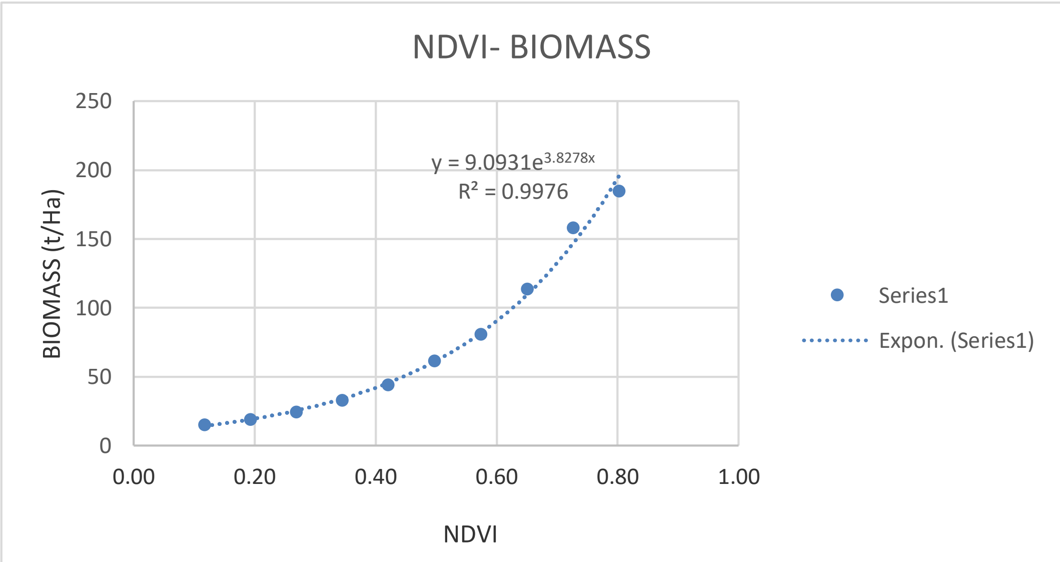

Figure 3.6: Exponential graph for tea biomass- NDVI

From the above graph, a regression equation was developed hence possible to estimate tea biomass using NDVI values provided by the equation; $y= 9.09e^{3.82x}$

Where y is the Biomass being sought and x being known a NDVI value Relative predictive power (R^2) for the model was also derived with a value 0.9976. This expression had the highest R^2 as compared to logarithmic and linear expressions which had R^2 of 0.70 and 0.89 respectively with expressions $y=81.34\ln(x) +148.79$ and $y=247.33x-40.17$. The exponential expression was the input on the raster calculator in the ArcGIS environment and the resultant map of biomass generated.

B. Estimation of above ground biomass for coffee

Coffee biomass for the predefined coordinates was determined using the same procedure as for tea. The field samples were obtained for each range of NDVI. The median values for NDVI were also determined and tabulated.

Table 3.7: Coffee NDVI-Coordinates

COFFEE NDVI COORDINATES					
LONGITUDE	**LATITUDE**	**NDVI_RANGE**	**MIN NDVI**	**MAX NDVI**	**MEDIAN NDVI**
36.986	-0.978	0.088 - 0.002	-0.89	0.00	-0.44
37.017	-1.031	0.002 - 0.093	0.00	0.09	0.05
37.018	-1.0278	0.093 - 0.184	0.09	0.18	0.14
36.717	-0.771	0.184 - 0.274	0.18	0.27	0.23
36.696	-0.744	0.274 - 0.365	0.27	0.37	0.32
36.697	-0.744	0.365 - 0.456	0.37	0.46	0.41
36.695	-0.745	0.456 - 0.547	0.46	0.55	0.50
36.694	-0.744	0.547 - 0.638	0.55	0.64	0.59
36.719	-0.742	0.638 - 0.729	0.64	0.73	0.68
36.721	-0.745	0.729 - 0.820	0.73	0.82	0.77

Coffee biomass were then measured from the identified locations as shown in the table 3.8.

Table 3.8: Coffee NDVI- Biomass Inventory

MEDIAN NDVI	-0.44	0.05	0.14	0.23	0.32	0.41	0.50	0.59	0.68	0.77
BIOMASS (g/m^2)	5	60	95	140	205	290	420	590	770	970

The resulting graph of biomass against NDVI was then plotted. Linear, logarithmic and exponential graphs were generated and their accuracy assessed. Exponential expression $y= 56.26e^{3.85x}$ was then adopted because of the high R^2 of 0.99. The R^2 for linear and logarithmic graph was 0.929and 0.66. The linear expression and logarithmic expressions were y=1243.1x-117.98 and y=290.74ln(x) +728.1 respectively.

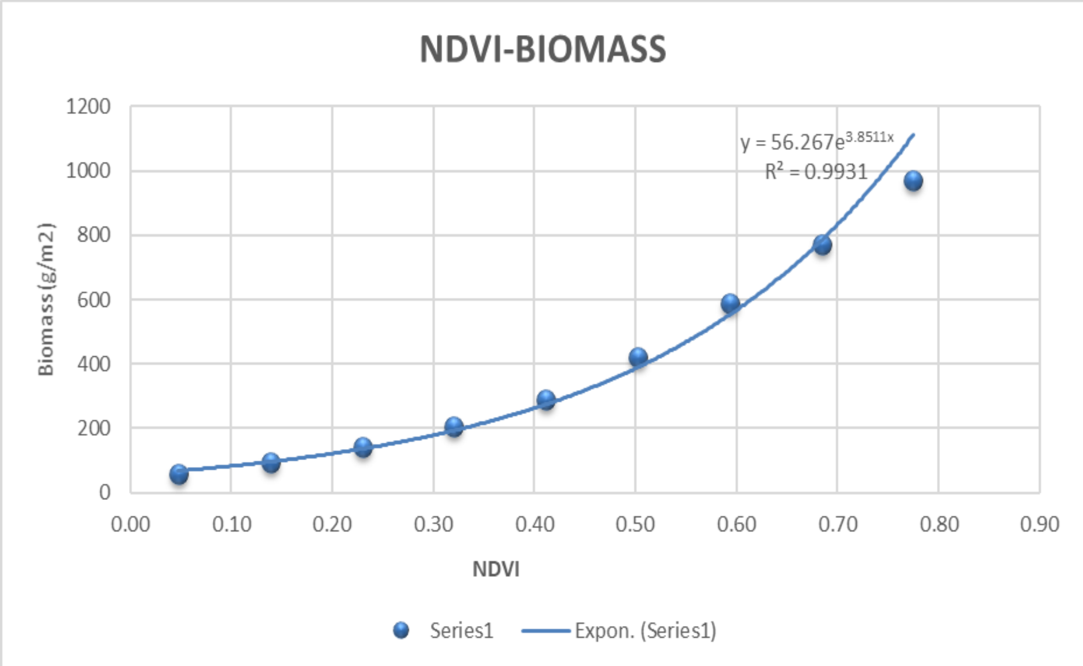

Figure 3.7: Coffee Biomass- NDVI Exponential graph

Given NDVI value for coffee within the study area, it's thus possible to estimate for Biomass using the following equation y= $56.267e^{3.85x}$.

Whereby; AGB (y) is the Above Ground Biomass

"X" denotes the generated Coffee NDVI in Raster format

C. **Estimation of above ground biomass for maize**

The biomass predictive model derived was obtained through the same procedure as one used for coffee and tea, where field samples were first randomly selected by the use of NDVI class range.

Table 3.9: Maize NDVI Coordinates

MAIZE NDVI COORDINATES					
LONGITUDE	**LATITUDE**	**NDVI_RANGE**	**MIN NDVI**	**MAX NDVI**	**MEDIAN NDVI**
36.715	-0.748	0.080 - 0.151	0.08	0.15	0.12
36.717	-0.743	0.151 - 0.223	0.15	0.22	0.19
37.000	-1.016	0.223 - 0.294	0.22	0.29	0.26
36.924	-0.956	0.294 - 0.365	0.29	0.37	0.33
36.888	-0.911	0.365 - 0.436	0.37	0.44	0.40
36.890	-0.911	0.436 - 0.507	0.44	0.51	0.47
36.893	-0.910	0.507 - 0.578	0.51	0.58	0.54
36.897	-0.911	0.578 - 0.650	0.58	0.65	0.61
36.894	-0.913	0.650 - 0.721	0.65	0.72	0.69
36.894	-0.913	0.721- 0.792	0.72	0.79	0.76

Above Ground Biomass was then measured from locations denoted by the coordinates within table 3.9. The AGB measured were recorded in table 3.9.

Table 3.10: Estimated Above Ground Biomass for maize

MEDIAN NDVI	0.19	0.26	0.33	0.40	0.47	0.54	0.61	0.69	0.76
BIOMASS (g/ m^2)	2.5	6.2	10.0	21.2	40.0	65.0	103.7	163.7	213.8

The AGB was then plotted against the NDVI. The correlation coefficient (R^2) for exponential, linear and logarithmic expression were then compared.

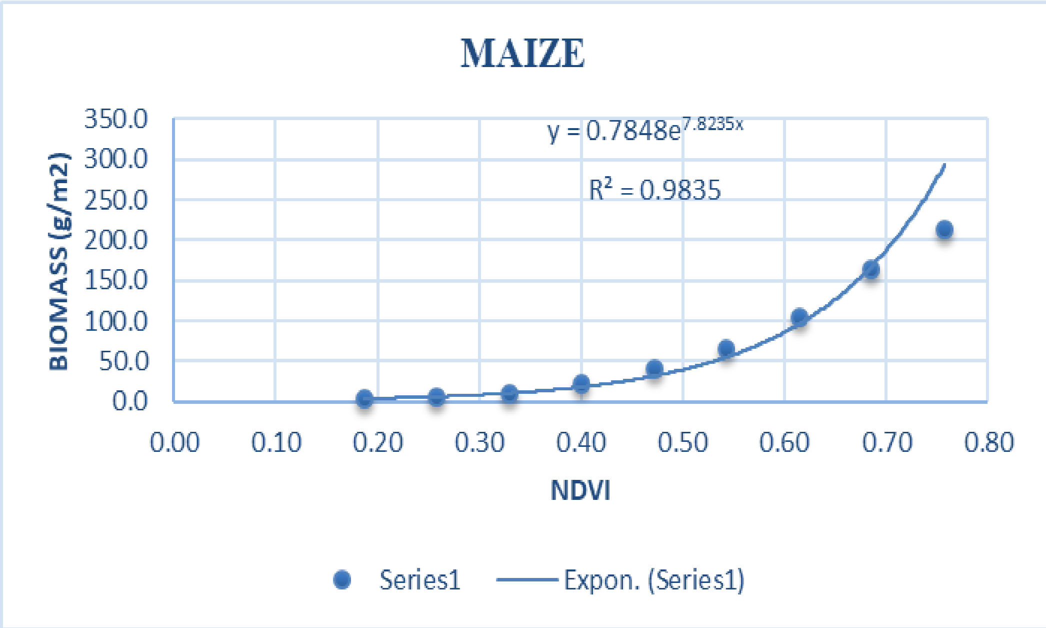

Figure 3.8. Maize Biomass- NDVI Exponential graph

The Relative predictive power produced from the exponential expression was 0.98, with a predictive equation $y= 0.78e^{7.82x}$, logarithmic expression $y=137.55\ln(x) +185$ had an R^2 of 0.71 and the linear expression $y=362.66x-101.67$ had an R^2 of 0.86. The exponential expression had the highest R^2 thus the expression $y=0.78e^{7.82x}$ was adopted. With the predictive equation generated, it was thus possible to estimate for Biomass in regions that contained Maize within the area of study.

D. Estimation of above ground biomass for shrub vegetation

Field samples were derived from NDVI class ranges just like in other biomass estimated from the above land use classes. Table 3.11 illustrates coordinates from where field samples were carried out.

Table 3.11: Shrub Vegetation NDVI Coordinates

SHRUB VEGETATION NDVI COORDINATES				
LONGITUDE	**LATITUDE**	**NDVI_RANGE**	**MEDIAN NDVI**	**BIOMASS (g/m2)**
36.714	-0.745	0.10 - 0.17	0.13	41
36.720	-0.749	0.17 - 0.24	0.21	119
36.720	-0.749	0.24 - 0.32	0.28	141
36.738	-0.781	0.32 - 0.39	0.35	228
36.739	-0.780	0.39 - 0.46	0.43	372
36.790	-0.833	0.46 - 0.54	0.50	332
36.795	-0.832	0.54 - 0.61	0.58	418
36.795	-0.832	0.61- 0.69	0.65	500
36.795	-0.831	0.69 - 0.76	0.72	653
36.795	-0.831	0.76 - 0.83	0.80	797

Consequently, biomass measured from the locations identified are as recorded from the Table 3.12.

Table 3.12: Shrub Vegetation NDVI- Biomass Inventory

MEDIAN NDVI	0.13	0.21	0.28	0.35	0.43	0.50	0.58	0.65	0.72	0.80
BIOMASS (g/m^2)	41	119	141	228	372	332	418	500	653	797

From variables above NDVI-Biomass graph was plotted as illustrated from Figure 3.9.

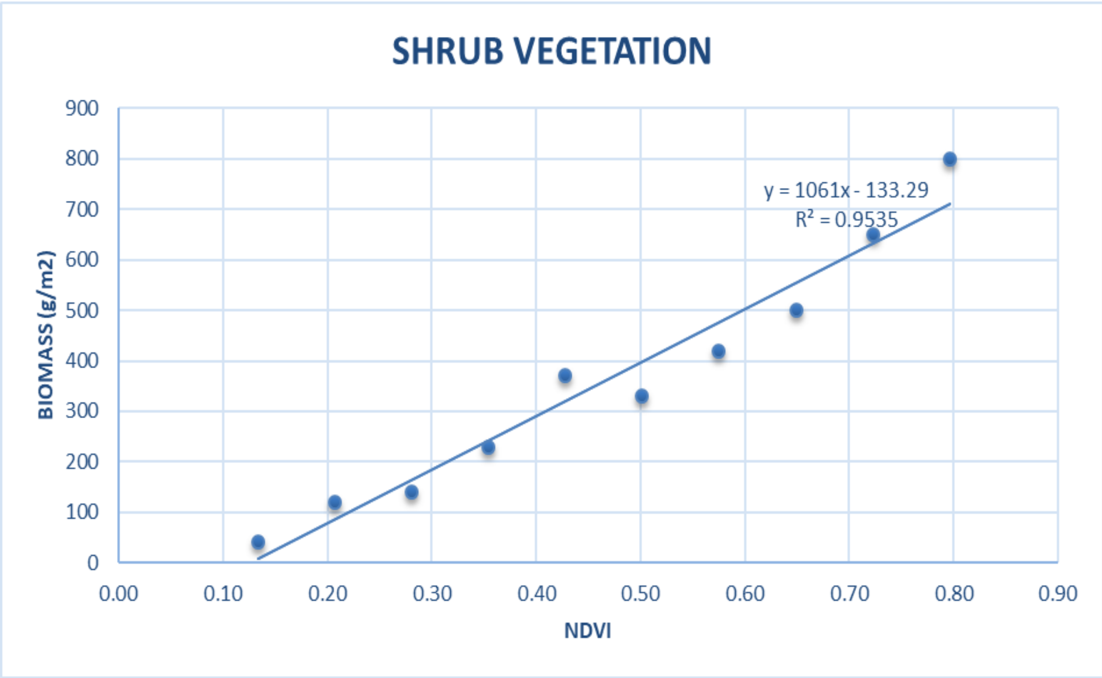

Figure 3.9: Shrub Vegetation Biomass- NDVI linear graph

The linear expression was used due to its high R^2. The Relative predictive power derived from the model was 0.95 with the predictive exponential equation y=1061x-133.29. Exponential and logarithmic expression had R^2 of 0.89 and 0.84 with equations $y= 44.89e^{3.85x}$ and y=385ln(x) +705.22 respectively. This therefore made it possible to predict an estimate of Shrub Vegetation Biomass within the study region given the NDVI values. The linear expression was later fed into ArcGIS' Raster Calculator tool substituting the "X" parameter with the generated Shrub Vegetation NDVI raster dataset.

E. Estimation of above ground biomass for wetland

For this the Biomass range was $55g/m^2$ to $600g/m^2$ within an NDVI range of 0.12 to 0.78 respectively as illustrated by table 3.13.

Table 3.13: NDVI-Biomass Inventory for wetland

WETLAND NDVI COORDINATES						
LONGITUDE	**LATITUDE**	**NDVI_RANGE**	**MIN NDVI**	**MAX NDVI**	**MEDIAN NDVI**	**BIOMASS (g/m2)**
36.714	-0.745	0.083 - 0.156	0.08	0.16	0.12	55
36.715	-0.749	0.156 - 0.230	0.16	0.23	0.19	100
36.711	-0.748	0.230 - 0.303	0.23	0.30	0.27	155
36.712	-0.744	0.303 - 0.377	0.30	0.38	0.34	215
36.711	-0.744	0.377 - 0.450	0.38	0.45	0.41	275
36.706	-0.742	0.450 - 0.524	0.45	0.52	0.49	340
36.704	-0.743	0.524 - 0.597	0.52	0.60	0.56	403
36.704	-0.741	0.597 - 0.671	0.60	0.67	0.63	460
36.703	-0.743	0.671 - 0.744	0.67	0.74	0.71	528
36.701	-0.741	0.744 - 0.818	0.74	0.82	0.78	600

When NDVI- BIOMASS graph for wetland vegetation was plotted a predictive model was established within which Biomass for Wetland areas that were not selected for field sample could be estimated using the given NDVI values.

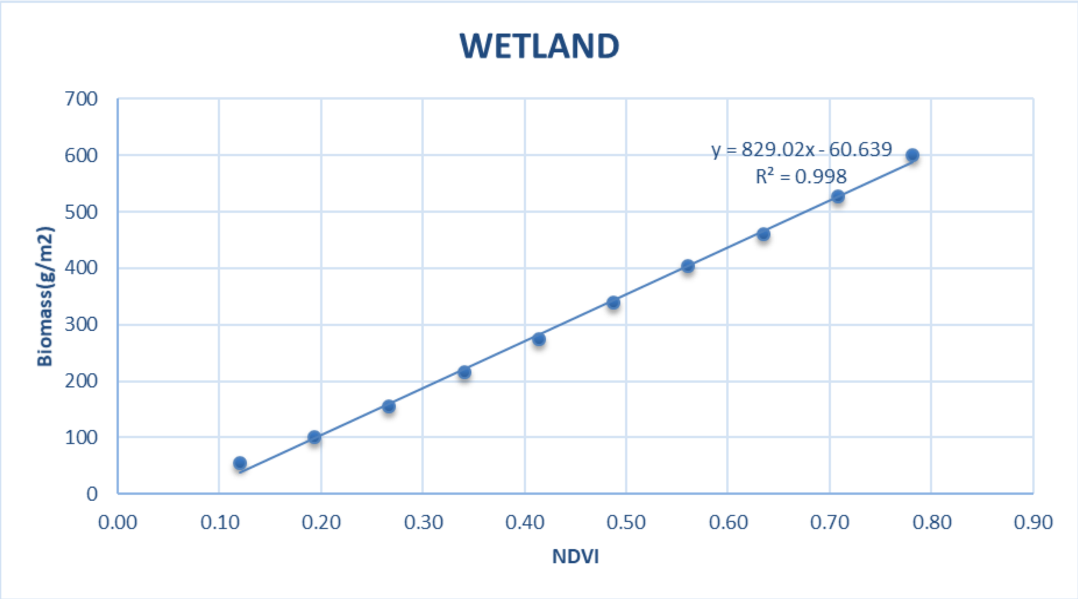

Figure 3.10: Wetland Biomass- NDVI linear Graph

Linear expression was used due to its high R^2. The Relative predictive power derived from the model was 0.99 with the predictive linear equation y=829.02x-60.63. Exponential and logarithmic expression had R^2 of 0.92 and 0.91 with equations $y=55.391e^{3.35x}$ and y=291.31ln(x) +586.47 respectively. This therefore made it possible to predict an estimate of wetland biomass within the study region given the NDVI values. The linear expression was later fed into ArcGIS' Raster Calculator tool substituting the "X" parameter with the generated wetland NDVI raster dataset.

F.Estimation of above ground biomass for young forest

Within this land cover vegetation was slightly heterogeneous with young trees being the predominant vegetation. Almost all the trees within this land cover had a DBH less than 10cm.

Table 3.14: Tabulated data for AGB- Biomass inventory

YOUNG FOREST NDVI COORDINATES						
LONGITUDE	LATITUDE	NDVI_RANGE	MIN NDVI	MAX NDVI	MEDIAN NDVI	BIOMASS (10^3g/ m^2)
36.606006	-0.732747	0.411 - 0.454	0.41	0.45	0.43	4.1
36.793182	-0.827762	0.454 - 0.497	0.45	0.50	0.48	4.5
37.002447	-1.003382	0.497 - 0.541	0.50	0.54	0.52	4.8
36.690656	-0.687764	0.541 - 0.584	0.54	0.58	0.56	5
36.690333	-0.68746	0.584 - 0.627	0.58	0.63	0.61	5.3
36.68822	-0.687726	0.627 - 0.670	0.63	0.67	0.65	5.6
36.688543	-0.687764	0.670 - 0.713	0.67	0.71	0.69	5.8
36.687896	-0.68706	0.713 - 0.756	0.71	0.76	0.73	5.9
36.689495	-0.689668	0.756 - 0.799	0.76	0.80	0.78	6.1
36.688277	-0.689268	0.799 - 0.842	0.80	0.84	0.82	6.2

Using the data tabulated in Table 3.14, a Biomass against NDVI map was plotted and an exponential model developed for the graph so as to test for the accuracy of the model as illustrated below.

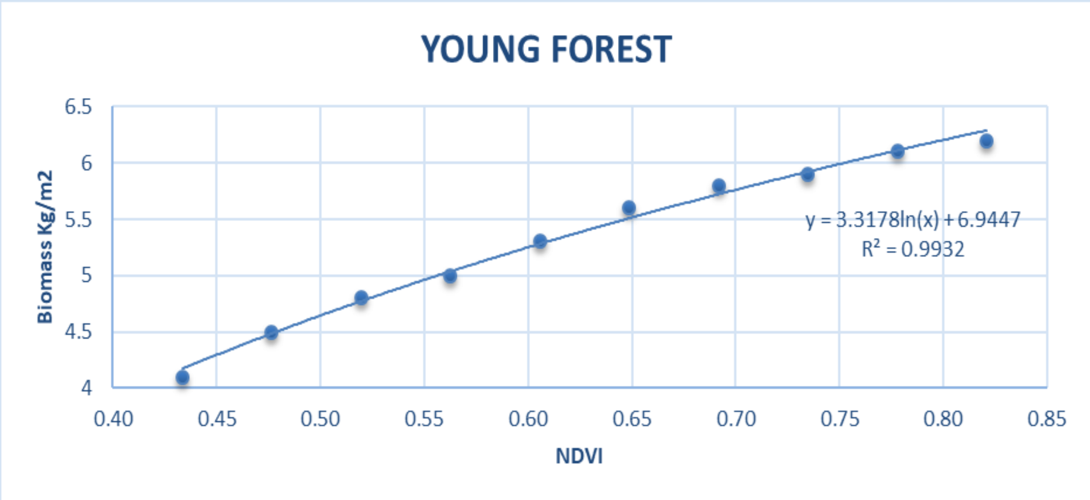

Figure 3.11: Biomass- NDVI logarithmic Model Graph

The logarithmic expression was used due to its high R^2. The Relative predictive power derived from the model was 0.99 with the predictive logarithmic equation y=3.31ln(x)-6.94. Exponential and linear expression had R^2 of 0.95 and 0.97 with equations $y= 2.75e^{1.03x}$ and y=5.38x+1.95 respectively. The logarithmic expression y=3.31ln(x)-6.94 was later fed into ArcGIS' Raster Calculator tool substituting the "X" parameter with the generated young forest NDVI raster dataset.

G. Estimation of above ground biomass for mature forest

This study borrowed greatly from various biomass estimation equations developed by their proponents. There are many regression models available for the estimation of AGB developed by many scientists considering stem diameter, wood density and tree height ((Chave *et al.*, 2005; Bao Huy *et al.*, 2012; Brown & Lugo,1982). The following allometric regression model (Brown *et al.*, 1989) was applied for individual plants to convert the inventory data into the above ground biomass for both Mature Forest. (Brown, 1989) states that the equation is only applicable for trees with a DBH $\geq$ 10 cm.

$$AGB = 13.2579 - 4.8945(DBH) + 0.6713(DBH)^2 \quad (19)$$

Whereby; AGB is Above Ground Biomass

DBH is Diameter at Breast Height

(Equation 19) was only applicable for above ground biomass since trees within this part of LULC were greater than 10cm in diameter at breast height.

Table 3.15: Measured AGB (Biomass) – NDVI values for mature forest

MATURE FOREST NDVI COORDINATES							
LONGITUDE	LATITUDE	NDVI_RANGE	MIN NDVI	MAX NDVI	MEDIAN NDVI	DBH (cm)	BIOMASS ($10^3 g/m^2$)
36.739879	-0.759388	0.298 - 0.352	0.30	0.35	0.33	8.8	22.5
36.739862	-0.759114	0.352 - 0.406	0.35	0.41	0.38	10.7	37.5
36.740165	-0.759661	0.406 - 0.460	0.41	0.46	0.43	10.7	37.5
36.739879	-0.759935	0.460 - 0.514	0.46	0.51	0.49	11.2	42.5
36.738198	-0.763783	0.514 - 0.568	0.51	0.57	0.54	12.0	51.5
36.780242	-0.836991	0.568 - 0.621	0.57	0.62	0.60	13.3	66.5
36.777729	-0.836452	0.621 - 0.675	0.62	0.68	0.65	13.7	72.0
36.774963	-0.843531	0.675 - 0.729	0.68	0.73	0.70	14.4	81.5
36.774398	-0.842222	0.729 - 0.783	0.73	0.78	0.76	16.6	117.5
36.831523	-0.871954	0.783 - 0.837	0.78	0.84	0.81	17.9	141.5

The study then plotted a graph for the tabulated NDVI-Biomass data so as to check for the accuracy of the model and also to derive an equation that was later on used to generate a map for estimated biomass within the entire LULC of Mature Forest.

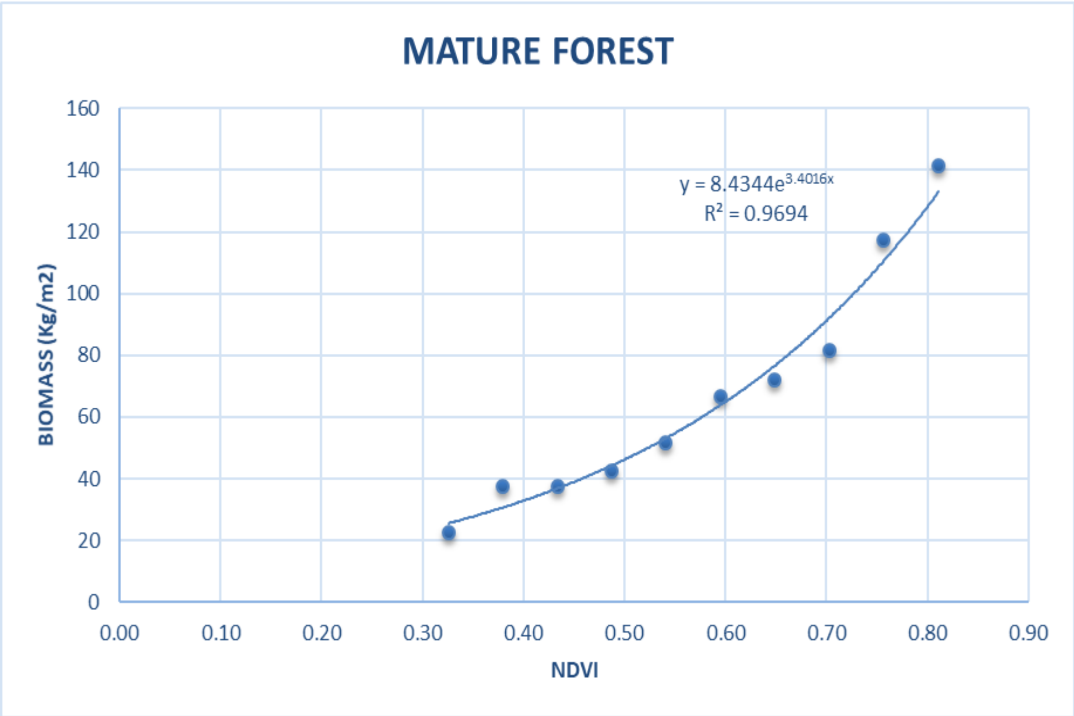

Figure 3.12: NDVI- Biomass exponential graph for mature forest

The exponential expression was used due to its high R^2. The Relative predictive power derived from the model was 0.96 with the predictive exponential equation y= $8.43e^{3.40x}$. Linear and logarithmic expression had R^2 of 0.897and 0.82 with equations y=219.69x-57.75 and y=113.08ln(x) +135.51 respectively. The exponential expression $y=8.43e^{3.40x}$ was later fed into ArcGIS' Raster Calculator tool substituting the "x" parameter with the generated young forest NDVI raster dataset.

Table 3.16 indicates the equations that were generated and subsequently applied in quantifying biomass for each LULC class.

Table 3.16: Regression equations generated for prediction of above ground biomass

LULC Class	Equation	Equation with (y) as Biomass (g/m^2) and (x) as NDVI
Tea	$y= 9.09e^{3.83x}$	$Biomass= 9.0931e^{3.83(NDVI)}$
Coffee	$y= 56.27e^{3.85x}$	$Biomass= 56.27e^{3.85(NDVI)}$
Maize	$y=0.78e^{7.82x}$	$Biomass=0.78e^{7.82(NDVI)}$
Shrub Vegetation	$y=44.90e^{3.86x}$	$Biomass=44.90e^{3.86(NDVI)}$
Wetland	$y=829.02x-60.64$	$Biomass=829.02(NDVI)-60.64$
Young Forest	$y=3.32\ln(x)-6.94$	$Biomass=3.32\ln(NDVI)-6.94$
Mature Forest	$y=8.43e^{3.40x}$	$Biomass=8.43e^{3.40(NDVI)}$

After the regression equations had been generated the AGB was represented spatially by feeding the equations in the 'Raster Calculator' tool of the ArcGIS software.

Below is a screenshot for the generation of tea biomass. The same procedure was applied for all LULC classes.

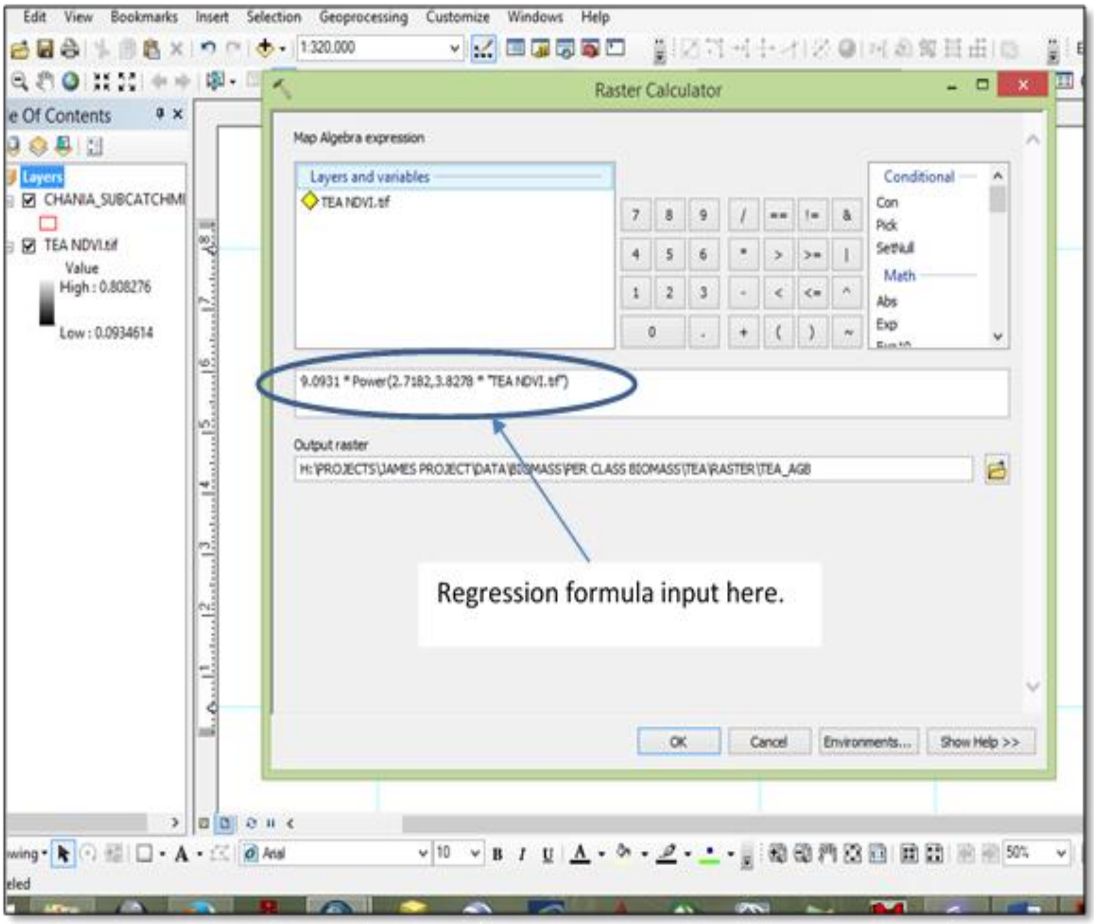

Figure 3.13: Using the regression formula to predict biomass-tea example

3.3.5.Validation of the above ground biomass estimation results

Ground truthing to verify accuracy of maps was carried out in the various areas through cutting, clipping, oven-drying and weighing of vegetation at the monitoring points and comparison with model results.

Table 3.17: A table of predicted above ground biomass and corresponding measured biomass

LONGITUDE	LATITUDE	PREDICTED AGB	MEASURED AGB	Deviation %	LULC CLASS
36.701	-0.741	528	602	-12.29	Wetland
36.712	-0.744	220	250	-12.00	Wetland
36.714	-0.745	56	55.1	1.63	Wetland
36.704	-0.743	399	455	-12.31	Wetland
36.998	-1.018	24	21	14.29	Tea
37.002	-0.989	110	125	-12.00	Tea
36.845	-0.889	178	145	22.76	Tea
36.715	-0.743	149	171	-12.87	Tea
36.986	-0.978	5	5	0.00	Coffee
37.017	-1.031	59	46	28.26	Coffee
36.717	-0.771	138	157	-12.10	Coffee
36.695	-0.745	422	500	-15.60	Coffee
36.715	-0.748	3	3	0.00	MAIZE
36.925	-0.956	9	12	-25.00	MAIZE
37	-1.016	7	8	-12.50	MAIZE
36.888	-0.911	23	21.5	6.98	MAIZE
36.795	-0.832	497	450	10.44	Shrub Vegetation
36.713	-0.745	38	55	-30.91	Shrub Vegetation
36.739	-0.78	368	299	23.08	Shrub Vegetation
36.72	-0.749	142	130	9.23	Shrub Vegetation

The measured AGB was plotted against the predicted biomass and the Pearson product moment correlation coefficient (R^2) determined.

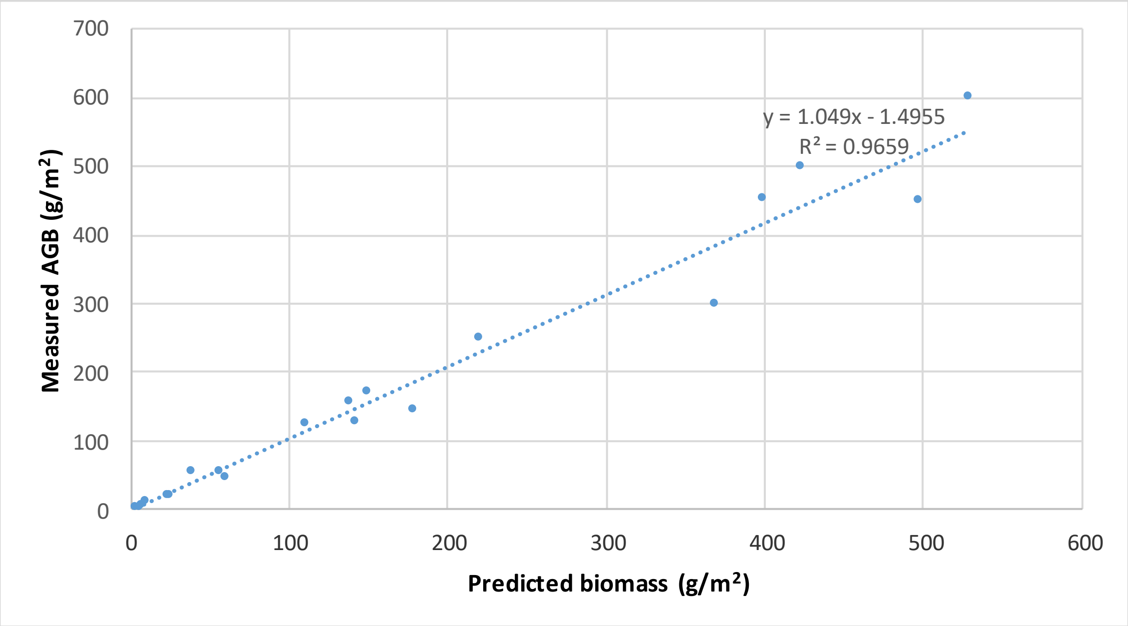

Figure 3.14: Accuracy assessment of predicted biomass

The validated regression equations were then used to estimate biomass for the whole year using the 'raster calculator' tool of ArcGIS with the NDVI maps used as the input files.Total AGB for each month in the period that the landsat images were downloaded was then estimated using the 'Zonal Statistics' tool of ArcGIS with biomass productivity map as the input file..The total monthly AGB established for the whole year was then plotted against each month (Figure 4.10) of the year and the trend used to give the annual biomass gain. The AGB gain for the undisturbed months was extrapolated to represent the annual values (see Table 4.11).

The biomass gain for 2016 represented the *biomass productivity.*

3.3.5. Calculation of Biomass Water productivity

Biomass Water productivity (BWP) was analysed by the ratio of biomass to ET, which can be refered to as the ratio of net benefits from the crop classes in the catchment to the amount of the water required for producing these benefits.

The following equation was used to determine the water productivity (Renato *et al.*, 2014).

$$\mathrm{BWP} = BP/ETa \tag{20}$$

Where BWP is the biomass water productivity in kg/m^3 , BP is the biomass productivity in kg/m^2 and ET_a is the actual evapotranspiration for each land use type.

3.4. Valuation of spatial productivity of the Chania catchment (yield water productivity)

This study apllied the equation of harvest index below to determine the economic productivity for the three commercial crops in the area (tea, coffee and maize).Harvest index is used to denote the fraction of economically useful products of a plant in relation to its total productivity

Economic Water Productivity = Harvest Index × Biomass Water Productivity

Biomass water productivity was determined as described in section 3.4. and harvest index of the different crops was derived from literature. The harvest index used for these crops were 0.012 for coffee, 0.048 for tea and 0.35 for maize (Nair, 1993).

To convert the economic water productivity into yield water productivity expressed in Kenya Shilling (KES), the EWP was multiplied by the market prices per kilogram of the various crops in 2016 (KES 369 for coffee, KES 250 for tea and KES 50 for maize according to Agriculture and Food Authority, Kenya 2016.

For young and mature forest the yield water productivity was expressed in terms of the carbon dioxide sequestered. To determine the weight of carbon dioxide sequestered in the tree, the weight of carbon in the tree was multiplied by 3.6663 which is the ratio of the atomic weight of carbon in CO_2 and the weight of CO_2. This is with the knowledge that CO_2 is composed of one molecule of Carbon and two molecules of Oxygen with the atomic weight of carbon being 12 and that of oxygen being 16. The amount of carbon by mass was assumed to be 50% of the AGB (Scott 2005)

3.5. The influence of built infrastructure on the natural ecosystem provisioning services

3.5.1 Mapping the built infrastructures

Built infrastructure of interest were derived from the Participatory GIS**.** Community and catchment scale mapping exercises identified important ecosystem services and their relative importance on the landscape. These ecosystem services are generated by the biophysical structures in catchment. The structures were then compared with the ones providing the ecosystem services listed by CICES v4.3 and TEEB.

This research confirmed water provisioning as one of the key ecosystem services of interest to the communities benefiting from the watershed. Constraints in water quality and quantity has been highlighted as the most affected.

It is also expected that a review of historical data will show a constriction of the natural ecosystem by human population and built infrastructure that support their well-being. Land use, biomass production and water balance is expected to be varying over the years because of climate change and change in seasons within the year. This research revealed the change in terms of spatial quantities.

The infrastructure that are important in altering the provision of ecosystem services (drivers) were also mapped. Based on the initial PGIS mapping some of the drivers identified were dam construction, diversions of wetlands, land use, release of polluted water effluents by factories and flower farms and overharvesting. Maps were then digitized using ArcGIS software.

3.5.2 Evaluation of the built infrastructure

The relationship between the built infrastructure and the natural ecosystem services were examined. The research tracked the changes in infrastructure development and their driving forces through PGIS. Historical data on the quantities and quality of the ecosystem services were analysed. The examination revealed impacts of drivers to ecosystems.

The drivers that were pointed out during the PGIS as of key importance were spatially mapped.

For the study to evaluate the influence of built infrastructure on the natural ecosystem, change detection was inevitable. Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times, Ashbindu (1989). Satellite remote sensing being the backbone of natural resource monitoring and management has over the years played an integral part in change detection.

This study therefore performed a change detection analysis within the catchment for a period of 10 years in order to evaluate the influence of built infrastructure towards the ecosystem. Anthropogenic factors play an important part within the ecosystem which may affect the ecosystem positively or negatively. The study had already carried out supervised classification for Landsat imagery for the period of February, 2016 thus the study sought to downloading and performing supervised classification of Landsat imagery for the period February 2005. Landsat 7 ETM+ was utilized since within the year 2005 Landsat 8 OLI had not yet been launched. Similar band composite and training sites were utilized in order to evaluate change detection, by this each land use was evaluated by what percentage change that had occurred. Land use change had been triggered by various factors such as increase in population prompting an increase in infrastructure such as housing, on the other hand change could have been triggered by conservatory measures undertaken by man in order to curb environmental degradation.

A. Change detection analysis

Following successful Landsat 8 image classification for the period dated February 2016, the study also performed Maximum Likelihood Supervision for the February 2005 Landsat 7 ETM+ imagery. For the Landsat 7 ETM+ imagery key pre-processing that was undertaken was to perform de-striping in order to cater for scan line corrector that caused striping of the imagery.

Other minor imagery pre-processing conducted were, layer stacking of the Near Infrared, Red and the Green band and layer stacking. This made it possible to perform land use land cover classification for the Landsat imagery for the period February 2005. Following the accuracy of results that yielded from land use land cover classification for the period February 2016, similar approach was utilized for the February 2005 Landsat imagery whereby Maximum likelihood supervised classification was used. For change detection, the study utilized the training data as the one used for Landsat imagery dated February 2016 supervised classification.

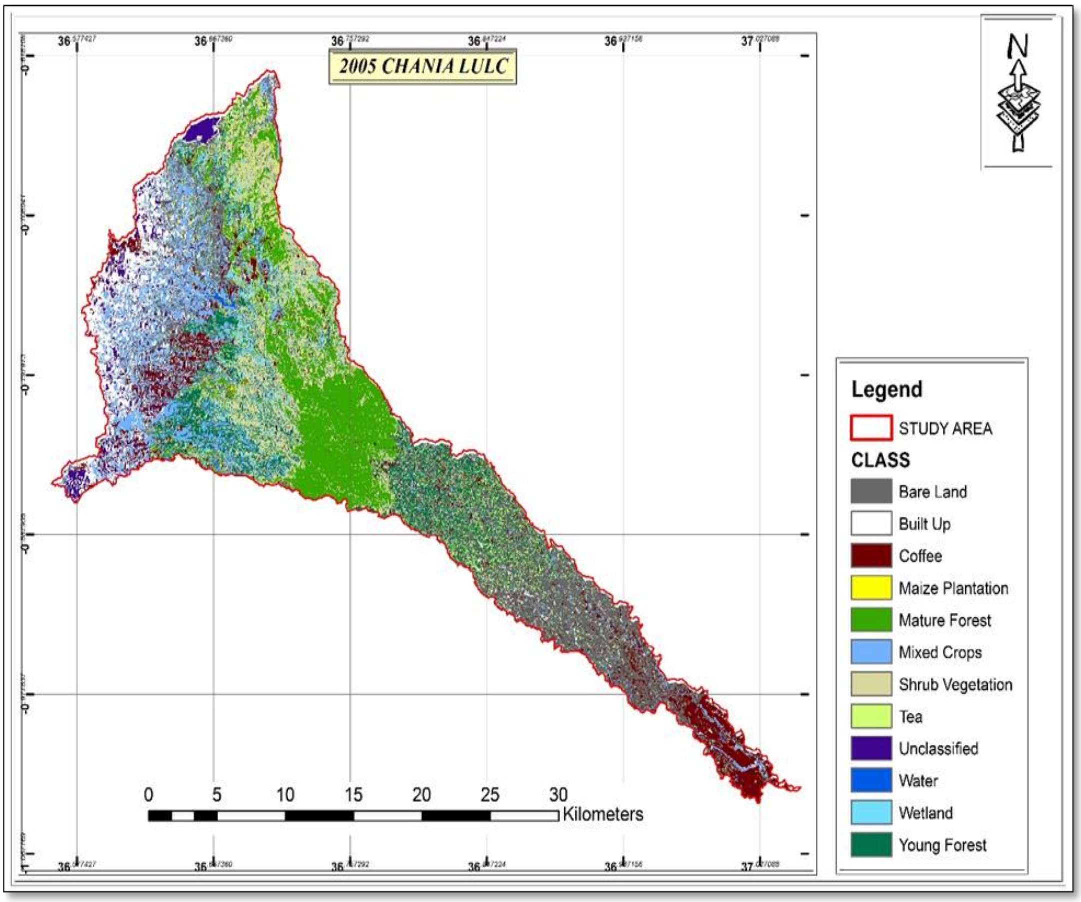

Figure 3.15: 2005 Land Use Land Cover supervised classification

The raster image generated from 2005 Landsat imagery supervised classification was then vectorised in order to compute for areas of each Land use. Areas developed were later on utilized to quantify land use change for each and every land use.

B. Effect of human activity on water quality

From the land use land cover maps the cumulative area of the built-up areas which constitute settlements, flower farms, factories and commercial farms increase downstream from Kimakia forest to Thika. Factories are also present in the last section of the catchment at Makongeni which is downstream of Thika town.

It was therefore necessary to enumerate how this infrastructure affected the water quality thus the water provisioning ecosystem services. The following parameters were relevant as the indicators of pollution. Alongside the parameters, the recommended WHO limits and method of enumeration are also outlined.

Table 3.18: Recommended method of measurements and the recommended WHO standards for different water quality parameters

PARAMETERS	Standard (WHO)	Recommended method of measurement
PH(-)	6.5-8.5	Use of $_{p}$H meter
CONDUCTIVITY(Us)	0-500	Conductivity meter
T.D.S(p.p.m)	<1200	Multiplying conductivity by a constant factor -0.67
TURBIDITY(NTU)	<300	Use of turbid meter
T.S.S (Mg/l)	<30	Sedimentation Method
CHLOROPYLL(Ug/l)	5-15	Photometrometry
PHOSPHATES (-)	<10	Absorption method
NITRATES(-)	<10	Modified Kjeldahl method
B.O.D (Mg/l)	<30	Dilution Method
FEACAL COLIFORM (counts / 100ml)	<30	Multiple tube dilution method
TEMPERATURE(^{0}C)	15-30	Thermometric method
D.O (mg/l)	> 5	Iodometric method

These samples were taken from the points indicated in Figure 3.16 and tested with the standard procedure for each parameter (Appendix 6)

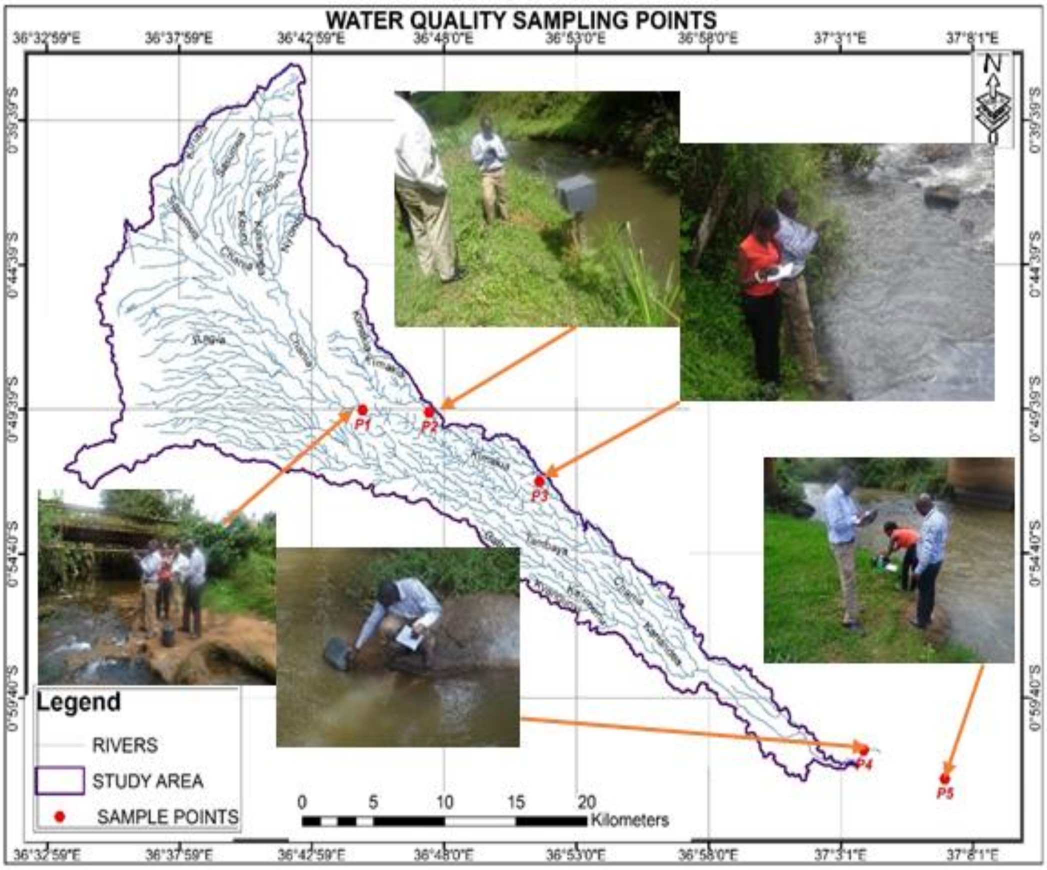

Figure 3.16: Water quality sampling points

3.5.3. Effect of human activity on water quantity

The amount of precipitation determines how much water will be made available through surface water or ground water recharge. Having established that there were increased built-up areas and reduced forest cover it was necessary to assess the consequence to the rainfall trend. Historic rainfall data therefore taken for the area from Kimakia forest station (station 9036/233) from 1971. Unfortunately, though, the data runs until 2003.

CHAPTER FOUR

RESEARCH ANALYSIS AND DISCUSSION

4.1. Important watershed ecosystem services of the river system.

The participatory mapping revealed the following ecosystem services and goods as crucial to the people living in the catchment.

a) Water Provisioning; both drinking and for irrigation
b) Food Provisioning; cash crops (tea on the watershed upstream, maize and coffee med-stream and coffee downstream) and subsistence crops.
c) Energy Provisioning; Fuel for heating

As depicted in Table 4.1, the degree of prioritization varied slightly for men and women.

Firewood for example featured quite prominently in the women's seasonal calendar as a commodity to source for throughout the year. However, men didn't give it any priority. For both genders however, water provisioning and food production was prioritized. Pasture for herding livestock was important to both men and women (although captured by women as milk production). Water as well was on top of the priority list for both genders. Interestingly, timber and material from forest was not given priority by both genders. The benefits from the forests was seen in the perspective of water provisioning. It was clear therefore that, although there was different prioritization of different ecosystem services by men and women water and food provisioning services were considered the most important services.

Table 4.1: Priritization of Ecosystem Services in the Chania River System

Location: Karangi	Gender: Men and Women	
Ecosystem Service	**Frequency - Men**	**Frequency -Women**
Water provisioning	14	14
Food production	11	12
Clean water	9	12
Pasture	9	3
Environmental cleaning (Air quality)	4	3
Climate regulation	2	0
Food regulation	1	0
Firewood	0	9
Timber	0	0
Honey	0	0
Charcoal	0	0

4.2. Quantification of the ecological production generated by the river system

In order to quantify the ecosystem services in was necessary to generate a land use and land cover map which would subsequently form the basis of carrying out biomass estimation and carrying out water balance analysis.

Based on CICES v4.3 (Table 3.1) biomass is key in measuring food/nutrition, material and energy provisioning services. Water balance was used to estimate water yield.

The results of the remote sensing quantification of ecosystem goods for different land use and land cover classes in the watershed are presented in this chapter.

4.2.1. Current land cover and land use

With a higher accuracy of 98% the study therefore adopted maximum likelihood. The output LULC file generated was subsequently clipped against the study area and the resulting LULC map is as presented in Figure 4.1.

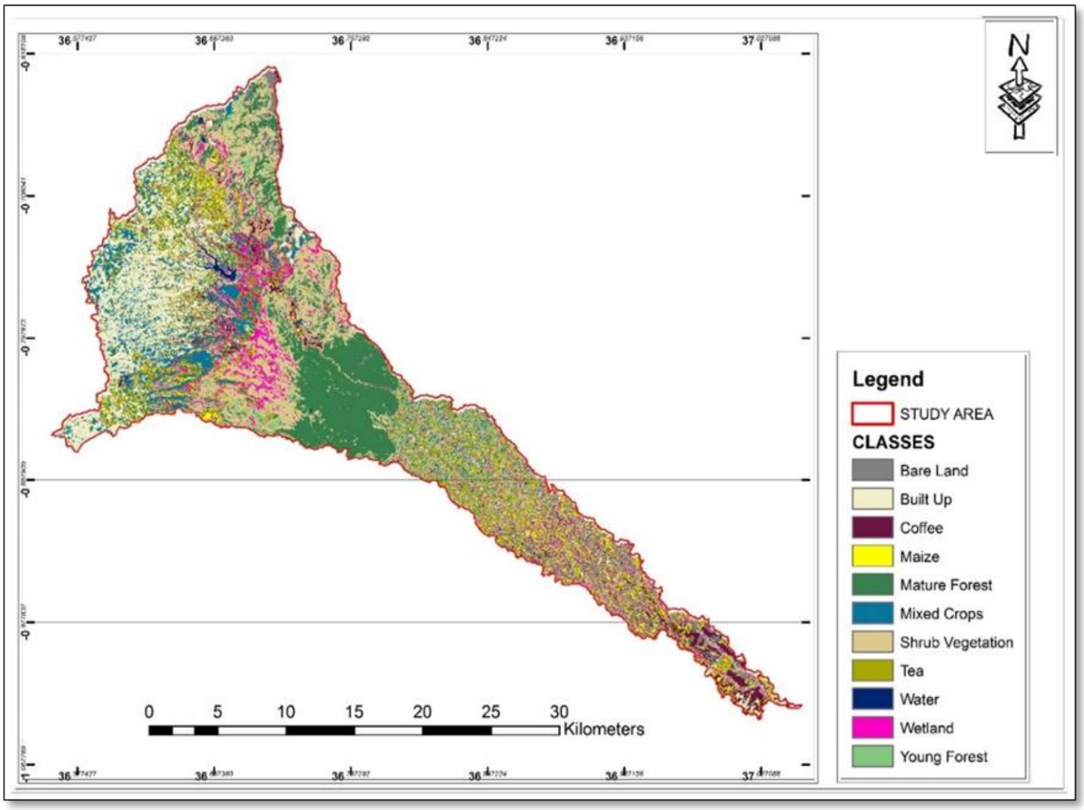

Figure 4.1: Land Use Land Cover Map Adopted for the year 2016

After vectorization was done as described in the methodology the resulting areas were as tabulated in Table 4.2.

Table 4.2: Area developed from vectorization as per class generated

CLASS	AREA (m^2)	AREA (Ha)	AREA (%)
BARE LAND	52,295,024.3	5,229.5	9.85
BUILT UP	80,306,421.3	8,030.6	15.12
COFFEE	27,342,810.1	2,734.3	5.15
MAIZE	27,508,038.1	2,750.8	5.18
MATURE FOREST	71,703,167.7	7,170.3	13.50
MIXED CROPS	50,350,388.8	5,035.0	9.48
SHRUB VEGETATION	108,365,921.8	10,836.6	20.40
TEA	62,251,511.6	6,225.1	11.72
WATER	3,095,165.9	309.5	0.58
YOUNG FOREST	16,438,515.0	1,643.8	3.10
WETLAND	31,429,754.8	3,143.0	5.92

From the Table 4.2 it was established that Shrub vegetation occupied the biggest area of the catchment at 10,837 ha, representing 20.4% of the watershed area. Water occupies the least area. This is largely Sasumua dam which supplies water to Nairobi. The forest and Tea occupies fairly big potions of the area. From PGIS it was established that tea was quite important in the upper areas of the catchment as a cash crop. The area of the young forest is also small. This area could however be higher given that tree are planted with maize thus Landsat could capture maize reflectance and leave out reflectance for young trees. The area covered by coffee and maize. Maize in the area is majorly for subsistence use. Coffee on the other hand is no longer as popular, which explains the reason as to despite being considered a cash crop, it does not occupy a large area as tea. The area for bare land and areas with mixed crop was equal at slightly higher than 9%. Wetlands covered 5.9%. The wetlands were mostly within the forested area promoting water retention as was revealed by the water balance analysis.

4.2.2. Water Balance for different LULC categories

As water was identified as a key provisioning ecosystem service it was necessary to quantify the water yield from the different land use and land cover in the watershed. The results of the water balance for different LULC were then generated from the procedures and methods described in the methodology and presented in Table 4.3.

Table 4.3: Water balance table for tea, coffee, maize and shrub vegetation LULC

TEA									
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	80.4	88.3	7.9	17.3	97.7	-6.4	10.9	10.9
Feb-16	40.3	58	80.5	22.5	8.4	66.4	-26.1	-17.7	-17.7
Mar-16	205.2	87.1	87.1	0	13.4	100.5	104.7	118.1	118.1
Apr-16	275.2	82.4	82.4	0	95.7	178.1	97.1	192.8	192.8
May-16	568.4	79.2	79.2	0	299.8	379	189.4	489.2	489.2
Jun-16	134	79.4	79.4	0	166.3	245.7	-111.7	54.6	54.6
Jul-16	50.5	64.1	64.1	0	82.3	146.4	-95.9	-13.6	-13.6
Aug-16	103.8	66.7	66.7	0	53	119.7	-15.9	37.1	37.1
Sep-16	79.3	70.5	71.2	0.7	29.9	100.4	-21.1	8.8	8.8
Oct-16	158.5	80.6	80.6	0	55.9	136.5	22	77.9	77.9
Nov-16	727.5	75.9	75.9	0	368	443.9	283.6	651.6	651.6
Dec-16	92.7	88.4	88.4	0	170.4	258.8	-166.1	4.3	4.3
TOTAL	**2526.7**	**912.7**	**943.8**	**31.1**	**1360.4**	**2273.1**	**253.6**	**1614**	**1614**

COFFEE									
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	55.6	68.2	-25.7	-93.9	15.5	52.7	2.9	18.4	-12.6
Feb-16	95.3	74.3	17.2	-57.1	11.2	63.1	32.2	43.4	21
Mar-16	134	87.1	40.2	-46.9	9.9	77.2	56.8	66.7	46.9
Apr-16	97.2	82.9	9.5	-73.4	6.4	76.5	20.7	27.1	14.3
May-16	105.9	79.2	21.4	-57.8	6.1	73.1	32.8	38.9	26.7
Jun-16	35.9	71.1	-41.4	-112.5	2.2	68.9	-33	-30.8	-35.2
Jul-16	4.4	50.8	-62.7	-113.5	0.4	50.4	-46	-45.6	-46.4
Aug-16	34.9	53.5	-36.5	-90	1.8	51.7	-16.8	-15	-18.6
Sep-16	36.1	55.1	-43.8	-98.9	1.9	53.2	-17.1	-15.2	-19
Oct-16	19.7	42.8	-61.4	-104.2	1	41.8	-22.1	-21.1	-23.1
Nov-16	405.6	76.9	308.5	231.6	86.5	-9.6	415.2	501.7	328.7
Dec-16	190.2	77.6	103.1	25.5	94.2	-16.6	206.8	301	112.6
TOTAL	**1214.8**	**819.5**	**228.4**	**-591.1**	**237.1**	**1056.6**	**158.2**	**395.3**	**395.3**

MAIZE									
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	77.7	88.3	10.6	17.3	95	-3.7	13.6	13.6
Feb-16	40.3	55.8	80.5	24.7	8.4	64.2	-23.9	-15.5	-15.5
Mar-16	205.2	87.1	87.1	0	26	113.1	92.1	118.1	118.1
Apr-16	275.2	82.4	82.4	0	111.2	193.6	81.6	192.8	192.8
May-16	568.4	79.2	79.2	0	307.5	386.7	181.7	489.2	489.2
Jun-16	134	79.4	79.4	0	170.2	249.6	-115.6	54.6	54.6
Jul-16	50.5	61.7	64.1	2.4	84.3	146	-95.5	-11.2	-11.2
Aug-16	103.8	67.1	66.7	-0.4	54	121.1	-17.3	36.7	36.7
Sep-16	79.3	63.1	71.2	8.1	30.4	93.5	-14.2	16.2	16.2
Oct-16	158.5	80	80.6	0.6	56.1	136.1	22.4	78.5	78.5
Nov-16	727.5	75.9	75.9	0	368.1	444	283.5	651.6	651.6
Dec-16	92.7	88.4	88.4	0	170.5	258.9	-166.2	4.3	4.3
TOTAL	**2526.7**	**897.8**	**943.8**	**46**	**1404**	**2301.8**	**224.9**	**1628.9**	**1628.9**

SHRUB VEGETATION									
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	71.3	88.3	17	17.3	88.6	2.7	20	20
Feb-16	40.3	50.2	80.5	30.3	8.4	58.6	-18.3	-9.9	-9.9
Mar-16	205.2	87.1	87.1	0	13.4	100.5	104.7	118.1	118.1
Apr-16	275.2	82.4	82.4	0	95.7	178.1	97.1	192.8	192.8
May-16	568.4	79.2	79.2	0	299.8	379	189.4	489.2	489.2
Jun-16	134	79.4	79.4	0	166.3	245.7	-111.7	54.6	54.6
Jul-16	50.5	62.2	64.1	1.9	82.3	144.5	-94	-11.7	-11.7
Aug-16	103.8	63.8	66.7	2.9	53	116.8	-13	40	40
Sep-16	79.3	63.5	71.2	7.7	29.9	93.4	-14.1	15.8	15.8
Oct-16	158.5	80.1	80.6	0.5	55.9	136	22.5	78.4	78.4
Nov-16	727.5	75.9	75.9	0	368	443.9	283.6	651.6	651.6
Dec-16	92.7	88.4	88.4	0	170.4	258.8	-166.1	4.3	4.3
TOTAL	**2526.7**	**883.5**	**943.8**	**60.3**	**1360.4**	**2243.9**	**282.8**	**1643.2**	**1643.2**

Figure 4.2 is the graph generated from Thornthwaite outputs to illustrate the dynamics of watershed water balance with regard to Precipitation (P) and Potential Evapotranspiration (PET) actual Evapotranspiration (AET) and runoff for these LULC classes. The graph has been reconstructed for interpretation as below

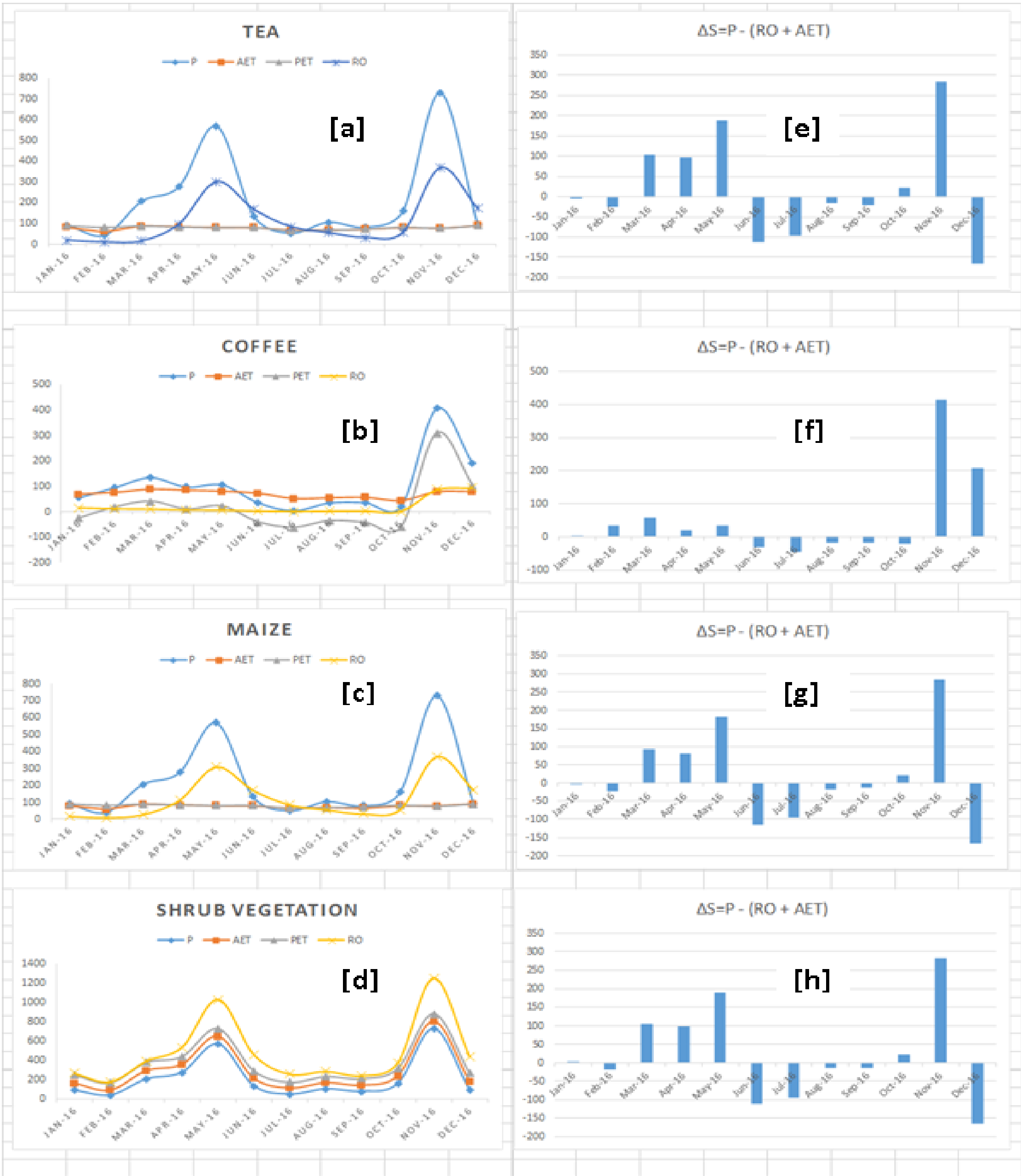

Figure 4.2: Graph of water balance parameters (a-d) and ΔS (e-h) for tea, coffee, maize and shrub vegetation.

In Months where the precipitation (P) was higher than Actual Evapotranspiration (AET) indicated that there was a change in water storage denoting a surplus, this was within the following Months; March – May (*Masika* season) and October- December *(Vuli)* season

The months with values above 0mm indicated a surplus change in soil water storage whereas areas with values below 0mm indicated water deficit as illustrated.

The volume of water yield was computed within the land uses to estimate the amount of water that was available within the period January to December, 2016. From Table 4.3, a depth of 1614mm, 395.3mm, 1628mm, and 1643.2mm was attained for tea, coffee, maize and shrub vegetation LULC respectively.

Water yield fluctuation across the period was then plotted by the study as illustrated from Figure 4.3

From the areas generated from LULC mapping, it was therefore possible to compute the volume of water yield per the LULC Class.

Table 4.4: Volumetric Water yield as per Land use

Class	**Tea**	**Coffee**	**Maize**	**Shrub Vegetation**
Area (m^2)	62,251,511.60	27,342,810.10	27,508,038.10	108,365,921.80
Annual yield(m)	1.61	0.40	1.63	1.64
Volumetric water yield (m^3)	100,473,939.72	10,808,612.83	44,807,843.26	178,066,882.70

For mature and young forests the water balance is as illustrated in Table 4.5.

Table 4.5: Water balance table for mature and young forest LULC classes

					YOUNG FOREST				
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	87.3	88.3	1	14.7	102	-10.7	4	4
Feb-16	40.3	54.1	80.5	26.4	8.1	62.2	-21.9	-13.8	-13.8
Mar-16	205.2	87.1	87.1	0	13.9	101	104.2	118.1	118.1
Apr-16	275.2	82.4	82.4	0	62	144.4	130.8	192.8	192.8
May-16	568.4	79.2	79.2	0	241.7	320.9	247.5	489.2	489.2
Jun-16	134	79.4	79.4	0	153.8	233.2	-99.2	54.6	54.6
Jul-16	50.5	64.1	64.1	0	90.8	154.9	-104.4	-13.6	-13.6
Aug-16	103.8	66.7	66.7	0	64.5	131.2	-27.4	37.1	37.1
Sep-16	79.3	71.2	71.2	0	41.2	112.4	-33.1	8.1	8.1
Oct-16	158.5	80.6	80.6	0	58.2	138.8	19.7	77.9	77.9
Nov-16	727.5	75.9	75.9	0	312.6	388.5	339	651.6	651.6
Dec-16	92.7	88.4	88.4	0	170.4	258.8	-166.1	4.3	4.3
TOTAL	**2526.7**	**916.4**	**943.8**	**27.4**	**1231.9**	**2148.3**	**378.4**	**1610.3**	**1610.3**
					MATURE FOREST				
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	87.5	88.3	0.8	12.2	99.7	-8.4	3.8	3.8
Feb-16	40.3	59.3	80.5	21.2	7.3	66.6	-26.3	-19	-19
Mar-16	205.2	87.1	87.1	0	14	101.1	104.1	118.1	118.1
Apr-16	275.2	82.4	82.4	0	22.5	104.9	170.3	192.8	192.8
May-16	568.4	79.2	79.2	0	172.8	252	316.4	489.2	489.2
Jun-16	134	79.4	79.4	0	122.1	201.5	-67.5	54.6	54.6
Jul-16	50.5	64.1	64.1	0	83.3	147.4	-96.9	-13.6	-13.6
Aug-16	103.8	66.7	66.7	0	66.5	133.2	-29.4	37.1	37.1
Sep-16	79.3	71.2	71.2	0	48.1	119.3	-40	8.1	8.1
Oct-16	158.5	80.6	80.6	0	59.8	140.4	18.1	77.9	77.9
Nov-16	727.5	75.9	75.9	0	257.3	333.2	394.3	651.6	651.6
Dec-16	92.7	88.4	88.4	0	159.3	247.7	-155	4.3	4.3
TOTAL	**2526.7**	**921.8**	**943.8**	**22**	**1025.2**	**1947**	**579.7**	**1604.9**	**1604.9**

In order to illustrate water balance dynamics output generated the outputs generated were plotted using graphs as illustrated in Figure 4.3.

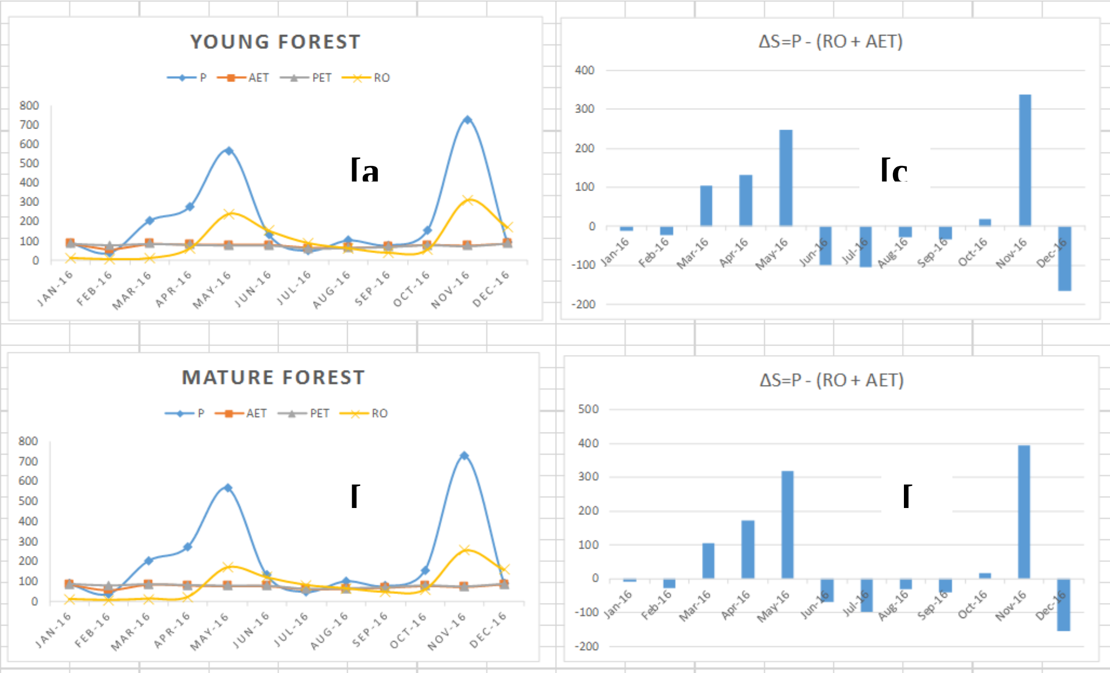

Figure 4.3: Graph of water balance parameters (a, b) and ΔS (c, d) for young and mature forests

Water surplus was as a result of higher Precipitation than Actual Evapotranspiration. From Figure 4.3 (a, b) this was in the months of March - May (*Masika* season), October- December (*Vuli* season). A combination of very low water yields and yield deficits were experienced in the months of January –February and June – September. In these months the actual evapotranspiration exceeded precipitation.

Forests followed in terms of storage with mature forest and young forest having storages of 579.7mm and 378.4mm respectively.

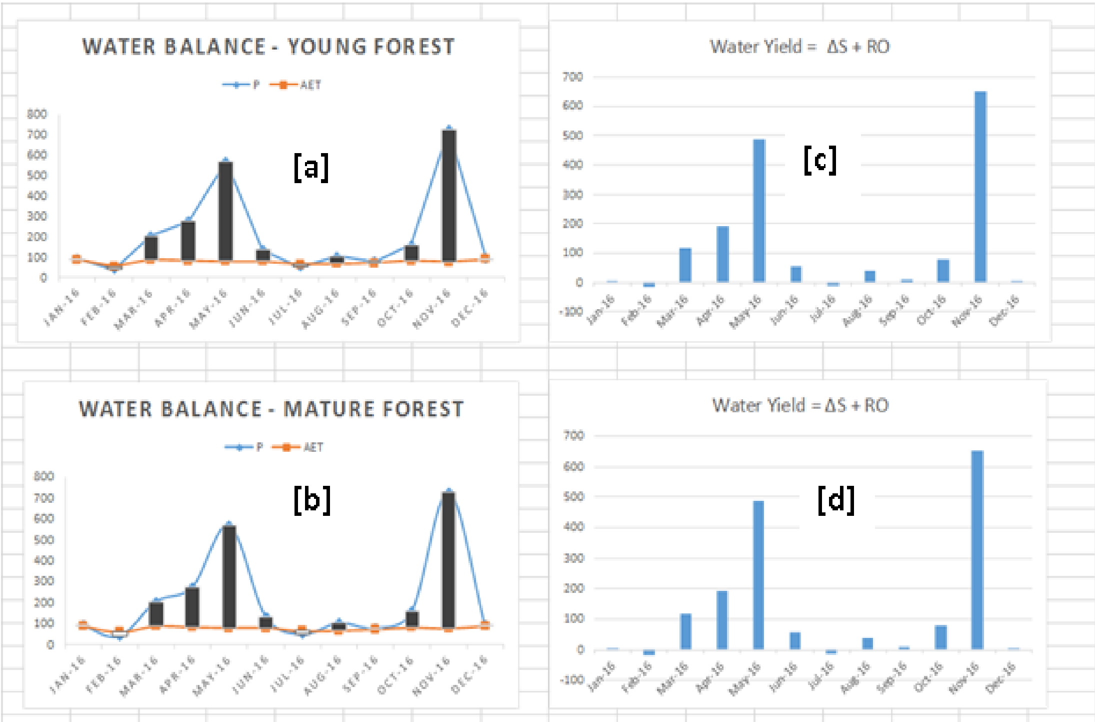

Figure 4.4: Water yield graphs for young and mature forest

Values above 0 from Figure 4.4 indicate water surplus while values below 0 indicate water deficit. The surplus was due to the forests ability to allow the soils to absorb the water as ground water which is released slowly as seeps and springs. This was validated by large number of springs near the forest area as revealed by the PGIS.

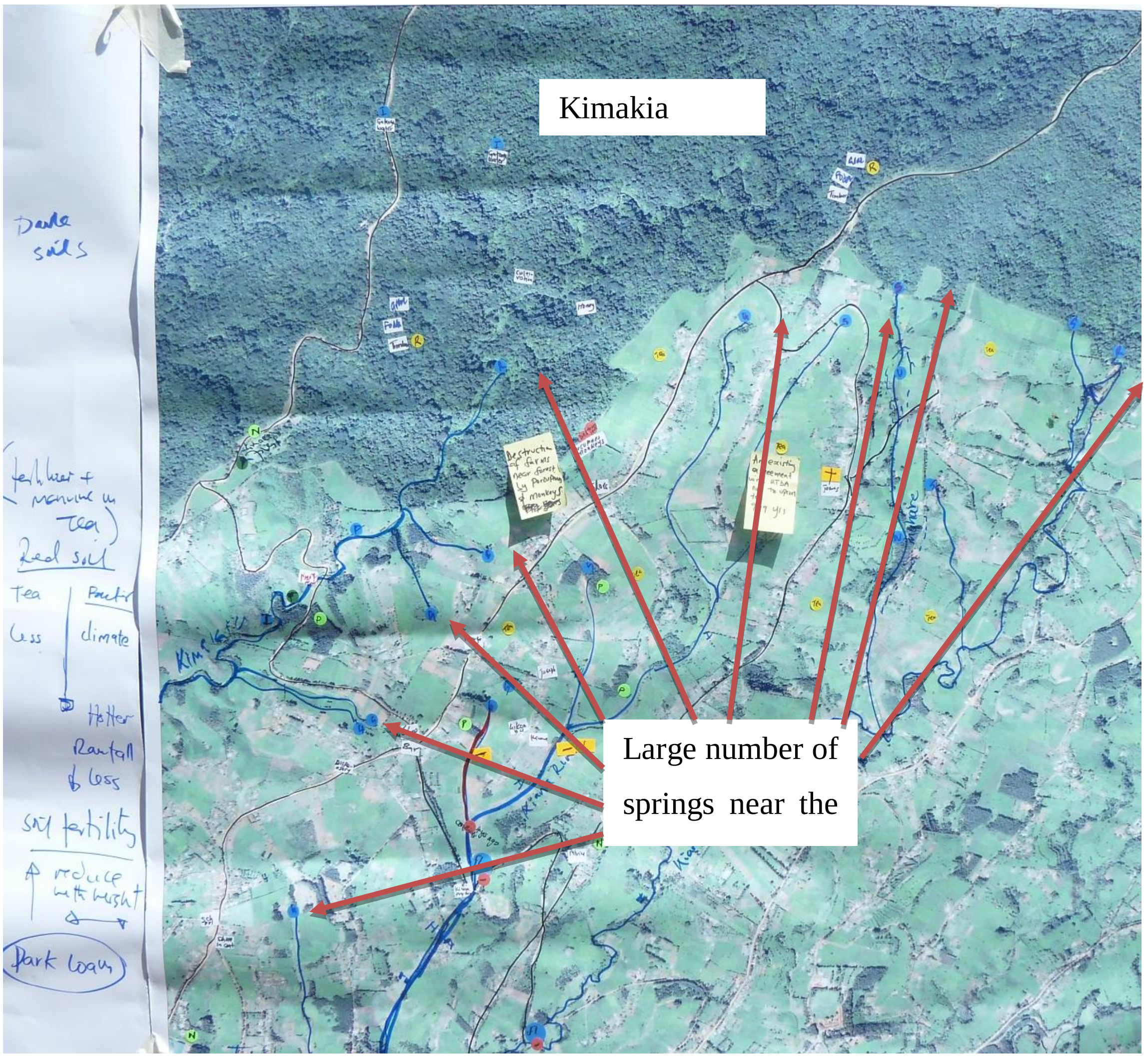

Plate 4.1: Water springs near Kimakia forest

Volumetric water yield computed for young forest and mature forest land uses is represented in Table 4.6 below.

Table 4.6: Water yield for mature and young forest

Class	Area (m^2)	Annual water yield (mm)	Volume_m^3 {Area * (Change in storage in mm/1000)m}
MATURE FOREST	71,703,167.70	1,604.90	115,076,413.84
YOUNG FOREST	16,438,515.00	1,610.30	26,470,940.70

In considering the wetland LULC, the results just as in other land uses were in tabular format as illustrated from Table 4.7.

Table 4.7: Water balance parameter for wetland

WETLAND									
MONTH	P	AET	PET	PET - AET	RO	AET + RO	ΔS=P - (RO + AET)	ΔS + RO	P - AET
Jan-16	91.3	88.3	88.3	0	4.6	92.9	-1.6	3	3
Feb-16	40.3	55.7	80.5	24.8	2	57.7	-17.4	-15.4	-15.4
Mar-16	205.2	87.1	87.1	0	10.3	97.4	107.8	118.1	118.1
Apr-16	275.2	82.4	82.4	0	13.8	96.2	179	192.8	192.8
May-16	568.4	79.2	79.2	0	28.4	107.6	460.8	489.2	489.2
Jun-16	134	79.4	79.4	0	6.7	86.1	47.9	54.6	54.6
Jul-16	50.5	64.1	64.1	0	2.5	66.6	-16.1	-13.6	-13.6
Aug-16	103.8	66.7	66.7	0	5.2	71.9	31.9	37.1	37.1
Sep-16	79.3	71.2	71.2	0	4	75.2	4.1	8.1	8.1
Oct-16	158.5	80.6	80.6	0	7.9	88.5	70	77.9	77.9
Nov-16	727.5	75.9	75.9	0	36.4	112.3	615.2	651.6	651.6
Dec-16	92.7	88.4	88.4	0	4.6	93	-0.3	4.3	4.3
TOTAL	**2526.7**	**919**	**943.8**	**24.8**	**126.4**	**1045.4**	**1481.3**	**1607.7**	**1607.7**

Wetlands had the lowest runoff of 126.4mm. This emphasizes the importance of wetlands in flood control. In order to obtain the soil water storage within the LULC class, the difference between Precipitation (P) versus the sum of actual evapotranspiration (AET) and run off (RO) was computed. Wetlands had the highest change in water storage with an annual storage of 1481.3mm. The trend was represented in a graph as illustrated in Figure 4.5.

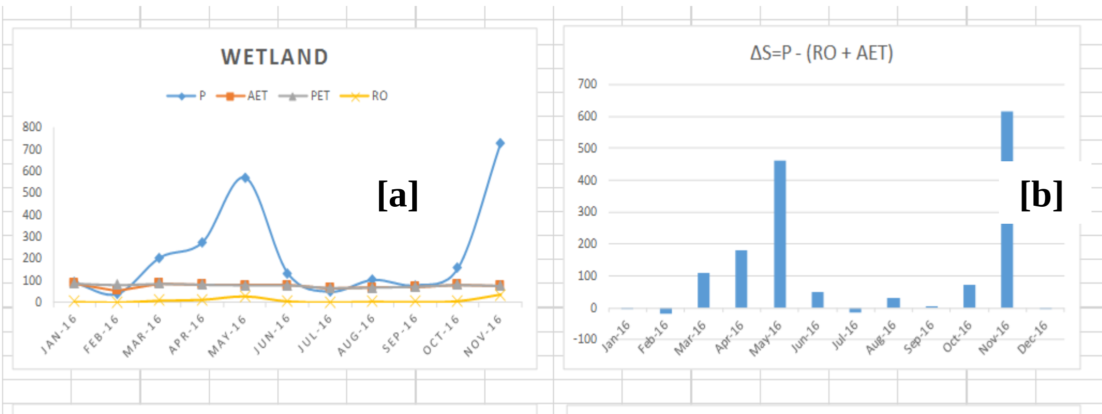

Figure 4.5: Graph of water balance parameters (a, b) and ΔS (c, d) for young and mature forests

Negative values indicated monthly soil water deficit whereas positive values indicated monthly soil water surplus

Water yield fluctuation was then plotted across the entire period as illustrated from Figure 4.6. The trend of the water yield was then derived from the differences of these two parameters and plotted as in Figure 4.6.

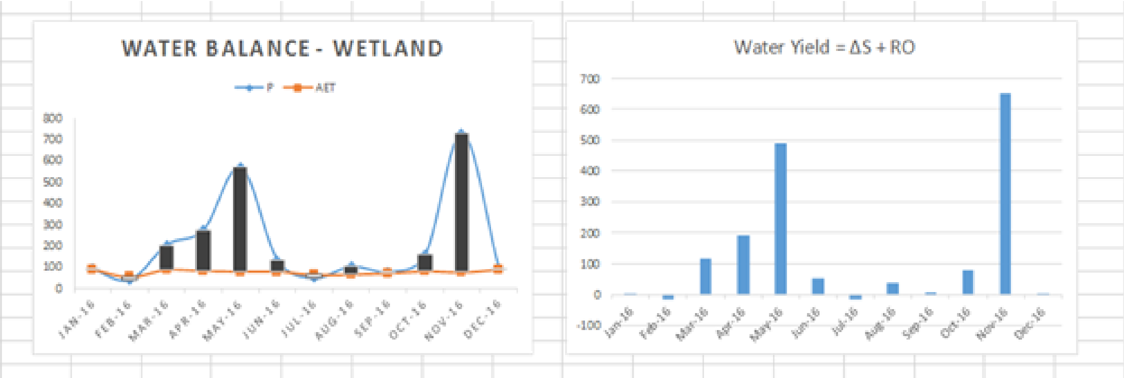

Figure 4.6: Graph Illustrating Precipitation versus Potential Evapotranspiration for wetland

Water yield for wetland land use was then computed across the period, which was totalling to 638.1mm. This was later on utilized by the study to calculate volumetric water yield for the entire period using total area acquired after supervised classification and vectorization of the same. Table 4.8 illustrates the volumetric water yield obtained.

Table 4.8: Volumetric water yield for wetland

CLASS	Area (m^2)	Annual water yield (mm)	Volume_m^3 {Area * (annual water yield in mm/1000)m}
Wetland	31,429,754.80	1,607.70	50,529,616.79

4.2.3. Total watershed water yield

From the water yield calculated within chapter three, volumetric water yield was estimated as a product of Land use areas and the land use water yield obtained as illustrated from Table 4.9.

Table 4.9: Total water yield

CLASS	Area (m)	Annual water yield (mm)	Volume_m^3 {Area * (Annual yield mm/1000)m}
Mature forest	71,703,167.70	1,604.90	115,076,413.84
Young forest	16,438,515.00	1,610.30	26,470,940.70
Wetland	31,429,754.80	1,607.70	50,529,616.79
Coffee	27,342,810.10	395.30	10,808,612.83
Tea	62,251,511.60	1,614.00	100,473,939.72
Shrub vegetation	108,365,921.80	1,643.20	178,066,882.70
Maize	27,508,038.10	1,628.90	44,807,843.26
TOTAL	**345,039,719.10**	**10,104.30**	**526,234,249.86**

The total water yield for the catchment from table 4.9 is **526,234,249.86 m^3.** In terms of distribution of the volumetric yield the pie chart below clearly shows the portion in percentage of the water yield of each land use. Shrub vegetation has the highest volume of production due to large area given that the yield volume is the product of yield height and the area. Coffee LULC has the least volumetric yield. because of low annual yield expressed in heights (mm) attributed to the relatively high actual evapotranspiration in relation to the precipitation in the coffee areas the area covered as well as the small area under coffee. Low volumetric yield in maize is attributed to the small area under this crop.

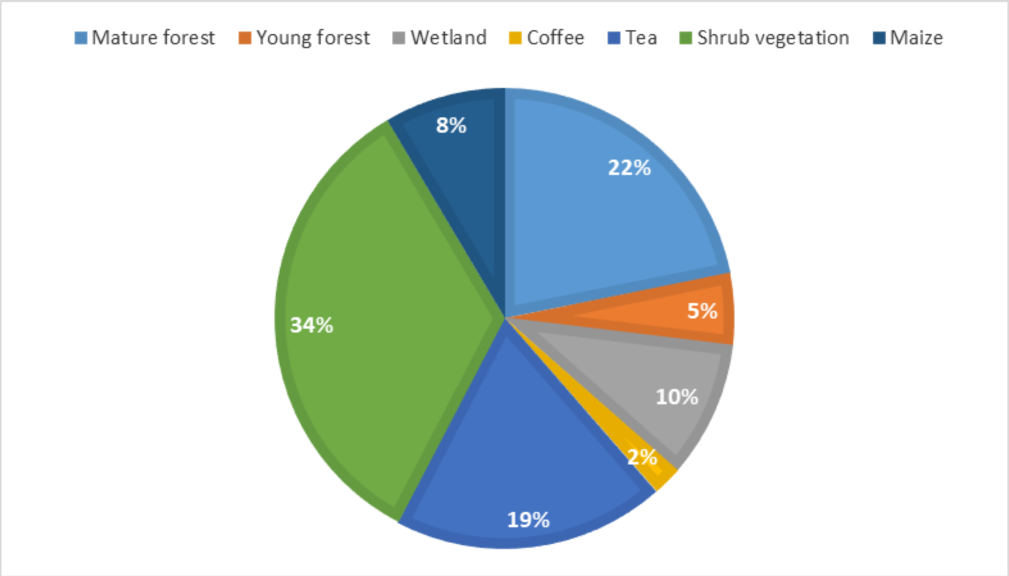

Figure 4.7: Percentage yield in volume for different land uses

Actual Evapotranspiration (ET_a) were filtered out and represented seperately from the water balance table because of their particular importance in determining the biomass water productivity (Equation 20). The filtered out ET_a results for each LULC are shown in Table 4.10

Table 4.10: Actual Evapotranspiration (ETa) different LULC classes

Actual ET_a/ Month	Tea	Coffee	Maize	Shrub Vegetation	Mature Forest	Young Forest	Wetland	Mixed Crop
Jan-16	80.4	68.2	77.7	71.3	87.5	87.3	88.3	65.7
Feb-16	58	74.3	55.8	50.2	59.3	54.1	55.7	74.3
Mar-16	87.1	87.1	87.1	87.1	87.1	87.1	87.1	87.1
Apr-16	82.4	82.9	82.4	82.4	82.4	82.4	82.4	82.9
May-16	79.2	79.2	79.2	79.2	79.2	79.2	79.2	79.2
Jun-16	79.4	71.1	79.4	79.4	79.4	79.4	79.4	65.2
Jul-16	64.1	50.8	61.7	62.2	64.1	64.1	64.1	44.8
Aug-16	66.7	53.5	67.1	63.8	66.7	66.7	66.7	51.9
Sep-16	70.5	55.1	63.1	63.5	71.2	71.2	71.2	54
Oct-16	80.6	42.8	80	80.1	80.6	80.6	80.6	42.3
Nov-16	75.9	76.9	75.9	75.9	75.9	75.9	75.9	76.9
Dec-16	88.4	77.6	88.4	88.4	88.4	88.4	88.4	77.6
TOTAL	**912.7**	**819.5**	**897.8**	**883.5**	**921.8**	**916.4**	**919**	**801.9**

When the monthly ET_a was plotted for each month, the trend represented below was achieved

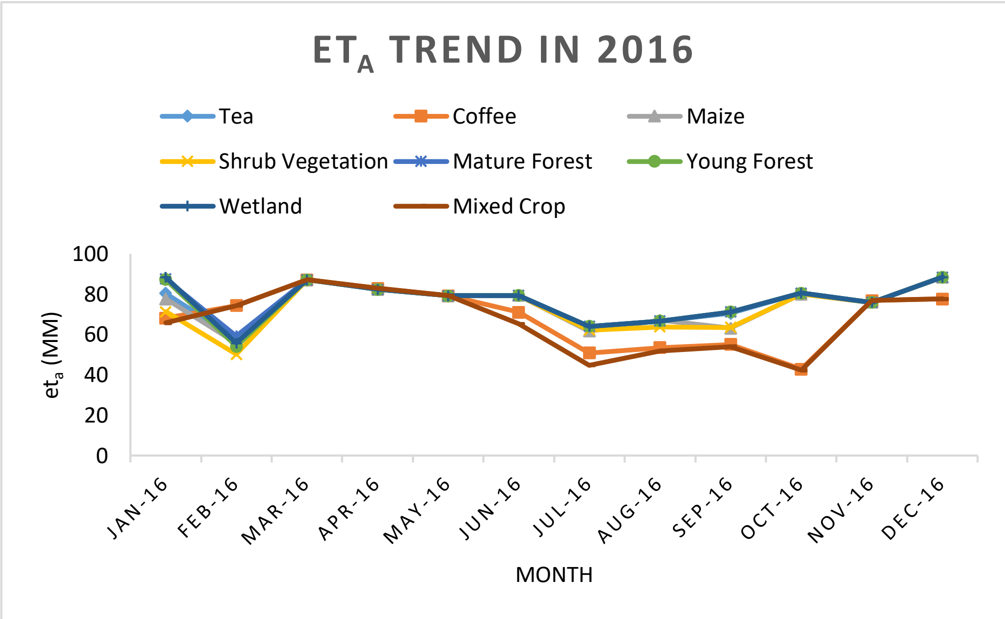

Figure 4.8: Monthly evapotranspiration trend for Chania in 2016

Mature forest, young forest and wetands type of land uses were found to have the highest ET_a values of 921mm, 916.4mm and 919mm respectively. Mixed crops had the lowest ET_a values.

The higher values of ET_a mature forest is due to the higher leaf area as compared to the young forest. Mixed crop and coffee had the lowest ET_a attributed to low transpiration of the crops due to the nature of the leaves and climatic conditions.

For all land uses it can be observed that there is ET_a between March and May and between September and November which are the two rain seasons *Masika* and *Vuli*. During this seasons, water availability is high thus the potential evapotranspiration translates to the highest actual transpiration possible.

Actual seasonal evapotranspiration (ET_a) in Chania study area is spatially represented in Figure 4.9.

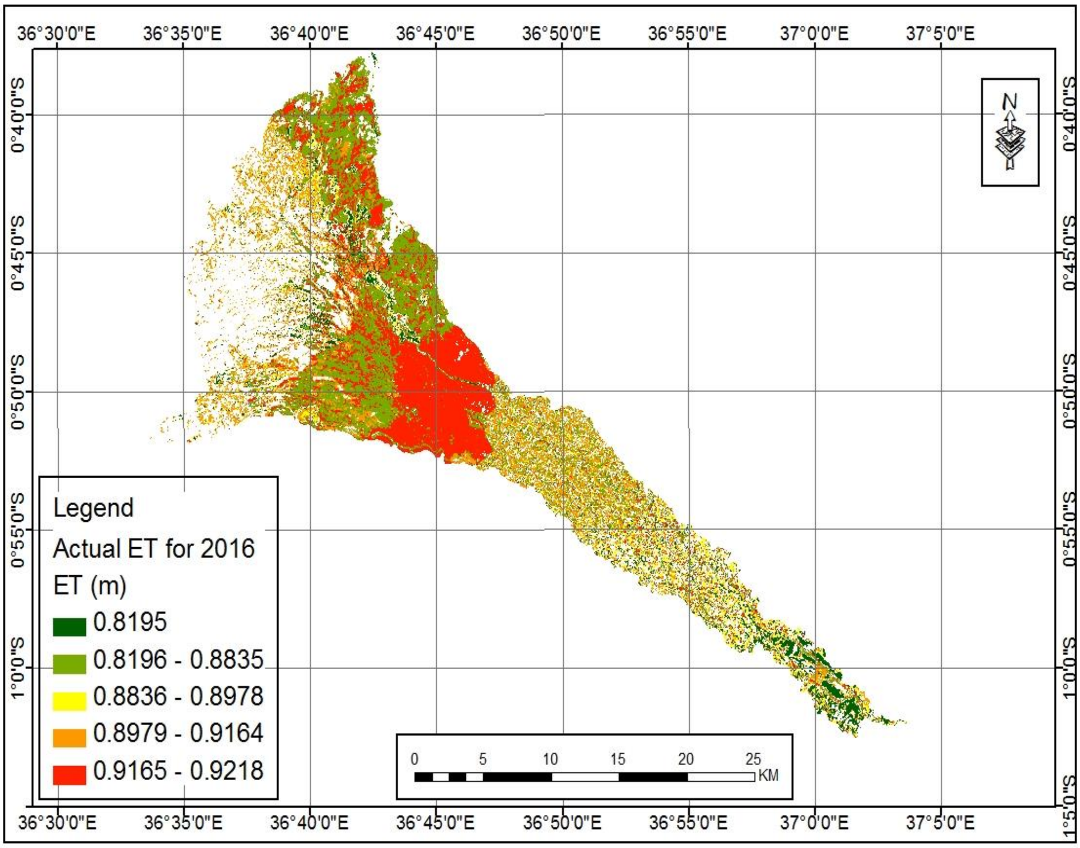

Figure 4.9: Annual actual evapotranspiration map for Chania – 2016

4.2.4. Biomass productivity for different LULC

For all the LULC classes, logarithmic, linear and exponential graphs were plotted. The graphs with the highest Pearson product moment correlation coefficient (R^2) in each class was adopted. Below is a table with the various predictive equations and the correlations (R^2). On the extreme right column of the table are the above ground equations with the highest correlation for each LULC.

Table 4.11: Prediction equations for various LULC classes in Chania and their corresponding correlation coefficients

LULC Class	Equation	R^2	Equation with (y) as Biomass and (x) as NDVI
Tea	$y= 9.09e^{3.82x}$	0.99	Biomass= $9.09e^{3.82(NDVI)}$
	$y=81.34\ln(x) +148.79$	0.70	
	$y=247.33x-40.17$	0.89	
Coffee	$y= 56.26e^{3.85x}$	0.99	Biomass= $56.26e^{3.85(NDVI)}$
	$y=290.74\ln(x) +728.10$	0.66	
	$y=1243.00x-117.98$	0.92	
Maize	$y=0.78e^{7.82x}$	0.98	Biomass=$0.78e^{7.82(NDVI)}$
	$y=137.55\ln(x) +185$	0.71	
	$y=362.66x-101.67$	0.86	
Shrub Vegetation	$y= 44.89e^{3.85x}$	0.89	Biomass=1061(NDVI)-133.29
	$y=38\ln(x) +705.22$	0.84	
	$y=1061x-133.29$	0.95	
Wetland	$y= 55.39e^{3.35x}$	0.92	Biomass=829.02(NDVI)-60.639
	$y=291.31\ln(x) +586.47$	0.91	
	$y=829.02x-60.63$	0.99	
Young Forest	$y= 2.75e^{1.03x}$	0.95	Biomass=3.3178ln(NDVI)-6.9447
	$y=3.32\ln(x)-6.94$	0.99	
	$y=5.38x+1.95$	0.97	
Mature Forest	$y=8.43e^{3.40x}$	0.96	Biomass=$8.4344e^{3.4016(NDVI)}$
	$y=113.08\ln(x) +135.51$	0.82	
	$y=219.69x-57.75$	0.89	

From the table four out of seven predictive equations are exponential. For the three other equations, the R^2 difference between the adopted predictive equation and the exponential equation is not significant. This means that for all the seven LULC classes exponential equations could be used exclusively with still a high accuracy level. This accuracy level of the exponential equations give a pointer towards establishing more accurately through other indepth researches the possibility of exclusively using exponential graphs for biomass estimation.

After inputting the equations in the raster calculator of the ArcGIS software the biomass range was established (Table 4.12).

Above ground biomass developed were later on utilized in valuation of spatial biophysical productivity of Chania river system. Following above ground biomass calculation, mature forest and Young forest had the highest above ground biomass respectively followed by Coffee, Shrub Vegetation and Wetland with Tea and Maize land uses having the least above ground biomass respectively.

The range of the AGB for each LULC is tabulated below

Table 4.12: The range of above ground biomass for each LULC

Land use types	**Tea**	**Coffee**	**Maize**	**Shrub**	**Wetlands**	**Young Forest**	**Mature Forest**
Biomass range(g/m^2)	12.23	3.25	1.62	44.84	54.25	4,001	21,240
	to	to	to	to	to	to	to
	90.47	980.26	153.01	631.59	528.08	6,376	146,354

Results indicate that mature forests have the highest biomass potential of between 21kg/m^2 to 146 kg/m^2. By interpolation, from the biomass mapdistribution of the range is concentrated around 73kg/m^2 to 109 kg/m^2

The range for young forest is between 4 and 6.4 kg/m^2 which conforms with studies from other parts of the world. Shendryk, (2014) established the biomass range of spruce forest in Boreal, Sweden to be between 1kg/m^2 for young forests to 94 kg/m^2 for mature forests. In Tanzania, Muragura, (2007) established biomass of theDuru-Haitemba forest reserve to be between 1 and 17kg/m^2.This range is within the range established by this study, although it is lower than the dorminant biomass range for mature forest biomass in Chania because Duru- Haitemba forest reserve is composed mainly of woodlands. Trees in the mature forest areas of Chania are predominantly pine. Other studies by Popescu, (2007), Mehtätalo, (2005) and Bortolot, (2005) found biomasses that fall within this range.Endre *et al.* 2015 found the maximum tropical rainforest biomass in Tanzania to be 115kg/m^2 which is within the range of biomass for mature forests found by this study. By breaking down the provisioning services derived from forest into material and energy, and considering that biomass is the quantifying unit for these provisioning services, it can be concluded that the commodity that provides the highest value of these services in Chania is the forests.

In order to determine the total AGB values from which the trend of monthly biomass gain would be deduced, the sum of AGB for each land use was determined by summing up the AGB represented by each pixel using the 'zonal statistics' tool of the ArcGIS image processing software. The resulting total AGB obtained across the year are represented in the Table 4.13.

Table 4.13: Monthly total AGB for Chania in 2016

Month \Land use type	Coffee	Tea	Young Forest	Mature Forest	Maize	Shrub Vegetation	Wetland
January	869075.0	804780.0	457675.0	1,529,607.0	29522.0	217105.2	752275.9
March	434537.5	1088002.6	663143.2	758285.6	31115.6	418972.2	943259.1
June	732719.7	702647.8	788922.0	766100.9	54382.6	564826.7	1068345.9
September	821644.8	653693.8	794530.7	1,182,625.0	60871.0	899537.4	1,106,319.7
December	1,079,121.1	896,726.7	1,115,609.0	1,606,100.0	71793.0	944,953.6	1,122,853.1

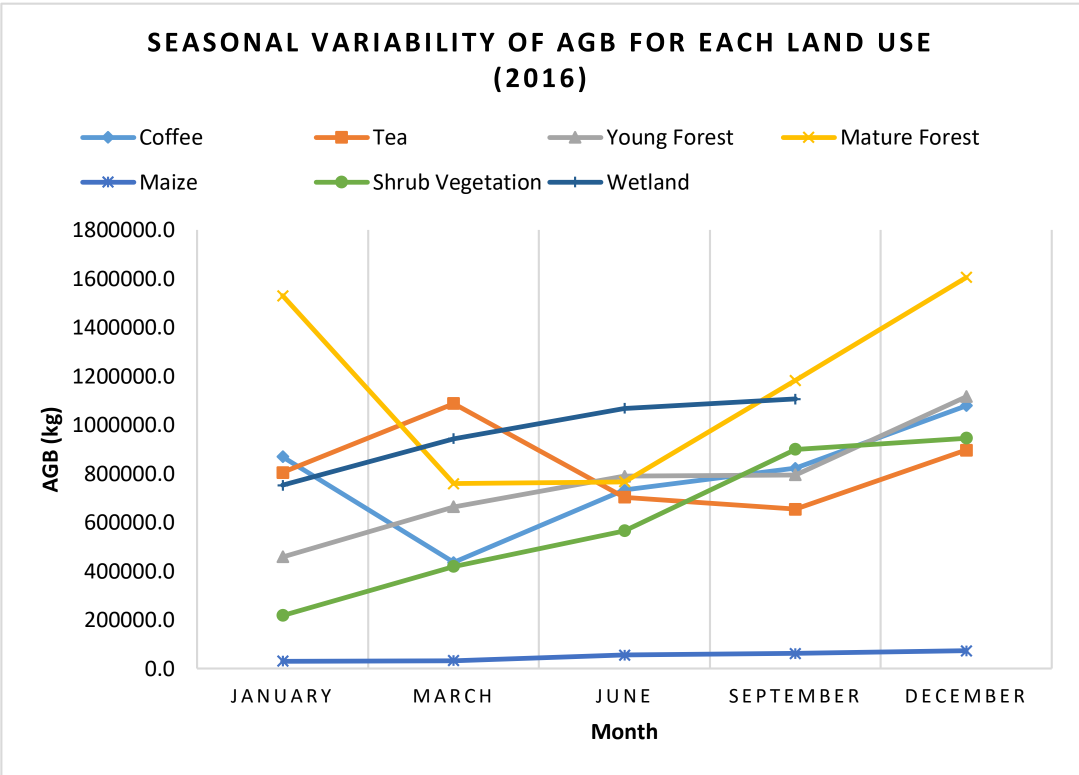

Figure 4.10: AGB variability for each land use in Chania in 2016

It was also observed that the gain of biomass for mature forest went up between June to December.. This can be attributed to the fact that mature trees have plenty of water even for dry periods, and as indicated earlier, the rain starts in March and reaches optimum in the months of April and May. This explains why for all landuses gain of biomass is experienced from March. Biomass productivity was calculated for months with consistent biomass gain and the results extrapolated to capture values for the whole season and spatially represented. (Figure 4.14). For all the land uses the biomass in December was high as compared to January meaning there was biomass gain due to crop grown within 2016.

AGB gains for 2016 obtained for each land use was as tabulated in Table 4.14.

Table 4.14: Biomass productivity for each land use in Chania catchment in 2016

Land use type	**Tea**	**Coffee**	**Maize**	**Shrub**	**Wetlands**	**Young Forest**	**Mature Forest**
Total biomass	972,131.6	257,476.3	43,688.2	181,664.8	370,577.2	1,284,313.2	1,679,998.2
Total Area (m^2)	62,251,511.6	27,342,810	27,508,038	108,365,921.8	31,429,754.82	16,438,515	71,703,167.7
Biomass Productivity (kg/m^2)	0.016	0.009	0.002	0.002	0.012	0.078	0.023

Forest class of land use had the highest biomass productivity of 0.078kg/m^2 and 0.023kg/m^2 for young and mature forests respectively. The lower biomass gain for mature forest can be attributed to lower light intensity which affect photosynthetic activity and depletion of the important nutrients that support plant growth. Due to higher light intesity reaching the young forest there is higher photosynthetic activity and thus higher biomass gain. Maize and coffee had the least biomass gain per square metre which is attributed to their growth nature which does not allow them to gain much biomass

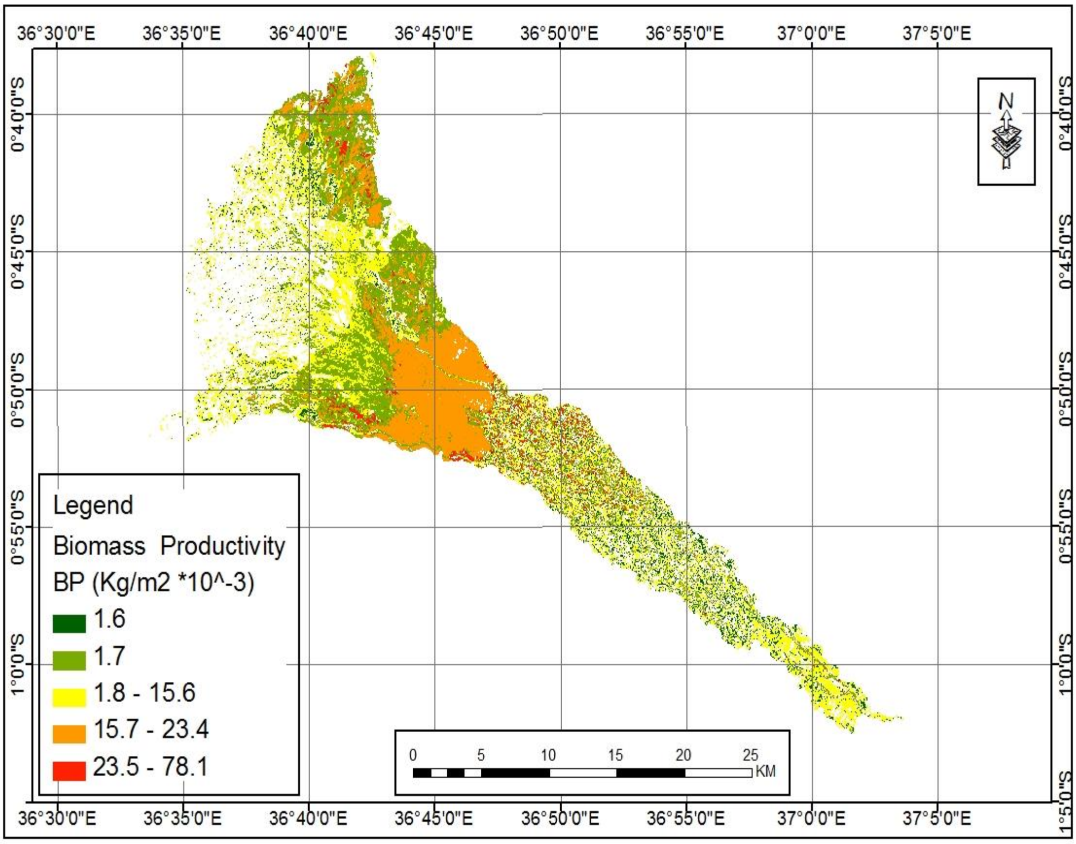

Figure 4.11: Biomass productivity map for Chania, 2016

4.2.5. Biomass Water Productivity

When biomass values for different LULC were converted to kg/m^{-2} , and divided by the value of ET , biomass water productivity for the different LULC classes were obtained in Kgm^{-3}

Table 4.15: Biomass Water Productivity for Chania

Land use type	**Tea**	**Coffee**	**Maize**	**Shrub**	**Wetlands**	**Young Forest**	**Mature Forest**
Biomass	0.016	0.009	0.002	0.002	0.012	0.078	0.023
Water use (ET_a) (m)	0.912	0.820	0.897	0.884	0.919	0.916	0.922
Biomass Water	0.018	0.011	0.002	0.002	0.013	0.085	0.025

The biomass water productivity for the catchment representing all land uses was spatially represented by dividing the raster layer of the biomass productivity by the water use (ET_a) raster layer in ArcGIS. The resulting biomass water productivity map is as shown in figure 4.12.

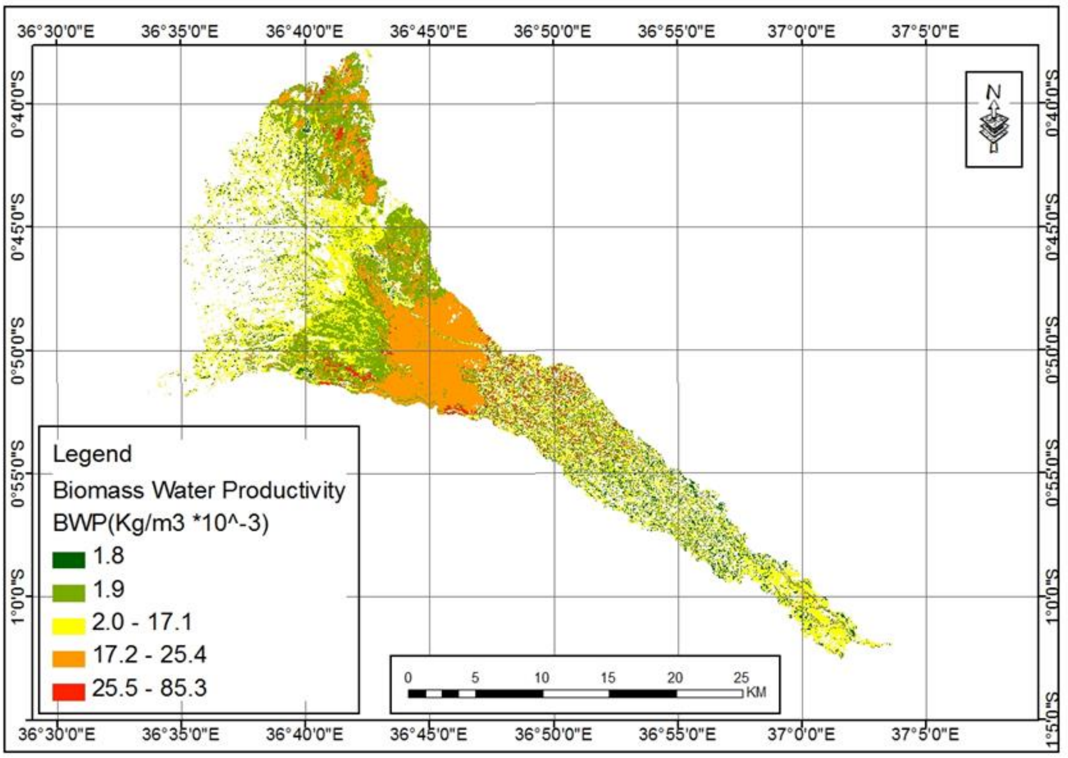

Figure 4.12: Spatially represented biomass water productivity for 2016

Young forest had the highest biomass water productivity while maize had the lowest. The low biomass water productivity relates to the fact that the maize crops are perennial crops which by nature have low biomass gain within their lifespan. In general the catchment had low biomass water productivity meaning that the catchment has more capacity for production with better and and water management practices.

4.3. Valuation of provisioning ecosystem services and goods (Yield Productivity)

By getting the product of biomass water productivity, harvest and unit prices for coffee, tea and maize, it was established that tea had the highest yield water productivity of KES 0.22/m^2 followed by coffee with yield water productivity of KES 0.05/m^2. Maize had the least yield water productivity of KES 0.04/m^2. It is noticed that the difference of yield water productivity of maize and coffee is small as compared to the biomass water productivity. This is due to the fact that in as much as there was high biomass gain for coffee (0.011 Kg/m^2) as compared to maize (0.002 Kg/m^2), the ratio of the useful biomass was small (0.012) as compared to maize which is 0.35). The yield productivity of tea is high because of the high harvest index and fairly high market price (KES 250 per Kg).

Mature forests had the highest amount of carbon and CO_2 sequestered (839,999.10 Kgs and 3,082,796 Kgs respectively) as compared to young forests which had 642,156.60 Kgs of carbon and 2,356,714.70 Kgs of CO_2 sequestered

4.4. Influence of built infrastructure on the natural ecosystem provisioning services

4.4.1. Change detection for 2005 and 2016

Table 4.16: Land use and land cover areas for the year 2005

Land use type	Area (Ha)
Bare land	11382.50
Built up	5019.35
Coffee	4839.98
Maize plantation	1014.33
Mature forest	7846.88
Mixed crops	5693.44
Shrub vegetation	6229.44
Tea	1682.74
Water	115.33
Wetland	2700.56
Young forest	5098.66

From table 4.17, the study was able to monitor land use change since a similar table had been developed for 2016. By comparing the two tables generated, the study was able to quantify land use change both by Hectares and by percentage as illustrated from Table 4.17.

Table 4.17: Land Use Change between 2005 and 2016

CHANIA LULC 2005		**CHANIA LULC 2016**		**LAND USE CHANGE**
CLASS	**AREA_HA**	**CLASS**	**AREA_HA**	**INCREASE (+) / DECREASE (-)**
Bare land	11,382.5	Bare land	5,229.5	-11.59%
Built up	5,019.35	Built up	8,030.64	+5.67%
Coffee	4,839.98	Coffee	2,734.28	-3.96%
Maize	1,014.33	Maize	2,750.8	+3.27%
Mature forest	7,846.88	Mature forest	7,170.32	-1.27%
Mixed crops	5,693.44	Mixed crops	5,035.04	-1.24%
Shrub vegetation	6,229.44	Shrub vegetation	10,836.6	+8.67%
Tea	1,682.74	Tea	6,225.15	+8.55%
Water	115.33	Water	309.517	+0.37%
Wetland	2,700.56	Wetland	3,142.98	+0.83%
Young forest	5,098.66	Young forest	1,643.85	-6.51%

From Table 4.17, Built up areas indicated tremendous increase this could be an indication of increase in population. Another probable reason for an increase in population could be as a result of tremendous decrease in the area under Bare Land from 11382.5 Ha within the year 2005 to 5229.5 Ha within the year 2016, which was 11.59% decrease in the Land under Bare Land. This could also be a probable explanation for an increase in land area under Tea Land use as most people within the catchment rely on Tea farming as one of the economic activities. This is so because area under tea land use was 1,682.74 Ha in 2005 while within 2016 the area was recorded as at 6,225.15 Ha which was 8.55% increase.

A probable reason for an increase in Tea farming could have been caused as a result of most people shifting from Coffee farming whereby the was a decrease in Coffee farming from 4839.98 Ha within the year 2005 to 2734.28 Ha in the year 2016.

There was a marginal increase in the area under water. By comparing the LULC for 2005 and 2016 it can be seen that there was expansion of the area of Sasumua Dam

4.4.2. Change in water quality

Below are the results obtained from laboratory samples tested for the wet and dry seasons

Table 4.18: Results of the laboratory tests carried out for samples taken during the dry season

PARAMETERS	STATION PT 1	STATION PT 2	STATION PT 3	STATION PT 4	STATION PT 5	Standard (WHO)
PH(-)	7.56	7.65	7.55	7.62	7.5	6.5-8.5
CONDUCTIVITY(Us)	39	44	73	86	147	0-500
T.D.S(p.p.m)	26.13	29.48	48.91	67.62	98.49	<1200
TURBIDITY(NTU)	-0.18	1.4	1.7	2.7	3.3	<300
T.S.S (Mg/l)	0.0065	0.008	0.0085	0.014	0.0185	<30
CHLOROPYLL(Ug/l)	0.0043	0.0046	0.00542	0.0228	0.0332	5-15
PHOSPHATES (-)	0.004	0.04	0.09	0.22	0.23	<10
NITRATES(-)	0.25	0.304	0.34	0.391	0.462	<10
B.O.D (Mg/l)	175	221	216.5	250	279	<30
FEACAL COLIFORM (counts / 100ml)	27	68	3	10	8	<30
TOTAL HARDNESS(p.p.m)	72	96	232	272	312	300
CHLORINE (mg/l)	3	8.5	12.5	15	17.5	250
TEMPERATURE(^{0}C)	13	15	19.5	21.5	22.5	15-30
D.O (mg/l)	7.7	6.8	6.9	6.1	5.6	> 5

Table 4.19: Results of the laboratory tests for samples taken during the wet season

PARAMETERS	STATION PT 1	STATION PT 2	STATION PT 3	STATION PT 4	STATION PT 5	Standard (WHO)
PH(-)	10.45	10.4	10.49	10.05	9.94	6.5-8.5
CONDUCTIVITY(Us)	44	52	65	110	169	0-500
T.D.S(p.p.m)	29.48	34.84	43.55	73.7	79.43	≤1200
TURBIDITY(NTU)	3.1	4.2	6	18.7	25.3	≤300
T.S.S (Mg/l)	0.0059	0.0083	0.0081	0.0185	0.0183	≤30
CHLOROPYLL(Ug/l)	0.00346	0.00404	0.00483	0.0218	0.03	5-15ug/l
PHOSPHATES (mg/l)	0.0032	0.038	0.073	0.187	0.193	≤10
NITRATES(mg/l)	0.237	0.292	0.329	0.376	0.444	≤10
B.O.D(Mg/l)	169	203	205	233	257	≤30
FEACAL COLIFORM(counts/100ml)	29	20	33	68	98	≤30
TOTAL HARDNESS(p.p.m)	79	110	253	297	342	300mg/l
CHLORINE (mg/l)	2.8	6.5	10.3	12.9	14.7	250mg/l
TEMPERATURE(^{0}C)	14	14.5	18	21	21.5	15-30
D.O(mg/l)	8.6	7.3	7.1	6.6	6	≥5mg/l

Across the river profile the level of acidity is fairly constant and within the acceptable levels. However, during the wet season, the acidity level was fairly constant in 3 sampling points but increases in the last 2 points. These increase of acidity can be attributed to the release of pollutants to the river by the factories and commercial farms that are concentrated on the downstream of the river basin. During the wet season, the level of acidity was lower than during the dry season. This can be attributed to the dilution of the river water by surface runoff.

There was no major difference in conductivity between the dry and wet season. In the two seasons the conductivity was within acceptable limits. It however increased sharply downstream to Thika. This indicated that the human activity contributed to the presence of inorganic dissolved solids. The increasing human activity also caused the TDS, Turbidity, phosphates, nitrates, temperature and TSS to steadily increase downstream in the two seasons. The increase of chlorophyll which is associated with biomass due to algal growth can be linked to the steady increase in nutrient level from phosphates and nitrates downstream. The BOD level which is a measure of organic pollution was worrying for the two seasons ranging from a minimum of 72mg/l during the dry season and a maximum 169mg/l during the wet season. This is way above the acceptable threshold of 30mg/l. Just like many other parameters tested the BoD levels increased downstream. This high BoD levels in the rivers are an indication of poor sanitation conditions of the population in the catchment and release of organic pollutants to the river. Apart from station two the faecal coliform was within range during the dry season However in the dry season, three out of the five stations had the values of faecal coliform measuring higher than the acceptable level of 30 counts/100ml. This can also be attributed to runoffs across areas with poor sanitation.

These results revealed that the effect of human activity on the water quality as described above affected the water quantity that is available for use as provisioning service. It is demonstrated as well that in as much as water yield can be established, the quantities available can be unpredictable based on pollution levels attributed to human activities.

4.4.3. Precipitation trends

The rainfall was on a downward trend from 1971. Figure 4.13 illustrates the trend with the best line of fit having a negative gradient. This could be as a result of deforestation having in mind that over the last 10 years there has been reduced area under forest cover.

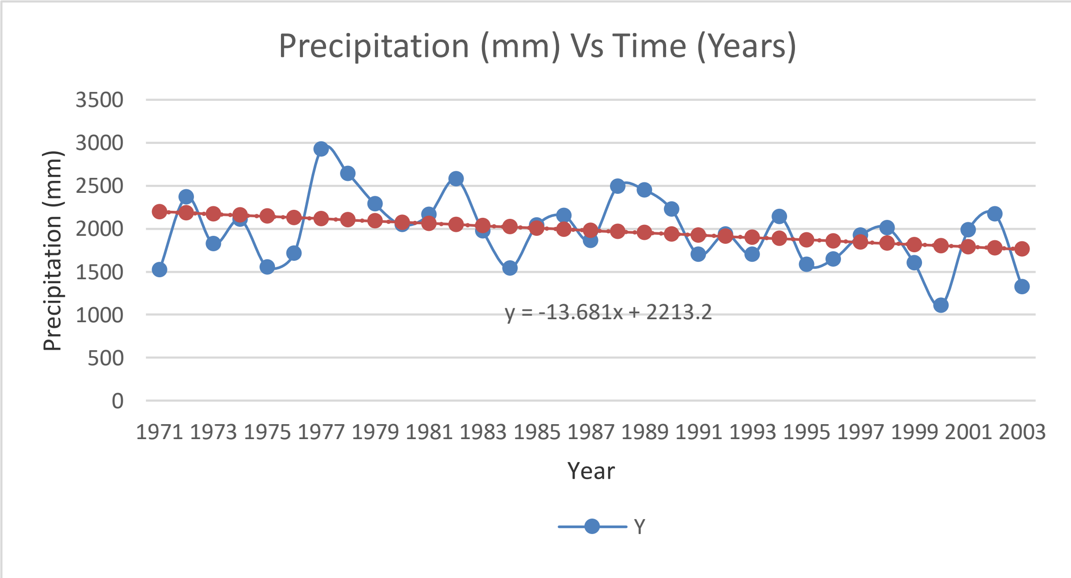

Figure 4.13: The trend of precipitation from 1971-2003

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In general it was concluded that there is severe data gap relating to the Chania river system. These data range from weather data, river gauging data, land use and land cover maps, water abstractions and soil data. Based on each objective the study drew the following conclusions:-

5.1.1 Important watershed ecosystem services differentiated by gender

PGIS exercise is an important tool to pinpoint important ecosystem system services supplied by a watershed as well as validating the spatial-temporal distribution of these services established through other advanced techniques such as remote sensing and GIS.

Water provisioning was considered number one ecosystem service by both gender in the river system, supplying provisioning ecosystem services in form of drinking water and non-drinking water. Prioritizing water provisioning services however did not mean that both gender had consensus on the order of priorities in terms of ecosystem services provided by the river system. Firewood for example was prioritised more by women and not men.

Food provisioning ecosystem services was given second priority in the watershed. This meant therefore that water and food provisioning are the most important ecosystem services in the watershed for both men and women.

5.1.2 Spatial quantification of ecological production of ecosystem services in the river system

The study proved that maximum likelihood gives the best results for land use type classification. Using this algorithm, it was established that shrub vegetation had the highest coverage (31.4%). This is supported by the fact that shrub vegetation stretches through the entire length of the catchment. Mature forests have the second highest area of coverage (20.8%). Combining with the young forest land use the total area covered by forests sums up to 25.6%. Wetlands occupied the least area (9.1%) when young forests and mature forest are combined.

A good correlation (R^2 = 0.97) was achieved when the NDVI derived from the Landsat imagery was used as a proxy for biomass estimation. It was established that the choice a good regression was dependent on the graph used. In overall exponential equation had high level of accuracy. Five out of the seven regression equation adopted were exponential. The exclusive use of exponential equations as predictive equation came out as an area that requires more research based on this pointer. Since this study did not have many LULC classes to prove this, the study opted to choose the graph with the highest correlation regardless of whether the equations were linear, exponential or logarithmic.

Young forest had the highest biomass water productivity (0.085 kg/m3) and maize had the lowest (0.002 kg/m3). The high productivity in young forest is due to the tree species combined with the fact that young forest receive high light intensity as compared to the mature forests and thus more photosynthetic activity. Despite the high biomass water productivity of young forest however, mature forests had the highest amount of CO_2 sequestered. The low maize water productivity can be attribute to the nature of the crop and its short lifespan (noting that the productivity analysis is annual). The catchment however had low biomass water productivity in 2016, meaning that it has more capacity for production if better land and water management practices are put in place.

Additionally, forest and wetlands were found to have good water storage ability. The two LULC have the lowest surface runoff which reduces the risk of flooding. The water stored in wetlands and forest are released slowly over a long period then as seeps and springs. This explains why there as such a big number of springs near Kimakia forest.

5.1.3 Valuation of provisioning ecosystem services and goods (Yield productivity)

In as much as biomass in an important indicator of biomass productivity, this study proved that it may not give an indication of the economic value of an ecosystem service or good without considering the market price and the harvest index. The harvest index used were 0.012 for coffee, 0.048 for tea and 0.35 for maize. Looking at the fraction of the coffee biomass that is useful and comparing it with maize for example, the useful biomass of maize is about 30 times that of coffee. Depending of AGB only therefore for valuation can be very misleading.

The study also proved that forests have a great importance in carbon storage. Mature forests had the highest amount of carbon and CO2 sequestered (839,999.10 Kgs and 3,082,796 Kgs respectively) as compared to young forests which had 642,156.60 Kgs of carbon and 2,356,714.70 Kgs of CO2 sequestered

5.1.4 Influence of built infrastructure on the natural ecosystem provisioning services.

The increase in areas under agriculture and built up areas indicated that there was increased human activity in the river system. This also affected the forest cover. On the lower side of the catchment towards Thika, there was a huge number of irrigated farms. This meant that there was built infrastructure to tap and discharge wastewater in the river system. By testing the water quality, it was confirmed that these built infrastructure had an effect on the water quality downstream. The effect on water quality affected the quantity of water that was available for use as water provisioning service. It is therefore concluded that the water provisioning services cannot be only quantified as water yield based on precipitation and actual evapotranspiration, but rather the balance of water yield when water quality is taken into account.

The study also concluded that the built infrastructure had negative effect on the rainfall trend based on the precipitation trend from 1971-2003 which had a negative gradient.

5.2 Recommendations

5.2.1. Recommendations derived from the findings of this study

i. The instrumentation of the weather stations in the catchment has to be improved to make data available other researches to be carried out in the catchment.

ii. Afforestation measures should be put in place in the catchment to reverse the reduction in forest cover.

iii. The high level of faecal coliform indicates faecal contamination in the catchment meaning there is need to improve sanitation in the catchment.

iv. The wetland should be preserved more. From the results the gain in terms of area in the last 10 years was only 0.83%.

5.2.2. Recommendations on future research

i. There should be a partnership between the university and the remote sensing and weather institutions to make research data available to students carrying out research. The data costs for remote sensing and weather data is currently extremely high

ii. More research to be carried out on the runoffs of the different LULC classes in the catchment. A runoff modelling tool will be useful in predicting floods given the high surface runoffs of the built-up areas and bare land LULC classes

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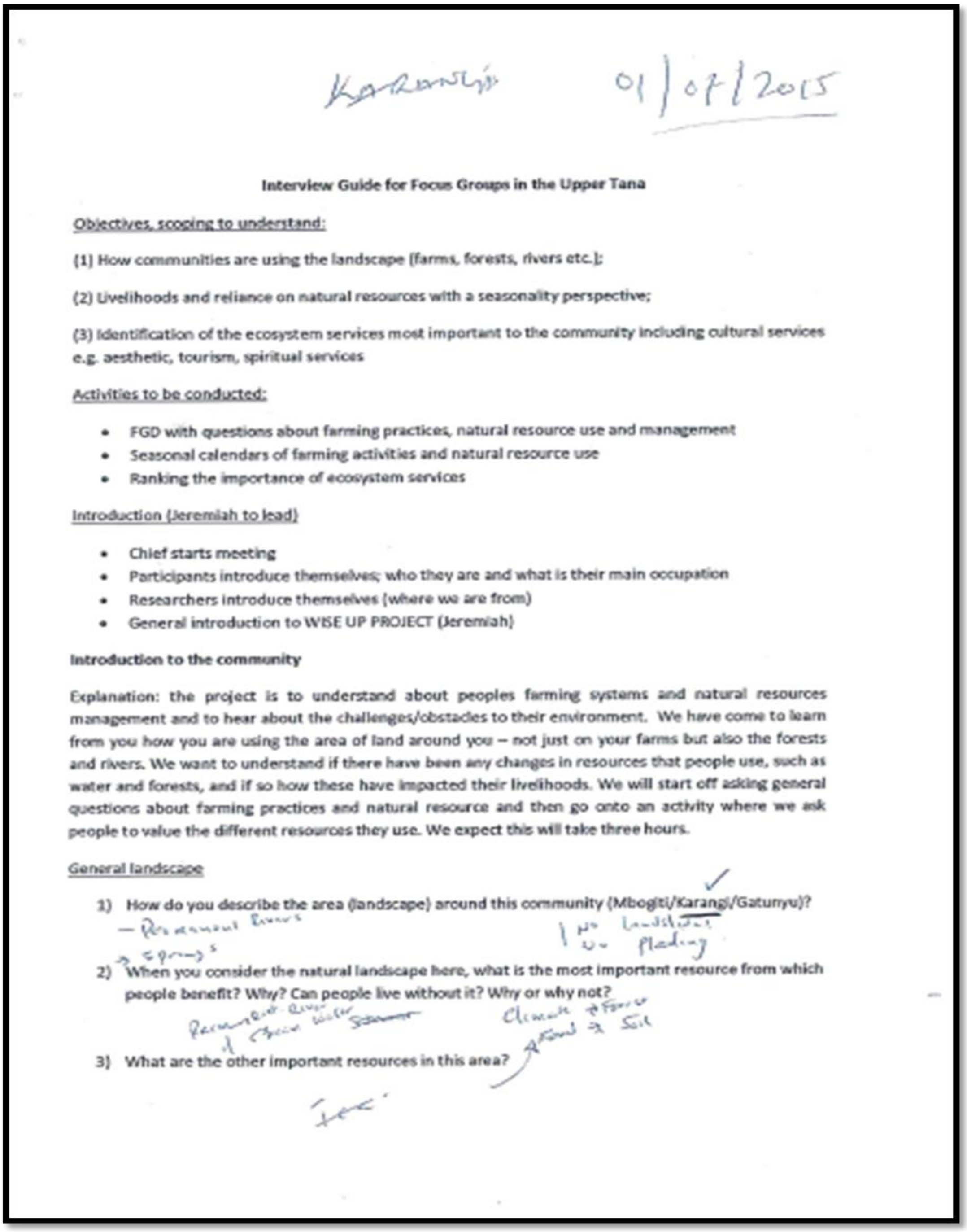
A P P E N D I C E S

Appendix 1: Sample questionnaire used for participatory GIS



Karangi 01/07/2015

Interview Guide for Focus Groups in the Upper Tana

Objectives, scoping to understand:

(1) How communities are using the landscape (farms, forests, rivers etc.);

(2) Livelihoods and reliance on natural resources with a seasonality perspective;

(3) Identification of the ecosystem services most important to the community including cultural services e.g. aesthetic, tourism, spiritual services

Activities to be conducted:

- FGD with questions about farming practices, natural resource use and management
- Seasonal calendars of farming activities and natural resource use
- Ranking the importance of ecosystem services

Introduction (Jeremiah to lead)

- Chief starts meeting
- Participants introduce themselves; who they are and what is their main occupation
- Researchers introduce themselves (where we are from)
- General introduction to WISE UP PROJECT (Jeremiah)

Introduction to the community

Explanation: the project is to understand about peoples farming systems and natural resources management and to hear about the challenges/obstacles to their environment. We have come to learn from you how you are using the area of land around you – not just on your farms but also the forests and rivers. We want to understand if there have been any changes in resources that people use, such as water and forests, and if so how these have impacted their livelihoods. We will start off asking general questions about farming practices and natural resource and then go onto an activity where we ask people to value the different resources they use. We expect this will take three hours.

General landscape

1) How do you describe the area (landscape) around this community (Mbogiti/Karangi/Gatunyu)?

— Permanent Rivers → Springs | No Landslides, No Flooding

2) When you consider the natural landscape here, what is the most important resource from which people benefit? Why? Can people live without it? Why or why not?

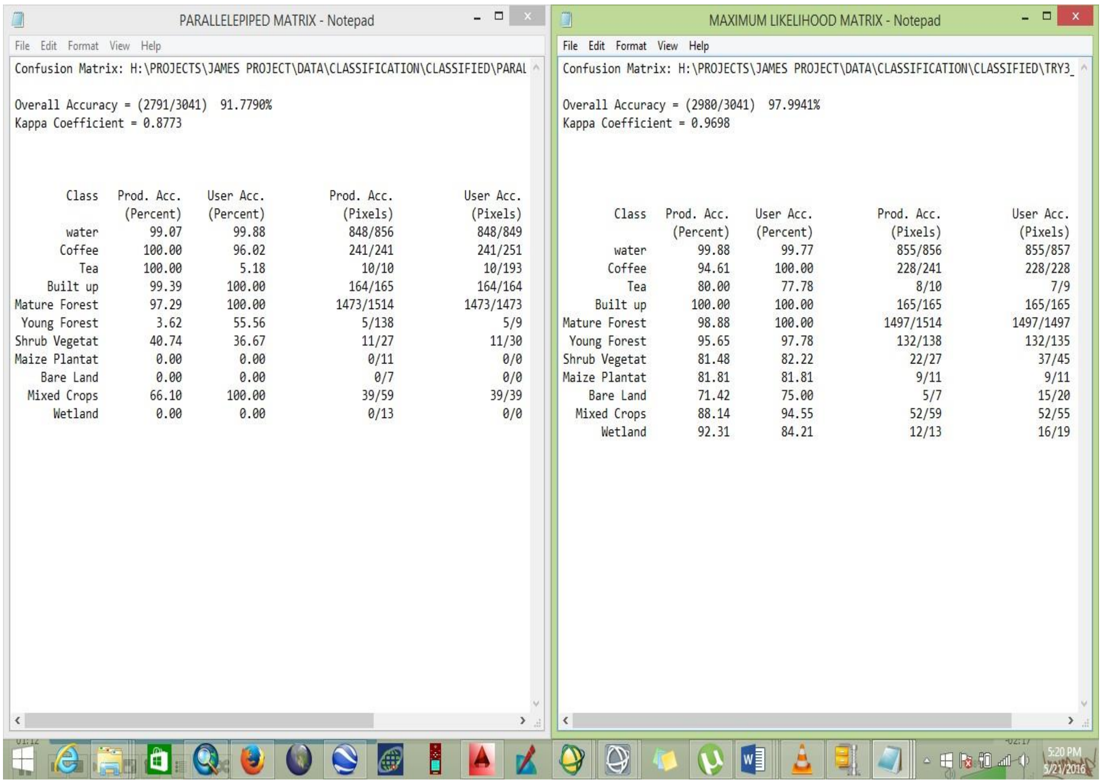
Permanent River & Clean Water ~~Stream~~ | Climate & Forest & Food & Soil

3) What are the other important resources in this area?

Tea

Figure A.1.: Questionnaire used for PGIS

Appendix 2: Confusion matrix for maximum likelihood and parallelepiped system of supervised classification for Chania catchment



PARALLELEPIPED MATRIX - Notepad

File Edit Format View Help

Confusion Matrix: H:\PROJECTS\JAMES PROJECT\DATA\CLASSIFICATION\CLASSIFIED\PARAL

Overall Accuracy = (2791/3041) 91.7790%

Kappa Coefficient = 0.8773

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
water	99.07	99.88	848/856	848/849
Coffee	100.00	96.02	241/241	241/251
Tea	100.00	5.18	10/10	10/193
Built up	99.39	100.00	164/165	164/164
Mature Forest	97.29	100.00	1473/1514	1473/1473
Young Forest	3.62	55.56	5/138	5/9
Shrub Vegetat	40.74	36.67	11/27	11/30
Maize Plantat	0.00	0.00	0/11	0/0
Bare Land	0.00	0.00	0/7	0/0
Mixed Crops	66.10	100.00	39/59	39/39
Wetland	0.00	0.00	0/13	0/0

MAXIMUM LIKELIHOOD MATRIX - Notepad

File Edit Format View Help

Confusion Matrix: H:\PROJECTS\JAMES PROJECT\DATA\CLASSIFICATION\CLASSIFIED\TRY3_

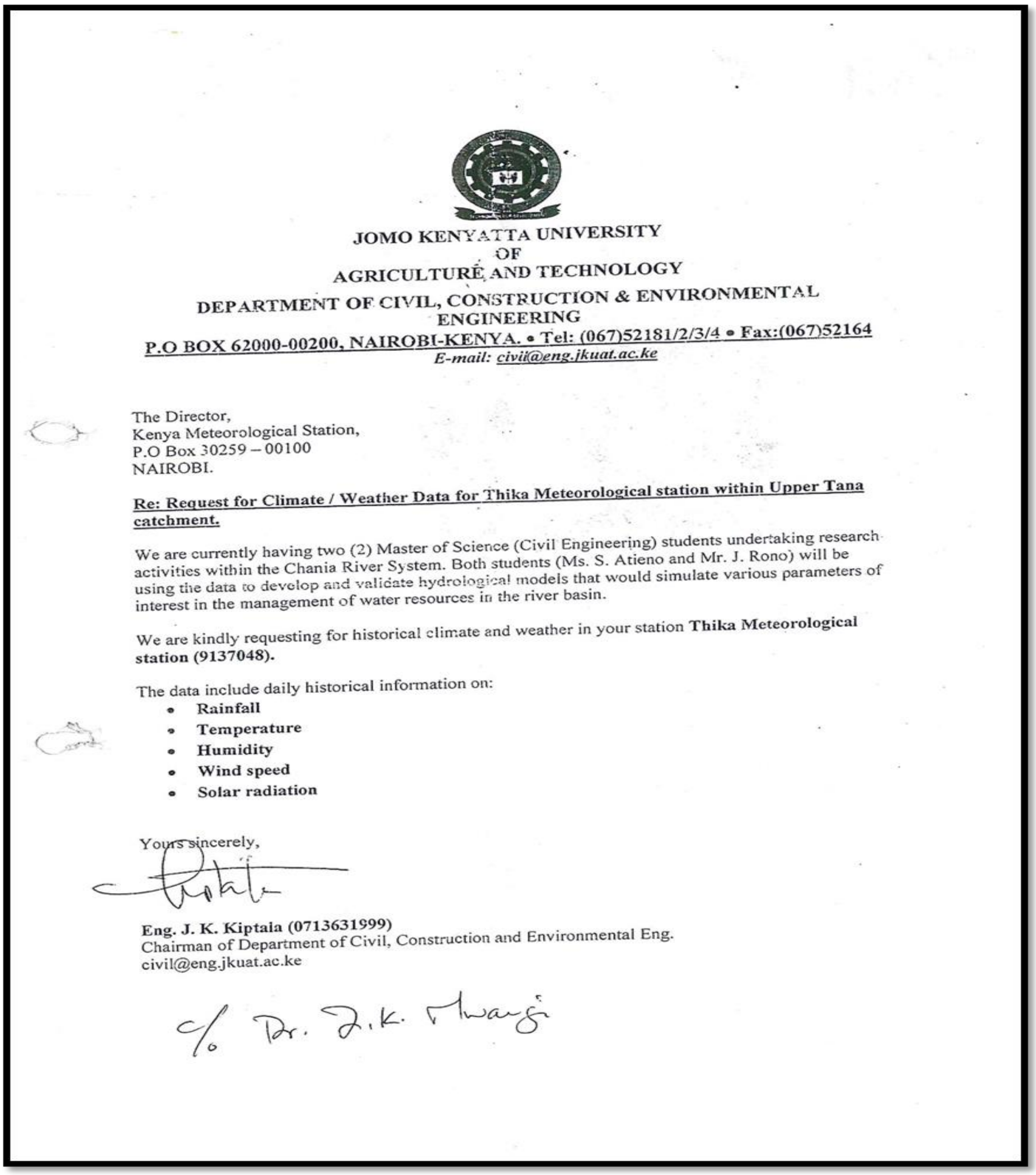
Overall Accuracy = (2980/3041) 97.9941%

Kappa Coefficient = 0.9698

Class	Prod. Acc. (Percent)	User Acc. (Percent)	Prod. Acc. (Pixels)	User Acc. (Pixels)
water	99.88	99.77	855/856	855/857
Coffee	94.61	100.00	228/241	228/228
Tea	80.00	77.78	8/10	7/9
Built up	100.00	100.00	165/165	165/165
Mature Forest	98.88	100.00	1497/1514	1497/1497
Young Forest	95.65	97.78	132/138	132/135
Shrub Vegetat	81.48	82.22	22/27	37/45
Maize Plantat	81.81	81.81	9/11	9/11
Bare Land	71.42	75.00	5/7	15/20
Mixed Crops	88.14	94.55	52/59	52/55
Wetland	92.31	84.21	12/13	16/19

Figure A.2.: Screen shot of the confusion matrix

Appendix 3: Request letter for weather data for Chania from meteorological department



JOMO KENYATTA UNIVERSITY
OF
AGRICULTURE AND TECHNOLOGY
DEPARTMENT OF CIVIL, CONSTRUCTION & ENVIRONMENTAL ENGINEERING
P.O BOX 62000-00200, NAIROBI-KENYA. • Tel: (067)52181/2/3/4 • Fax:(067)52164
E-mail: civil@eng.jkuat.ac.ke

The Director,
Kenya Meteorological Station,
P.O Box 30259 – 00100
NAIROBI.

Re: Request for Climate / Weather Data for Thika Meteorological station within Upper Tana catchment.

We are currently having two (2) Master of Science (Civil Engineering) students undertaking research activities within the Chania River System. Both students (Ms. S. Atieno and Mr. J. Rono) will be using the data to develop and validate hydrological models that would simulate various parameters of interest in the management of water resources in the river basin.

We are kindly requesting for historical climate and weather in your station **Thika Meteorological station (9137048).**

The data include daily historical information on:

- **Rainfall**
- **Temperature**
- **Humidity**
- **Wind speed**
- **Solar radiation**

Yours sincerely,

Eng. J. K. Kiptala (0713631999)
Chairman of Department of Civil, Construction and Environmental Eng.
civil@eng.jkuat.ac.ke

c/o Dr. J. K. Mwangi

Figure A.3. Screenshot of the data request letter to the Meteorological Department of Kenya

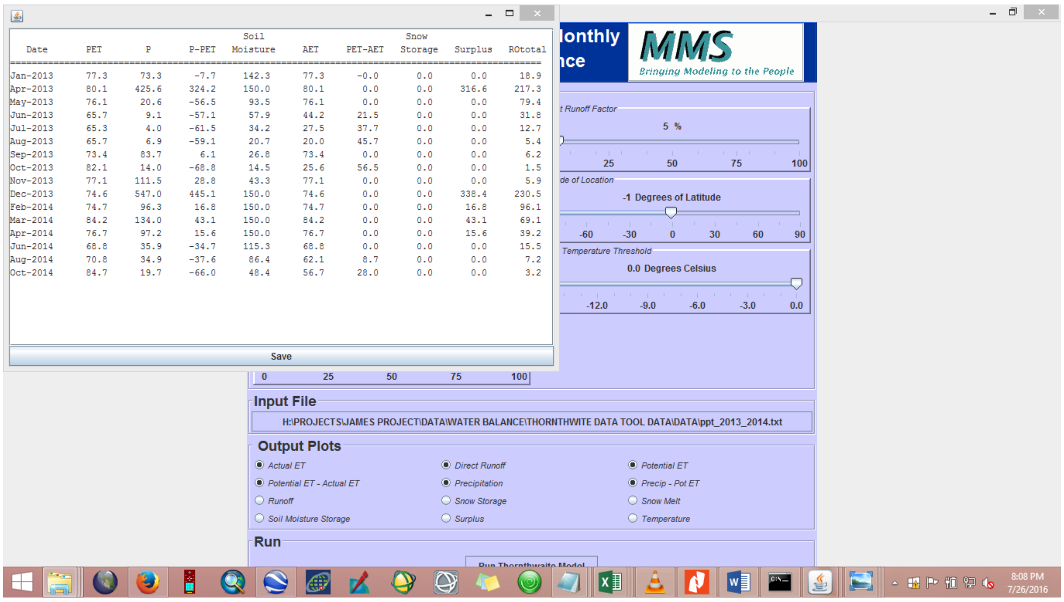
Appendix 4: Weather data for Chania from meteorological department

Station ID	Station Name	Element Name	Year	1	2	3	4	5	6	7	8	9	10	11	12
9137048	THIKA AGROMET STATION	Precipitation; daily total	1995	11.4	49.2	129.9	153.7	40	10.7	6.2	31	3.6	171.2	137.3	162.5
9137048	THIKA AGROMET STATION	Precipitation; daily total	1996	20.8	76.4	161.4	52.1	49.6	36.3	28.7	1.5	0.2	0	375.2	63.1
9137048	THIKA AGROMET STATION	Precipitation; daily total	1997	0	0	59.3	487.2	91.8	9.8	1.8	63.6	0.9	238.8	416.6	229
9137048	THIKA AGROMET STATION	Precipitation; daily total	1998	344.7	236.1	181.4	176.4	356.5	131.9	61.7	8	2.7	10.5	92.5	13
9137048	THIKA AGROMET STATION	Precipitation; daily total	1999	9.7	2.6	0	264.3	10.3	2.3	21.8	11.1	2.6	29.1	318.8	221.6
9137048	THIKA AGROMET STATION	Precipitation; daily total	2000	3.5	0	18.8	74.9	29.4	5	5.9	2.2	7.9	11.5	136.1	62.1
9137048	THIKA AGROMET STATION	Precipitation; daily total	2001	358.4	32.7	170.2	106	66.5	4.6	0.8	16.1	1.7	48.7	233.2	20.7
9137048	THIKA AGROMET STATION	Precipitation; daily total	2002	16.3	22.1	227.5	313.4	250.5	3.7	2.2	5.5	80.2	83.1	137.7	243.1
9137048	THIKA AGROMET STATION	Precipitation; daily total	2003	14.2	3	93.5	215.9	254.3	1	3.6	17.3	0	83.3	180.9	44.2
9137048	THIKA AGROMET STATION	Precipitation; daily total	2004	53.5	74.7	47.9	376.2	120.9	1.2	0	0	20.9	78.2	93.3	98.7
9137048	THIKA AGROMET STATION	Precipitation; daily total	2005	21.4	25.1	52.3	252.9	259.2	2.6	7.5	9.7	5.5	38.1	154.3	2.1
9137048	THIKA AGROMET STATION	Precipitation; daily total	2007	30.8	102.9	24.1	239.3	85.2	3.3	14.7	13.7	20.2	55.9	114.2	25.6
9137048	THIKA AGROMET STATION	Precipitation; daily total	2008	104.8	27.1	100.4	271.1	7.4	6.4	28.3	10.2	11.7	63.9	135.7	42.7
9137048	THIKA AGROMET STATION	Precipitation; daily total	2009	49.3	19	51.5	173.7	91.1	10.1	1.1	1.7	0	134.5	119.2	94.2
9137048	THIKA AGROMET STATION	Precipitation; daily total	2010	138.3	113.5	209.5	176.1	152.4	24.9	4.8	6.3	1.3	98.5	153	80.6
9137048	THIKA AGROMET STATION	Precipitation; daily total	2011	10.8	47.9	0	109.6	71.2	50.3	1	10.7	39.4	135.2	177.2	63.2
9137048	THIKA AGROMET STATION	Precipitation; daily total	2012	0	20.9	0	248.5	179.4	38.1	7.9	41.4	19.9	49.9	177.1	70.2
9137048	THIKA AGROMET STATION	Precipitation; daily total	2013	73.3	0	239.7	425.6	20.6	9.1	4	6.9	83.7	14	111.5	547
9137048	THIKA AGROMET STATION	Precipitation; daily total	2014	55.6	96.3	134	97.2	105.9	35.9	4.4	34.9	36.1	19.7	405.6	190.2
9137048	THIKA AGROMET STATION	Temperature; daily maximum	1995	26.5	28	26.3	25.8	24.9	24.7	22.7	24	25.9	25.9	24.7	24.2
9137048	THIKA AGROMET STATION	Temperature; daily maximum	1996	25.8	27.6	27.3	26.2	24.9	22.5	21.7	23.7	24.2	24.8	25.3	24.7
9137048	THIKA AGROMET STATION	Temperature; daily maximum	1999	26.2	27.8	26.8	26.0	24.9	23.6	22.2	23.9	28.3	26.9	25.1	24
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2000	25.7	28.2	28.6	26.8	26.3	24.5	24.6	24.5	25.9	28	25.8	25.7
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2001	25.4	27.5	27.2	25.5	25	23.5	22.4	24.8	26.7	27	24.1	24.8
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2002	26.3	28	26.8	25.4	24.8	23.7	24.1	22.6	25.8	26.1	24.9	25
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2003	26.3	29.2	28.7	27.3	24.7	23.9	22.6	22.7	25.5	26.6	24.9	24.9
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2004	26.3	26.7	27.9	25.6	25.1	23.3	24.6	23.8	27	26.2	24.9	25.4
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2005	27.2	28.6	28.9	26.5	25.3	23.6	21.9	23.3	25.2	27.1	25.2	26.3
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2007	25.6	28.3	27.8	26.3	25.5	25	23	23.3	26.3	26.8	25.7	26.2
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2008	26.9	27.3	28.2	25.8	25.3	23.7	23.1	23.3	25.8	27.0	25.5	26.3
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2009	28.6	29.2	30.4	28.2	26.6	28	25.4	25.2	28.6	26.9	26	25.8
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2010	26.4	27.3	26.6	26.7	25.5			23.7	26.7	28	24.8	26.5
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2011	27.9	29.2	29.6	26.9	26	25.3	25.8	23.8	26.3	26.5	25.5	26.1
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2012	28.2	29.3	30.3	26.6	25.8	24.1	22.9	25			26.2	
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2013	27.4			27.2	26.4	24.1	24.5	23.6	27.8	29.1	26.7	25.5
9137048	THIKA AGROMET STATION	Temperature; daily maximum	2014		28.6	28.2	26.9		24.6		25.6		28.6		
9137048	THIKA AGROMET STATION	Temperature; daily minimum	1995	12.7	13.1	15.1	16	15.6	13.4	12.6	12.7	13.6	14.9	15.1	14.3
9137048	THIKA AGROMET STATION	Temperature; daily minimum	1996	12.8	14	15.1	15.8	15.6	14.9	13.2	11.8	12.8	13.9	15.2	13.3
9137048	THIKA AGROMET STATION	Temperature; daily minimum	1997	12.9	11.1	15	15.6	15.2	13.9	12.9	12.9	12.8	15.4	16.3	16
9137048	THIKA AGROMET STATION	Temperature; daily minimum	1998	16.5	15.2	15.4	16.6	15.8	13.8	12.7	13.4	13.8	13.2	14	11.9
9137048	THIKA AGROMET STATION	Temperature; daily minimum	1999	12	11.3	12.7				12.1	12.6	12.1	13.9	14.6	14.7

Station ID	Station Name	Element Name	Year	1	2	3	4	5	6	7	8	9	10	11	12
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2000	11.7	9.8	14.2	15.4	14.1	13.5	12.3	12.6	13	14.8	15.8	15
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2001	14.7	14.8	14.5	16	15.2	13.4	12.7	11.9	13.5	14.5	15.5	14.1
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2002	13.8	13.2	15.2	16.3	15.4	13.5	12.2	13.6	13.3	15.1	15.9	15.6
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2003	13	12.6	14.3	16.1	16.2	14.2	12.6	12.5	13.8		15.5	13.5
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2004	14.3	14.6	15	16.3	14.8	12.8	11.2	12.6	13.8	15.2	15.6	14.7
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2005	13.6	13.3	15.7		16		12.8		13.5	14.5	15.5	12.9
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2007	15	14	14.8	16.1	16	14.1	13.5	13.9	13.4	15.6	15.5	14
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2008	13.6	13.3	15.8	15.8	15	13.5	13.3					
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2009	12.9	13.9	14.7	16.5	15.8	14	11.5	12.9	14.1	15.4	16	15.4
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2010	14.2	16.4	15.5	17	16.2			12.8	12.9	15.2	15.5	13.9
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2011	12.2	12.1	12.9	16.8	15.9	14.3	11.7	13.5	14.2	15.7	16.1	14.9
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2012	10.8	11.9	13.4	16.2	15.4	14	13.2	12.3			15.2	
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2013	13.7			16.5	14.7	13.4	11.7	12.7	13	14.1	15.4	14.4
9137048	THIKA AGROMET STATION	Temperature; daily minimum	2014		14.8	15.9	15.4		14.4		13.1		15.6		
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	1995	70	75	82	85	85	84	86	85	78	79	83	85
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	1996	80	77	83	83	84	90	88	84	80	72	88	77
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	1997	73	55	75	84	84	82	82	84	76	81	88	84
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	1998	88	82	84	86	86	86	90	91	82	76	84	80
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	1999	72	67	77				81	86	76	76	86	86
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2000	70	62	75	78	78	80	77	78	78	71	87	79
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2001	78	79	81	82	82	84	84	80	77	74	84	80
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2002	73	69	82	88	84	84	84	83	77	82	84	84
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2003	78	69	75	81	86	85	83	85	78		81	75
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2004	80	81	75	88	84	81	79	80	77	80	85	81
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2005	70	68	80		83		84		78	70	81	71
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2007	77	72	80	88	83	84	87	86	77	79	83	71
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2008	74	75	78	83	79	82	83					
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2009	70	74	71	80	83	78	77	81	72	77	82	83
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2010	79	83	85	86	85			86	79	76	86	78
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2011	74	70	70	81	83	84	80	86	82	81	84	77
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2012	63	69	67	84	82	84	85	81			83	
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2013	81			85	82	84	84	86	77	69	82	84
9137048	THIKA AGROMET STATION	Relative humidity at 06Z	2014		82	82	85		85		79		73		
9137048	THIKA AGROMET STATION	Radiation; total downward	1995	25.56	25.45	21.49	18.77	16.2	2.34	10.69	16.85	18.97	14.1	17.75	20.41
9137048	THIKA AGROMET STATION	Radiation; total downward	1996	24.35	25.13	23.61	21.63	14.87	11.08	11.72	12.63	17.79	20.81	16.04	22.53
9137048	THIKA AGROMET STATION	Radiation; total downward	1997	23.96	27.47	21.31	18.51	18.49	14.25	13.19	16.58	21.9	16.34	15.59	20.23
9137048	THIKA AGROMET STATION	Radiation; total downward	1998	17.81	21.9	21.75	17.63	14.62	13.72	9.82	8.85	15.71	19.71	16.94	22.27
9137048	THIKA AGROMET STATION	Radiation; total downward	1999	22.62	25.09	10.62				11.82	12.46	18.03	19.05	17.51	15.84
9137048	THIKA AGROMET STATION	Radiation; total downward	2000	23.86	25.72	22.83	20.15	16.8	14.03	14.9	13.42	17.7	19.64	17.99	23.6
9137048	THIKA AGROMET STATION	Radiation; total downward	2001	21.46	25.95	22.53	19.29	17.01	14.6	13.01	17.9	21.37	19.73	18.55	22.05
9137048	THIKA AGROMET STATION	Radiation; total downward	2002	23	25.24	22.99	19.43	16.68	15.31	17.02	12.81	21.12	19.62	21.46	20.41
9137048	THIKA AGROMET STATION	Radiation; total downward	2003	24.84	26.7	25.23	20.95	16.42	15.37	14.29	14.55	17.22		20.15	22.66
9137048	THIKA AGROMET STATION	Radiation; total downward	2004	22.19	22.77	22.15	17.9	19.03	15.04	18.1	15.18	19.85	19.49	18.84	22.82

Station ID	Station Name	Element Name	Year	1	2	3	4	5	6	7	8	9	10	11	12
9137048	THIKA AGROMET STATION	Radiation; total downward	2005	25.11	25.02	23.49		17.67		12.6		17.82	20.97	20.66	25.53
9137048	**THIKA AGROMET STATION**	**Radiation; total downward**	**2007**	**24**	**24.64**	**22.36**	**19.71**	**16.84**	**15.28**	**11.5**	**12.3**	**17.34**	**19.1**	**20.24**	**22.07**
9137048	THIKA AGROMET STATION	Radiation; total downward	2008	24.18	23.8	21.32	20.13	17.26	14.89	12.88					
9137048	THIKA AGROMET STATION	Radiation; total downward	2009	25.87	25.78	25.65	22.84	19.38	20.74	16.66	15.12	21.6	19.51	22.75	22.99
9137048	THIKA AGROMET STATION	Radiation; total downward	2010	25.28	22.89	22.95	22	17			14.43	19.59	21.63	18.59	24.5
9137048	THIKA AGROMET STATION	Radiation; total downward	2011	25.72	26.65	26.46	21.81	17.41	15.56	17.56	12.57	17.96	20.48	17.51	21.35
9137048	THIKA AGROMET STATION	Radiation; total downward	2012	25.37	25.56	26.39	16.53	17.69	16.38	15.89	17.72			19.41	
9137048	THIKA AGROMET STATION	Radiation; total downward	2013	19.34			19.59	17.64	12.22	16.01	12.6	19.58	23.12	18.19	17.85
9137048	THIKA AGROMET STATION	Radiation; total downward	2014		23.37	23.75	18.94		12.5		15.67		20.2		
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	1995	45	41	49	55	60	55	59	54	44	52	58	59
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	1996	53	43	47	53	56	65	64	54	45	39	61	50
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	1997	42	29	39	58	58	57	56	51	40	59	69	64
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	1998	66	54	53	59	66	62	68	65	50	43	55	47
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	1999	40	34	50									
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2004	52	46	41	57	54	53	43	49	41	45	59	55
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2005	39	35	38		58		58		45	39	52	43
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2007	54	41	45	55	57	54	60	59	47	46	52	48
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2008	47	44	43	55	52	54	57					
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2009	41	36	33	48	57	45	48	49	38	48	51	58
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2010	53	53	57	57	63			58	45	52	64	50
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2011	41	36	35	53	55	54	47	57	48	53	63	54
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2012	34	33	33	56	59	57	61	52			55	
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2013	52			58	55	57	52	56	40	36	54	61
9137048	THIKA AGROMET STATION	Relative humidity at 12Z	2014		47	47	55		56		46		40		

Appendix 5: Sample output of the Thorn Thwaite monthly model



Date	PET	P	P-PET	Soil Moisture	AET	PET-AET	Snow Storage	Surplus	ROtotal
Jan-2013	77.3	73.3	-7.7	142.3	77.3	-0.0	0.0	0.0	18.9
Apr-2013	80.1	425.6	324.2	150.0	80.1	0.0	0.0	316.6	217.3
May-2013	76.1	20.6	-56.5	93.5	76.1	0.0	0.0	0.0	79.4
Jun-2013	65.7	9.1	-57.1	57.9	44.2	21.5	0.0	0.0	31.8
Jul-2013	65.3	4.0	-61.5	34.2	27.5	37.7	0.0	0.0	12.7
Aug-2013	65.7	6.9	-59.1	20.7	20.0	45.7	0.0	0.0	5.4
Sep-2013	73.4	83.7	6.1	26.8	73.4	0.0	0.0	0.0	6.2
Oct-2013	82.1	14.0	-68.8	14.5	25.6	56.5	0.0	0.0	1.5
Nov-2013	77.1	111.5	28.8	43.3	77.1	0.0	0.0	0.0	5.9
Dec-2013	74.6	547.0	445.1	150.0	74.6	0.0	0.0	338.4	230.5
Feb-2014	74.7	96.3	16.8	150.0	74.7	0.0	0.0	16.8	96.1
Mar-2014	84.2	134.0	43.1	150.0	84.2	0.0	0.0	43.1	69.1
Apr-2014	76.7	97.2	15.6	150.0	76.7	0.0	0.0	15.6	39.2
Jun-2014	68.8	35.9	-34.7	115.3	68.8	0.0	0.0	0.0	15.5
Aug-2014	70.8	34.9	-37.6	86.4	62.1	8.7	0.0	0.0	7.2
Oct-2014	84.7	19.7	-66.0	48.4	56.7	28.0	0.0	0.0	3.2

Figure A.4. : Thornthwaite Water Balance outputs for bare ground in Chania Catchment

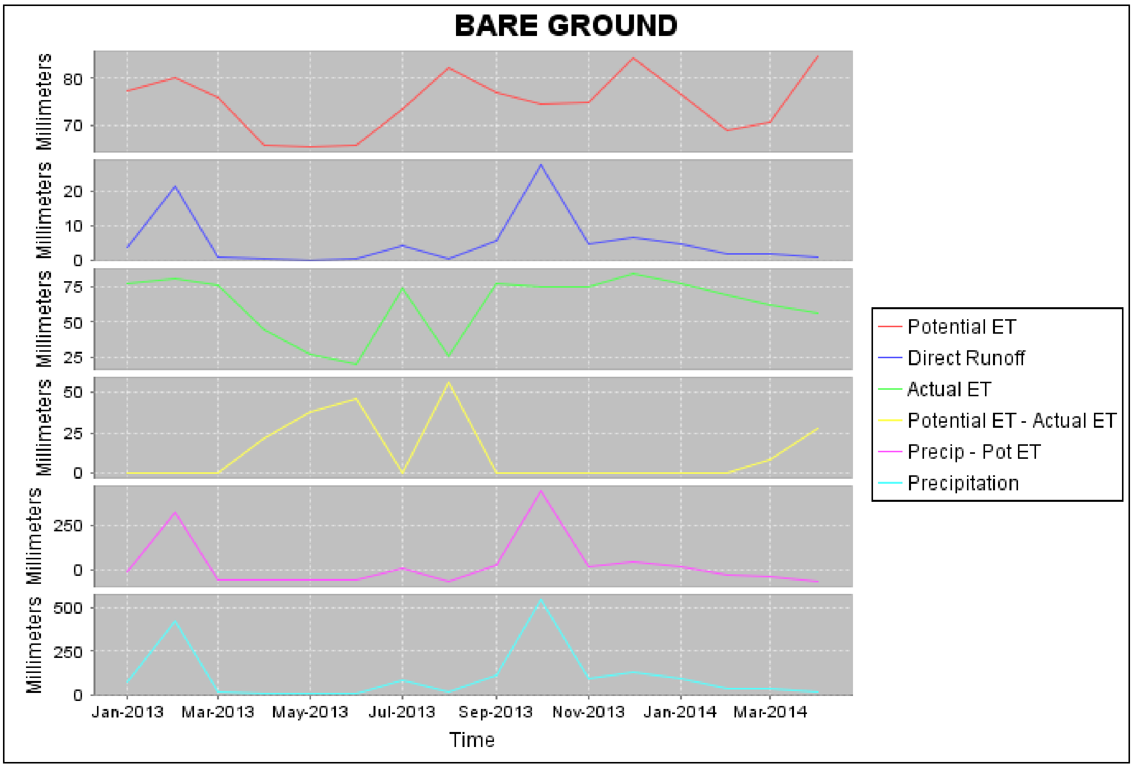


Figure A.5.: Thornthwaite Monthly Water Balance graphs for bare ground in Chania Catchment

Appendix 6: Standard procedures for water quality tests

A: Biochemical Oxygen Demand - Alkali Azide Modification Method

Reagents:

I. Manganous sulphate solution. $MnSO_4.7H_20$.

II. Alkaline azide iodide solution.

III. Sulphuric acid solution.

IV. Starch indicator.

V. Standard sodium thiosulphate solution, 0.025N

Procedure

1. Dilution water was first prepared. This was done by mixing 1L of distilled water with 10ml of chemicals A (I), B(II), C(III) and D(IV) each then aerated for one hour.

2. The sample was then diluted in two different ratios according to the categories of dilution. In our case the ratios were 2%, 3% and 5% sample of a volume of 250ml.

3. A 100ml of the resultant mix was then put in a beaker for DO1 determination while the remaining was filled in a well labeled BOD bottle sealed using cellophane and aluminum foil and placed in an incubator at 20 degrees for 5 days.

4. In order to determine the dissolved oxygen in the water samples, 1 ml of manganous sulphate was added to the sample while stirring, 1ml of alkaline azide iodide was then added to the sample as the precipitate formed.

5. After leaving the solution for a few minutes for the precipitate to form well and settle, 1ml of concentrated sulphuric acid was added to dissolve the precipitate.

6. 5 drops of starch indicator were then added to the mixture, making it turn blue – brown.

7. The mixture was then titrated against standard sodium thiosulphate solution until the solution became clear. The titer value was then read off.

8. The value of BOD5 would then be determined by

$BOD_5=(DO_1-DO_5)$ /p

Where P = Decimal Volumetric fraction of sample

B. Total solids

Apparatus

i) Evaporating dishes
ii) Analytical balance
iii) Drying oven
iv) Glass fiber filter papers
v) Filtration apparatus

Procedure

1) The disk was inserted into the filtration apparatus with the wrinkled side up

2) vacuum was applied

3) The disk was washed with three successive 20ml volumes of distilled water.

4) Suction was continued to remove any traces of water.

5) The washings were discarded

6) The evaporating dishes were heated in an oven at 105oC for 1 hour in an oven.

7) The dishes were stored in a desiccator until when needed.

8) They were weighed immediately before use.

9) A measured volume of sample was measured through the glass fiber.

10) It was washed 3 successive times with 10ml volumes of distilled water allowing complete drainages between washings and suction was continued for about 3 minutes after filtration was complete.

11) They were put in an oven for 1 hour until they dried and then they were weighed again.

C. FECAL COLIFORM TEST

Reagents

a) Lauryl Tryptose Broth

35.60g of Lauryl Tryptose Broth in was suspended in 1000ml in distilled water. 9ml of the solution was distributed into 9 tubes containing Durham tubes. It was then sterilize by autoclaving at 15lbs pressure (121oC) for 15minutes.

b) Ringer salt solution

4.455g of Ringer salt solution powder was mixed in 500ml. It was heated to dissolve the medium completely It was then sterilized by autoclaving at 15 lbs. pressure (121oC) for 15minutes 9mls of the solution into was distributed into the 3 tubes

c) Red blue agar

20.765g of Red blue agar was measured and heated while stirring to boiling to dissolve the medium completely. Cool to 45oC and was immediately poured into sterile petri plates containing the inoculum The medium was be sterilized by autoclaving at 15lbs pressure (121oC) for 15minutes

Materials

Sample

Water samples from river

Media: double lactose fermentation broths and single strength lactose fermentation broth

Equipment

i) Bunsen burner
ii) Sterile 10-ml pipettes
iii) Sterile 1-ml pipettes
iv) Mechanical pipetting devices
v) Glassware
vi) marking pencil

Procedure

1. Three separate device series were set up consisting of three groups, a total of nine tubes per series, in a test-tube rack; for each tube, the water source was labeled and volume of sample inoculated as illustrated.

2. The sample was mixed thoroughly by shaking.

3. 1ml of the sample was transferred into 1 of the 3 test tubes containing Ringer solution. And then 1ml of the solution mixed with the sample was added to the second test-tube and then 1ml of the second test-tube was added into the third test-tube.

4. From each of the three test tubes with the Ringer solution, 1ml from each test tube was added to three of the 9 test tubes with the Lauryl Tryptose Broth.

5. All test tubes were incubated for 48 hours at 37 degrees centigrade.

6. Count the tubes with gas in the Durham tubes were counted and the MPN tables for three test tubes was referred to get the MPN.

7. The following formula was used to calculate the total coliforms.

MPN/100ml = No. of microorganisms × dilution factor of middle set of tubes

8. The Violet Red Blue agar solution was spread on petri dishes and for each of the petri dishes, 1ml of the dilution solution made in step 3above was spread.

9. They were then incubated for 24hrs 35oC.

10. The colonies appearing on the dish were counted.

D. PHOSPHATES

APPARATUS;

i) Autoclave
ii) Dilution bottles
iii) pH meter
iv) Spectrophotometers

Reagents

a) Standard stock solution (to make 0.1mg/ml as stock solution)

b) Calibration

10ml of the stock solution was taken and diluted to 500ml and was calibrated as follows by taking 0, 5, 10, 15, 20, 25 and diluting them to 50ml.

c) Persulphate solution (K2S2O4)

d) Molybdate reagent

e) Ascorbic acid

7.2g of the acid was dissolved in distilled water and dilute to 100ml Sodium hydroxide solution

f) Phenolphthalein indicator

Procedure

1) An appropriate volume of sample (Vs) was taken and diluted to 50ml

2) Stock solution was taken and used to make 4-5 standards plus one blank.

3) They were Autoclaved for 120oC for 30minutes, cooled and put into test tubes

4) Molybdate reagent and ascorbic acid solution were mixed in the ration of 5:1just enough required to in step 5 above

5) Add 3.5ml of No. 6 and was added and the solution shaken gently

6) It was left to stand for 15 minutes and absorbance was taken at 880nm starting with blank and the standards followed by samples

7) The calibration curve was plotted to obtain the concentration of phosphorous in mg/l

8) The total Phosphorous was calculated in mg/l.

E. NITRATES

Apparatus

i) Autoclave
ii) Dilution bottles
iii)Spectrophotometer

Reagents

i) 1/50 sodium hydroxide
ii) Dilute sulphuric acid
iii) 1 +15 hydrochloric acid
iv) Stock solution of Potassium nitrate (0.722g in 1000ml distilled water 1ml = 0.1mgN)
v) 1+ 500 hydrochloric acid
vi) $K_2S_2O_8$

Preparation of standard solutions

From the stock solution, a standard solution of 0.004mg/cN was prepared. Take 10ml of the stock solution was taken and diluted to 250ml.

A standard solution was prepared by taking 0, 10, 20, 30, and 40 and diluted it to 50ml

Procedure

1) The sample was taken and diluted to 50mls

2) It was then Autoclaved at 120^{o}C for 30minutes

3) The samples were then cooled to room temperature

4) They were then transferred into tall form dilution tubes and 1+15 hydrochloric acid was added plus the standards

5) They were left for 15 minutes and absorbance was taken at 220nm

6) The calibration curve was plotted and used to obtain the concentration of Total Nitrates in mg/l

Appendix 7: GIS Procedures screenshots

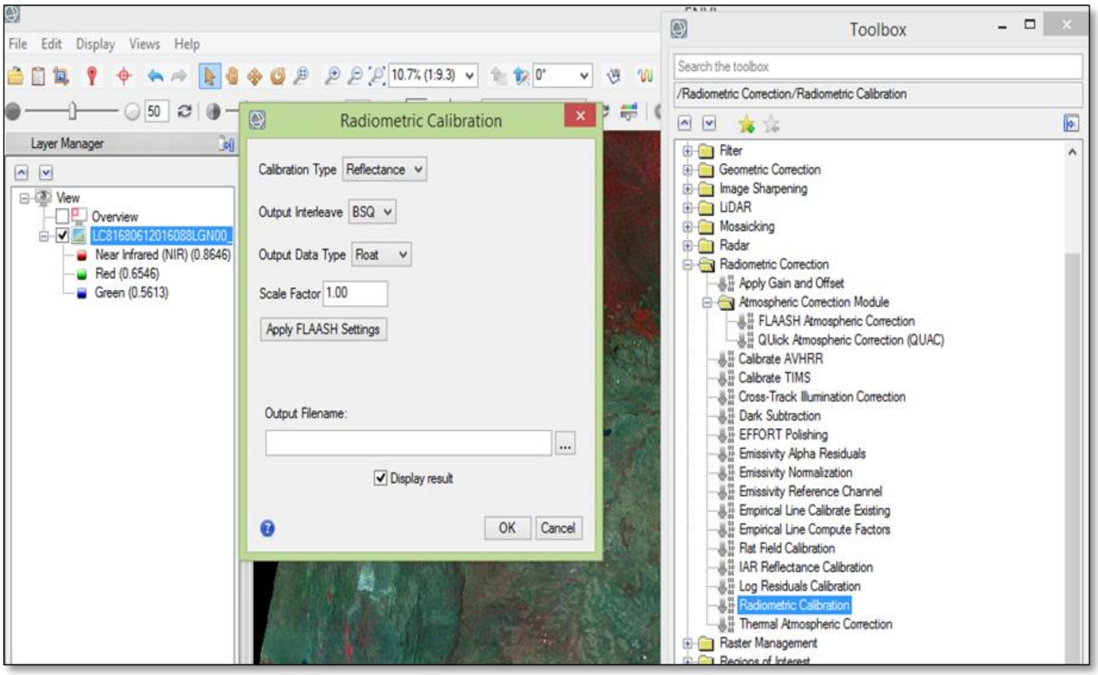


Figure A.7.1: Screenshot of conversion of the raw DN values to reflectance

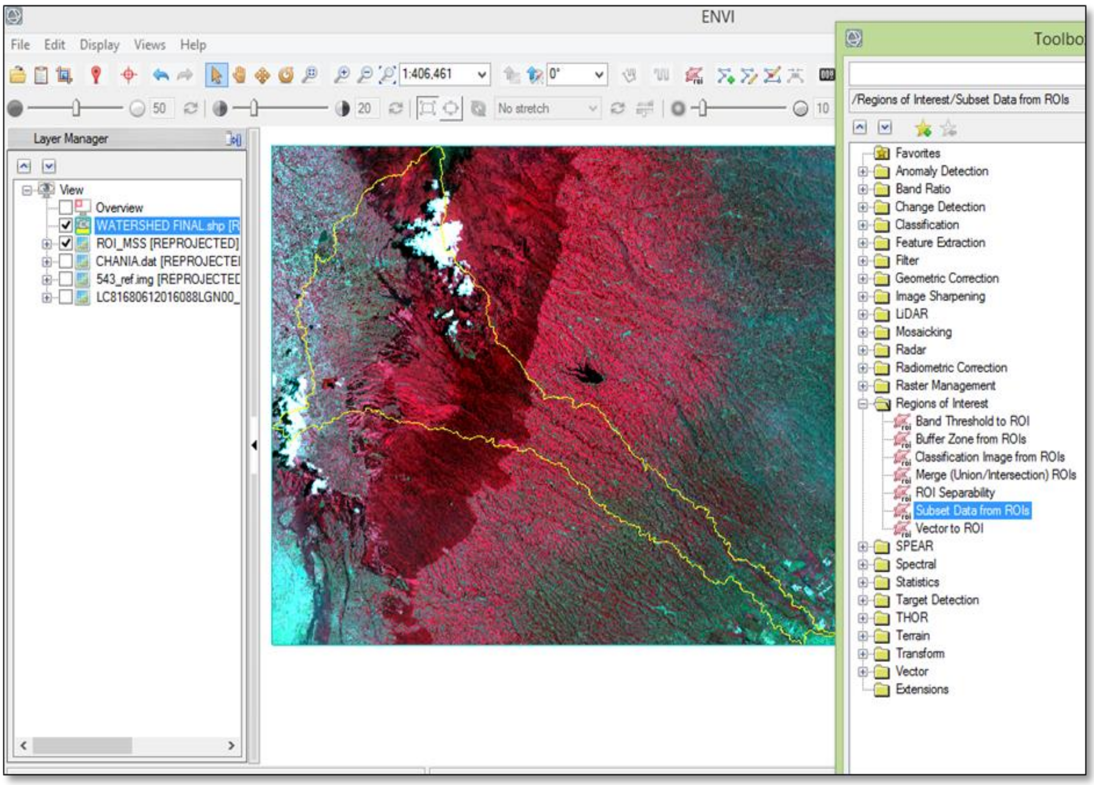


Figure A.7.2: A screenshot of layer sub-setting

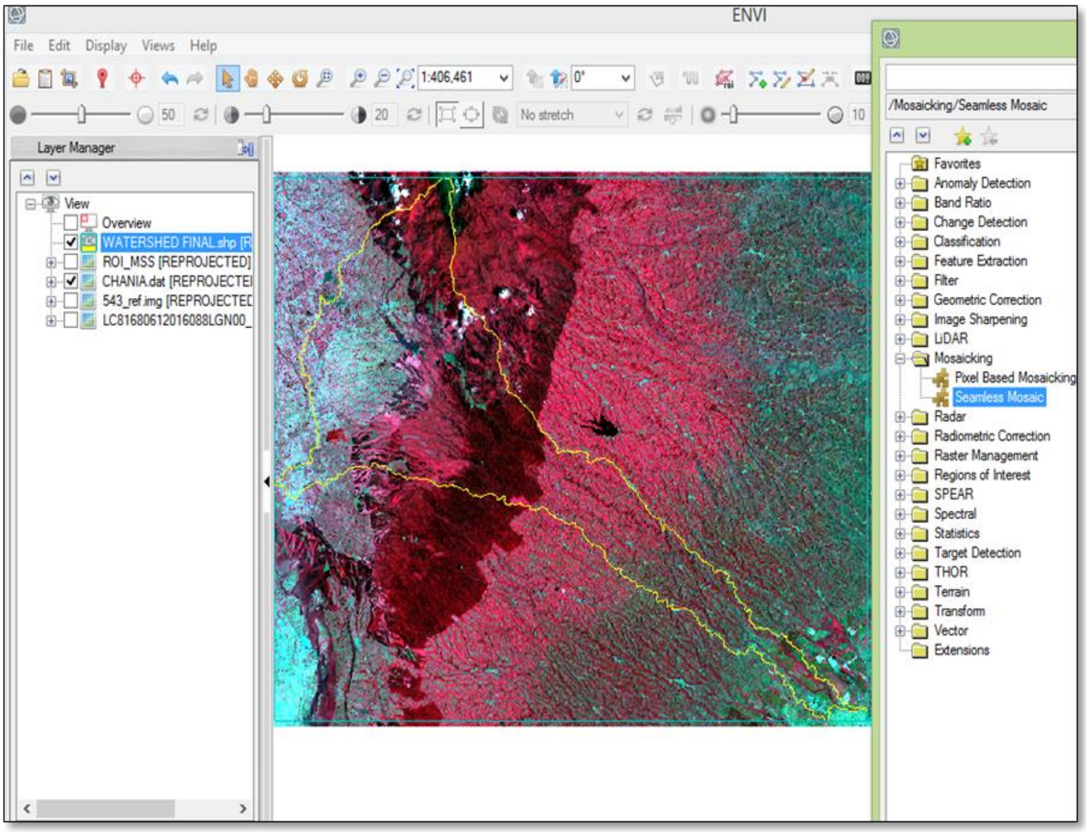


Figure A.7.3: A screenshot of image obtained after cloud and shadow removal procedure

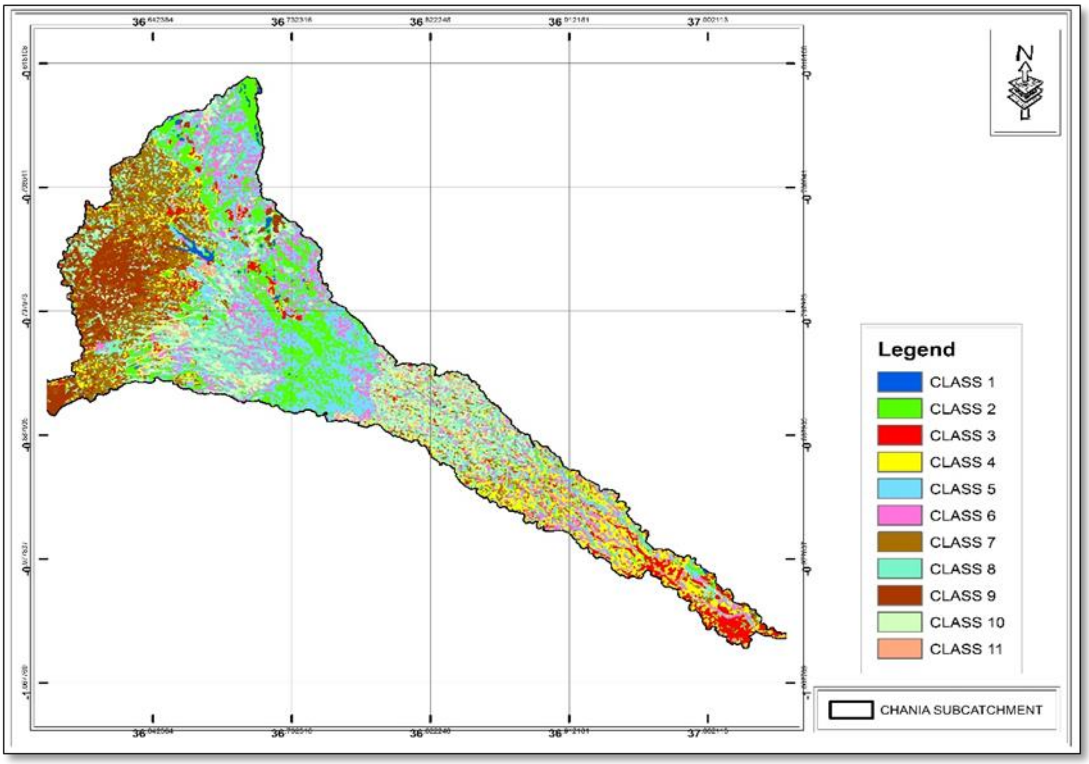


Figure A.7.4: LULC generated from unsupervised classification

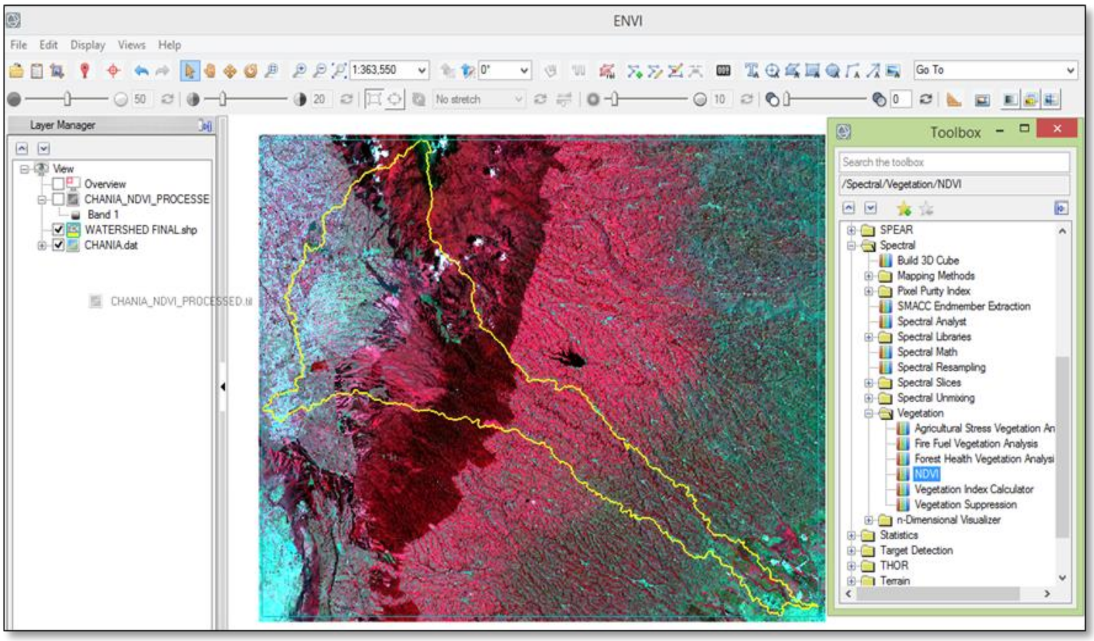


Figure A.7.5: Pre-processed Landsat Imagery used in generation of NDVI

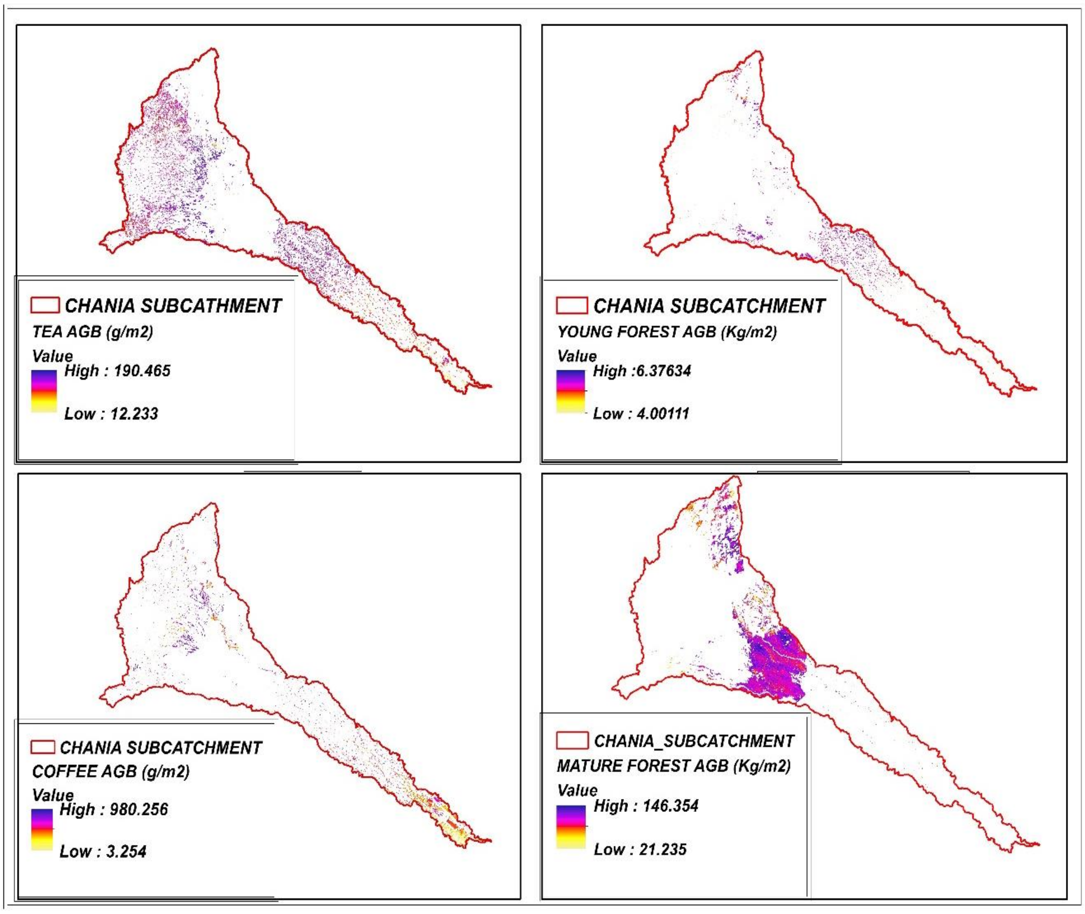


Figure A.7.6: Tea, Young Forest, Coffee and Mature Forest above ground biomass

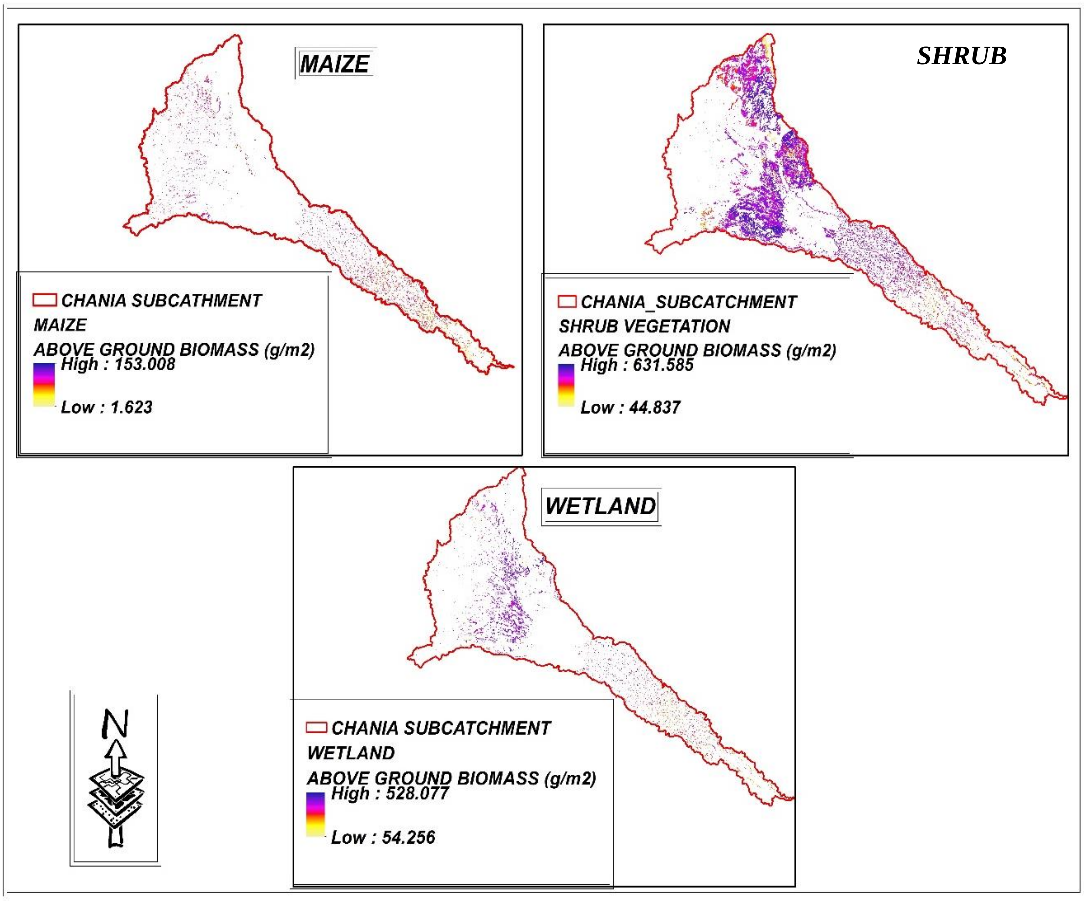


Figure A.7.7: Maize, Shrub Vegetation and Wetland above ground biomass

Appendix 8: pictures

Plate A.8.1: Focus group discussion for PGIS in Karangi, Chania (a) women group (b) men group

Plate A.8.2: Focus group discussion for PGIS in Mbugiti, Chania (a) men group (b) women group

Plate A.8.3: Data collection for LULC classification in Kimakia forest

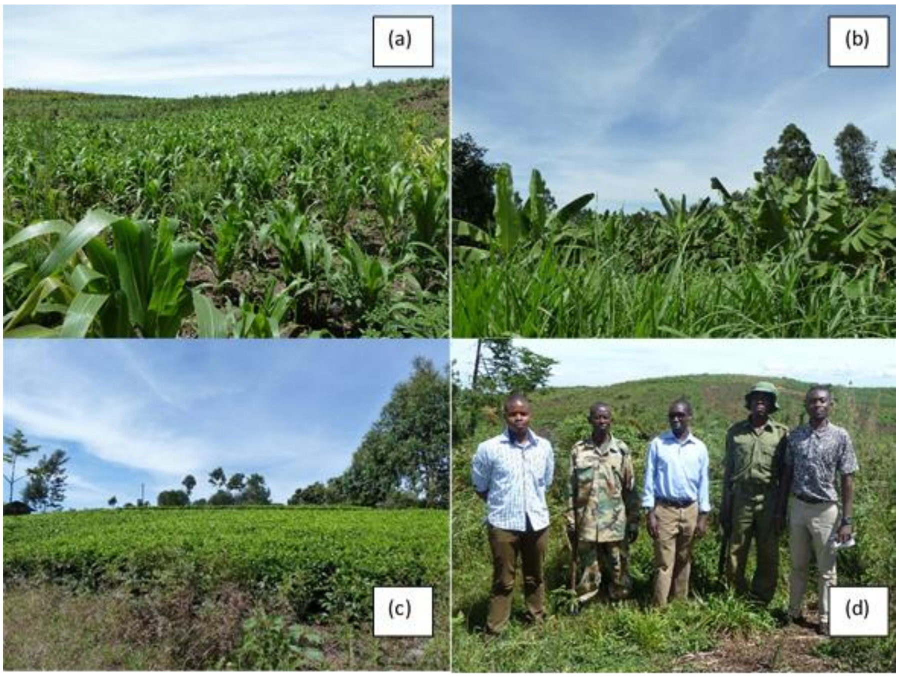


Plate A.8.4: Different land uses in Chania and the fieldwork team (a) Maize (Trees planted in within maize farms) (b) mixed crops (c) tea (d) the team that supported field work

Plate A.8.5: Different land uses in Chania and the fieldwork team (a) Bare land with mixed crops (b) Shrub vegetation and mature forest at the background (c) Shrub vegetation in the middle of mature forests (d) Wetland