The Status of Wetlands and their Influence on Stream Flow and Sediment Yield in Maragua Watershed, Murang'a County, Kenya

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DECLARATION

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

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DEDICATION

I dedicate this thesis to my daughter Ivy, son Ethan, my husband Michael, mum Alice and sister Esther for their unlimited support during my studies.

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ABBREAVIATIONS /ACRONYMS

ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information Systems
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation
ASAL	Arid and Semi-Arid Land
AWBM	Australian Water Balance Model
DEM	Digital Elevation Model
ERDAS	Earth Resource Development Assessment System
FAO	Food and Agriculture Organization
FDC	Flow Duration Curve
HSPF	Hydrological simulation program-Fortran
KMD	Kenya Meteorological Department
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multispectral Scanner System
MSAVI	Modified Soil Adjusted Vegetation Index
MUSLE	Modified Universal Soil Loss Equation
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NDWI	Normalized Difference Vegetation Index
NEMA	National Environment Management Authority
OBIA	Object Based Image Analysis
RCMRD	Regional Center for Mapping of Resources for Development
RUSLE	Revised Universal Soil Loss Equation
SDR	Sediment Delivery Ratio
SWAT	Soil and Water Assessment Tool
TM	Thematic Mapper
TOPAZ	Topography Parameterization
TWI	Topographic Wetness Index
USLE	Universal Soil Loss Equation
WEPP	Water and Erosion Prediction Project
WRA	Water Resource Authority

ABSTRACT

Wetlands are areas on the surface of the earth that are either seasonally or permanently saturated with water or have soil moisture higher than the surrounding uplands. Wetlands attenuate peak flows, reduce sediment loads in surface water bodies, recharge ground water and are home to a wide range of biodiversity. Wetlands in Murang'a County are under stress due to agricultural intensification and urbanization, which have resulted in the shrinkage of wetlands. This study aimed at evaluating the status of wetlands in Maragua watershed and their effect on stream flow and sediment yield. Landsat images and Digital Elevation Model (DEM) were used to identify and map the wetland conditions in 1987, 1999 and 2018. Index-based classification method was adopted for wetland identification using Normalized Difference Vegetation Index (NDVI), Normalized Difference Water Index (NDWI) and Topographic Wetness Index (TWI) indices and the ERDAS Imagine software. Interviews, a focus group discussion, a stakeholder workshop, storytelling events and observation were used to gather data on community's perceptions of wetlands and the challenges facing wetland conservation. Stream flow data for Githanja catchment was generated using the Australian Water Balance Model (AWBM), a hydrological model with Karurumo catchment as the donor catchment while the GeoWEPP model was used to determine the effect of land use in wetland on stream flow and sediment yield in Githanja catchment. Three modeling scenarios were done in the study: (i) Cultivated wetlands on 9.5% of the catchment area (CULT9.5%); (ii) Wetlands with tall grass on 9.5% of the catchment area (GRASS9.5%); and (iii) Wetlands with tall grass with on 16.6% of the catchment area (GRASS16.6%). AWBM simulated stream flow data and TSS data from WRA was used to calibrate and validate GeoWEPP model. Between 1987 and 2018, the area under wetlands decreased by 58% from an area of 24.1 ha. Wetland cultivation, planting of exotic tree species and fodder crops were the main human activities taking place within the wetlands. However, residents were not aware of the adverse effects their activities have on wetlands. Also, conflict in existing land ownership policies and wetland regulations and inadequate community awareness creation were the main impediments against wetland conservation. The simulation study showed the annual average runoff in Githanja catchment for CULT9.5% was 190,121m^3/year while the annual average runoff for GRASS9.5% was 161,886m^3/year which worked out to about 15% reduction in runoff. For 16.6%GRASS, the annual average runoff 134,817 m^3/year which was 29% reduction compared to CULT9.5%. Furthermore, the average annual sediment yield in Githanja catchment for CULT9.5% 2,201Tonnes/ha/year while for GRASS9.5% it was 1,423Tonnes/ha/year, which works out to about 35% less sediment yield. For the 16.6%GRASS average annual sediment yield was 1,103Tonnes/ha/year which is about 50% the sediment yield under CULT9.5%. Transforming wetlands from cultivated land units to conserved grassland attenuates peak flows and reduces sediment yield. Finally, reclaiming lost wetlands will further reduce sediment yield and runoff.

CHAPTER ONE

INTRODUCTION

1.1 Background

Wetlands are areas on land that are characterized by permanent or seasonal flooding or soil moisture higher than that of the surrounding uplands (Baker, Lawrence, Montagne, & Patten, 2006). Their presence is essential to the well-being of humans and ecosystem at large. Wetlands can be natural or human made. Natural wetlands include bogs, marshes, swamps, wet meadows and forested wetlands (Zedler & Kercher, 2005). Human made wetlands comprise farm ponds, aquaculture and permanently or temporarily inundated agricultural land such as reservoirs, salt pans, rice paddies, canals, sewage farms and gravel pits (Ramachandra, Rajinikanth, & Ranjini, 2004).Constructed wetland are consist of areas previously on terrestrial environment modified to poorly drained soil conditions and wetland vegetation for the purpose of waste water treatment. The pioneer constructed wetland was done by the Splash Water World wastewater treatment facility in Kenya in the 1993 and commissioned in 1994. Constructed in Kenya have been used to treat sewage water in place of stabilization ponds (Kelvin & Tole, 2011).

Wetlands in a watershed store runoff during high flows such that they attenuate large flows. The improve water quality by trapping sediment and other adsorbed pollutants transported by the runoff to surface water sources (Ramachandra et al., 2004; Zedler & Kercher, 2005). Wetlands well-being however is compromised by increased land development as well as agriculture to meet food demand for the growing population in the world (Verhoeven & Setter, 2018). In Kenya, wetlands have not been spared. Competing interests and ideas about their use i.e. agriculture, restoration/conservation or development, has created tension within communities living around the wetlands (Keche, Ochieng, Lekapana, & Macharia2, 2007).

Wetlands in the past were sustainably exploited for hunting, gathering, harvesting of thatching material and used as grazing land. However, this is no longer the situation in many of these wetlands since they have been converted to farmlands (Sakané et al., 2011). Examples of wetland that have been encroached into include the Yala swamp and Tana delta which have been reclaimed for agriculture. There is very little effort to conserve wetlands. Threats against the existence of wetlands in Kenya include: (1) poverty causes farmers to use all available land food production; (2) local communities have the perception that the value of wetlands can only be realized when they are converted into agricultural land; (3) citizens view wetlands as reservoirs for diseases vectors; (4) presence of alien plant species which undermine indigenous wetland plant species; and (5) most communities do not understand the benefits of wetlands thus refer to them as wasteland (Keche et al., 2007). Although wetlands in Kenya occupy about 2.5% of the land mass, 80% lie in unprotected areas (Hughes & Hughes, 1992). Only wetlands of international importance such as Lake Naivasha, Lake Bogoria, Lake Nakuru and Saiwa swamp have management plans and financing in Kenya. The greater percentage of wetlands lack functional program for monitoring thus they are often neglected in planning and receive limited financing thus continue to suffer degradation

(Mwita et al., 2012). Additionally, riparian land which in some places becomes riparian wetlands when the soil is saturated is supposed to be conserved but this is rarely enforced (Government of Kenya, 2017). It is important to establish a proper database for wetlands in order to monitor them. This requires mapping with an aim of identifying the geographical location as well as the size of the wetlands (Munyati, 2000).

In Kenya, the main source of fresh water is rivers. There are five main water towers in Kenya where all the main rivers originate except Tsavo River (Ontumbi, Obando, & Ondieki, 2015). The water towers are Aberdare, Cherangani, Mau complex forests, Mount Kenya and Mount Elgon. The Aberdare and the Mount Kenya towers are the main catchment areas in the upper Tana catchment. However, a report from the Ministry of Environment and Natural Resources, (2016) indicated that these water towers have suffered encroachment resulting to destruction of the natural vegetation and wetlands. Furthermore, there are three main land tenure systems: public, private and community land. Under private ownership there is freehold and lease of land. Most of the wetlands in Kenya are found in the privately owned land. For example in Trans Nzoia, 91% of the wetlands are privately owned (Keche, et al. 1992). This makes conservation and monitoring of these wetlands difficult because the land owners have rights over them (Macharia, Thenya, & Ndiritu, 2010).

Nearly 80% of world population is exposed to high levels of water security threat (Vörösmarty et al., 2010). This is because of rampant water pollution and scarcity. Water pollution exists due to the presence of excessive dissolved solids, organic matter, fecal material and suspended solids in drinking water. Access to food supply is a great priority and it is second to availability of drinking water. The pressure to produce enough food has continued to increase thus leading to encroachment of marginal land for both subsistence and commercial farming (FAO, 2015). Africa, with 70% of her population in the rural areas, depends directly on land for its livelihood and wellbeing (Kieti, Kauti, & Kisangau, 2016). Majority of watershed in Africa contribute to non-point source pollution. The characteristics of the surface of a watershed influences production of runoff and production of sediment (Zhang, Degroote, Wolter, & Sugumaran, 2009).

Wetlands in a watershed have been shown to be very valuable in removal of non-point pollution from agricultural fields (Gilliam, 1994). Farmlands compared to forests and other forms of vegetation have been found to have higher erosion rates (Borrelli et al., 2017). A study carried out by Benvenuti et al., (2015) in Oregon showed that agriculture contributes to the production of sediments, nutrients, bacteria and water pollution which can harm people. In their study on the impact of sediment and nutrients on coastal environment, Ikeda et al., (2009), found that sediment yield from farmland is almost four times the yield from forests. Their study showed that land use significantly influences the level of sediment and nutrients in surface water. Krhoda, (2006) found that the common pollutants in the surface waters of the Tana basin in Kenya included agrochemicals and suspended solids. The benefits of wetlands in a watershed however can only be recognized if the wetlands are not encroached (Ramachandra et al., 2004). The use of physically distributed model allows study of the hydrological responses of a catchment to be studied and the impact of wetland management to be estimated without implementing such on ground (Potter, 2011). GeoWEPP model is one of the models that can be used to predict the amount of runoff and sediment yield from a watershed under different wetland conditions (Laflen, Elliot, Flanagan, Meyer, & Nearing, 1997).

1.2 Problem Statement

Over the years wetlands in Kenya have been encroached into at an alarming rate but there is no documentation for the wetlands to quantify how much has been lost (Ministry of Environment and Natural Resources, 2016). Encroachment has led to loss of their benefits but the impacts are not fully known. It is therefore imperative to quantify the amount of wetland area lost and understand why they are being lost. Furthermore, although the influence of land use/ cover and rainfall variation on soil erosion and sediment yield has received attention in the past studies in Maragua Watershed, the influence of wetlands on runoff and sediment yields is still unknown. In this regard, it is necessary to assess the relationship between wetland and stream flow and sediment yield. Remote sensing was used to map changes in wetlands in Maragua and determine their influence on stream flow and sediment yield using a hydrologic model.

1.3 Objectives

1.3.1 Main objective

The general objective of this study was to determine the status of wetlands and their influence on stream flow and sediment yield in Maragua watershed, Murang’a County, Kenya

1.3.2 Specific objectives

1) To determine the status of wetlands in Maragua watershed, Murang’a County, Kenya.

2) To assess the impacts of changes in land use within wetlands on stream flow and sediment yield in Githanja catchment of Maragua Watershed.

1.4 Research questions

i. How have wetlands in Maragua watershed changed in time and space and what are the causes of the changes?
ii. What are the effects of changing land use within wetlands on stream flow and sediment yield?

1.5 Justification

Increased population has affected the way land resources are used (Mathooko, M'Erimba, Kipkemboi, & Dobson, 2009). Population pressure has resulted in increased human activities within wetlands. This shift has caused negative impacts on the ecological and hydrological functions on the wetlands (Masarirambi, Manyatsi, & Mhazo, 2010). In the past, policies have focused on strategies to conserve big wetlands while ignoring small wetlands which play a crucial role preserving environmental health. Given that these small wetlands are mainly privately owned, they are more vulnerable to intensive human activities. There is therefore need to quantify wetland losses in Kenya and how human activities affect their function. Additionally, there have been no studies on the extent to which wetlands influence runoff and sediment yield in Maragua. To fill in this gap, an analysis of the relationship between wetlands, overland flow and sediment yield was carried out in Githanja catchment, in Maragua Watershed. Measuring stream flow and sediment yield as a way of monitoring the effect of changes in the status of small wetlands would be costly and time consuming (Potter, 2011). Therefore, a physically-based model was used to predict the effects of wetlands on stream flow and sediment yield. Githanja catchment was chosen for modeling because unlike other catchments, it had some stream flow and sediment data.

1.6 Scope

The study was carried out in Maragua watershed, Murang'a County, Kenya. In order to determine the temporal and spatial status of the wetlands within the watershed, two spectral indices, NDVI and NDWI together with one topographic index, TWI were used to map the wetlands in 1987, 1999 and 2018. Qualitative data was collected and analysed to evaluate the residents' perceptions on wetlands and the challenges facing the conservation of such wetlands. Hydrologic modelling using GeoWEPP model was done to predict the influence of different wetland use and area conditions on stream flow and sediment yield in Githanja catchment within Maragua watershed.

1.7 Limitation of the study

Due to limited funds in the research, it was only possible to use free to download Landsat images and digital elevation model that are of medium resolution (30m resolution) for mapping of wetlands. Lack of sediment yield data in Maragua River made it impossible to calibrate the model for the entire watershed. Inconsistencies in the stream flow data available for Githanja necessitated the use of a rainfall runoff model with Karurumo as a donor catchment to generate stream flow for Githanja catchment.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter presents the theoretical and empirical works done on wetland identification methods, the perceptions of the people living around wetlands and challenges facing the wetlands and modelling studies on wetland use and area on stream flow and sediment yield.

2.2 Definition of wetlands

The Ramsar Convention of 1971 defines "Wetlands as areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, including areas of marine water, depth at which at low tide does not exceed six meters"(Ramachandra, et al., 2004). Wetlands cover 6% of the global land's surface. Wetlands can be peatlands or mineral-soil wetlands. The Ramsar convention 1971 classifies wetlands into three broad categories namely inland wetlands, marine/coastal wetlands and human-made wetlands. Human made wetlands include farm ponds, aquaculture and permanently or temporarily inundated agricultural land such as reservoirs, salt pans, rice paddies, canals, sewage farms and gravel pits. Other classification of wetlands can be based on vegetation characteristics and or hydrogeomorphology. They include: Marine wetlands include coastal lagoons, coral reefs and rocky shores. Estuarine wetlands include tidal marshes, deltas and mangrove swamps. Lacustrine wetlands are those that are associated with lakes while riverine are rivers and wetlands along rivers and streams. Lastly there is palustrine wetlands that include marshes, bogs and swamps (Demissie, Misganaw, Akanbi, & Khan, 1997). Kenya has adopted the wetland definition by Ramsar Convention 1971 (Keche et al., 2007). Global climate change and human encroachment however make their future unknown as regards element dynamics and matter fluxes (Erwin, 2009).

2.3 Importance of wetlands

The ecological, biological, cultural, social and economic values of wetlands form an important component of the environment (Ramachandra et al., 2004). Wetlands improve water quality by removing organic matter, nutrients and sediments carried in runoff and breakdown organic matter. Most of these wastes come from agricultural lands on the upstream of the wetland. Wetlands also discharge to surface water resources and recharge ground water resources (Keche et al., 2007).

Wetlands act as reservoirs for runoff and soil filters during heavy rains thereby ensure flood control. Destruction or over extraction of wetlands increases the risk of saline water intrusion which deprives people, industries, agriculture and ecological community’s fresh water. Wetland vegetation such as papyrus reeds can be harvested to make mats, canoes, baskets and fish traps for economic gain. Finally, wetlands can offer grazing fields and natural salt licks during the dry season and can be of significant religious importance to the local community (Keche et al., 2007).

A research was carried out on the influence of wetlands on watershed hydrologic responses in Illinois State using the ANSWERS model by Demissie et al., (1997) by varying wetland areas from 0 to 70 percent of the study area with one inch of rainfall on the watershed for one hour. Several simulation runs were made and flow hydrographs calculated at the outlet of the watershed. The results showed that flood is attenuated as a result of changing the percentage wetland (Figure 2.1). However, they used hypothetical rainfall data and wetland coverage in their study.

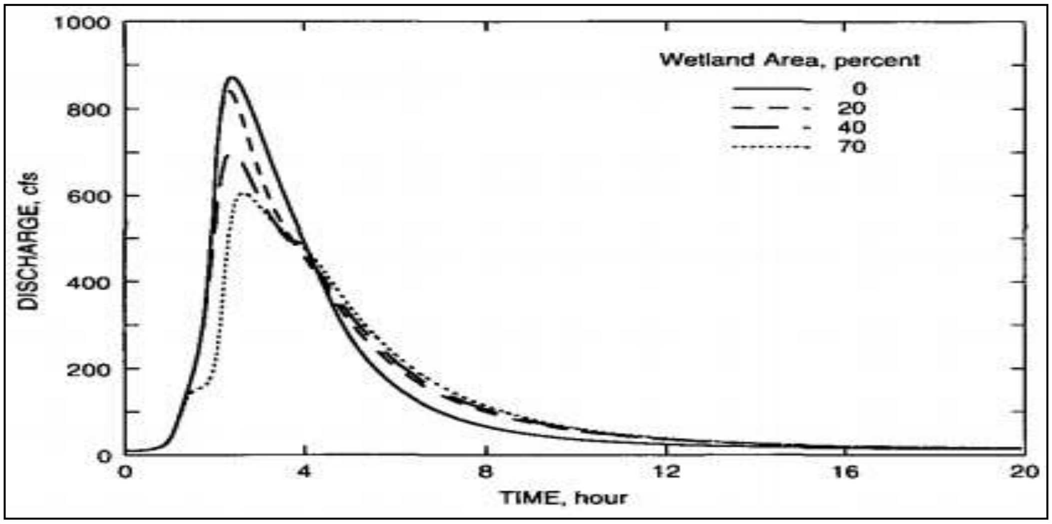


Figure 2.1: Discharge hydrographs for varying wetland percentage at a watershed outlet (Source: Demissie et al., 1997)

2.4 Role of Remote Sensing and Geographic Information System (GIS) in Wetland Mapping

Wetlands differ in shape, vegetation, aspect ratio, hydrologic and soil conditions. Aspect ratio affects the water-storage relationship of a wetland. Identification of wetlands on the field can be easy or difficult depending on the distinctive features. Field identification of wetlands is labor intensive, time consuming and impractical where they cover large areas (Baker et al., 2006). Remote sensing and GIS can be used to facilitate identification and delineation of wetlands. The required geospatial data for mapping of wetlands include satellite imagery (Baker et al., 2006). Aerial photography has been used extensively for a long time to map wetlands. However, it is time consuming because of the manual visual interpretation compared to multispectral satellite imagery which provides a standardized environmental data (Xiaojun & Liu, 2005). In addition to visible portions i.e. the red, green and blue and near infrared (NIR), information on longer wavelengths such as the thermal infrared and short wave infrared is collected. The commonly used multispectral satellite sensors for mapping are Landsat MSS/TM/ETMplus/OLI, AVHRR, SPOT 4/5/6/7, MODIS, QuickBird eye, IKONOS, world view- 1/2/3/4, rapid eye, sentinel-2, GeoEye-1 (Sarun, Vineetha, & Kumar, 2016). Other than aerial photography and multispectral images, LiDAR data has been incorporated into wetland mapping (Wu, 2018). Classification methods include pixel based, object based and index based classification (Kaplan & Avdan, 2017).

2.4.1 Index based classification

Identification and delineation of wetlands can done through analysis of different combination of various wetland indicators such as vegetation, hydrology, topographic positions and soil types (Wu, 2018).

2.4.1.1 Hydrology

Hydrology can be considered the most important factor of a wetland as it affects the formation and the functions of a wetland (Hassan & Moniruzzaman, 2009). Lands are designated wetlands if they are wet for a long period. Based on the frequency of soil saturation, wetlands can be classified as either seasonal, semi-permanent, ephemeral or permanent (Brinson, 1993). In the United States, the minimum wetness for a federally regulated wetlands defined by saturation within 30cm of the surface for at least 2 weeks during the growing season. Generally, wetlands with high wetness are relatively easier to identify than dried ones using remote sensing (Wu, 2018).

The Normalized Difference Water Index (NDWI) is commonly used to detect and delineate water features and high moisture areas. It is calculated as in Equation 2.1. NDWI ranges from -1 to +1, where +1 signifies the presence of extensive deep waters and -1 for vegetation (Sarun et al., 2016). Chowdary et al., (2008) mentioned that the NDWI for waterlogged areas ranges from 0 to +1.

$$\mathrm{NDWI} = \frac{\mathrm{Green}-\mathrm{NIR}}{\mathrm{Green}+\mathrm{NIR}} \tag{2.1}$$

Where Green- green band and NIR- Near-infrared band in a remotely sensed image.

2.4.1.2 Hydrophytic vegetation

Wetland plants are known as hydrophytic vegetation (Verhoeven & Setter, 2018). They are a distinctive feature of wetlands in terms of their life form and pattern. The wetland vegetation species are adapted to prolonged flooded conditions.

Normalized Difference Vegetation Index (NDVI) can be described as an array of values derived from satellite data which are used for vegetation mapping. It is based on visible red and near infrared channels whereby vegetation is indicated by a higher reflectance of NIR and higher absorption of red channels. It is calculated as in Equation 2.2 (Sarun et al., 2016).

$$\mathrm{NDVI} = \frac{\mathrm{NIR}-\mathrm{Red}}{\mathrm{NIR}+\mathrm{Red}} \tag{2.2}$$

Where NIR is the Near-infrared band and Red is the red band in remotely sensed images.

NDVI is a non-linear function with values ranging from -1 to +1, where rocks, water and bare soils are indicated by -1 and dense vegetation indicated by +1 (Szabó, Gácsi, & Balázs, 2016).

2.4.1.3 Topographic location

Wetlands are associated with topographic lows even in mountainous regions (Tiner, 2003). Topographic positions can be used as supplementary indicators of wetlands. Primary topographic metrics (curvature, aspect and slope) derived from DEMs are used to compute secondary topographic metrics by combining two or more primary metrics (Różycka, Migoń, & Michniewicz, 2016). Topographic Wetness Index (TWI) is one of the most common secondary metric used to identify wetlands. TWI quantifies the tendency of a grid cell to receive and accumulate water. It is defined by Equation 2.3 (Wu, 2018).

$$\mathrm{TWI} = \mathrm{Ln}\left(\frac{\mathrm{A}}{\mathrm{Tan}(\beta)}\right) \tag{2.3}$$

Where A is the upslope contributing area in $m^2$and β is the local angle slope in radians.

A higher value of TWI value indicates a higher tendency to accumulate water thus a high likelihood of a wetland presence (Zhu & Woodcock, 2012).

However, the method adopted for wetland mapping depends on availability and resolution of geospatial data (Hassan & Moniruzzaman, 2009). Analysis of different combination of various wetland indicators such as vegetation, hydrology, topographic positions and soil types (Wu, 2018).

2.4.2 Pixel based classification

Common land use/cover classification methods available can broadly be categorized into two: supervised and unsupervised classification. For supervised classification, the analyst selects training samples for each land cover class then uses them to guide the software to identify spectrally similar areas and group them as one class. Common methods in supervised classification are maximum likelihood, decision tree, minimum distance, random forest, parallelepiped and support vector machine (Lane et al., 2016). Unsupervised classification on the other hand specifies the number of classes required and then the computer groups together statistically similar pixels using clustering algorithms. Cluster algorithms include K-means, agglomerative hierarchical and Iterative Self-Organizing Data Analysis Technique (ISODATA). Hybrid combines field data, unsupervised and supervised classification (Wu, 2018). However, pixel based classification solely rely on digital data which often result in ‘salt and pepper’ appearance of the classified image (Weih & Riggan, 2010).

2.4.3 Object based image analysis (OBIA) classification

Object-based image classification uses an algorithm to group pixels into representative sizes and shapes through the process of multi-resolution segmentation. The OBIA method incorporates spatial, spectral, textural and contextual information in the classification process (Weih & Riggan, 2010). Trimble eCognition is the most popular software for OBIA classification (Wu, 2018). Although OBIA can give a greater accuracy for wetland mapping than traditional pixel-based approach, it requires high resolution images such as the IKONOS (Kaplan & Avdan, 2017).

Kaplan & Avdan, (2017) used sentinel-2 launched in June 2015 to map wetlands in Sakarbasi spring in Eskisehir, Turkey. They applied three different approaches for classification that is the pixel-based, index-based and object-based. They proposed that wetlands can be successfully extracted with the combination of object-based and index-based methods. Object-based classification for extraction of wetland boundaries and NDVI and NDWI for classification of wetland contents within the boundaries. The results showed a successful mapping and monitoring of wetlands with kappa coefficient of 0.95. However, this study only gives the possibility of extracting wetlands from sentinel-2 was launched in 2015 thus cannot be used to analyze trends in wetlands over a long period of time. Also, object-based classification requires high resolution images.

Hassan & Moniruzzaman, (2009) classified wetlands of Godagari Thana of Bangladesh based on spectral rules of Enhanced Thematic mapper (ETM+) image and Shuttle Radar Topographic Mission (SRTM). They used the spectral values from the green, blue, Near Infrared (NIR), NDVI, a wetness image of Tasseled Cap Transformation (TCT), relative elevation and slope from Digital Elevation Model (DEM) to generate the rules for wetland classification. They generated seven rules using the reflectance properties. All the rules in their study were structured by IF and THEN syntax and later implemented on ENVI decision tree module. The study showed that wetlands have increased by approximately 50% over 55 years in the study area with an overall accuracy of 87.56%.

Sarun et al., (2016) utilized the semi-automated methods (remote sensing and GIS), ASTER DEM and Landsat ETM+ to evaluate the Tsunami affected Panchayats of Allapad and Arratupuzha, Kerala India which lies in the coastal area with lowland plains. They used various spectral and terrain indices such as NDVI, Tasseled Cap Wetness Index (TCWI), NDWI and terrain slope to extract wetland areas. They used trial and error method to finalize on the thresholds for the indices. This was done to avoid overestimation or underestimation of the wetland areas. Accuracy assessment was done by comparing the output of the semi-automated method and Google Earth data and nearly 80% accuracy was achieved. The thresholds in this study were set by trial and error which coiled result to wider ranges as opposed to using actual ground collected georeferencing data.

2.5 Accuracy assessment of the wetland maps

Accuracy assessment also known as validation is an important step in processing of geodata (Xiaojun & Liu, 2005). It establishes the value of information of the result after analysis of remote sensing data to a user. Accuracy assessment compares the classified pixels to the definite land cover conditions corresponding to collected ground truth data. Accuracy assessment is carried out by collecting reference data using a GPS and specific class types then determined at the specific locations known as ground truth (Adam, Elhag, & Salih, 2013). Kappa coefficient (k) indicates the proportion of agreement beyond that expected by chance in land classification studies. Observed agreement is determined by diagonal in error matrix and chance agreement incorporates off diagonal. It is always less or equal to 1, where 1 implies a perfect agreement (Table 2.1) (Viera & Garrett, 2005). It is calculated based on the difference between observed agreement and expected agreement and takes the form in Equation 2.4 In their research on ‘accuracy assessment of land use/ land cover classification using remote sensing and GIS’, Rwanga

& Ndambuki, (2017), obtained a kappa value of 0.722 and overall accuracy of 81.7%. The Kappa coefficient obtained was considered substantial thus the image was fit for further research.

$$\mathrm{k} = \frac{\text{observed agreement} - \text{chance agreement}}{1 - \text{chance agreement}} \tag{2.4}$$

Table 2.1: Kappa interpretation table (Viera & Garrett, 2005).

Interpretation of Kappa						
	Poor	Slight	Fair	Moderate	Substantial	Almost perfect
Kappa	0.0	0.20	0.40	0.60	0.80	1.0

2.6 Threats against wetlands

Human beings are the main drivers of both positive and negative changes in wetlands occasioned by survival instincts (Zedler & Kercher, 2005). Drainage of wetlands is one of the direct impacts while climate change is an indirect impact. Both globally and locally wetlands have been drained to provide land for agriculture and settlement (Masarirambi et al., 2010). Wetlands are so vulnerable to change in climate. Climate change can lead to shifts in wetland distribution, the extent to which they function and also the seasonal variation (Price et al., 2000). The extent to which climate change will affect wetlands depends on the ecosystems and their spatial location. The different diversity and their individual characteristics, the impacts of climate change can be customized and so is the restoration remedies (Erwin, 2009).

Land use/ land cover are the most important factors affecting the frequency and intensity of surface runoff and overland wash erosion. Some of the main causes of erosion include inappropriate agricultural practices, overgrazing, forest fires, deforestation, and urbanization. Of these factors, agriculture produces the highest erosion (Nuneset al., 2011).

2.7 International conventions for wetland protection

Although wetland inventory at a global scale exist, inconsistencies exist in terms of wetland definition, classification method, classification system data type and spatial resolution. Despite the inconsistencies, these inventories provide important information about the extent of wetlands globally and serve as valuable data sources for wetland conservation, management and research (Wu, 2018). The Ramsar convention is an international treaty for promoting conservation and sustainable use of wetland habitats with 269 states by 2016. By November, 2016 the Ramsar convention had designated 2243 sites covering 2.6 million Km^2 as wetlands of international importance (Plate 2.1). The United Kingdom has the highest number of sites with i.e. 170 sites while Bolivia with 148,424 Km^2 has the highest total area of wetlands in the Ramsar convention. Africa has recorded 394 sites with six in Kenya (Ramsar convention, 2016). Although Ramsar convention 1971 is aims at wetlands conservation, it is more favorable to wetlands that provide home for migratory birds

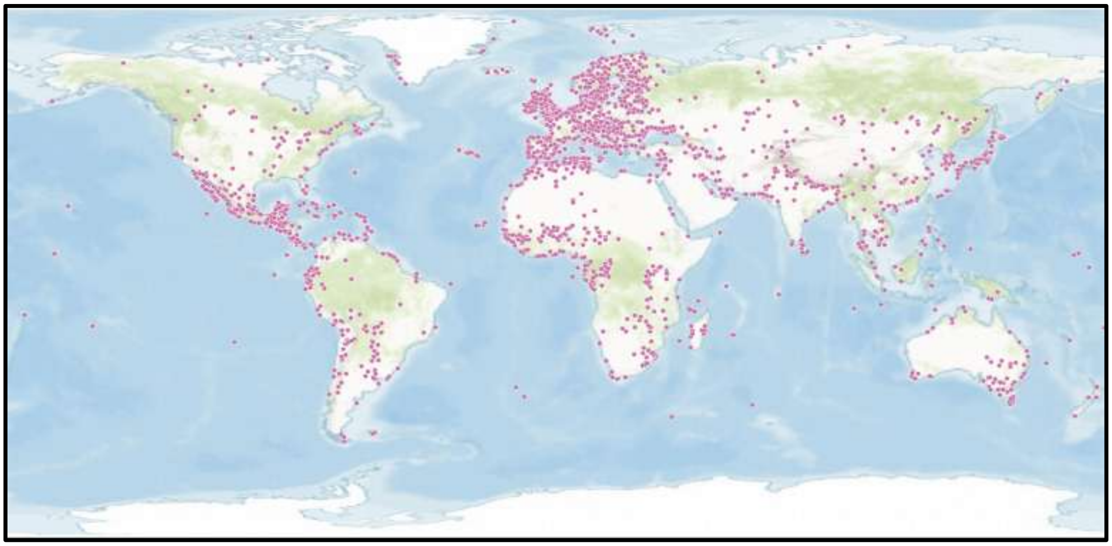


Plate 2.1: Published Global distribution of Ramsar sites. (*Source Ramsar convention, 2016)*

In Kenya there are six designated wetlands of international importance (Ramsar sites) namely Tana River delta, lake Elmenteita, lake Nakuru, lake Bogoria, Lake Naivasha and lake Baringo (Table 2.2). They cover a total of 265,449 hectares (Ramsar convention, 2016). Therefore, there is need to identify and conserve other wetlands that are not defined under the Ramsar Convention.

Table 2.2: Ramsar sites in Kenya and their areal coverageand date designated as a Ramsar site (Ramsar Sites Information Service, 2013)

Ramsar Site	**Area (ha)**	**Date designated as a Ramsar site**
Lake Elmenteita	10,880	05/09/2005
Tana River delta	163,600	07/09/2012
Lake Nakuru	18,800	05/06/1990
Lake Bogoria	10,700	27/08/2001
Lake Baringo	31,469	10/01/2002
Lake Naivasha	30,000	10/04/1995

2.8 Soil erosion

Soil erosion refers to the detachment and movement of soil particles by erosion agents; water and wind. Eroded soil can be transported through sheet erosion, rill or gulley erosion. Sediment yield is the portion of the eroded material that is transported through a stream network to some point of interest (Asselman, 2000). The sediment rate at a cross section is controlled by the amount of erosion in the watershed and the capacity of the stream to carry the sediments (Wilcock, Asce, & Crowe, 2003).

2.8.1 Sediment delivery ratio

The sediment delivery ratio (SDR) is the fraction of gross soil erosion that is transported from an area at a given time interval (Equation 2.5). It is a measure of sediment transport efficiency (Lu, Moran, & Prosser, 2006; Zhou & WU, 2008)

$$\mathrm{SDR} = \frac{\mathrm{Y}}{\mathrm{E}} \tag{2.5}$$

Where Y is the average annual sediment yield per unit area and E is the average annual erosion over the same area.

Equation 2.5 is only applicable when Y is the average annual sediment yield from sheet and rill erosion because SDR is traditionally defined as the catchment transport efficiency in terms of upland gross erosion. Sediment yield from river banks and gully erosion should be excluded. SDR ranges between 0 and 1 and is influenced by rainfall, landscape, wetlands and reservoir storages (Lu et al., 2006). An empirical based method can be adopted as a method of determining SDR (Equation 2.6).

$$\mathrm{SDR} = \alpha \mathrm{A}^{\beta} \tag{2.6}$$

Where A is the catchment area in Km^2 and α and β are empirical parameters. The scaling exponent β contains physical information of sediment transport processes in a catchment. However, empirical relationships for calculating SDR may be misleading because it implies that a single A produces a single SDR whereas SDR is affected by vegetation, land use and landscape which can vary within the area.

2.8.2 Global impact of soil erosion

Globally soil erosion is one of the major threats to the sustainable and productive capacity of agriculture globally (Lai, 2001). During their study on the assessment of global soil erosion, Bridges et al., (1999) reported that during the last 40 years, nearly a third of the world's arable land had been lost to erosion. They estimated that the rate continues at more than 10 hectares/ year. In a recent study by Yang et al., (2003), estimated soil erosion potential using the RUSLE model to be about 0.38mm/year of topsoil around the globe. This is equivalent to 10.2 ton ha^{-1} $year^{-1}$ (assuming a bulk density of 2.6 ton m^{-1}) and is projected to increase by 17% by 2090s. Soil erosion is aggravated by human activities on land through alteration of land cover which causes disturbance to soil structure (Bridges & Oldeman, 1999; Pimentel et al., 1995). It is estimated that 60% of the present soil erosions are induced by human activities especially land development (Yang et al., 2003). Of soil degradation types, erosion by water is the most common type causing about 55% of the global erosion, followed by wind (28%), nutrient decline (7%) and compaction (3%) (Bridges & Oldeman, 1999).

2.8.3 The spatial scales of soil erosion

Detached soil particles may be transported over considerable distances. The main offsite impact of soil erosion is the movement of sediment (eroded material) and nutrients into watercourses (Janeau, Maglinao, Lorent, Briquent, & Boonsaner, 2003; Smith & Wilcock, 2011). The eroded soil leads to an increase in sediment in rivers causing siltation of river channels. Sediment is transported by river water to reservoirs on the downstream, this leads to silting up of reservoirs and loss of useful storage space (Naden, 2010; Palmer et al., 2000). Sediment increase the turbidity levels in water thus increasing the cost of water treatment used for drinking. Additionally, adsorbed chemicals on sediments such as fertilizers, herbicides etc. have a significant effect on water quality (FAO, 2015). Sediments transported to hydroelectric power generation plants can damage turbines and mechanical equipment through abrasion which increases the maintenance costs and shorter life span of the machinery (Njogu & Kitheka, 2017).

Both structural and non-structural management practices are designed to reduce the adverse effects of agricultural activities on water quality. Structural soil conservation methods include parallel terraces, bunds, and benches among others. Non-structural include methods such as cover crops, conservation tillage and grassed waterways (Mohammad & Adam, 2010). Grassed or forested wetlands are also non-structural methods of conservation because they trap sediment from non-point sources such as agricultural fields (Zedler, 2003).

2.9 Role of wetlands in watershed management

Drainage or restoration of wetlands affects water levels on the downstream. Restored wetlands store water and attenuate or delay downstream flood peaks. Where the wetland does not have a direct connection to downstream surface connections, drainage increases the total contributing downstream area. Water balance in a wetland is another mechanism of regulating floods; restored wetlands have high evapotranspiration rates thus increase local losses particularly for large areas. This is possible ion dry areas where evapotranspiration is high (Potter, 2011).

Wetlands store water either in the short-term or in the long-term. In the case of short term storage, flood peaks are attenuated. In long-term storage, flood volumes are reduced. As the water is stored in both cases, the sediment and other pollutants transported with it settle thus wetlands trap sediment (Hey et al., 1994). When a wetland is drained, its capacity to store water is no lost except where they are filled. Instead, what changes is how flood waters interact with the storage capacity of the wetland, particularly the storage-outflow relationship for upland wetlands. A drained wetland has a steep portion on the storage-outflow relationship. This means that, for a given amount of water in storage, the outflow is much greater for a drained wetland than in a restored/ a wetland in its original status (Potter, 2011).

Riparian wetlands are wetlands adjacent to small streams in the uplands. They act as buffers between the rivers and farmland. The riparian wetlands have been shown to be very valuable in removal of non-point source pollution from agricultural fields. They have been shown to filter greater than 90% of sediment and nitrogen but their ability to remove phosphorus is limited (Gilliam, 1994). Three ecosystem services: water quality improvement, flood abatement and loss of biodiversity declined in the Upper Midwestern Region of the US when 60% of the region's wetlands were drained mostly for agriculture (Zedler, 2003).

2.10 Hydrologic modelling

2.10.1 Classification of hydrological models

Hydrologic models are a promising tool in the prediction of hydrological dynamics in a watershed (Smith & Wilcock, 2011). The required time series data includes local climate, land use/cover, slopes, stream channel properties and soil properties. Typically, these models are calibrated using stream flow data collected at a specific location within the watershed. Over the past, most of the models have been incorporated into Geographic Information Systems (GIS) (Putz et al., 2003).

Hydrologic simulation models can either be mechanistic or empirical. Mechanistic models also known as physically based models, describe a process using a set of scientific principles. If all the principles are known and described as mathematical equations that can be solved, then the model is an accurate representation of the physical system being simulated. However, most of these models simplify the physical system description and often include empirical components. Models that incorporate empirical components are termed as conceptual models. A model that does not consider the physical principles governing a system rather uses mathematical representation of the physical processes is termed as a wholly empirical model (Al-Mukhtar, Dunger, & Merkel, 2014; Ascough, Baffaut, Nearing, & Flanagan, 1995)

Hydrologic models can also be classified as lumped or distributed models depending on the manner in which they account for spatial variations of a watershed (Putz et al., 2003). Lumped models utilize average values of the watershed characteristics and input data. Because of non-linearity of parameters, lumping can result into significant errors in representation of hydrologic processes. In distributed models, a watershed is represented as a spatial grid of elements. Physical characteristics of the input data are assigned to each grid. Distributed models explicitly account for spatial variability of the physical characteristics of a watershed and in principle, perform better than lumped models (Nabi et al., 2017). However, fully distributed models require huge amounts of data. Interpolation of available data is usually done to assign values to each element. This however defeats the initial purpose of the distributed model (Jain, Tyagi, & Singh, 2010). As a result, there is gradation between lumped and distributed models. Hydrologic models are commonly semi-distributed; only represent the watershed as a number of sub-watersheds. A semi-distributed model can be formulated from a lumped model that is capable of subdividing the watershed into smaller sub-watersheds or from a model that utilizes groupings of averaged input data (Yang et al., 2003). The capabilities of lumped and distributed hydrologic models are presented and compared in Figure 2.3. The choice of the model however depends on the availability of data to calibrate it. A distributed model requires more empirical data than a lumped model.

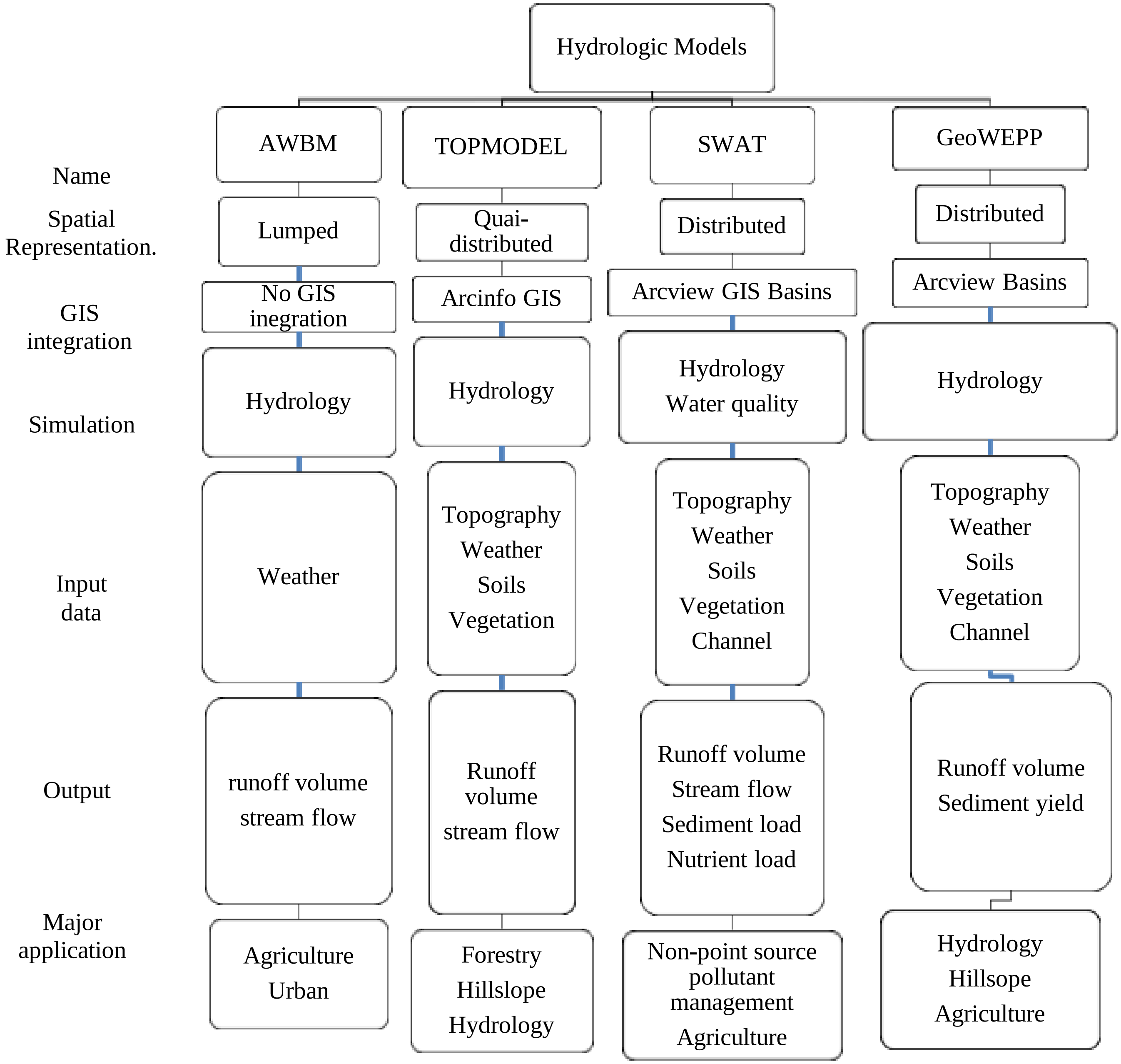


Figure 2.2: Summary of the features and applications of four hydrologic models (Putz et al., 2003).

2.10.2 Rainfall runoff modelling

Rainfall–runoff model describes the relationship between rainfall and runoff of a catchment area. The model estimates the surface runoff in the channel or river system as a response to rainfall input data for the target catchment (Ramly & Tahir, 2016). Precipitation and evapotranspiration are the key weather parameters that drive the hydrology of a watershed. The hydrological cycle is governed by a water balance equation describing how water flows into and out of a system for a specific period of time (Equations 2.7-2.9) (Senent-Aparicio, López-Ballesteros, Pérez-Sánchez, Segura-Méndez, & Pulido-Velazquez, 2018).

$$\frac{dS(t)}{dt} = P(t) - E(t) - Q(t) \tag{2.7}$$

$$\frac{dS}{dt} = R_t - E_t - Q_t \tag{2.8}$$

Where S is the bulk catchment storage, t is time, R_t is the rainfall input at time t, E is the actual evapotranspiration and Q is the discharge from the outlet.

$$Q_s = P - ET - \Delta SM - \Delta GW \pm \Delta S \tag{2.9}$$

Where Q_s is surface runoff, ΔSM is change in soil moisture, P is precipitation, ΔGW is change in groundwater storage, ET is evapotranspiration, and ΔS is change in surface storage.

A rainfall-runoff model is calibrated either manually or using generic equations within the model and stream flow data observed at an outlet (Boughton & Chiew, 2007). However, stream flow data is not always available. Catchments without runoff data are termed as ungauged catchments. In such catchments, runoff can be calculated using rainfall-runoff models with rainfall and other climate parameters as inputs. The main challenge in rainfall-runoff modelling is the lack of runoff data that can be used to calibrate the model parameters. However, model parameters can be transposed from similar gauged catchments (Ramkar & Yadav, 2015).

2.10.3 Hydrological similarity in Rainfall runoff modelling

Similar rainfall-runoff processes in two catchments result to similar hydrologic responses too. However, similarity of hydrological responses can be defined in a number of ways. Runoff processes in catchments are mainly controlled by physioclimatic controls. Wagener et al., (2004) identified three main types of such controls: infiltration excess generated from partial surface areas with low hydraulic conductivities, saturation excess generated from areas with shallow water tables or adjacent to wetlands; and subsurface storm flow most dominant and active on steep humid forested hillslopes and with permeable soils. Although these processes may not be known in fully, various similarity concepts have been proposed:

- Spatial proximity: catchments that are close to each other are assumed to behave in a similar manner hydrologically. The rainfall runoff relationships are likely to vary smoothly in space thus spatial proximity is a good indicator of catchment similarity. This is one of the traditional methods of regionalizing parameters of rainfall runoff model (Skøien & Blöschl, 2006).
- Similar catchment attributes: this concept consists of the measurable catchment attributes including vegetation type, soil type, and topographic characteristics. The assumption is if these attributes are similar, then the hydrologic response of the catchments would be similar (Bloschl, 2005).
- Similarity indices: these are dimensionless numbers that are based on the understanding of the structure of runoff generation and routing. Two catchments would behave the same way if the similarity indices are the same (Aryal,

O'Loughlin, & Mein, 2005). Two catchments are deemed similar if the indices are identical. Sivapalan et al., (1987) identified five non dimensional similarity parameters that represent the interrelationships of soil, topography and rainfall which lead to similar catchment responses.

However, there are several limitations and challenges to this method resulting to poor performance of the models. They include the measurable catchment attribute may not be very representative of the hydrologic functioning of the catchment. Additionally, there may be significant uncertainty in the calibrated parameters which cloud the underlying relationship between the model and catchment attributes. Lastly the model structure relating the catchment attributes and the model parameters may not be suitable. Some of the lumped hydrologic models used for rainfall runoff modeling are HEC-HMS and AWBM (Bloschl, 2005). Although lumped model can be used in rainfall runoff modeling, their use depends on the quality data available for calibration, method of calibration and the uniqueness of the catchments. While HEC-HMS is suitable for simulating large catchments as well as small catchment, AWBM is be suitable for small catchments since it uses only one weather station. However, AWBM was developed to model rainfall-runoff in ungauged catchments and it has been proved to work well with calibrated parameters from a donor catchment (Boughton & Chiew, 2007; Onyutha, 2016).

2.10.4 Description of the Australian Water Balance Model (AWBM)

The Australian Water Balance Model (AWBM) was developed by the cooperative research Centre for catchment hydrology (CRCCH) in Australia in the early 1990s. It is available in the public domain. It is a conceptual, lumped model that develops the relationship between rainfall and runoff in a catchment. The model takes daily time series rainfall, evapotranspiration and runoff data as input and give daily catchment runoff as output (Boughton, 2004). The model has eight parameters involved in its structure to aid in calibration (Figure 2.4). The runoff is simulated using 3 surface stores; A_1, A_2, and A_3 being the smallest, middle and largest respectively. C1, C2 and C3 are the capacities of A_1, A_2, and A_3 respectively. When it rains, rainfall is added to the 3 stores and evapotranspiration is subtracted simultaneously, if the evapotranspiration is greater than the moisture content, the value becomes negative and is set to zero, if it is greater, and then runoff is generated (Chouhan, Tiwari, & Galkate, 2016). When runoff occurs in any of the stores, part of it is used to recharge ground water, this fraction is known as the Base Flow Index (BFI). The remaining flow (Equation 2.10) becomes the surface runoff. The rate of recharge of the ground water is determined by the current moisture in the Base Flow Store (BS) and the base flow recession constant (K) (Equation 2.11). The surface store operates in a similar manner as the base flow store (Equation 2.12) (Boughton & Chiew, 2007).

$$\text{surface runoff} = (1 - \text{BFI}\,) \times \text{runoff} \qquad (2.10)$$

$$\mathbf{Baseflow\ rate} = (\mathbf{1} - \mathbf{K}) \times \boldsymbol{BS} \qquad (2.11)$$

$$\mathbf{Surface\ flow\ rate} = (\mathbf{1} - \mathbf{K}\boldsymbol{S})\boldsymbol{SS} \qquad (2.12)$$

Where KS is the surface runoff recession constant and SS is the current moisture in the surface runoff store.

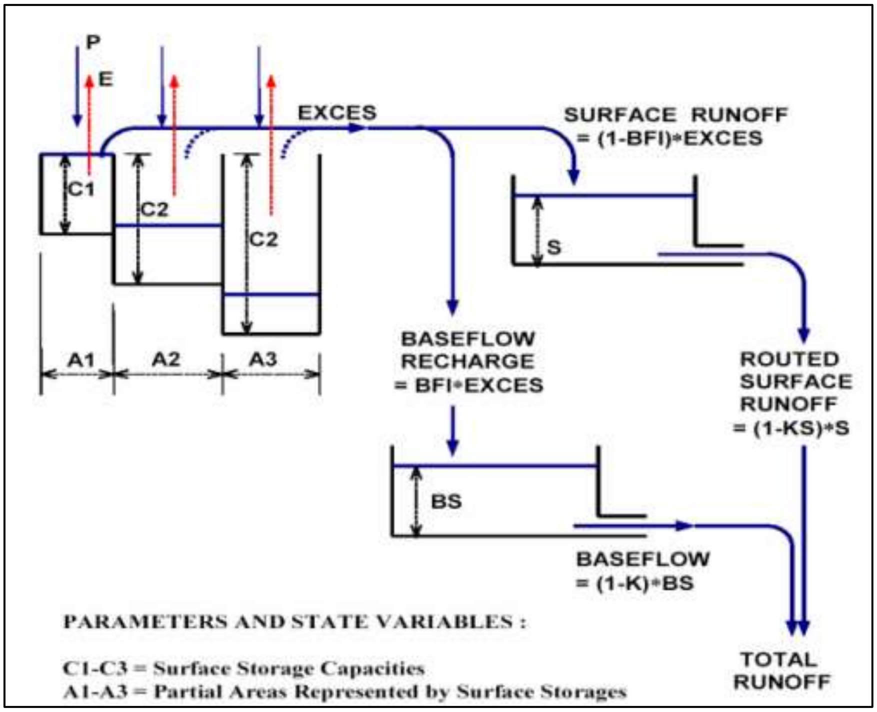


Figure 2.3: Structure of the AWBM (*Source:* Chouhan et al., 2016)

2.10.5 Modelling impacts of wetlands on stream flow and sediment yield

The values of the functions of wetlands are important to humans. However, their functions can easily be overwhelmed by heavy human development those lessening or even losing these values. The value of wetlands is partially dependent on where they occur in the landscapes. Wetlands appear to work best in landscapes as spatially distributed systems (Mitsch & Gossilink, 2000). Hydrological models incorporate hydrologic, hydraulics and statistic principles. The common method used in flood mitigation projects is design events. However, this method has limitations that make it unsuitable for evaluating benefits of wetlands. Wetland evaluation requires continuous hydrologic simulation, which takes in to account storm and inter-storm processes rather than a few events. Such models do exists and therefore it is possible to evaluate the benefits of wetlands like the Water and Erosion Prediction project (WEPP) and its geo-spatial interface GeoWEPP, Danish Hydrologic Institute model (DHI) and Hydrological Simulation Program Fortran (HSPF), Soil and Water Assessment Tool (Potter, 2011).

Modelling effects of wetlands at watershed level is important because it will show their potential benefits in improving water quality and attenuating flood peaks (Gilliam, 1994). Also, modelling wetlands can be used to decide how much of a watershed should be wetland. Mitsch et al., (2000) suggested that to achieve the full benefits of flood attenuation, sediment and nutrient yield control, 3% to 7% of watersheds in temperate zones should be wetlands. Obropta et al., (2008) used SWMM model to evaluate the effect of urban wetland hydrology for the restoration of a forested riparian wetland ecosystem in Teaneck Creek. They calculated the monthly average change in storage. They concluded that the wetlands gains water in the spring and fall rains and loses water in the summer in average precipitation years. This implies that wetlands store flood water therefore attenuate floods downstream.

However, DHI and HSPF are lumped models and thus do not include the spatial variation of wetlands thus not suitable for this study (Putz et al., 2003). The SWAT model is a continuous distributed parameter model that can be used to model the effects of changing land use within wetlands. However, it is most suitable for large catchments and requires a long-term data to calibrate and validate (Shawul, Alamirew, & Dinka, 2013). GeoWEPP performs better in small catchments and does not require long-term data to calibrate (Melaku et al., 2017).

2.11 GeoWEPP model

The Water and Erosion Prediction Project (WEPP) is a process-based, semi-distributed parameter continuous model founded on the fundamentals of soil erosion mechanisms, hydrology, open channel hydraulics and plant growth (Laflen et al., 1997). However, WEPP was not developed with a flexible Graphical User Interface (GUI) for spatial and temporal applications. Thus, geo-spatial interface for WEPP (GeoWEPP) was developed. The model was developed as a collaborative project by the Agriculture Research Service, Purdue University, and the USDA National Soil Erosion Research Laboratory. GeoWEPP integrates WEPP model and Topography Parameterization (TOPAZ) software within GIS. The model uses topographic parameterization tool software (TOPAZ) with the DEM for evaluation of topography, drainage identification, watershed segmentation and sub-catchment delineation (Renschler, 2003). The current version of GeoWEPP allows users to process digital data such as soil survey and land use maps, digital elevation models (DEM) and precise farm data (Renschler, 2003).

The processes considered in modelling include rill and interrill erosion, sediment transport and deposition, soil consolidation, infiltration and tillage effects on soil among others. The channel element represents flow in terraces channels, major flow concentrations where topography has caused surface flow to converge, graded rows, grass waterways and tail ditches. However, the WEPP model does not describe large stream channel or gully erosion (Ascough et al., 1995). The model accommodates spatial and temporal variability in topography, soil properties, land use conditions and hill slopes (Laflen et al., 1997).

Regarding soil erosion modelling, two processes are considered: interrill and rill erosion. Interrill is described as the process of soil detachment by a rain drop impact, transport by shallow sheet flow and delivery into rill channel. Rill erosion on the other hand is a function of the ability of flow to detach sediment, its transport capacity and the existing sediment load in the flow (Flanagan & Nearing, 1995). In a steady state of sediment continuity, Equation 2.13 describes the movement of sediment.

$$\frac{dG}{dX} = D_f + D_i \tag{2.13}$$

Where G is the sediment load (kg s^{-1} m^{-1}), X is the distance down slope (m), D_f is the rill erosion rate (kg s^{-1} m^{-1}) and D_i is the interrill erosion rate (kg s^{-1} m^{-1}).

In surface hydrology modelling, the sequences of calculations are infiltration, rainfall excess, depression storage and peak discharge. In filtration in GeoWEPP is calculated using the Green-Ampt Mein-Larson model for unsteady intermittent rainfall (Equation 2.14). Rainfall excess occurs when the rainfall rate is greater than the infiltration rate (Mays, 2005).

$$F(t) = Kt + \varphi\Delta\theta \ln\left(1 + \frac{F(t)}{\varphi\Delta\theta}\right) \tag{2.14}$$

Where F is the accumulated infiltration (mm), K is the hydraulic conductivity (mm/h), φ is the wetting front suction head and θ is the water content.

Yüksel et al., (2008) calibrated and validated GeoWEPP model for Orcan Creek watershed in Kahramanmaras region for sediment yield and runoff results and reported that the model provided good results. Reza Meghdadi, (2013) used GeoWEPP to determine the most prone areas to erosion and evaluate the best management practices for Kasilian watershed in Iran. They concluded the model was efficient for evaluation of effective management practices for watershed conservation.

2.12 Sensitivity Analysis of Hydrologic Models

Sensitivity analysis (SA) is the process of determining the rate of change in a model output with respect to changes in the model input (Pechlivanidis, Jackson, Mcintyre, & Wheater, 2011). Distributed parameter models involve many parameters. Dealing with such large number of parameters at the calibration stage is not feasible (Fadil, Rhinane, Kaoukaya, Kharchaf, & Bachir, 2011). Sensitivity analysis is therefore necessary to identify the key parameters and the required precision for calibration (Moriasi et al., 2007). SA methods can be categorized into four typical groups namely (Song et al., 2015): (i) mathematical, graphical and statistical methods (Frey & Patil, 2002), (ii) local and global methods (Saltelli & Annoni, 2010), (iii) screening and refined methods (Zhan, Song, Xia, & Tong, 2013), and (iv) qualitative and quantitative SA methods (Liu & Sun, 2010). These methods are summarized in Table 2.3.

Table 2.3: Summary of four typical categories of SA methods

S/No.	Methods	Description of the methods	Characteristics	Application cases
1	Mathematical	Estimate the local/ linear sensitivity of an output to individual parameters	Provides the uncertainty effects of parameters on an output but does not address variation in the output	Inputs for linear models, deterministic analysis and validation
	Statistical	Analyse the effect of various inputs	Estimates either quantitative or qualitative sensitivity indices with huge computational demands based on many model runs	Joint effects of multiple inputs, probabilistic analysis, verification
	Graphical	Complement mathematical or statistical methods	Graphical representation for better visual representation	Used for screening method before further analysis
2	Local	Calculates the response of a model output based on derivatives of the model output with respect to parameter values evaluated at a single location in the parameter space	Easy to calculate and interpret, local effect of individual parameters, no self-verification	Local sensitivity measures
	Global	Evaluate the influence in the entire range of uncertain parameters	Estimating the influence of all the inputs or their combined effect on the variation of the output based on several model runs	Main and joint effects of multiple inputs
3	Screening	Used to make preliminary identification of sensitive inputs	Ease of operation, relatively simple, not robust for some inputs,	Many input factors
	Refined	Adequately consider complex model characteristics, need great expertise and resources to implement	Provides quantitative results higher accuracy, relatively difficult to implement	Main and joint impacts of multiple inputs, require more data

2.13 Model Calibration and Validation

Model calibration is the process of selecting suitable parameters for the model such that the hydrological behaviour of the watershed be simulated closely (Pechlivanidis et al., 2011). This is important inorder to reduce the uncertainity associated with model prediction. Calibration and validation of the WEPP model ideally would contain detailed soil, topographic, climate and plant/management data for an experimental plot or watersheds (Flanagan, Frankenberger, & Ascough, 2012). WEPP has previously been applied successfully in previous studies without any calibration and given reliable results. WEPP model can be calibrated manually at a hillsope level using available data (Baffaut, Nearing, & Liu, 1995). For runoff and erosion studies, the effective hydraulic conductivity, rill and interill erosion, climatic parameters can be calibrated on WEPP model (Laflen et al., 1997).

2.14 Conceptual framework

The study involved identifying and mapping the temporal and spatial distribution of wetlands using Landsat images and DEM and modelling their impacts on runoff and sediment yield (Figure 2.1)

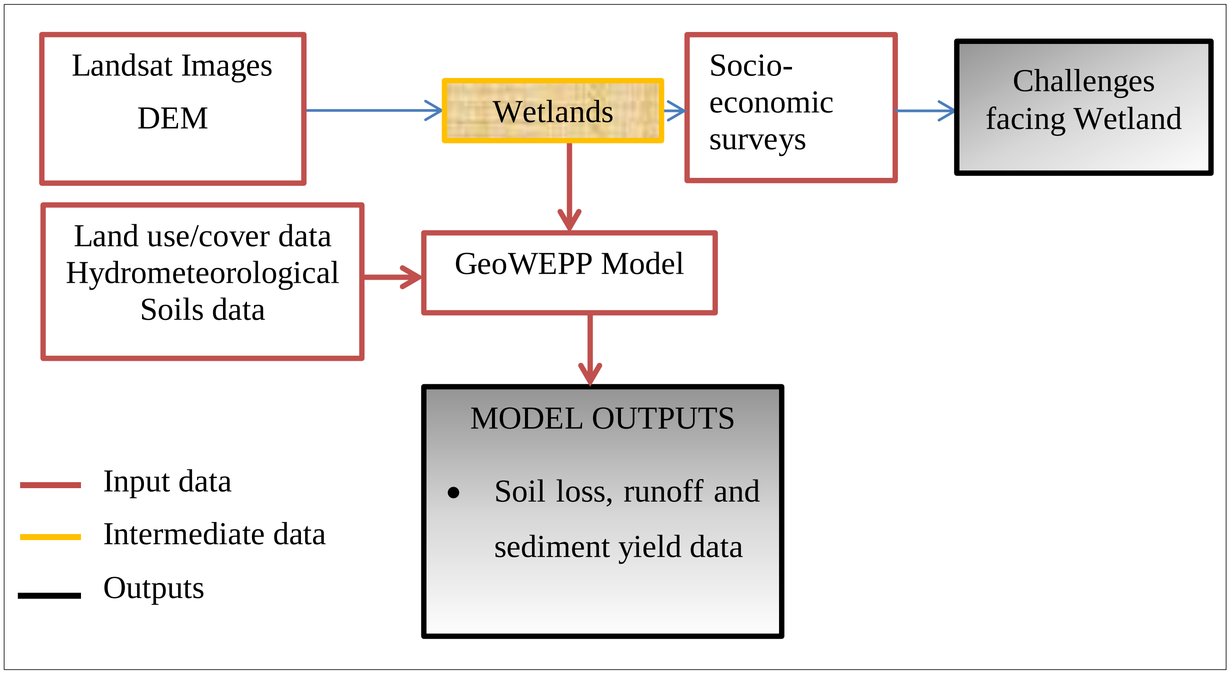


Figure 2.4: Logical framework followed during the study

2.15 Research gap

The status of wetlands and their influence on stream flow and sediment yield has been undertaken in some areas in the world but has not been done in Maragua watershed. From the literature review, factors influencing stream flow and sediment yield have been based on changes in land use/cover, climate change and rainfall variation. This however does not incorporate changes in wetland use and areal coverage. Therefore, to fill this gap, this research on determining the status of wetlands in Maragua watershed, Murang'a County, Kenya and their influence on stream flow and sediment yield was carried out.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview of Study Methodology

This study involved mapping wetlands in Maragua watershed, identifying the challenges facing their conservation and assessing their influence on stream flow and sediment yield. Wetlands were mapped using rule-based index classification. Analysis of the resident's perceptions about the value of wetlands and … Analysis of the challenges facing wetlands were evaluated with an aim of deriving the most concerning to the least concerning challenges. Interviews, stakeholder workshop, observations and focus group discussions were the methods used to collect the qualitative data. Finally, GeoWEPP hydrologic model was used to predict the influence of wetlands on stream flow and sediment yield in Githanja catchment of Maragua watershed.

3.2 Study area

3.2.1 Location

The study focuses on Maragua watershed of Murang'a County in Kenya (Figure 3.1). It covers an area of 420 Km^2 and extends from 0° 37' 12" to 0° 50' 0" S and 36° 42' 0" to 37° 9' 0"E. It originates from the Aberdare ranges and flows from the west towards the east. The watershed traverses Kigumo, Kiharu, Maragua, and Kahuro sub-counties in Murang'a County.

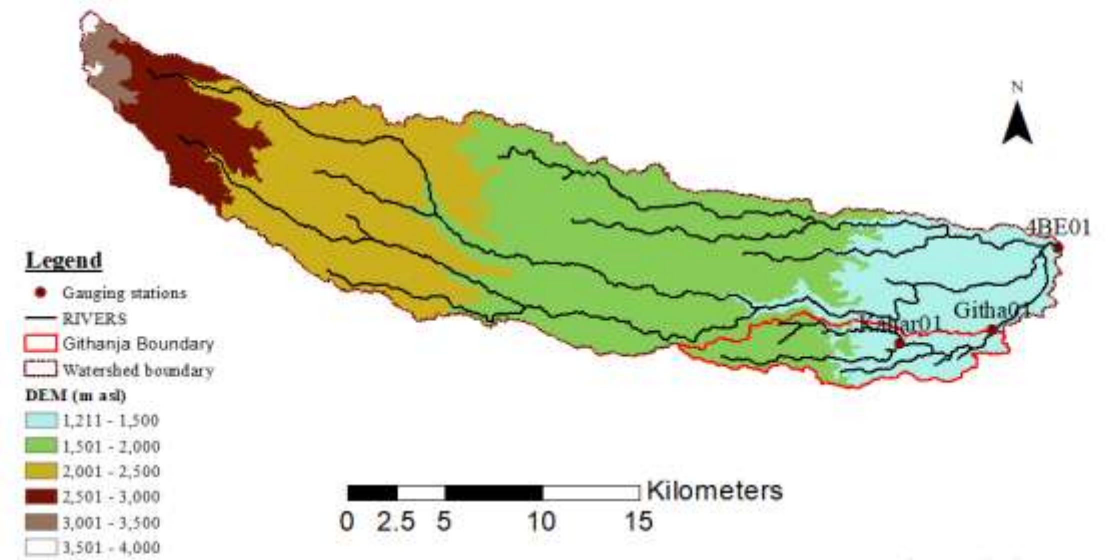


Figure 3.1: Digital elevation model and river gauging stations in Maragua watershed

3.2.2 Topography and drainage

The topography of Maragua watershed ranges from 1191m near the gauging station 4BE01 to 3769m on the slopes of Aberdare Mountains. The western highlands are deeply dissected and drain into various rivers. The river has its main tributaries as Kayahwe, Githanja, Gikigie and Irati rivers. The Maragua River drains its water to Tana River.

3.2.3 Climate

Maragua watershed receives bimodal rainfall, with long rains between March and June; and short rains between October and December. The average annual rainfall is 700mm-1300mm. Temperatures range from less than 10^{o}C in the uplands to 27^{o}C in the semi-humid zone.

3.2.4 Soils and Geology

The higher part of the watershed such as the slopes of the Aberdare ranges is dominated by volcanic ash soils (Andosols). Nitisols are mainly found in the middle and lower parts of the catchment with few patches of fluvisols, cambisols and vertisols (Table 3.1 and Figure 3.2). The surface geology of the watershed comprises of metamorphic rocks of the Mozambique belt (Wilschut, 2010).

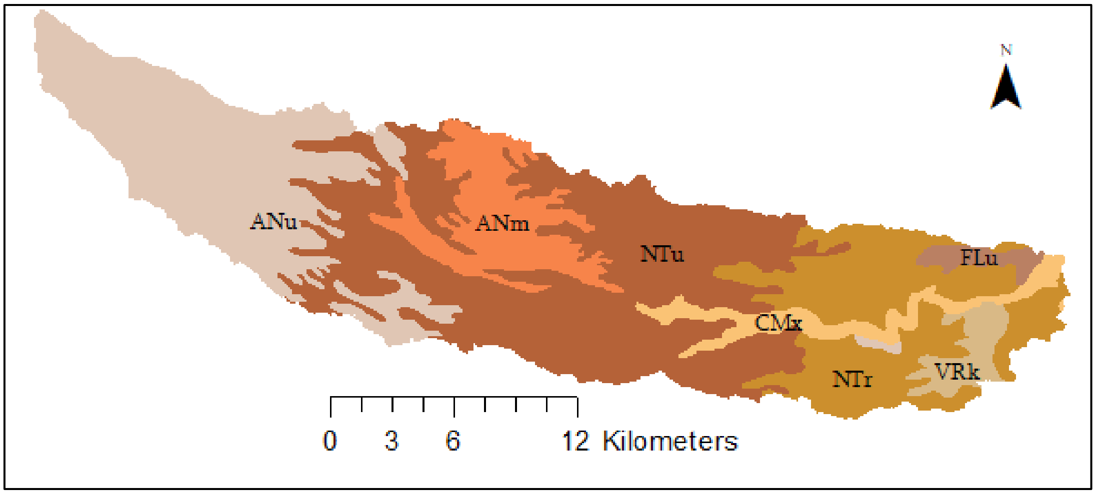


Figure 3.2: Soil map of Maragua watershed, Murang’a County (Batjes, 2011)

Table 3.1: Soil codes

Soil code	Soil name
VRk	Calcic Vertisols
ANu	Umbric Andosols
CMx	Chromic cambisols
NTu	Humic Nitisols
NTr	Rhodic Nitisols
ANm	Mollic Andosols
FLu	Umbric Fluvisols

3.3 Status and challenges facing wetlands in Maragua watershed

3.3.1 Reconnaissance survey

A reconnaissance survey was conducted to obtain geo-referencing data on a few wetlands in the watershed. The georeferencing data was used to calculate the accuracy of wetland identification

3.3.2 Wetland identification and mapping

Wetland status in the Maragua watershed of Murang'a County was studied using Landsat 5 (TM) for 1987, Landsat 7 (ETM+) for 1999 and Landsat 8 (Operational Land Imager OLI) for 2018 and a 30m resolution digital elevation model (DEM) (Table 3.2) downloaded from https://earthexplorer.usgs.gov/. The satellite images collected were path/row 168/060. Cloud free, radiometric and geometrically corrected dry season Landsat scenes were downloaded. Images used included those of February 1987, February 2018 and September 1999.

Table 3.2: Geospatial datasets used in the study

S/No	Data type	Date	Scale	Source
1	Landsat image (TM)	25/02/1987	30m	https://earthexplorer.usgs.gov/
2	Landsat (ETM+)	14/09/1999		
3	Landsat (Operational Land Imager OLI)	29/1/2018		
4	Digital elevation model		30m	SRTM

Wetland mapping in the watershed was performed using rule-based index classification. Three indices were used. They were the Normalized Vegetation Difference Index (NDVI), Normalized Difference Water Index (NDWI) and Topographic Wetness Index (TWI). The NDVI and NDWI were used to classify vegetation and water bodies while

TWI identified the tendency of water to accumulate at a place. The classification process entailed setting a threshold for each index estimated from the georeferencing data. The following thresholds were set: NDVI between -0.15 to 0.4; NDWI values -0.3 to 0.15; and 6 to 15 for TWI. The outputs of each index were added in a layer stack before the script was run for each individual year.

Three rules were generated using the indices. All rules in this study were structured by **IF and THEN syntax** and implemented on ERDAS Imagine decision tree module. The specific rules used to identify the wetlands are as follows:

NDVI >-0.15 and <0.3

ANDIF NDWI >0.15 and <-0.3

ANDIF TWI >6 and <15

THEN WETLAND

The decision tree uses a series of binary decisions rules on multispectral data. Each decision divides the pixels in two classes, (yes, no) based on an expression. Accuracy assessment was performed using 45 points.

3.3.3 Socioeconomic survey to establish the human perceptions and challenges facing wetlands

Interviews, observations, focus group discussion, storytelling events and a stakeholder workshop were used to establish the human perceptions and challenges facing wetlands within the watershed.

3.3.3.1 Interviews

The mapped wetlands in 2018 were divided into two categories depending on area. Category one consisted of wetlands greater than 1 ha and category two consisted of areas less than 1ha. 20 wetlands were found in category one and selected for the study. A total of 20 farmers bordering selected wetlands, who had been settled in the area for not less than 20 years, were interviewed. The farmers were asked questions to confirm (i) their awareness about the importance of wetlands; (ii) the changes in land use and land cover; and (iii) the ownership of wetland areas;

3.3.3.2 Stakeholder workshop

A stakeholder workshop with 42 participants, including key players in wetland conservation and management, was held to discuss the role of the different stakeholders and document the challenges facing wetland conservation in the study area. The stakeholders filled questionnaires outlining their roles in wetland management and conservation. Depending on their roles, the stakeholders were divided into four groups sitting around four tables. Each table had a facilitator who took notes and reported the key findings of the group in a plenary session. Seven categories of challenges were identified and using pairwise ranking (Mikhailov, 2003) the challenges were ranked from the one raising most concern to the least concerning.

3.3.3.3 Focus group discussions

A focus group discussion was conducted. It involved four members of the Maragua River Water Resources Users Association (WRUA). This group provided information relating to human activities within the wetlands and their impact on the wetlands. Additionally, they provided information on their views regarding the measures that could be put in place to protect these wetlands.

3.3.3.4 Story telling events

Story telling approach (STA) was used to collect data on wetlands within Gakoigo, Gikindu, Kagaa and Kaharati villages. Locals living within and around the wetlands were asked to tell stories about perceptions on the wetlands. STA captures information that would otherwise be left out in a formal guided interview survey. From the stories, vital information was synthesized and conclusions drawn.

3.3.3.5 Observations

In this study, field visits were conducted between February 2018 and April 2018 and direct observation was done to enlighten the researchers on the current land use, any conservation measures and general condition of the wetlands.

3.4 Influence of wetlands on stream flow and sediment yield in Githanja catchment

3.4.1 Description of Githanja catchment

The catchment lies in the lower catchment of Maragua watershed and covers an area of 36.7Km^2 (Figure 3.3). It slopes towards the east and the main land use is small-scale food crop and coffee farming.

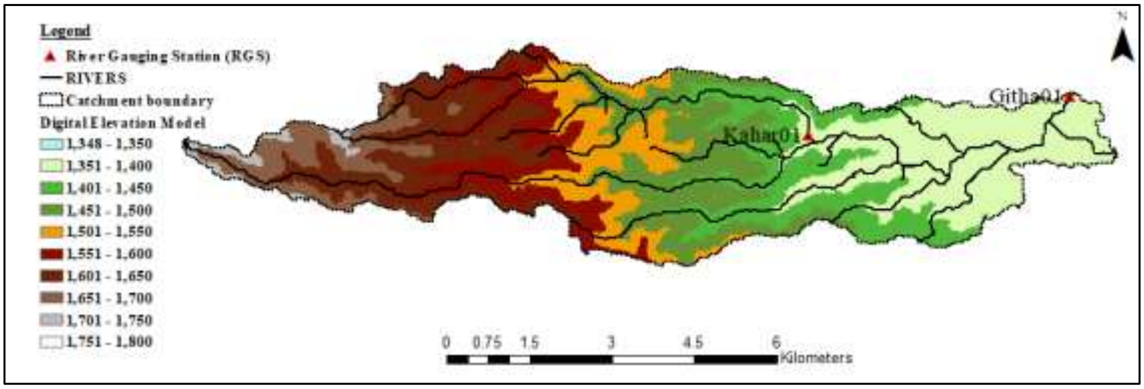
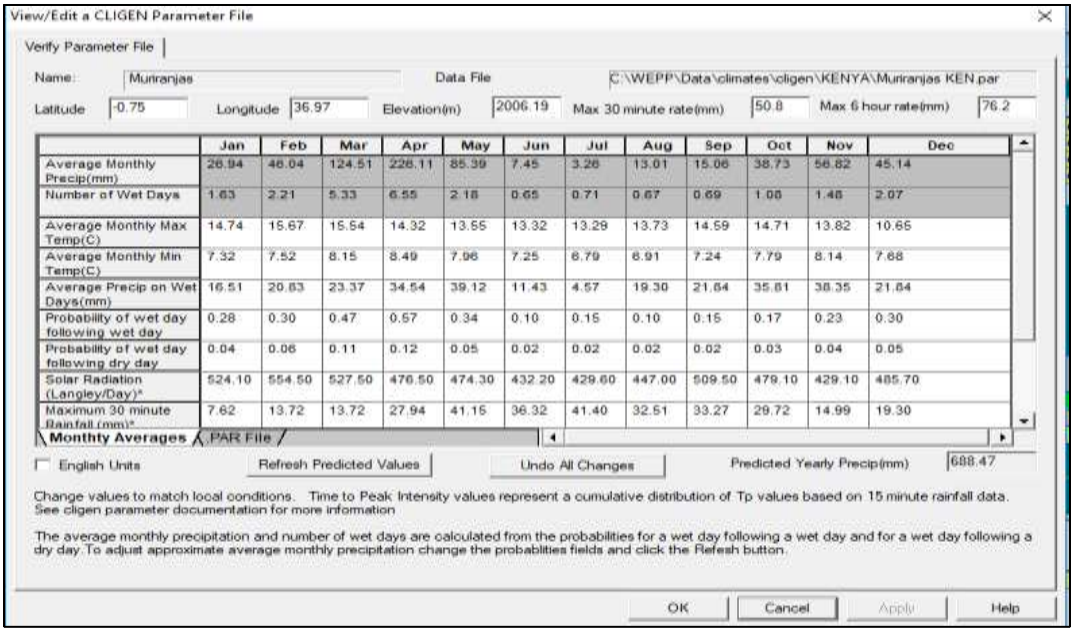


Figure 3.3: Digital elevation model and river gauging stations in Githanja catchment

3.4.2 Meteorological data

The rainfall data input for the GeoWEPP model was that of one station with daily data available from 1981 to 2018. It was obtained from the Kenya Meteorological Department (KMD) for the Murang’a water supply station (latitude -0.733 and longitude 37.150). Temperature, solar radiation, dew temperature, relative humidity and wind speed were obtained from the National Aeronautics and Space Administration (NASA) (latitude -0.733 &longitude 37.150). Instat software was used to calculate long-term monthly climate parameters required to generate climate parameter data in GeoWEPP

(Plate 3.1) using observed data from 1981 to 2017 and NASA Power data. The required parameters include average monthly maximum and minimum temperature, average precipitation on wet days, probability of wet day following wet day, probability of wet day following dry day, solar radiation and dew point. Murang'a water supply station was then added to the climates database in GeoWEPP on the WEPP CLIGEN parameter file interface.



Name: Murranjas
Data File: C:\WEPP\Data\climates\cligen\KENYA\Murranjas KEN.par
Latitude: -0.75
Longitude: 36.97
Elevation(m): 2006.19
Max 30 minute rate(mm): 50.8
Max 6 hour rate(mm): 76.2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Monthly Precip(mm)	26.94	46.04	124.51	226.11	85.39	7.45	3.26	13.01	15.06	38.73	56.82	45.14
Number of Wet Days	1.63	2.21	5.33	6.55	2.18	0.65	0.71	0.67	0.69	1.08	1.48	2.07
Average Monthly Max Temp(C)	14.74	15.67	15.54	14.32	13.55	13.32	13.29	13.73	14.59	14.71	13.82	10.65
Average Monthly Min Temp(C)	7.32	7.52	8.15	8.49	7.96	7.25	6.79	6.91	7.24	7.79	8.14	7.68
Average Precip on Wet Days(mm)	16.51	20.83	23.37	34.54	39.12	11.43	4.57	19.30	21.64	35.81	38.35	21.84
Probability of wet day following wet day	0.28	0.30	0.47	0.57	0.34	0.10	0.15	0.10	0.15	0.17	0.23	0.30
Probability of wet day following dry day	0.04	0.06	0.11	0.12	0.05	0.02	0.02	0.02	0.02	0.03	0.04	0.05
Solar Radiation (Langley/Day)*	524.10	554.50	527.50	476.50	474.30	432.20	429.60	447.00	509.50	479.10	429.10	485.70
Maximum 30 minute Rainfall (mm)*	7.62	13.72	13.72	27.94	41.15	36.32	41.40	32.51	33.27	29.72	14.99	19.30

Predicted Yearly Precip(mm): 688.47

Change values to match local conditions. Time to Peak Intensity values represent a cumulative distribution of Tp values based on 15 minute rainfall data. See cligen parameter documentation for more information

The average monthly precipitation and number of wet days are calculated from the probabilities for a wet day following a wet day and for a wet day following a dry day. To adjust approximate average monthly precipitation change the probablities fields and click the Refesh button.

Plate 3.1: WEPP climate: parameter file window

3.4.3 Soils data

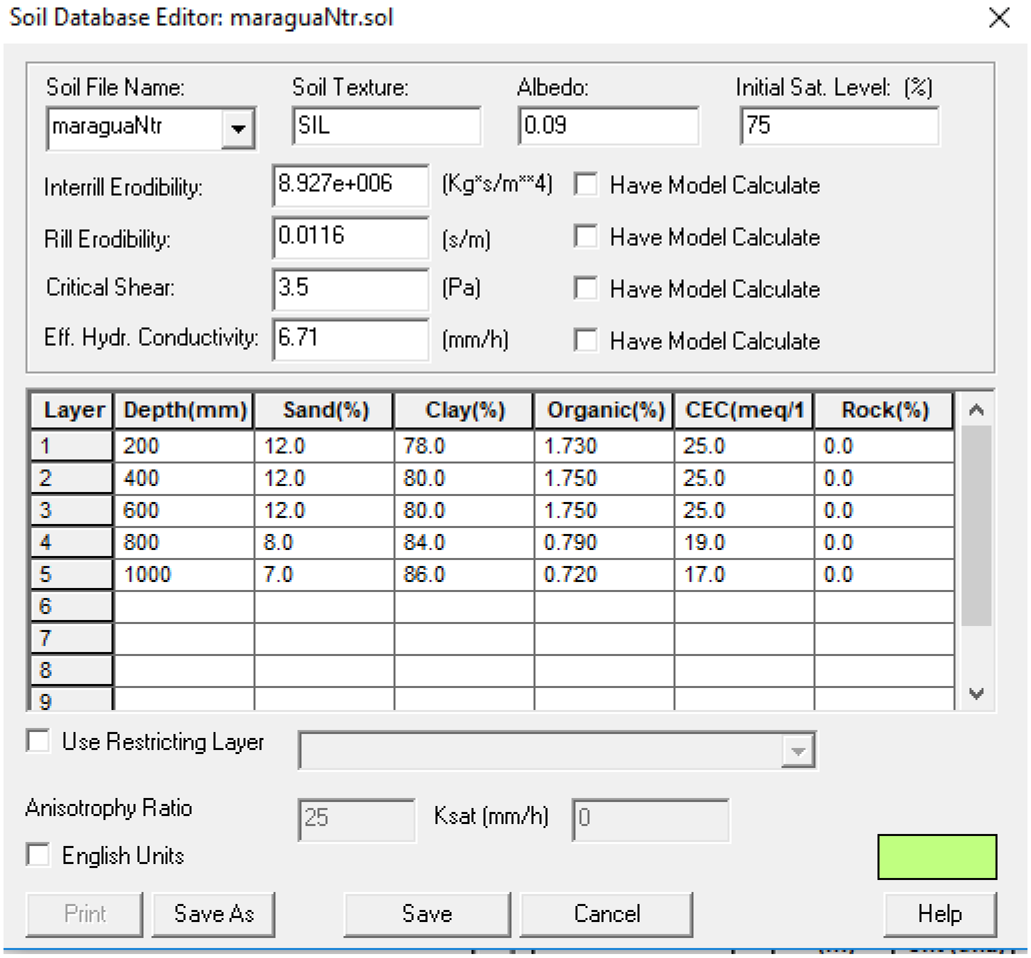
Soils data was obtained from the Kenya Soil and Terrain (KENSOTER) database (Batjes, 2011) at a scale of 1:1,000,000. The database contains soil hydraulic properties required to predict runoff, soil loss and sediment yield in GeoWEPP. These properties include total organic carbon, cation exchange capacity (CEC) and texture at intervals of 20cm to a depth of one meter. The soil's hydraulic conductivity was obtained from

SPAW hydrology software (Saxton & Rawls, 2006). The percentage organic matter of the soil was calculated from the total carbon using Equation 3.1. Soil albedo was also calculated using the Baumer Equation (3.2) (Al-Mukhtar et al., 2014).

$$\%\ \text{organic matter} = \%\ \text{total organic carbon} \times 1.72 \qquad (3.1)$$

$$\text{soil albedo} = \frac{0.6}{e^{0.4*\text{organic matter}}} \qquad (3.2)$$

Soil parameters for the study area were created on the WEPP Soil database editor window on WEPP interfaces (Plate 3.2). Two text files: soilsmap.txt and soilsdb.txt were created in order to link the GIS data to WEPP.


Soil Database Editor: maraguaNtr.sol

Soil File Name: maraguaNtr

Soil Texture: SIL

Albedo: 0.09

Initial Sat. Level: (%) 75

Interrill Erodibility: 8.927e+006 (Kg*s/m**4) ☐ Have Model Calculate

Rill Erodibility: 0.0116 (s/m) ☐ Have Model Calculate

Critical Shear: 3.5 (Pa) ☐ Have Model Calculate

Eff. Hydr. Conductivity: 6.71 (mm/h) ☐ Have Model Calculate

Layer	Depth(mm)	Sand(%)	Clay(%)	Organic(%)	CEC(meq/1	Rock(%)
1	200	12.0	78.0	1.730	25.0	0.0
2	400	12.0	80.0	1.750	25.0	0.0
3	600	12.0	80.0	1.750	25.0	0.0
4	800	8.0	84.0	0.790	19.0	0.0
5	1000	7.0	86.0	0.720	17.0	0.0
6						
7						
8						
9						

☐ Use Restricting Layer

Anisotrophy Ratio 25

Ksat (mm/h) 0

☐ English Units

Plate 3.2: WEPP Soil database editor window for the new soil parameters.

3.4.4 Land use/ land cover data

Supervised classification was used to generate a land use/cover map for 2018 using Landsat image for 29th, January 2018. Seven land use/ land cover classes were produced namely: forests, grass and shrub land, cropland, tea, wetlands, built-up and bare land (Wilschut, 2010). The generated land use/cover map was mosaicked with wetland maps identified using rule-based index classification for 2018 and 1987 wetlands. Land use parameters were adjusted to the local situation in the WEPP interface. The area under croplands was assumed to be under corn and beans. Planting season for the long rains on croplands was set to begin in mid-march, first tilling was done in the second week of April, second tilling at the end of April and harvesting in August. For the short rains planting was set to begin on the second week of October, first and second tilling in early and late November respectively while harvesting took place in February. For forest land, shrub land, built-up and bare land, was picked as the default provisions in the GeoWEPP model.

3.4.5 Hydrologic data

Water levels and total suspended sediment (TSS) data for Karurumo and Githanja at the Kahar01 and Githa01 gauging stations were acquired from Water Resource Authority (WRA). Water levels data was available from August 2014 to January 2018 for Karurumo and August 2014 to February 2015 for Githanja. A stage-flow rating curve for Kahar01 was used to compute discharge data from the water levels. TSS data for Githanja was available for two seasons: April 2016 and April 2018. The mean rainfall and mean runoff for Karurumo catchment were compared to obtain a rainfall-runoff relationship. Karurumo and Githanja catchment attributes were compared (Table 3.3) and found to be similar as suggested by Bloschl, (2005) hence Karurumo was used as the donor catchment for Githanja catchment. Rainfall runoff simulation was carried out using the Rainfall Runoff Library (RRL) Australian water balance model (AWBM).

Table 3.3: Hydrologic attributes of Karurumo and Githanja catchments

	Karurumo	Githanja
Catchment area (km^2)	10.5	40.7
Mean topographic elevation (m)	1496	1486
Mean topographic slope (%)	18.6	15.1
Dominant soil texture of the top 20cm	Silt-loam	Silt-loam
Forest (%)	29.9	23.6
Cropland (%)	37.8	36.9
Wetlands (%)	3.3	9.5
Grass and shrub land (%)	27.4	26
Build up area (%)	0.8	1.2
Bare land (%)	1.6	2.8

3.4.6 Generation of stream flow and sediment data

The AWBM model was calibrated with flow data from Karurumo RGS for the period 14/07/2014 to 30/1/2018. The warm up period was six months (14/7/2013 to 15/1/2015). The model has eight parameters which were calibrated manually until the flow duration curve of the observed and simulated runoff matched. Visual assessment was used to judge the goodness of fit between the two flow duration curves. After calibrating the model, flow for Githanja catchment was simulated keeping the rainfall, evapotranspiration and model parameters constant and changing the area of the catchment**.** Daily stream flow data for the Githanja catchment outlet was generated using the AWBM rainfall runoff library. This was converted to average monthly stream flow.

A sediment rating curve was developed using the power function and a correction factor applied as suggested by Asselman, (2000) (Equation 3.3 and 3.4). TSS was calculated from the AWBM flow outputs. Also, total suspended sediments were converted to average monthly sediment yield in tons.

$$\mathrm{TSS} = \mathrm{a}\mathrm{Q}^{\mathrm{b}} \times \mathrm{CF} \tag{3.3}$$

Where TSS is the sediment concentration (mg/l) at a discharge Q, a and b are regression coefficients and CF is a correction factor (equation 2.4).

$$\mathrm{CF} = \exp(2.651S^2) \tag{3.4}$$

Where S^2 = mean square error of the log-transformed regression.

3.4.7 Digital Elevation Model (DEM)

A 30m resolution DEM downloaded from the USGS website was used and clipped for the study area (https://earthexplorer.usgs.gov).

3.4.8 GeoWEPP data pre-processing

The required data is a DEM, Land use/cover, soil maps in ASCII format and text files. The DEM, land use and soil map as were converted to ASCII format as required in GeoWEPP. The text files bridge soil and land use datasets in GIS to WEPP parameter files. The text files describing each raster values corresponding to the soil type and land use layers were created from the attribute table of each layer. The soil and land cover text files corresponding GeoWEPP soil and land use database were created through the file builder within the WEPP interface. A text file containing actual observed rainfall, maximum and minimum temperature data station was prepared. Murang’a water supply station was then added to the climates database in GeoWEPP on the WEPP interface. Simulations were done using Murang’a water supply station.

3.4.9 GeoWEPP simulation scenarios

The DEM, land use and soil maps were used to initiate the GeoWEPP model. A critical source area (CSA) of 5 ha and minimum source channel length (MSCL) of 100m were used to control the sub-catchment area. Githanja catchment was sub-divided into 474 hillslopes and 201 channels. To determine the influence of wetland cover and area on stream flow and sediment yield, simulations were run on three scenarios. Scenario one (CULT9.5%): wetland cover in Githanja catchment for 2018 which was equivalent to 9.5% of the entire area. Wetlands were modeled under cultivation of crops; scenario two (GRASS9.5%): wetland cover in Githanja for catchment for 2018 which was equivalent to 9.5%. wetlands were modeled under tall grass without tillage and scenario three (GRASS16.6%): wetland cover for Githanja in 1987 which was equivalent to 16.6% of the entire area. Wetlands were modeled under tall grass with no tillage (Table 3.4). WEPP simulation parameters were set in the WEPP/TOPAZ Translator window and 5-year simulations using both the Watershed and Flow-paths method run.

Table 3.4: Scenarios of wetland change in land use investigated

Scenario	Scenario Code	Change represented
Scenario 1	CULT9.5%	2018 wetland coverage in Githanja catchment which was 9.5% of the entire area was modeled under cultivation of crops.
Scenario 2	GRASS9.5%	2018 wetland coverage in Githanja catchment which was 9.5% of the entire area was modeled under tall grass with no tillage.
Scenario 3	GRASS16.6%	1987 wetland coverage in Githanja catchment which was 16.6% of the entire area was modeled under tall grass with no tillage.

3.4.10 GeoWEPP model sensitivity analysis

The evaluation of a hydrological model is needed to provide a quantitative estimate of the model's ability to reproduce a historic or future watershed behavior (Krause, Boyle, & Bäse, 2005). In this study, input parameters were calculated as recommended in the WEPP documentation (Lane et al., 1989). Then one at a time sensitivity analysis of the soil parameters was performed on the interill erodibility, rill erodibility, critical shear stress, effective hydraulic conductivity to identify the most critical and sensitive parameters using Equation 3.5 (McCuen, 1973).

$$S = \frac{\lfloor (O_2 - O_1)/\bar{O} \rfloor}{\lfloor (I_2 - I_1)/\bar{I} \rfloor} \qquad (3.5)$$

Where S is the sensitivity ratio, I_1 and I_2 are the minimum and maximum values of the input parameters, $\bar{I}$ is the average of I_1 and I_2 . O_1 and O_2 are the minimum and maximum values of the output from input parameters, and $\bar{O}$ is the average of the two outputs. The input parameters were taken as -20% and +20% of the initial calculated values.

3.4.11 GeoWEPP model calibration and validation

Five years runoff and sediment yield data (2013-2017) measured at the catchment outlet was used to calibrate and validate the monthly results of the GeoWEPP model. The period 2013-2015 was used for calibration and 2016-2017 was used for validation. The Nash-Sutcliffe efficiency (NSE) (Equation 3.6) and the coefficient of determination (R^2) (Equation 3.7) were used to compare the observed and simulated values. R^2 ranges between 0 and 1 with greater values indicating a better agreement. Nash-Sutcliffe efficiency E lies between 1 and −∞, with 1 indicating perfect fit and NSE>0.5 considered satisfactory (Krause et al., 2005; Moriasi et al., 2007).

$$\boldsymbol{NSE} = \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3.6}$$

$$\boldsymbol{R^2} = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \tag{3.7}$$

Where O is observed and P is predicted modeled values.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter consists of two subsections that present the results and discussions of the study. The first subsection focuses on the status and challenges facing wetlands in Maragua watershed. The second subsection consists of the influence of wetland on stream flow using the GeoWEPP model.

4.2 Status of Wetlands in Maragua Watershed, Murang'a County, Kenya

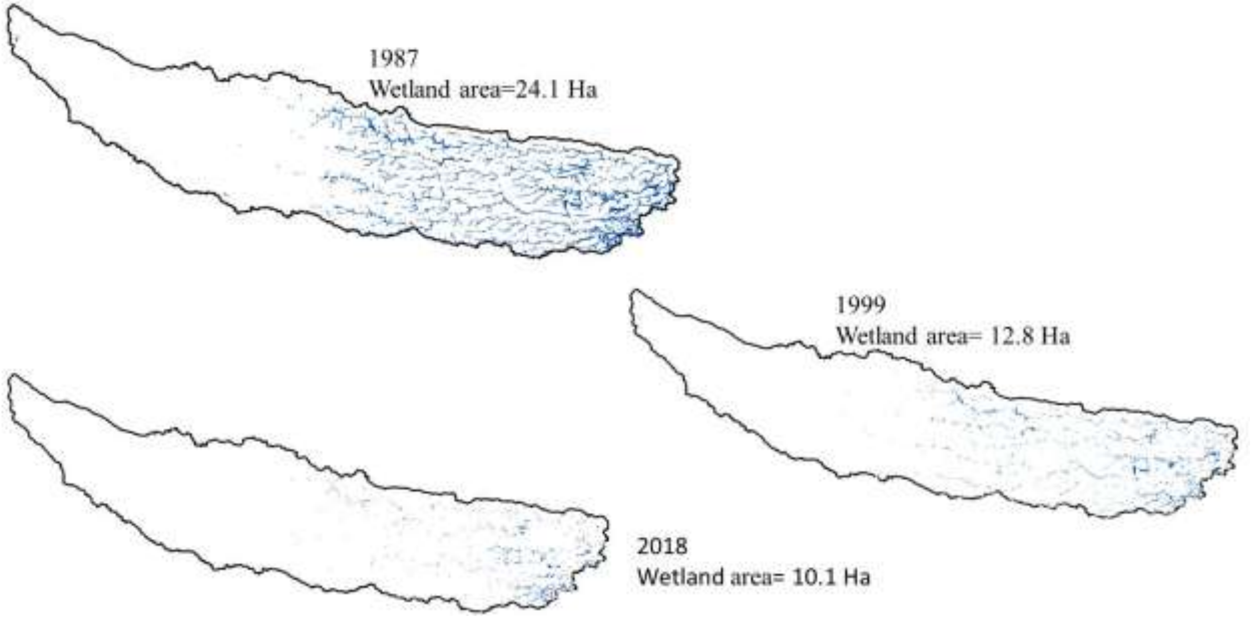
4.2.1 Spatial and temporal variation of wetlands in Maragua watershed

In 1987 the area under wetlands was 24.1 ha; in 1999 the wetland area was 12.8 ha while in 2018, wetlands covered only 10.1 ha. The area covered by wetlands in 2018 was less than 50% of the area covered by wetlands 30 years before (Figure 4.1). The overall accuracy of mapping wetlands was 75%. Some 90% of wetlands in Maragua watershed were located in the middle and lower sections of the watershed.

The wetlands identified in the watershed were generally narrow inland valleys. Using the hydrogeomorphic wetland classification (Brinson, 1993), the wetlands were classified as riverine wetlands or depressional wetlands. Riverine wetlands however dominate the available wetlands in the Watershed. Furthermore, land units less than 500 hectares that are characterized by permanent or seasonal flooding or by moisture availability in the soil higher than that of surrounding uplands are classified as small wetlands (Harper &

Mavuti, 1996). In this study, the wetlands identified were less than 10 hectares and thus classified as small wetlands.

The results of this study agree with those of a Ugandan study (Norbert Henninger & Florence Landsberg, 2009) which established that most riparian wetlands were located at valley bottoms or along streams. In Swaziland, small swamps and flood plains were found to occur along rivers and streams in the Middleveld and Lowveld regions. Although small in size, the wetlands provided important water supply, grazing resources, raw materials for cultural ceremonies and handicrafts and are utilized in dry seasons as farmlands (Masarirambi et al., 2010).



Year	Wetland cover (Ha)	Percent wetland cover	Wetland disappearance (Ha/year)
1987	24.1	0.05	
1999	12.8	0.03	0.94
2018	10.1	0.02	0.30

Figure 4.1: Spatial Variation of Maragua Watershed Wetland Area for Years 1987, 1999, and 2018

4.2.2 Land use within the wetlands in 1987 and 2018

Land use within the wetlands in the study area was assessed for the periods 1987 and 2018. Based on observations made during field visits and information gathered from interviews, storytelling and focus group discussions, about 20% of the wetlands had exotic trees, mainly the eucalyptus species. Based on observations made in 20 wetlands, about 5% of the wetlands were under natural grass in 2018, while 20% were predominantly under exotic trees (Figure 4.2). According to the residents interviewed during the study, in 1987 35% of the wetlands were dominantly under natural grass and there were no exotic trees in the wetlands. Furthermore, while in 1987 only 20% of the wetlands were cultivated, in 2018 some 45% of the wetlands were under cultivation. In 2018 there were buildings in some 5% of the wetlands (Figure 4.2).

A study in central Kenya (Sakané et al., 2011) analyzed the changes in land use and noted that increasing human population had resulted in expansion of agriculture into previously uncultivated land in Central Kenya. Based on the findings of this study, farmers grow vegetables, arrow roots, flowers, maize and beans in wetlands. The farmers confessed that they used open ditches to drain the wetlands. Indigenous trees were cleared to create room for human activities within the wetlands.

During interviews respondents provided information that since 1987, human settlement within wetlands has increased. This has been accompanied by increased number of exotic trees and grass which are perceived to be more valuable. Introduction of invasive alien species to wetlands alters their biodiversity and makes them more vulnerable (Mwita et al., 2012).

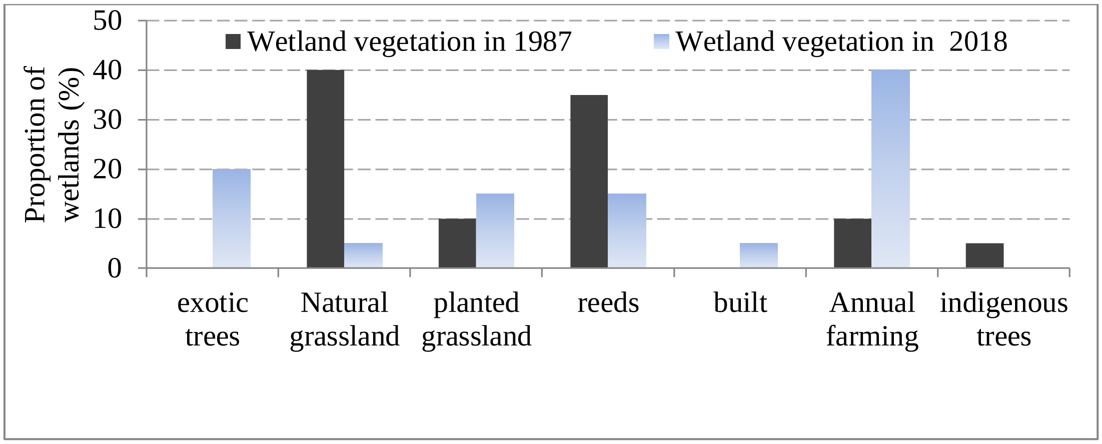


Figure 4.2: Comparison of land use within the wetlands for the periods up to 1987 and 2018

4.2.3 Perceptions about the Value of Wetlands

During the interviews respondents were questioned about what they thought was the value of wetlands. Some 50% of the respondents said wetlands were a source of livelihoods, while 35% viewed wetlands as sources of water for irrigation and domestic use. Only 15% attached aesthetic value to wetlands (Figure 4.3). Of all those interviewed, 40% were unaware of the hydrologic value of wetlands. About 45% had a little knowledge and only 15% were aware of the hydrologic benefits of wetlands (Figure 4.4). During the study, it was also noted that little effort is made to promote awareness about the importance of these wetlands, thus their continued exploitation.

A study in Chingombe community in Zimbabwe (Hardlife, David, Godfrey, Somandla, & Proud, 2014), found that the residents of Chingombe attached some value to the ability of wetlands to sustain their livelihoods, provide water and improve the aesthetics of their environment. The residents of Maragua watershed had similar views.

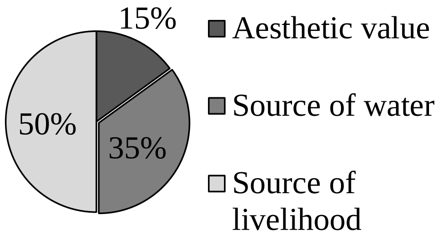


Figure 4.3: Community perception about the value of wetlands

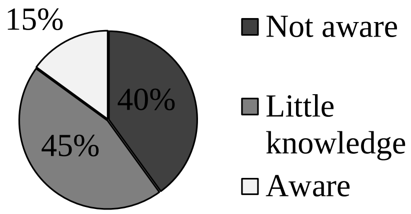


Figure 4.4: Awareness about the hydrologic value of wetlands

Although residents viewed wetlands as assets, they were not aware of the adverse effects of their activities on the wetlands. This was attributed to a breakdown of communication between the stakeholders, particularly natural resource managers, policy makers, local communities and law enforcers on one side and researchers on the other side. A population that only sees wetland as potential farming areas will not care to conserve them. This contributes to loss of wetland area. There is therefore need to conduct public awareness campaigns on the potential benefits of conserved wetlands in order to promote sustainable use of wetlands in Maragua watershed.

4.2.4 Wetland management in Maragua watershed

There were 42 participants in the stakeholder workshop. One represented the national government (administration); 17 represented the national government ministries (water, agriculture and environment); 9 represented academia; 9 were from the County government; and 3 were from the mainstream media (Figure 4.5 and Table 4.1). The stakeholders were put into five categories namely: policy developers; policy implementers; financiers, wetland users and researchers based on their roles.

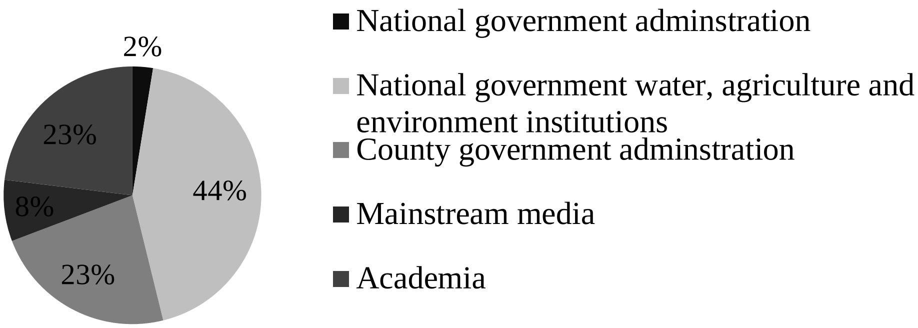


Figure 4.5: Proportion of participants from each sector

Table 4.1: List of institutions and departments represented in the stakeholder workshop

Institution	Departments	No. of attendees
National government administration	County commissioner	1
National government water, agriculture and environment institutions	▪ Fisheries department	2
	▪ Kenya Meteorological Department (KMD)	1
	▪ National Environment Management Authority (NEMA)	1
	▪ Upper Tana Resources	1
	▪ Water and sanitation companies	4
	▪ Water Resources Users Association (WRUA)	11
	▪ Water Resource Authority (WRA)	1
County government administration	▪ County Environmental Committee (CEC)	4
	▪ County climate change committee	3
	▪ Member of county assembly (MCA)	1
Mainstream media		3
Academia		9

i. Policy developers

The County Environmental Committee and the County Environmental & Climate Change Department were involved in policy development. Their responsibilities included making laws and policies regarding conservation of wetlands, and ensuring budgetary allocation for the water department. They are also expected to conduct regular inspections to ensure laws on conservation of wetlands are enforced. The Kenya Meteorological Department provides the data that is analyzed to inform policy formulation.

ii. Policy implementers

Policy implementers include the Water Resources Authority (WRA); the office of County Commissioner and Water Resource Users Associations (WRUAs) (Table 4.2). Their roles included implementing and enforcing the set policies.

Table 4.2: Roles of policy implementers in wetland management and conservation

Stakeholder	**Roles**
Water Resource Authority (WRA)	• Formation of WRUAs • Water quality and quantity monitoring • Protection of wetlands from encroachment
The County Commissioner	• Awareness creation • Enforcement of laws and regulations • Coordination of different players
Water Resource Users Association (WRUAs)	• Marking, demarcating and fencing wetlands • Discourage community encroachment into wetlands • Identification and rehabilitation of encroached wetlands

iii. Financiers

Under this category of stakeholders, Upper Tana Natural Resource Management Project (UTaNRMP) was identified. The financier funded the activities of WRUAs and had the task of building the capacity of different players for water resources protection.

iv. Wetland users

These are stakeholders who carry out human activities within wetlands. In addition to the general citizenry, this category also includes the Water and sanitation companies, the County Irrigation Department and the Fisheries Department which has constructed some fish ponds within the wetlands. The roles of wetland users included ensuring sustainable use of wetlands and creating public awareness on the sustainable use of wetlands.

The majority of wetlands in the study area were on private land. This study found that the owners were not adequately empowered to protect existing wetlands. There is need to develop a strategy for capacity building among identified stakeholders.

v. Researchers

Academic researchers carry out studies on wetlands in order to inform policy makers on sustainable use of wetlands.

4.2.5 Challenges facing wetlands

The challenges facing wetland conservation in Maragua were identified and ranked. The challenges identified were grouped into seven categories namely: encroachment, pollution, and conflict in legislation; lack of community empowerment, limited resources, bad governance and inadequate planning. Supplemental information is provided in an attribute table in (Table 4.3). A pairwise ranking matrix was drawn (Table 4.4) and the challenges ranked. The frequency of each challenge was determined (Table 4.5). Shortcomings in legislation, planning, and community empowerment policy implementation were identified as top three factors affecting wetland conservation. Other challenges were identified as bad governance, limited resources, encroachment and pollution.

Conflict in legislation was identified as the key challenge facing wetland conservation. Stakeholders highlighted the conflicting aspects of the land ownership policies in the Land Act No. 6 of 2012 (PART V-Administration and Management of Private Land) and WRA regulations on wetlands. Physical boundaries such as rivers are used in cadastral survey as demarcations between land portions. In such cases, the riparian wetlands are allocated to private owners (Government of Kenya, 2012). From the visited wetlands, 95% of the wetlands were on private land whereas only 5% were on public land. Most of the land in Kenya, including riverine wetlands, is privately owned. A recent study found that one of the major impediments to conservation of swamps in Kikuyu Sub-County of Kiambu County was the fact that the land was privately owned (Macharia et al., 2010). Wetlands allocated to private land owners during land demarcation are difficult to conserve since the rights to use of the land is vested on the owner.

The Environmental Management and Co-ordination Act (EMCA) cap 387, 2017 amendments provides regulations for the conservation and management of wetlands. Section 12 prohibits human activities within the wetlands without a permit and an environmental impact assessment (Government of Kenya, 2017). This was not found to be the case as wetland cultivation was a dominant activity within the wetlands, and this was done without any permits. When asked whether they would be willing to conserve wetlands, only 30% of the respondents were willing to conserve wetlands while the remaining 70% viewed restoring natural wetlands as a loss of farmland and loss of livelihoods. When it was suggested that farmers cultivating wetland could consider alternative livelihoods, many could not think of any viable alternatives to wetland cultivation. However, since 30% of the private wetland owners were willing to conserve wetlands, this should be recognized as an opportunity to undertake wetland conservation.

Another opportunity also exists to educate the 70% who viewed wetland conservation as a loss of livelihood.

Table 4.3: Supplemental information on Challenges facing wetland conservation

Challenge	**Components**
Encroachment	Cultivation, draining of wetlands, lack of proper demarcations to wetlands, invasive species.
Conflict in legislation	Non-compliance to laws, conflicting policies within WRA and Land Act of parliament, conflicts of interest in conservation activities, uncoordinated policy implementation.
Lack of community empowerment	Lack of public campaigns on promoting awareness of wetlands, lack of awareness within the farmers, poverty.
Pollution	Disposal of carwash wastes, agricultural chemicals, and sewage in urban centers.
Bad governance	Corruption, delayed justice, non-compliance to laws.
Limited resources	Funding for public awareness creation and implementation conservation activities.
Inadequate planning	Lack of deliberate planning.

Table 4.4: Pairwise Ranking Matrix of Challenges facing wetlands

	Lack of proper planning	Encroachment	Conflict in legislation	Pollution	Lack of community empowerment	Limited resources	Bad governance
Lack of proper planning		PL	L	PL	PL	PL	BG
Encroachment			L	E	CE	R	BG
Conflict in legislation				L	L	L	L
Pollution					CE	R	BG
Lack of community empowerment						CE	CE
Limited resources							R
Bad governance							

Key

PL-Inadequate planning	E-Encroachment	P-Pollution	L- conflict in legislation	R-limited resources	CE- lack of community empowerment	BG-bad governance

Table 4.5: Frequency Summary of the challenges

Inadequate planning	Encroachment	Conflict in legislation	Pollution	Lack of community empowerment	Limited resources	Bad governance
4	1	6	0	4	3	3

In Kenya, only wetlands of international importance such as Lake Naivasha, Lake Nakuru and Saiwa swamp have management plans and financing (Mwita et al., 2012). Small wetlands are often neglected in planning and receive limited financing thus continue to suffer degradation. Bad governance also ranks highly. Officers in charge receive bribes from people encroaching wetlands instead of reclaiming them.

Existence of conflicts in current laws and regulations has been identified as a major impediment against wetland conservation. There is need to harmonize the policies and regulations that govern wetlands in EMCA and the Land ownership and demarcation policies and regulations in the Land Act.

4.3 Influence of wetlands on stream flow and sediment yield in Githanja catchment of Maragua watershed

4.3.1 Soils in the Githanja catchment

The study area has three main types of soil types: 59.5% Rhodic Nitisols (NTr); 24% Humic Nitisols (NTu); 15.6% Calcic Vertisols (VRk) and 1% Umbric Andosols (ANu) (Figure 4.6). These soils are fine textured, deep and well drained (Geertsma, Wilschut, & Kauffman, 2011). The soil parameters included texture, total organic carbon (TOC), organic matter (OM), saturated hydraulic conductivity (Ksat), cation exchange capacity (CEC), interill and rill erodibility, initial saturation level, critical shear and effective hydraulic conductivity, Rhodic Nitisols, Humic Nitisols and Calcic Vertisols (Table 4.6-4.8). Soil texture is the principal characteristic of a soil affecting soil erosion but organic matter, structure and permeability contribute too. Soils with organic matter content and faster infiltration rates are more resistant to erosion. Likewise, sand, loam and sand-loam textured soils offer greater resistance to erosion than fine sand, some clay and silt textured soils (Lu et al., 2006).

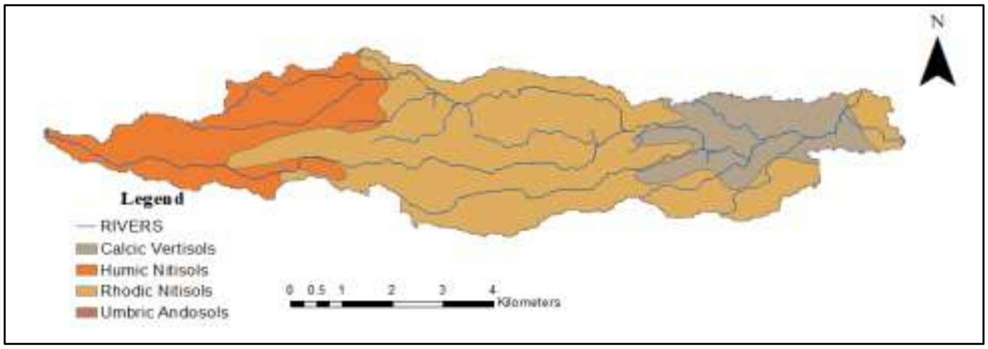


Figure 4.6: Soil types in Githanja catchment

Table 4.6: Soil properties for Rhodic Nitisols used on GeoWEPP

Soil Name					Rhodic Nitisols (NTr)
Texture					Silt Clay
Initial saturation level (%)					75
Albedo					0.09
Interill erodibility (kg.s/m4)					8.93E+06
Rill erodibility (s/m)					0.0116
Critical shear (Pa)					3.5
Effective hydraulic conductivity (mm/h)					6.71
Depth (mm)	Sand (%)	Clay (%)	Organic matter (%)	CEC (meq/100g)	Rock
0-200	12.0	78.0	1.730	25.0	0.0
201-400	12.0	80.0	1.750	25.0	0.0
301-600	12.0	80.0	1.750	25.0	0.0
601-800	8.0	84.0	0.790	19.0	0.0
801-1000	7.0	86.0	0.720	17.0	0.0

Table 4.7: Soil properties for Calcic Vertisols used on GeoWEPP

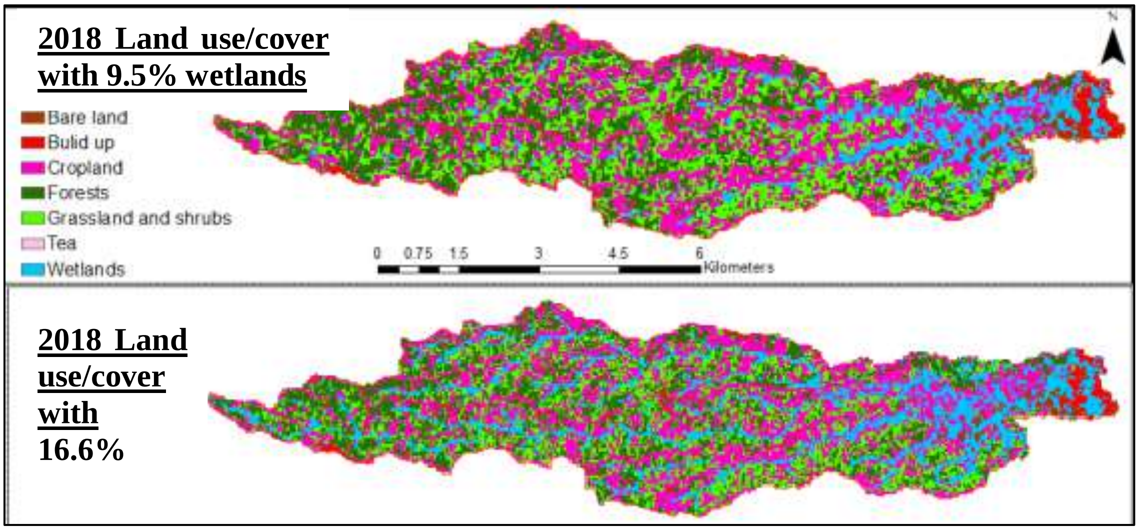
Soil Name					Calcic VertisolsVRk
Texture					Silt Clay
Albedo					0.23
Initial saturation level (%)					75
Interill erodibility (kg.s/m4)					9.50E+06
Rill erodibility (s/m)					0.0125
Critical shear (Pa)					2.8
Effective hydraulic conductivity (mm/h)					1.0
Depth (mm)	Sand (%)	Clay (%)	Organic matter (%)	CEC (meq/100g)	Rock
0-200	35.0	42.0	2.250	14.0	0.0
201-400	30.0	47.0	1.120	14.0	0.0
301-600	34.0	42.0	1.030	14.0	0.0
601-800	33.0	44.0	0.830	14.0	0.0
801-1000	36.0	58.0	0.520	16.0	0.0

Table 4.8: Soil properties for Humic Nitisols used on GeoWEPP

Soil name					Humic Nitisols (NTu)
Texture					Silt Clay
Albedo					0.09
Initial saturation level (%)					75
Interill erodibility (kg.s/m4)					5.42E+06
Rill erodibility (s/m)					0.0202
Critical shear (Pa)					3.5
Effective hydraulic conductivity (mm/h)					5.44
Depth (mm)	Sand (%)	Clay (%)	Organic matter (%)	CEC (meq/100g)	Rock
0-200	12.0	78.0	1.730	25.0	0.0
201-400	12.0	80.0	1.750	25.0	0.0
301-600	12.0	80.0	1.750	25.0	0.0
601-800	8.0	84.0	0.790	19.0	0.0
801-1000	7.0	86.0	0.720	17.0	0.0

4.3.2 Land use / land cover in Githanja catchment

During the supervised classification, six classes were identified namely: Forest, cropland, grassland and shrubs, build up area and bare land. It was difficult to identify wetlands using this method because of spectral mixture within the wetlands and other uses (Kaplan & Avdan, 2017). After mosaicking, wetlands with the supervised land cover map, it was found that in 1987, wetlands covered 16.6% of the total area, which reduced to 9.5% in 2018 (Figure 4.7). Land use/cover affects runoff and sediment yield in a catchment. Crop lands yield more runoff than forested land in a catchment whereas a higher percentage of wetlands in a catchment reduces the amount of runoff and sediment yield (Mohammad & Adam, 2010).


2018 Land use/cover with 9.5% wetlands

2018 Land use/cover with 16.6%

Figure 4.7: The 2018 Land use/ cover for Githanja Catchment

4.3.3 Hydrological results

Davie (2008), suggested that the proportion of total precipitation that returns to runoff in humid climate areas is about 30% while Budyko suggests that 20% of the precipitation in the catchment would be runoff (Chýlek & Coakley, 1975). From computation 25% of the precipitation becomes runoff in Karurumo catchment. Therefore Karurumo stream flow data was selected to calibrate the AWBM model. The flow duration curve was used to check the goodness of fit for the AWBM. The flow duration curves of the observed and simulated for Karurumo agreed reasonably (Figure 4.8). The observed runoff for Karurumo was 235,197mm and the predicted using AWBM was 194577mm. The underestimation could be explained by the difference in peak flows in the observed data which could be as a result of errors in the measurement of peak flows (Figure 4.9). Githanja stream data was simulated for five years (Figure 4.10). The simulated data for Githanja was compared with existing data between 21/8/2014 and 31/1/2015 and the flow duration curves were found to agree with some degree of accuracy (Figure 4.11).

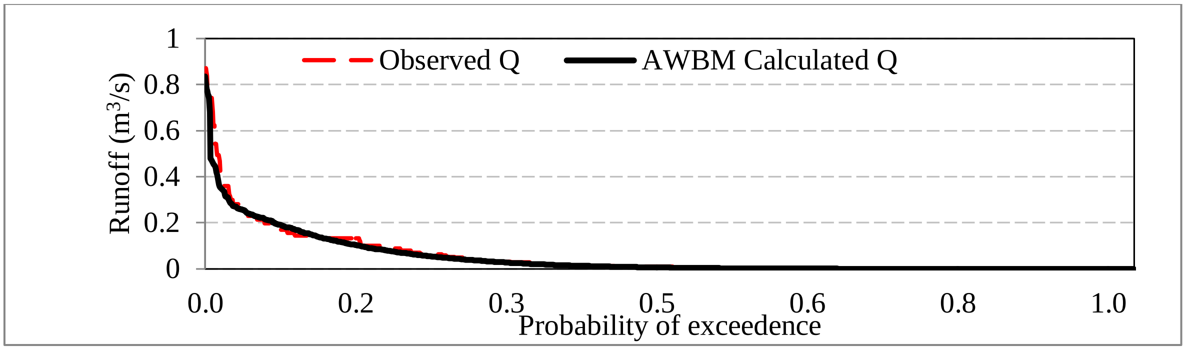


Figure 4.8: Model calibration using the flow duration curve and the parameter set that was obtained after calibration

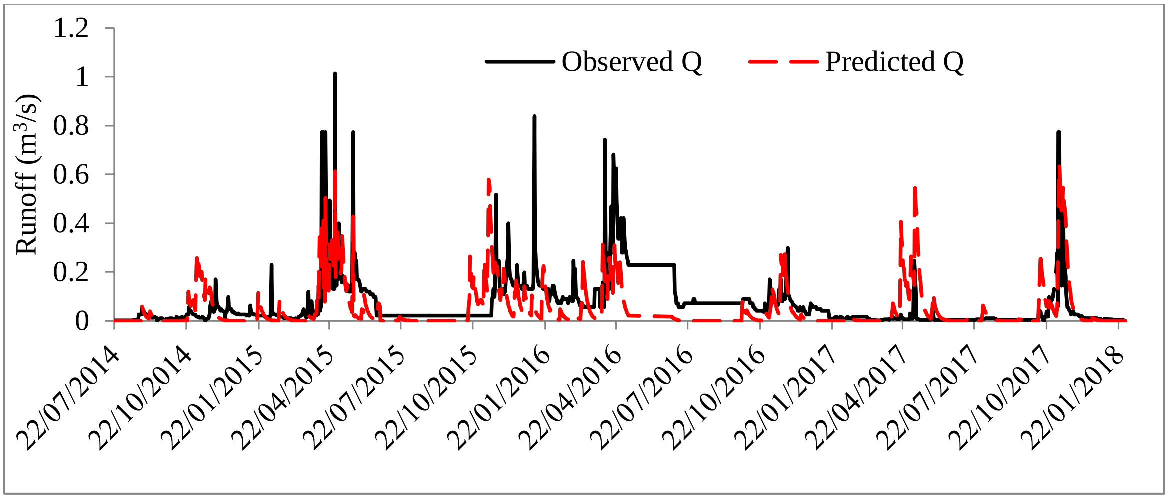


Figure 4.9: Observed and AWBM calculated stream flow at Karurumo RGS from 2014 to 2018

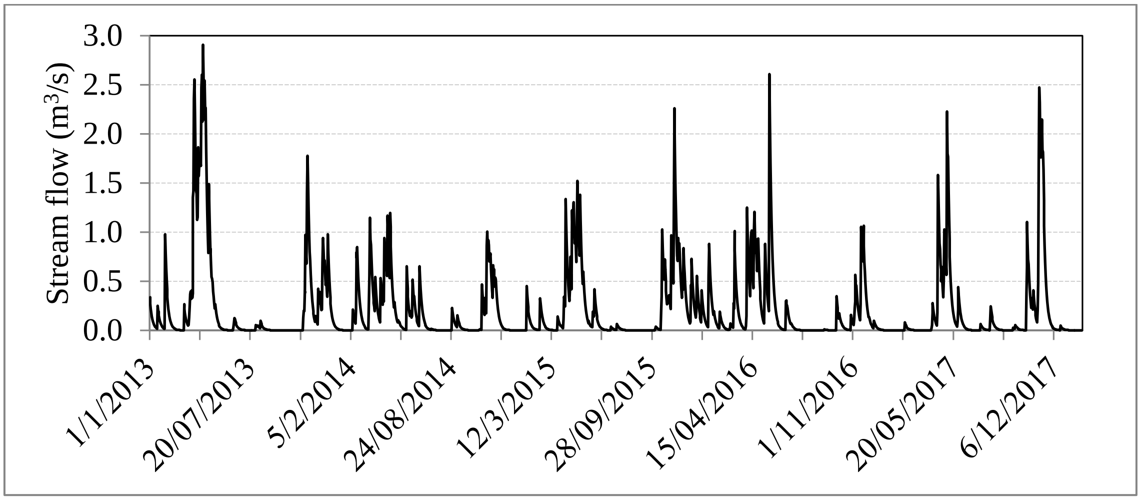


Figure 4.10: The 2013 to 2017 AWBM calculated stream flow for Githanja River at the RGS

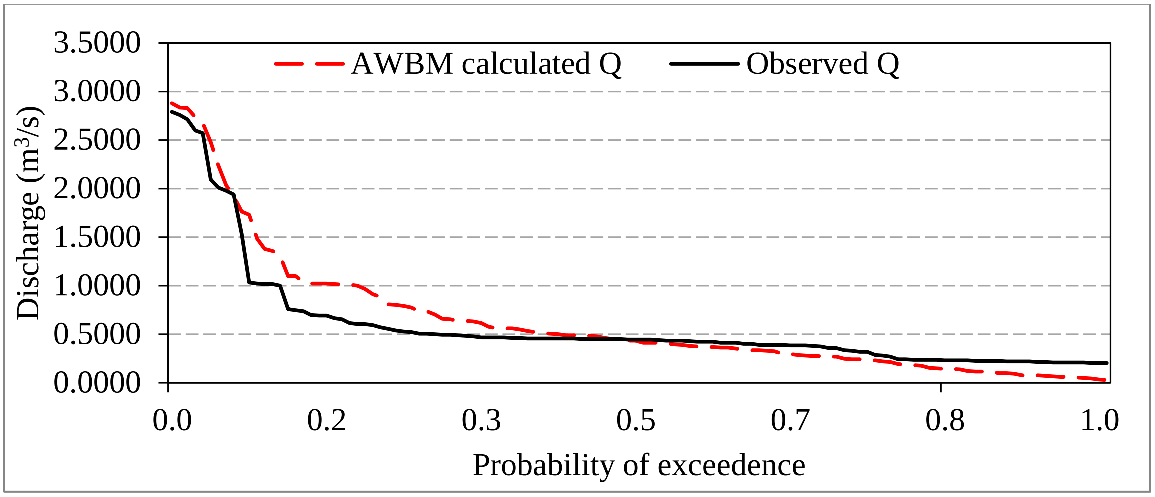


Figure 4.11: Flow duration curves for observed and calculated runoff for Githanja catchment

The correlation coefficient between discharge and TSS is 0.56 (Figure 4.12); this implies that there is a moderate positive relationship (Asuero, Sayago, & González, 2006) between the discharge and TSS. The relationship is weak because there is a large scatter in points. One of the major reasons behind the scatter is that the soil erosion rate in the catchment is not uniform during different times of the season (Asselman, 2000). The rule of thumb for this case was used: that when working with limited data, the slope of the straight line on a log transformed scatter graph of TSS versus Q should be at least 2 (ASCE, 1989) . A sediment rating curve was constructed for Githanja RGS using log-transformed data and corrected for bias (Figure 4.12). Equation 4.1 gives the relationship for TSS concentration at Githanja river gauging station. The coefficient of determination for the rating curve was 0.34. Sediment yield was calculated from runoff estimated from the AWBM model. Rainfall runoff models can be used to simulate runoff data for ungauged catchments. Further, there exists a relationship between discharge and TSS. Since discharge is cheaper to monitor than TSS, the discharge can be monitored and a TSS rating curve used to obtain the sediment in a catchment.

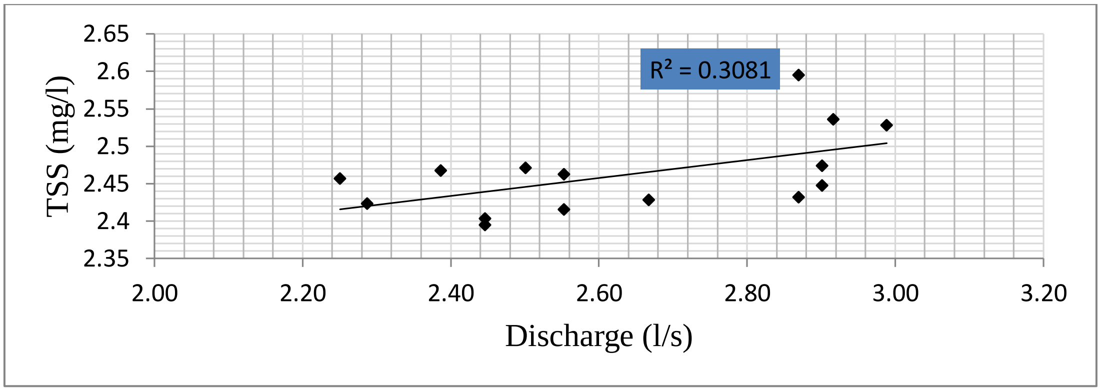


Figure 4.12: Githanja river sediment rating curve

$$\mathrm{TSS} = 140\mathrm{Q}^{0.1198} \times 1.2 \qquad (4.1)$$

4.3.4 GeoWEPP model performance

4.3.4.1 Sensitivity analysis

The results of the sensitivity analysis show that the runoff is sensitive to the effective hydraulic conductivity whereas the sediment yield is sensitive to rill erodibility, effective hydraulic conductivity and critical shear stress as indicated by ratios greater than zero (Table 4.9). The negative prefix indicates an inverse relationship between the input parameter and the corresponding output parameter while the positive sign indicates a proportional relationship (Al-Mukhtar et al., 2014). The results revealed that changes in soil types affected the model prediction. For example, the sensitivity ratio of the effective hydraulic conductivity for runoff ranged from -0.760 in silt loam to -0.031 in clay soil. For sediment yield, the sensitivity ratio ranged between -0.324 in silt loam to -

0.004 in clay soils. The higher ratios in the rill erosion than the interill erosion indicate that rill contributes more amount of sediment. Further the positive values of rill erosion sensitivity indicate that increase in rill erosion leads to increased sediment yield and vice versa.

The results of the sensitivity results were in agreement with the sensitivity studies on WEPP model (Al-Mukhtar et al., 2014; Pandey et al., 2008). The soil parameters were adjusted within acceptable ranges to minimize the discrepancies between the observed and simulated (Baffaut et al., 1995; Nearing et al., 1990). The calibrated parameters were interill erodibility and rill erodibility factor, critical shear and the effective soil conductivity (Table 4.10)

Table 4.9: Sensitivity ratio of soil parameters for soil types

Soil type	Texture	Runoff				Sediment Yield			
		K_e	K_i	K_r	T_c	K_e	K_i	K_r	T_c
Rhodic Nitosols (NTr)	Silt-loam	-0.760	0	0	0	-0.324	0	0.130	-0.114
Humic Nitisols (NTu)	Silt-Loam	-0.712	0	0	0	-0.226	0	0.128	-0.109
Calcic Vertisol (VRk)	Clay	-0.031	0	0	0	-0.004	0.001	0.006	-0.007

K_e effective hydraulic conductivity, K_i interill erodibility, K_r rill erodibility, T_c critical shear stress

Table 4.10: Calibrated soil parameters in Githanja catchment

Soil texture	K_e (mm/h)	K_i (kg s /m^4)	K_r (s/m)	T_c (Pa)
Silt-loam	0.15	6,622,000	0.00797	3.5
Silt-Loam	0.15	5,085,200	0.00557	3.5
Clay	0.20	9,503,500	0.01247	4.0

4.3.4.2 Calibration and validation

Monthly simulated and observed runoff and sediment yield for the calibration period (2013-2015) and validation period (2016-2017) were graphically compared (Figures 4.13, 4.14, 4.15 and 4.16). It can be noticed that from Figures 4.13 and 4.15 that the observed and simulated peak runoffs are consistent. Although the simulated runoff is closely distributed about the regression line, (Figures 4.14), the points are below the line 1:1 model indicating that the model seems to under estimate the runoff during calibration. During the validation period, for higher values of monthly observed runoff, the simulated values are above the line 1:1, meaning that WEPP over-predicted storm runoff. However, the statistical analysis shows a satisfactory performance with a coefficient of determination R^2 of 0.83 during calibration and 0.65 during validation. Additionally, NSE value of 0.70 was obtained during calibration and 0.61 during the validation period. This could imply that the GeoWEPP model was accurate and thus can be used in Githanja catchment.

Similarly, the monthly simulated and observed sediment yield was graphically plotted (Figures 4.17 and 4.19). Although the model tends to over predict the sediment yield, the peaks are consistent. This is further shown on the scatter graphs (Figures 4.18 and 4.20) where for values of monthly observed runoff, the simulated values are above the line 1:1, meaning that WEPP over-predicted sediment yield. However, this can be as a result of the sediment rating curve used which under predicted the peak sediment yield. The coefficient of determination was 0.53 and NSE of 0.5 during the calibration period and 0.63 and 0.51 during the validation period. This indicates a rather close relation between observed and simulated sediment yield. This implies that GeoWEPP model can be used sufficiently to predict sediment yield in Githanja catchment.

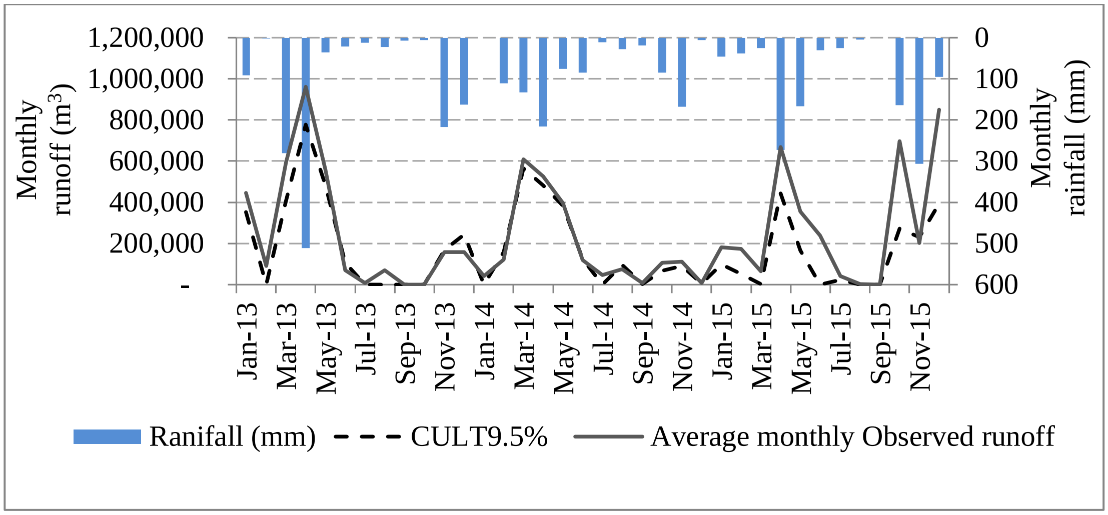


Figure 4.13: Observed and simulated monthly runoff during the calibration period

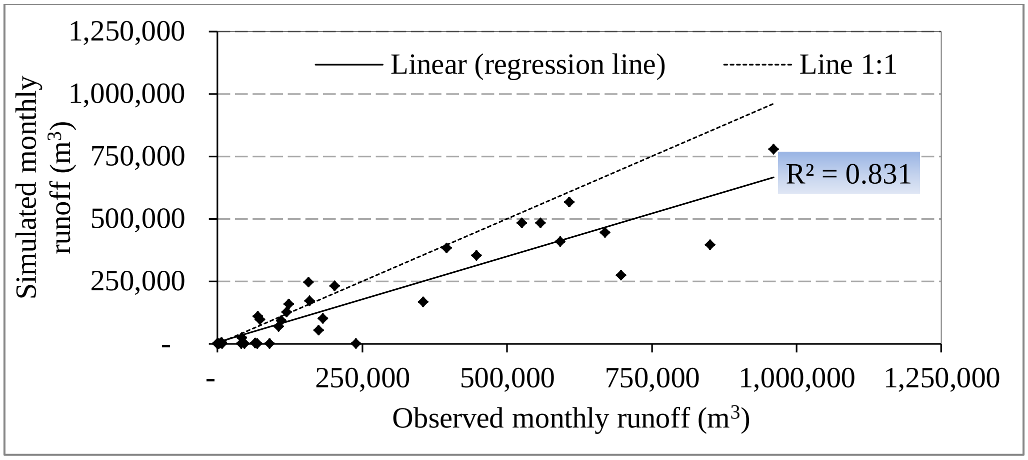


Figure 4.14: Scatter diagram of observed and simulated monthly runoff during the calibration period

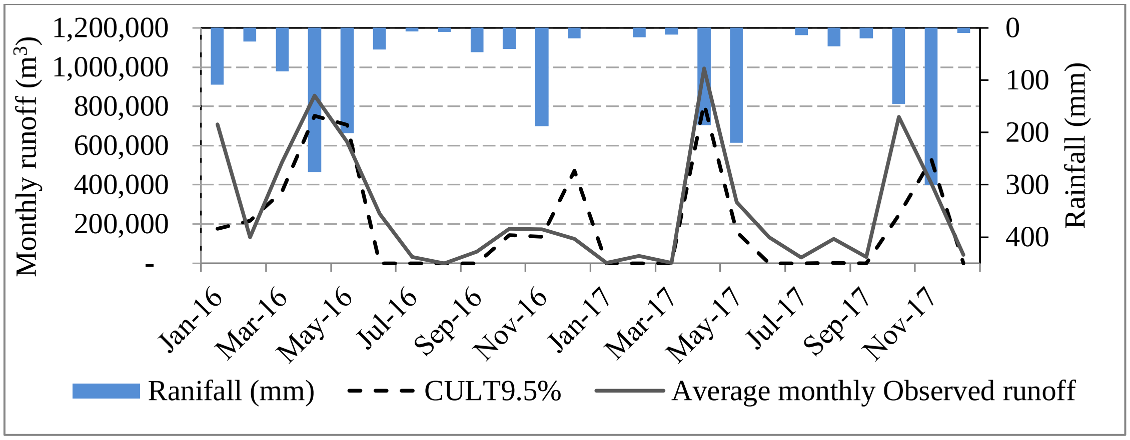


Figure 4.15: Observed and simulated monthly runoff during the validation period

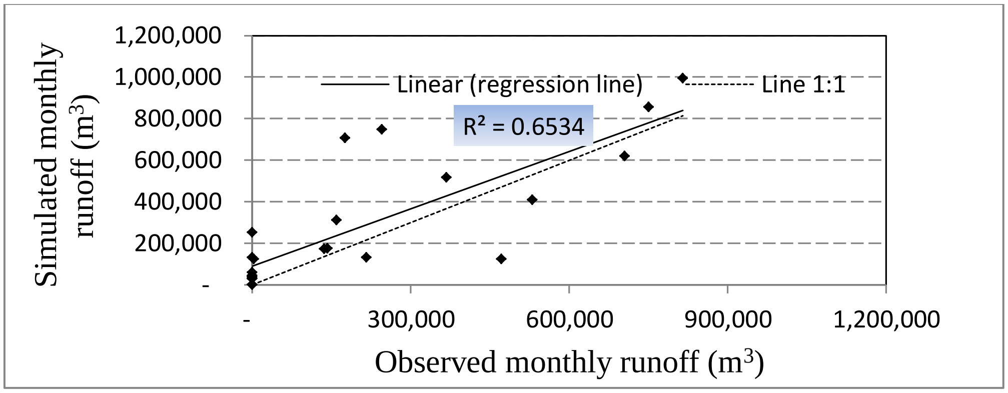


Figure 4.16: A scatter diagram of monthly observed and simulated sediment yield during the validation period

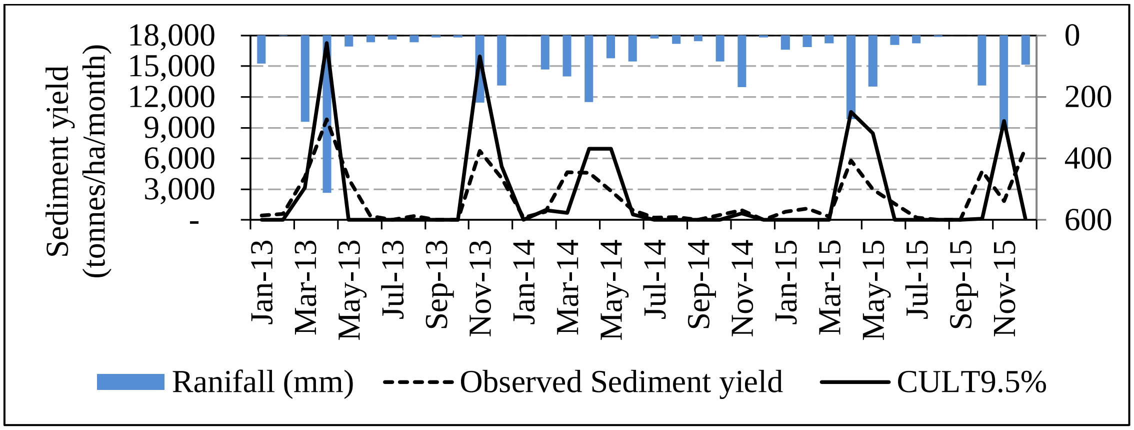


Figure 4.17: Observed and simulated sediment yield during the calibration period

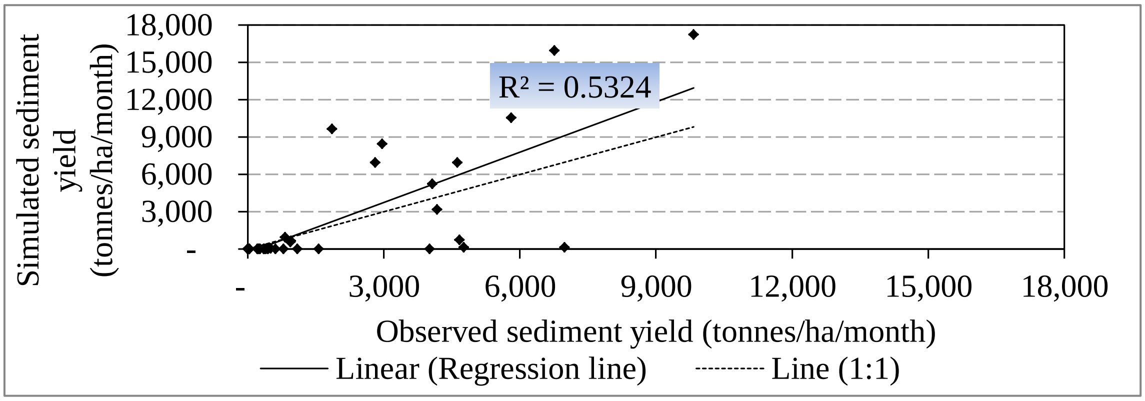


Figure 4.18: A scatter diagram of monthly observed and simulated sediment yield during the calibration period

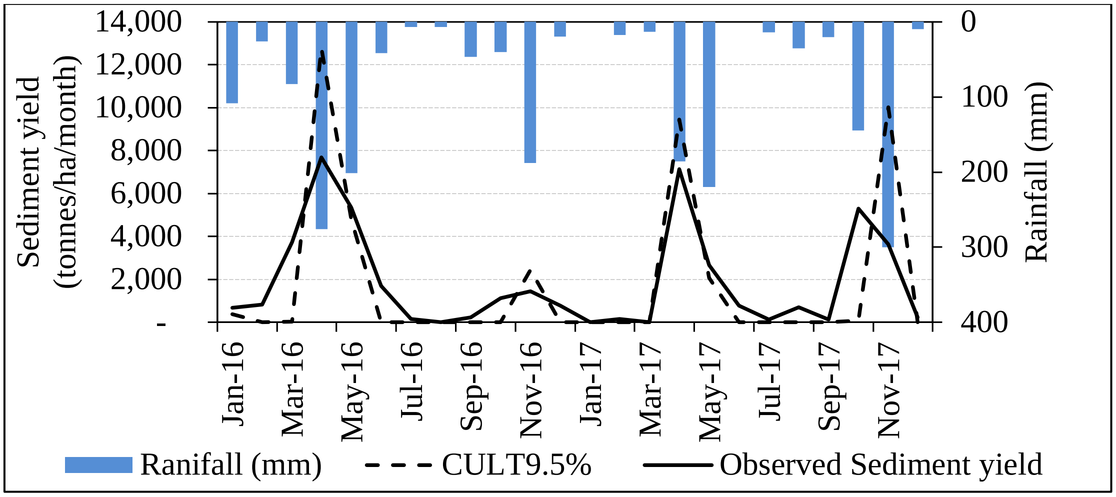


Figure 4.19: Observed and simulated sediment yield during the validation period

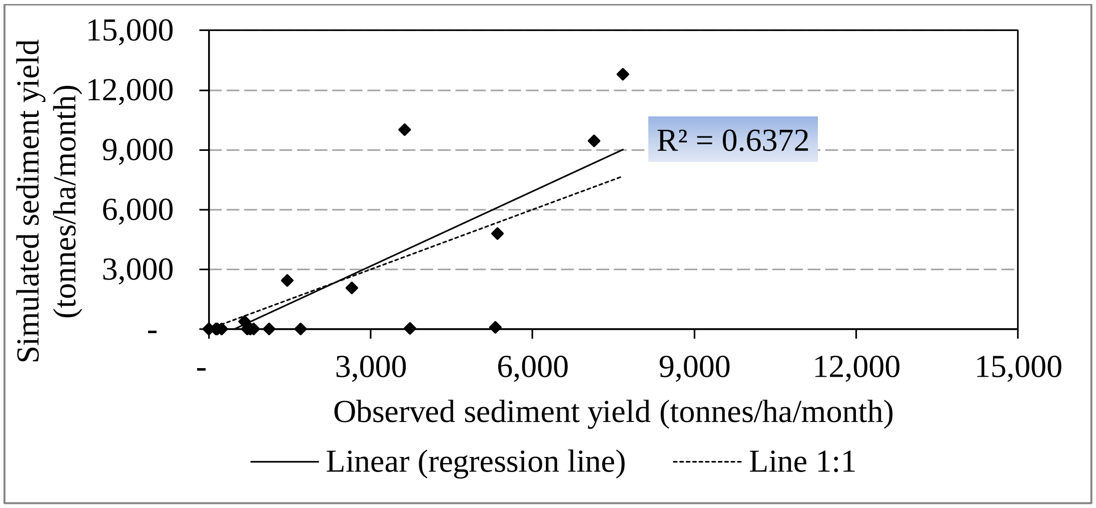


Figure 4.20: A scatter diagram of monthly observed and simulated sediment yield during the validation period

4.3.5 Effects of land use within the wetlands on runoff

The runoff volume at the outlet of Githanja catchment varied with wetland characteristics. It was noted that wetlands under grass cover tended to attenuate peak flows (Figure 4.21). In his study, Crumpton, (2001), suggested that absence of human interference in wetlands within a catchment reduces the velocity of runoff, thus attenuating peak flows. From this study, it was noticed that the there is a reduction in peak runoff when wetland are under grass compared to cultivated wetlands. For instance, the annual average runoff in Githanja catchment when 9.5% of the catchment area was cultivated (CULT9.5%) was 190,121m^3/year while the annual average runoff when 9.5% of wetlands are grassed (GRASS9.5%) was 161,886m^3/year which worked out to about 15% reduction in runoff.

In a situation where 16.6% of the catchment area was under grassed wetlands (GRASS16.6%), the annual average runoff 134,817 m^3/year which was 29% reduction compared to CULT9.5%. This suggests that transforming wetlands from cultivation land units to grass with no till reduces peak flow. Wetlands by definition store water either in the short-term or in the long-term and the amount of water stored is proportional to their size (Potter, 2011). Thus, restoring lost wetlands in Githanja catchment so as to increase the wetland area would reduce the peak flow further.

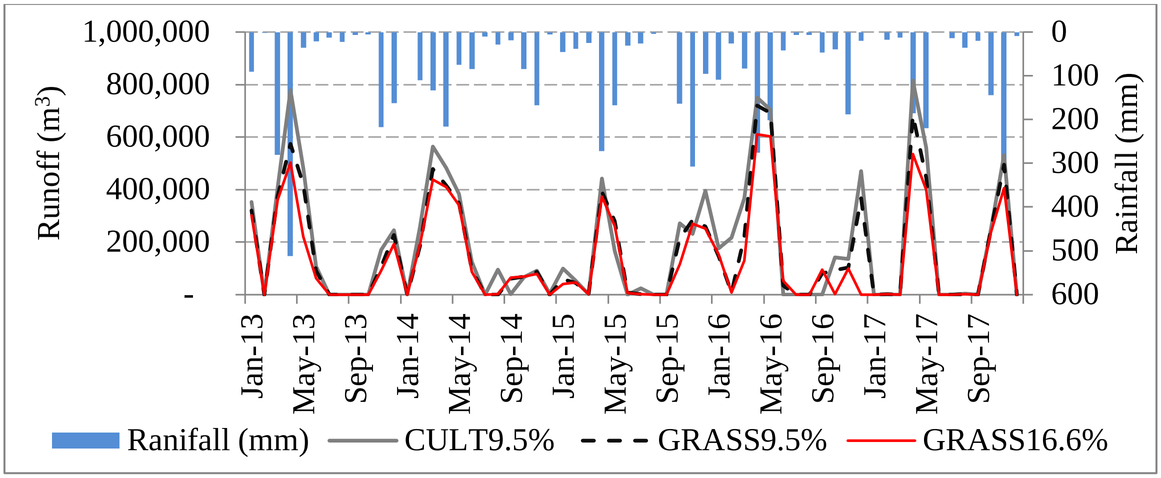


Figure 4.21: Effect of land use in wetlands on runoff

4.3.6 Effects of land use within the wetlands on sediment yield

Spatial distribution of soil loss and deposition with a tolerable limit of 10t/ha/year (Zhou & WU, 2008) was compared for the three modeling scenarios (Figures 4.22). Soil deposition is indicated on the map by yellow color, soil loss less than the tolerable limit is shown by green color whereas soil loss beyond the set tolerable is shown by red color. From the results, deposition occurred mostly along the rivers, this implies that riparian wetlands trap sediment transported to the river by the runoff.

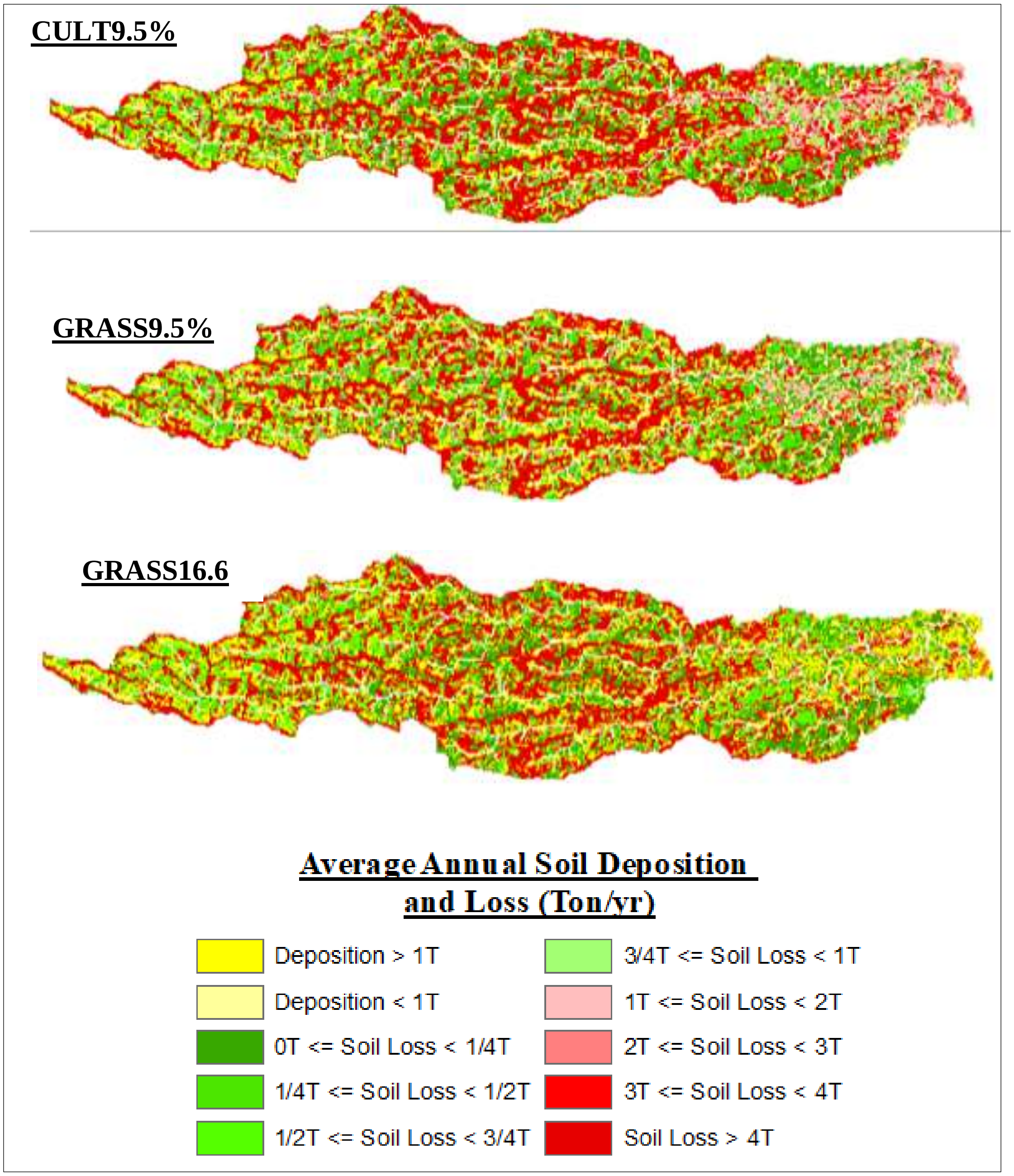


Figure 4.22: Average annual onsite soil deposition and loss in Githanja catchment

The sediment delivery ratio was less than one for all the scenarios, indicating not all the eroded material was discharged at the outlet. However, the sediment delivery ratio varied with wetland area and use (Figure 4.23). When erosion occurs, not all the eroded material find their way to the outlet, some materials are deposited within the catchment (Zhou & WU, 2008). The presence of wetlands within the catchment provide deposition grounds since they slow velocity of runoff (Mitsch & Gossilink, 2000). The sediment delivery ratio was higher for CULT9.5% (0.92), than GRASS9.5% (0.62) and had the least value (0.48) for increased wetland GRASS16.6%. This indicated that presence of grass wetlands in Githanja catchment increased deposition of sediment and that deposition is higher when the wetlands cover larger areas.

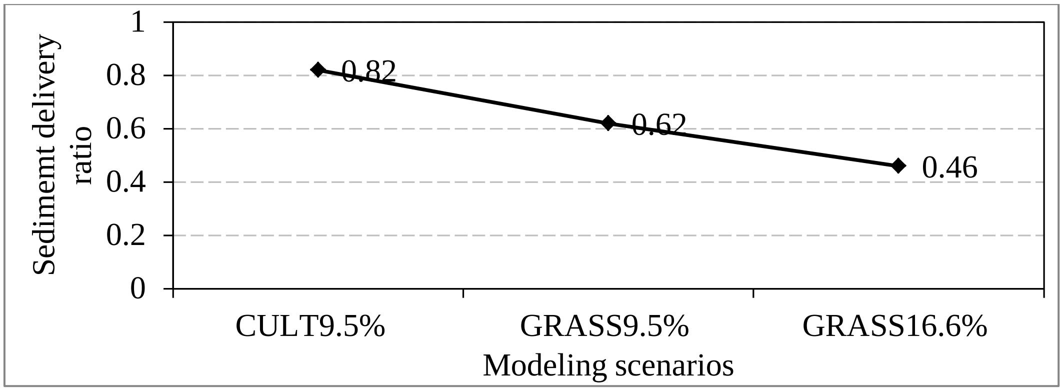


Figure 4.23: Sediment delivery ratio at the watershed outlet

The sediment yield varies with wetland area and use (Figures 4.24). Gilliam, (1994) reported wetlands are the most important factor influencing non-point source pollutants entering surface water bodies in the USA. This study noted that sediment yield reduced with increasing wetland area under conservation. For instance, the average annual sediment yield, for Githanja catchment when 9.5% of the catchment area is under cultivated catchment (CULT9.5%) was 2,201Tonnes/ha/year while under 9.5% grassed wetlands (GRASS9.5%) was 1,423Tonnes/ha/year, which works out to about 35% less sediment yield. When 16.6% of the catchment area was grassed wetlands, the average annual sediment yield was 1,103Tonnes/ha/year which is about 50% the sediment yield under CULT9.5%. Therefore, stopping encroachment into riparian wetlands reduces the peak flows and sediment yield. Mitsch et al., (2000) found out that the amount of sediment trapped by wetlands is dependent on their size. Their findings are similar to those of Githanja catchment in this study. Thus, it can be seen that restoring lost wetlands in Githanja catchment would help reduce sediment yield.

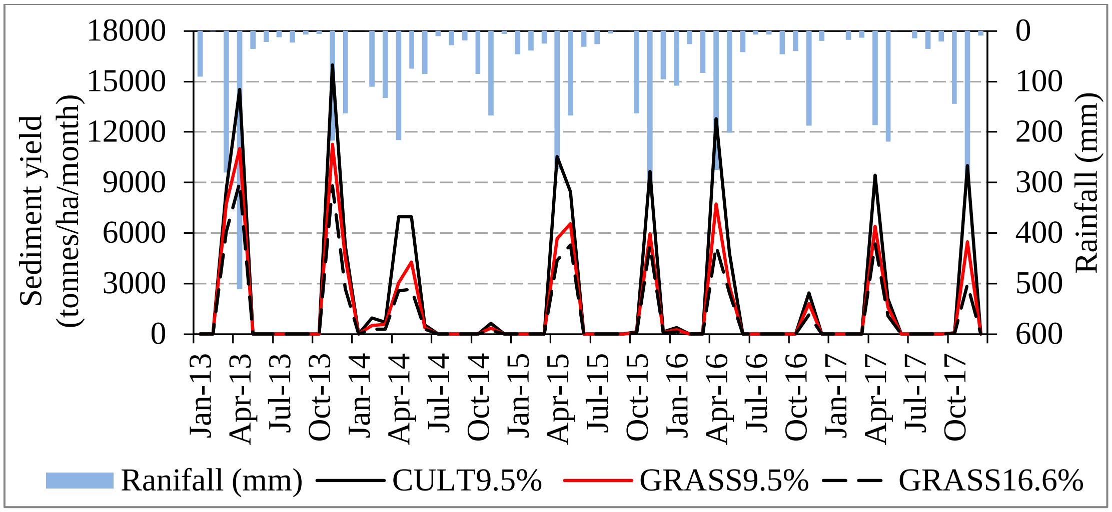


Figure 4.24: Effect of land use in wetlands on sediment yield.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study determined the status of wetlands in Maragua and their influence on stream flow and sediment yield. The spatial and temporal distribution, perceptions of the residents about the value of wetlands and the challenges impeding their conservation were identified. Further, the impacts of changes in land use within wetlands were assessed. The main findings of the study are:

1) For the period between 1987 and 2018, Maragua watershed had lost 58% of its riparian wetlands. The wetlands were lost to cultivation land and exotic trees. Also, the residents of Maragua watershed were not aware of the adverse effects of their activities to the wetlands. Existence of conflicts in current policies and regulations on wetland ownership and conservation were identified as the major impediment against wetland conservation.
2) This study has demonstrated that GeoWEPP model could be used to understand the impacts of destruction of wetlands in a catchment. From this study, peak runoff and sediment yield is affected by the use and area of riparian wetlands. It was found out that stopping cultivation on riparian wetlands and planting grass could attenuate peak flows and reduce sediment yield. Additionally, restoring the lost wetlands so as to increase the wetland area reduced the peak flow and sediment yield further.

5.2 Recommendations

1) This study recommends that there is need to conduct public awareness campaigns on the potential benefits of conserved wetlands. This will promote sustainable use of wetlands within the study area. There is also need to harmonize the policies and regulations that govern wetlands in EMCA and the Land Act so that riparian wetlands are not allocated to individual land owners, rather left as government land.
2) Again, the study recommends that there is need to target conservation of riparian wetlands so as to achieve their potential benefits of increasing water quality and damping peak flow. Conserving these wetlands by planting natural grass could help the wetlands in performing their functions.

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