International Journal of Science and Research (IJSR)
ISSN: 2319-7064
ResearchGate Impact Factor (2018): 0.28 | SJIF (2018): 7.426

Application of Remote Sensing and Runoff Modelling to Identify Environmental Conservation and Water Harvesting Sites

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Abstract: ***Land cover has changed variably in Athi Catchment Area as a result of environmental and human activities. The Catchment hydrological response has also changed resulting in high surface runoff, depleted ground water, flash floods and soil erosion during rainfall events. This study assesses the land cover change extent and its impact on surface runoff in upper Athi Catchment Area, between 1990 and 2013, using remote sensing, GIS and hydrological modelling in order to advice on catchment conservation options and identify areas water harvesting potential. Satellite images from Landsat 7 ETM+ and Landsat 8 were classified using ERDAS Imagine, change detection analysis in Terrset and runoff modelling using ArcSWAT Model. The study results showed overall decrease of forest cover and an increase of settlement and grassland and increased runoff values in the areas that experienced conversion forests to cropland, shrubland and grassland. Areas with increased forests with reduced shrubland and cropland recorded decreased runoff values in some cases. This study aims at opening viewpoints concerning land cover change impact on runoff, and alternatives that can be adopted for sustainable land and water resource use.***

Keywords: Land cover, Runoff, Sub-basin, SWAT Model, Area of Concern

1. Introduction

Never-ending growth of environmental problems of degradation and water scarcity in arid lands as driven by non-monitored unsustainable land cover change, degradation, and climate change circus is becoming more difficult to remedy in Athi Catchment Area. It is notable that despite the short-term benefits such as increased pasture, food production and urbanisation, the environmental consequences of land cover change may realise higher costs to remedy than any benefits previously generated. While land cover change does not automatically infer degradation of land, negative land cover change particularly loss of vegetation has been taking place at an unprecedented degree in Athi Catchment Area. Over the years, the Government of Kenya has provided policies and legislation to regulate utilization of water resources and management of catchments through environmental and water laws. In addition, government institutions, non-governmental organizations and locals through Water Resource Users Association (WRUAs) are constantly working on the management of resources in the study area and solutions to water scarcity. However, the catchment area experiences water shortages all year round and this can be attributed to inadequate site-specific information on hotspot areas for land cover change and high runoff generation. There is a growing need to understand the extent of change occurring in the catchment area and resulting consequences of the change in order to find solutions to degradation and alternative water sources such as runoff water harvesting and combined application of remote sensing analysis and runoff modelling can be a significant solution.

Studies on remote sensing applications in cover change monitoring, runoff modelling, and runoff water harvesting have been carried out globally and in Kenya. In Kenya, while applying the Automated Geospatial Watershed Assessment (AGWA) tool for SWAT model parameterization, [1] observed that change in land cover over a period of 17 years in Njoro watershed led to reduction in groundwater recharge and increments in surface runoff. [2], concluded from a study in Molo River Basin that land use changes had insignificant impact on the catchment hydrological response between 1986 and 2001. [3], conducted a study in Upper Mara River and concluded that land use and climate change have both positive and negative impacts on hydrological responses. While applying topographic and ariel maps as input to SWAT model while assessing suitability of SWAT for verification of generated pedotransfer functions in the estimation of surface runoff, [4], highlighted the need for development of databases that may provide intricate and better quality hydrological modelling data. In Athi Catchment Area, studies have been carried out in different regions to assess land cover change with respect to water quality such as sedimentation, erosion and pollution. [5], in an examination of impact of land use change on sediment transportation and soil erosion in the larger Athi Catchment, argued that regions in the basin were exposed to human factors including population pressure and need for agricultural land which impacted sediment transportation and erosion. The study documented the trend in erosion and transportation of sediment downstream by assessing the basin hydrology, land use and measures for soil conservation. A study in the Upper-Athi River catchment to assess the impacts of land use type on the water quality concluded that pollution and water quality degradation increased downstream as a result of land use change in the upstream regions. It was recommended that research to assess the effect of land use changes along Athi River be conducted [6]. [7], in an assessment of the impact of conservation practices on water and sediment yield in Sasumua Watershed, Kenya, concluded that changes in land cover which are supplemented by practices such as terracing reduced runoff intensity and resulting sedimentation. Despite the physiographic and climatic differences in the regions considered and difference in methodologies applied, the studies have been separately successful but can be combined to benefit environmental conservation.

The constant growing population, increasing demand for resources and decreasing supply of the existing resources have caused many parts of upper Athi Catchment Area to experience significant land cover change. Land cover change in the area include reduction of forests and encroachment in of wetlands for agriculture (cropland and livestock rearing), settlement and extraction of raw materials for industries. The excision of forests for settlement and the expansion of roads in parts of upper Athi Catchment Area have altered land cover and accelerated the degradation [8]. Upper Athi Catchment Area is subject to extreme water shortages in both the upper and middle subbasins. The upper subbasins well-endowed with water resources and harbour large populations hence extremely high demand for household, agricultural and industrial use. The scarcity has led to over exploitation of groundwater resources which are not getting recharged as a result of decreased infiltration. Water supply problems in the area has resulted in water use conflict due to inappropriate usage. Water harvesting is a challenge in the area and while a few systems are developed for rooftop rainwater harvesting other water sources such as runoff water is not harvested.

Understanding the extent and dimensions of land cover change, its drivers and impact on hydrological responses for catchments that are exposed to- and/or are prone to changes is a step towards formulating effective resources' mapping and management strategies especially in Athi Catchment Area which harbours among the highest populated urban areas in Kenya, a population which continues to grow despite the depleting available resources. Despite the studies in Athi Catchment Area, lack of ingenious combined application of such approaches with focus to identify cover change hotspot areas to target for environmental conservations as well as suitable catchment for runoff water harvesting. This paper will therefore provide insight to extent of land cover change in parts of Athi Catchment Area and the impact of change on surface runoff, over a period in the past (1990 to 2013), in order to identify areas of concern which have undergone extensive land cover change and areas with water harvesting potential.

2. Materials and methods

2.1 Study area

The study area lies in the upper parts of Athi Catchment Area transecting Upper Athi, Nairobi and Mid Athi Sub-regions Figure 1.

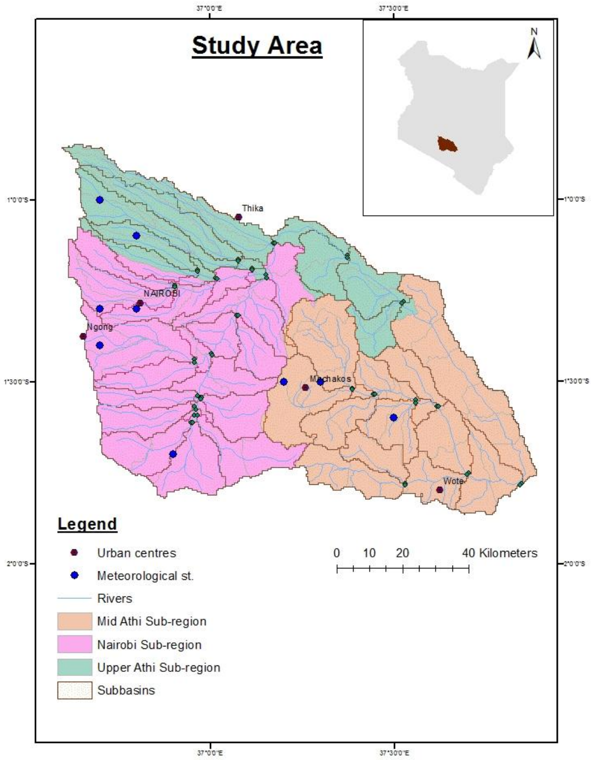

Figure 1: Study Area

It covers a total area of 11,565 km² and is bound by longitudes 36.54º and 37.9º East and latitudes 0.824º and 1.88º South. The climate varies from sub-humid in the Upper Athi and Nairobi Sub-regions to semi-arid in the Mid Athi Sub-regions. The Upper Athi and Nairobi Sub-regions (humid areas) receive 1200 mm of rainfall annually, Mid Athi Sub-regions (arid and semi-arid areas) receive 500–700 mm and in some parts less than 500 mm annually. The short and long rains occur in October-December and March-May, respectively. The mean daily maximum and minimum range from 35°C to 23°C and 24°C to 12°C respectively.

The study area comprises diverse land cover types depending on rainfall occurrence, climatic conditions and socio-cultural activities of people. The land cover in the study area comprises mainly forests, settlement, shrubland, grassland and cropland. There are a number of forests in the area including natural forests such as Aberdare, Kinare, Karura, Ngong Hills, Ngong Road, Dagoretti, Kilungu hills, Oldonyo-Sabuk and Iveti forests. Other forests include plantation forests such as Katunga and Nunguni; and farm forested areas distributed in different parts of the study area. Shrubland and grassland in the study area lie within the Upper Athi and Nairobi Sub-regions; they transect reserved wildlife parks and conservancies, and private ranches. In the Mid- and Upper Athi Sub-regions lie arable cropland and perennial cropland especially along hill slopes and along river banks.

2.2 Data

2.2.1 Land cover change analysis

In order to carryout change analysis, land cover data is required for the same area, over the periods being considered. The satellite images used to generate land cover maps were taken over Path/Rows 168/062,168/061,167/061 and 167/062 from Landsat 5 Thematic Mapper for 1990 and Landsat 8 for 2013 images. The satellite images were obtained from USGS Global Visualization, GLOVIS [9]. The land cover maps development involved mosaicking the orthorectified images over the Path/Rows above in ERDAS Imagine and clipping of the images to the area of interest.

2.2.2 Runoff modelling

The SWAT Model requires land use, soil texture and climate data as input to facilitate modelling and estimation of runoff.

1. DEM- The digital elevation model (DEM) used in the study was generated by the Shuttle Radar Topography Mission (SRTM) with a 90m by 90m resolution.
2. Land cover- Land cover imagery was required to generate land cover classification data and maps for change detection analysis and creation of Hydrological Response Units (HRUs) in the SWAT model.
3. Climate data- The climate data required in the SWAT model comprised daily precipitation, wind speed, temperature, humidity and evapotranspiration data. This study considered application of satellite derived Climate Forecast System Reanalysis (CFSR) weather data obtained from Global Weather Data for SWAT [10]. The spatial distribution of the weather stations in the study area was wanting and this raised concern on the adequacy of the data from unevenly located stations in the study area hence using Climate Forecast System Reanalysis (CFSR) weather data which is considered reliable for ungauged watersheds and watersheds with few rain gauges and incomplete data since the data is derived for data that is averaged spatially. Previous studies have concluded that accurate spatially distributed climate data are the most essential input parameters for hydrological modelling in SWAT in areas with inadequate rainfall data, satellite derived data that is comprehensive can be used [11]. To validate satellite data, comparison with the ground observation meteorological data can be carried out or prediction of stream flow using hydrological models applying such data [12; 13]. In order to determine the suitability of CFSR weather data, total discharge is calculated for different meteorological stations and CFSR stations. [14], stated that CFSR data enable comprehensive watershed modelling in areas without recorded weather data or containing longer gaps in recorded rain gauge data.
4. Soil data- Soil parameters that are required as input to the SWAT Model include Hydraulic Soil Group, crack volume, texture, soil depth, available water capacity, moist bulk density and saturated hydraulic conductivity. The soil data for this study was acquired from the updated 1:2000000 Soil Terrain Database of East Africa (KENSOTER) since the SWAT soils database does not include soil classes in Africa. The KENSOTER soil database was verified with soil data obtained from Survey of Kenya. The soil classifications were appended to the SWAT Model soil table to facilitate HRU creation.
5. River flow data- The SWAT model was developed for catchments whose general conditions and parameters are not similar to the study area therefore, it was necessary to validate the model performance using data specific to the catchment. In this study, river flow data was used for validation of the SWAT Model. The recorded river flow data between 1990 and 2013 was obtained from Water Resources Management Authority [15], Athi Sub-Catchment Office.

2.3 Identification of cover change and sub-catchments for runoff generation

2.3.1 Land cover and change detection

The classification method used for the study was supervised classification since the study aimed to generate as much as possible, classes that are representative of features on the ground. According to [14], supervised classification is mostly preferred by researchers since results reported from this classification show more accuracy. Supervised classification was carried out to generate the land cover maps using ENVI software. The training sites were identified from initial data in form of GPS coordinates on sites in the study area which are the Athi River waterways, existing built-up areas and agricultural lands. Spectral signatures for the delineated areas were developed in ENVI based on training sites which were mapped on the images by defining polygons representing each training site. Maximum Likelihood method was employed to assign each pixel in the images to the classes they are most likely to belong to. The land cover classes selected were settlement, cropland (perennial and annual), grassland, shrubland, water and forest.

The land cover classification was based on FAO Classification Systems and regrouped to classes for the study described as follows:

- Forest- include natural and plantation forests
- Water- rivers and their tributaries, ponds and dams
- Grassland- areas composed predominantly of grass and bare patches
- Shrubland- areas comprising a mix of shrubs and herbs with patches of grass.
- Perennial cropland- areas with cultivated crops, whose cycle is over a year and are, harvested a couple of times each year. These include fruit trees.
- Annual cropland- areas with cultivated crops, which complete their cycle in one year or less before they are harvested. These croplands are predominantly arable cropland.
- Settlement- built up areas comprising structures such as houses, industries and roads.

As an input for the SWAT Model, land cover classes were reclassified to SWAT land use classes as shown in Table 1.

Table 1: Land cover classes in the study area as SWAT classes

Land cover classification	*SWAT classification*
Forest	Mixed forest (FOMI)
Shrubland	Shrubland (SHRB)
Grassland	Grassland (GRAS)
Perennial cropland	Agricultural Land-Generic (AGRL)
Annual cropland	Agricultural Land-Generic (AGRL)
Settlement	Residential (URBN)
Water	Water (WATR)

2.3.2 Accuracy Assessment

Accuracy assessment was carried out to determine accuracy of the classification. Sampling points for each land cover category were identified through marking of historical land cover classes which have not undergone significant changes over the period of study such as protected forests, Athi River waterway, buildings and cropland. A total of 39 sites which represented land cover classes in the study area were selected. From ground truthing (GPS coordinates and photographs), reference data which were compared to classification data, were obtained. The data was used to generate the classification confusion matrix and to calculate Overall, User's and Producer's accuracies, and Kappa coefficient.

2.3.3Change detection

Change detection was carried out for land cover images between 1990 and 2013 by application of Land Change Modeler (LCM) in Terrset Evaluations of gains and losses, persistence, specific transitions and net change in graphs and maps were generated from LCM. The totals for each land cover type were tabulated and the trend between the periods examined by computing the areas of change.

2.3.4 Areas of concern for land cover change

The areas of concern were identified as sub-basins that have undergone significant change during the period. The changes were classified based areas of specific land cover class conversions. The sub-basins identified as areas of concern are presented in Table 2.

Table 2: Areas of concern in the study area.

Change	*Conversion*	*Sub-basin*	*Area (km²)*
Increased shrubland	Forest to Shrubland	23	7292.05
	Annual Cropland to Shrubland	23	7442.01
	Grassland to Shrubland	44	5240.66
Increased forests	Shrubland to Forest	46	4570.68
	Grassland to Forest	33	425.98
	Annual Cropland to Forest	17	4680.50
Increased cropland	Shrubland to Annual Cropland	16	3048.16
	Forest to Perennial Cropland	6	2518.28
	Forest to Annual Cropland	8	3814.89
Increased settlement	Shrubland to Settlement	16	2620.84
	Forest to Settlement	14	4169.03
	Annual Cropland to Settlement	14	3071.92
Increased grassland	Forest to Grassland	18	7006.31
	Annual Cropland to Grassland	18	5655.32
	Shrubland to Grassland	45	3344.10

2.3.5 Runoff generation areas in the SWAT Model

(a) SWAT Model

The Soil Water Assessment Tool (SWAT) is a physically based model that utilises data on weather, vegetation/land cover, land management practices, soil parameters and topography as inputs to simulate the physical processes associated with water flow, crop growth, nutrient transport and sediment movement. SWAT model has been considered ideal for separating hydrologic responses to specific variables like land cover change and climate factors. SWAT was selected for this study for the following reasons:

- It has been used for impact surveys for land cover/land use change and climate change in heterogeneous regions globally successfully.
- It simulates most of the key processes in hydrology.
- It is not demanding with respect to data.
- It is free and readily available.

SWAT model is considered suitable for carrying out hydrological modelling for ungauged stations that are widespread and Africa and Kenya including the Athi Catchment area. SWAT is used to ascertain the impact of other input data such as climate, land use and land management activities on surface and groundwater quantity and quality. SWAT can efficiently be used to run simulations of large catchments [16]. In Njoro River Catchment, [1] reviewed land cover maps over a 17-year period which acted as inputs for the Automated Geospatial Watershed Assessment (AGWA) tool which parameterized the SWAT model. From the results, it was clear that change in land cover had led to reductions in groundwater recharge and increments in surface runoff. From the study, it was recommended that further land cover change studies were required to establish a relationship between land cover changes and locally recorded hydrologic response to facilitate monthly model calibration. Land cover change effects on river flow in Mara river basin by use of USGS geospatial stream flow model [17] and SWAT model [16], both reported that the Mara River hydrology has been significantly altered and recorded increase in flood peak flows which interpreted to increased sediment loads and silt build-up in downstream regions. In Molo River, analysis of catchment hydrologic response as a result of land use changes was conducted using land cover maps from 1986 to 2001 and SWAT model [2]. The results from the simulation showed that land use changes had insignificant impact on the catchment hydrological response.

(b) Sensitivity Analysis, Model Calibration and validation.

The SWAT Model validation involved re-running the simulation with different time-series for input data, without changing any parameter values, which may have been adjusted during calibration [18]. The graphical and numerical performance criteria used in the study were Nash-Sutcliffe coefficient (NSE) and coefficient of determination (R^2). The SWAT model was calibrated based on daily recorded discharge data obtained from WRMA for Kamiti Sub-basin (3BB) for years 2007 to 2010 and validated for the years 2011 to 2013. After the validation, simulation was carried for the period between 1990 and 2013.

(c) Simulations.

The SWAT Model simulations were carried out for 1990 and 2013 and the resulting runoff values compared. The change in runoff quantities were also compared for the areas of concern in the study area.

3. Results

3.1 Land cover change and Areas of Concern

The land cover classification generated for 1990 and 2013 is presented in figure 2. The bar graph in figure 3 presents land cover class variation in terms of area of coverage between 1990 and 2013.

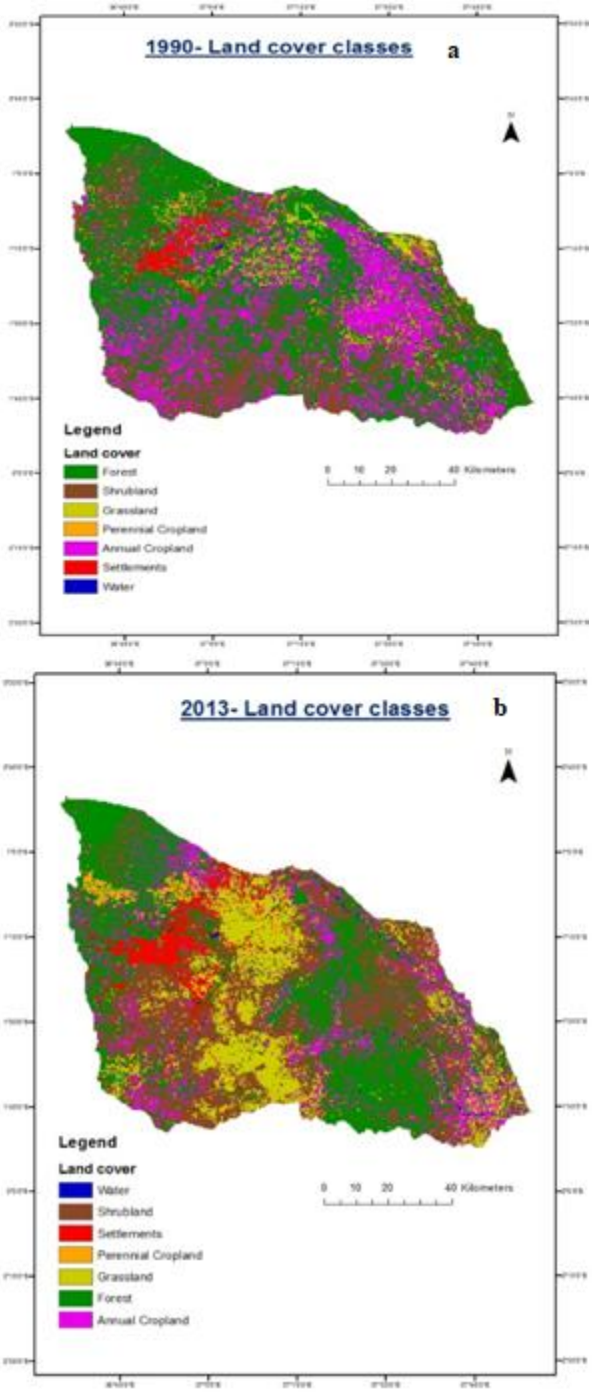

Figure 1: (a) Land cover classification for the study area for 1990 and (b) Land cover classification for the study area for 2013

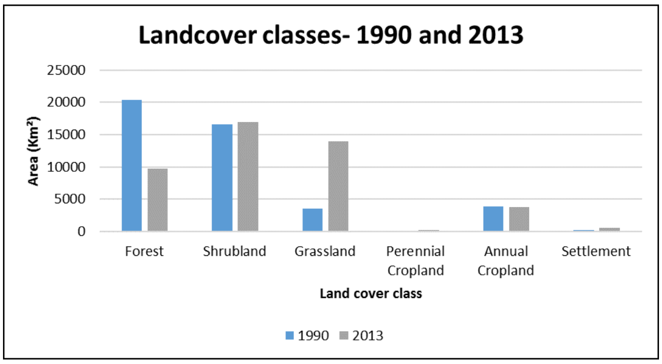

Figure 3: Land cover classes' area change in 1990 and 2013

3.1.1 Accuracy assessment

Accuracy assessment carried out produced an overall accuracy (OA) of 76.9%, a user's accuracy (UA) of 73.6% and a producer's accuracy (PA) of 82.9%. The Kappa coefficient (K) was 66%. The following table 3 shows the confusion matrix for the classification.

Table 3: Error matrix for land cover classification in the study area

	Crop land	*Forest*	*Settle ment*	*Shrub land*	*Water*	*Grand Total*	*UA (%)*
Crop land	5		2		1	**8**	62.5
Forest	1	5	2		1	**9**	55.6
Settle ment			14			**14**	100
Shrub land			1	2	1	**4**	50
Water					4	**4**	100
Grand Total	**6**	**5**	**19**	**2**	**7**	**39**	
PA (%)	83.3	100	73.7	83.3	100	57.1	
OA (%)	76.92						
K (%)	66.2						

3.1.2 Change detection

Change detection showed that overall, forest cover decreased in the study area with percentages from 44.93 to 21.53 % in 1990 and 2013 respectively. Settlements have increased from 0.44% in 1990 to 1.31% in 2013. Grassland increased exponentially from 7.85% in 1990 to 30.64% in 2013. During the period between 1990 and 2013, percentage cover of forests and shrubland decreased and agricultural lands and grassland increased as shown in Table 4.

Table 4: Land cover change trend in the study area

Land cover class	*1990-2013*	
	Area(km²)	*(%)*
Forest	-10,578.13	-23.4
Shrubland	325.20	0.4
Grassland	10,359.34	21.63
Perennial Cropland	122.25	0.27
Annual Cropland	-52.53	-0.14
Settlement	397.82	0.87

Between 1990 and 2013 the land cover classes that contributed loss of forests and shrubland were settlement, grassland and perennial cropland. Also, net contributors to increase in settlement and cropland were forests, shrubland and grassland as shown in Table 5.

Table 5: Net contributors to change 1990-2013

		Land cover Class contributing to increase in land cover class (a)					
		Forest	Shrub land	Settle ment	Grass land	A. cropland	P. crop land
Land Cover class (a)	Forest						
	Shrubland	✓				✓	
	Settlement	✓	✓		✓	✓	✓
	Grassland	✓	✓			✓	
	Annual cropland	✓					
	Perennial cropland	✓	✓		✓		

The results showed that the greatest change trend in the study area between 1990 and 2013 were loss of forests contributed mainly to increased shrubland and grassland by 42.5% and 37.8% respectively, conversion of cropland to shrubland and forests and conversion of forests to cropland. The land cover conversions for the period between 1990 and 2013 is presented figure 4.

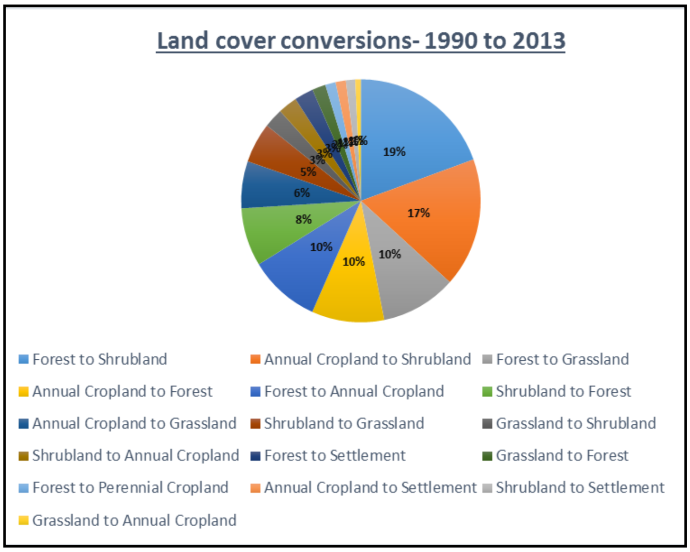

Figure 4: Land cover conversions in the study area

3.1.3Land cover Areas of Concern (AOCs)

The conversions presented in figure 4 were used as measures for identification of areas of concern (AOCs) and the sub-basins in the study area which experienced a greater area of change for all the conversions noted over the study period were selected as shown in Table 2. Figure 5 represents land cover change trend between 1990 and 2013 and the AOCs identified for this study.

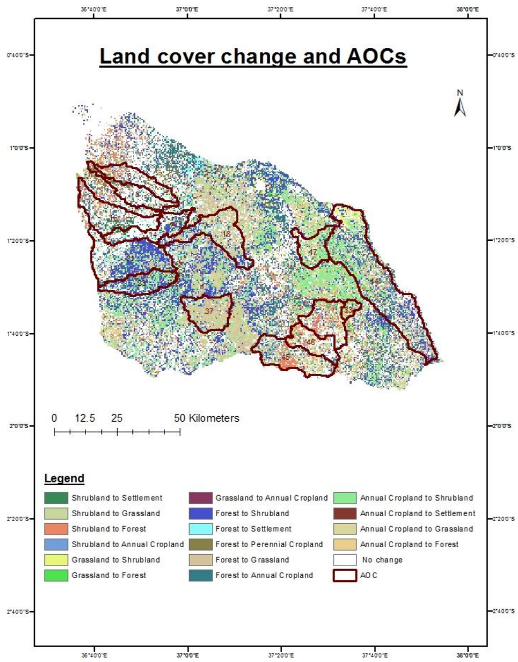

Figure 5: Land cover change trend between 1990 and 2013 and AOCs

3.2 Runoff generation in Areas of Concern

3.2.1Model calibration and validation

Model calibration and validation is important to ensure that results of simulation are accurate since the outputs of models are considered to be as accurate as the input and model equations [19]. The SWAT simulated flow data and the observed stream flow data for Kamiti sub-basin, obtained from WRMA, was compared for calibration and validation. Calibration and validation were performed for 2010 to 2012 and 2011 to 2013 respectively. The simulated daily flows vary from the observed flow values for the periods with R^2= 0.52 and NSE = 0.53 for calibration and R^2= 0.74 and NSE = 0.6 for validation. The calibration and validation values showed that the model simulation was satisfactory.

3.2.2Runoff in AOCs

A comparison of average simulated surface runoff and the major land cover change in the AOCs between 1990 and 2013. The, hydrographs showing the surface runoff depths between 1990 and 2013 in the AOCs is presented in figure 6.

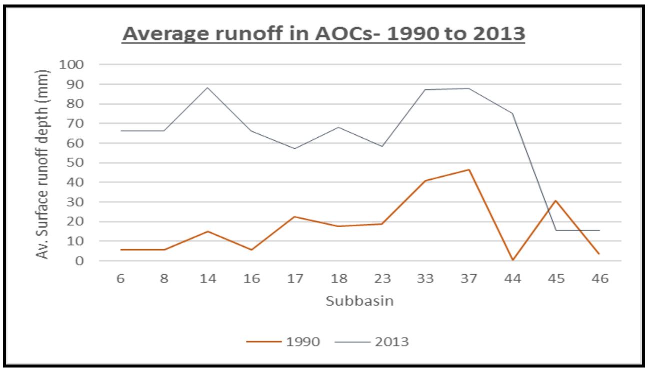

Figure 2: Surface runoff depth in AOCs

The simulated surface runoff depth has increased significantly in the year 2013 from 1990 in all the sub-basins except sub-basin 45 which recorded a decrease in average runoff of 15.15mm. In sub-basin 45, there was a combined increase in forests of 28.3% with loss of shrubland and cropland; and 11.8% increase in grassland due to loss of shrubland. The highest difference in runoff was observed in sub-basin 44 which recorded increase of 74.8mm; the area is dominated by cropland and recorded increase in shrubland by 6.3%. Sub-basin 14 where settlement increased by 36.3% due to loss of forest and cropland, recorded an increase in runoff of 73.2mm as shown in figure 7.

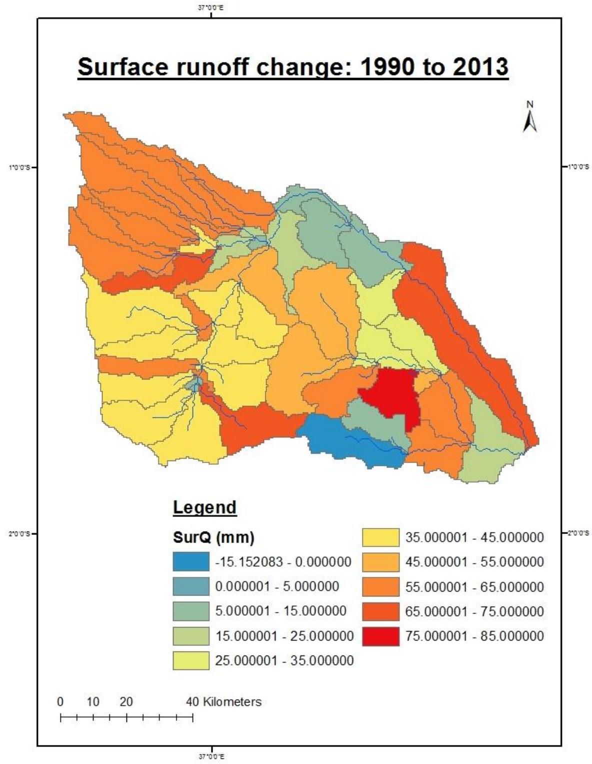

Figure 3: Change in surface runoff depth between 1990 and 2013

4. Discussion

4.1 Land cover change and Areas of Concern

The land cover class that experienced the greatest total loss between 1990 and 2013 was forests by 23.4% contributed mainly by conversion to shrubland and grassland mainly in Nairobi and Mid Athi Sub-regions. The loss of forests to shrubland and grassland is attributed to logging and land clearing leaving behind remaining fewer natural trees and younger trees of shorter heights. Between 1990 and 2000, in upper Athi Catchment Area, deforestation occurred in natural forests such as Ngong, Karura and Aberdare forests and measures have been put in place to conserve them through reforestation programmes and Government policies. The study showed that shrubland and cropland contributed to 36% increase in forests in Mid Athi Sub-region, predominantly in Sub-basins 45, 46 and 15 which can be attributed to increased reforestation and advocacy for conservation agriculture through community forestry activities.

Agricultural land and urban centres have increased by 69.72 km² and 397.82 km² respectively, between 1990 and 2013. The major driver to this increase in areas was highlighted as population growth and demand for resources that come with increased population. As per the population census in Kenya in 2009, the major counties in the study area: Nairobi, Machakos and Kiambu, recorded population growth rate of 4.1%, 3.0% and 2.0% with projections of 20.4%, 8% and 5.2% increase in population by 2013 respectively [20]. The demand for raw materials for various industries and space for constructing homes or cropland and pastures has resulted in the loss of forests and shrubland especially in Upper- and Mid Athi Sub-regions where increased settlement and cropland is recorded in sub-basins 6, 8 and 16. According to [21] rapid population increase led to rapid urbanization in major cities, towns and trading centres in the rural areas. Also, along with population growth, the need for food in urban areas caused conversion of forests and shrubland to cropland. This conversion to cropland was rapid near water bodies and town centres. As a result of expansion of agricultural land along the river banks and unplanned cropping up of built up impermeable infrastructure such as buildings and roads, flash floods have been a frequent occurrence in the study area. Erosion, siltation and water pollution also affected River Athi, its tributaries and the catchment area as a whole. [22], argued that as a result of rapid population growth and demand for development there was increased pressure for conversion forests to cropland and urban centres since more land was required to provide food and other needs. [23] mentioned that population growth and shifting cultivation were linked to deforestation. A study to improve smallholder productivity in Machakos region, which is part of the study area, concluded that land cover changes were caused by increase in population and infrastructure [24].

4.2 Runoff generation in Areas of Concern

4.2.1 Areas with environmental conservation

A number of environmental interventions have been in place in the study area including afforestation and conservation agriculture practices as a result of Government of Kenya and Athi Catchment Area legislation as well as intervention by local Water Resources Users Associations (WRUAs) in Mid Athi Subregion has seen increased forests and shrubland in the areas despite large areas of cropland and existing forest reserves in some areas such as Utangwa Forest Reserve in Sub-basin 46 and Mango Forest in Sub-basin 17. The subbasins which were highlighted as comprising large areas of environmental conservation which were increased forests and shrubland also recorded varying changes in runoff. In Sub-basin 46 where 27.3% of shrubland was converted to forest and 28.3% of cropland converted to forests, the result was an increase in runoff depth of 15mm/year, the lowest recorded increase in runoff for the study period. In Sub-basin 45 which recorded the largest change of shrubland to grassland relative to its area also recorded high conversions of shrubland and cropland to forest of 13.2% and 15.1% respectively and simulation results showed a decrease in runoff depth by 15.15mm/year. This can be attributed to the lower runoff coefficient of forests compared to cropland and shrubland. In Sub-basin 31 which recorded the greatest increase in runoff depth of 83.57 mm/year underwent increase in forests by 51% of its area with the remaining 49% dominated by cropland. This implies that conversion of cropland to forests may not reduce runoff in areas with steep slopes and clay soils. Change in land cover impacts runoff generation such that increasing forests from cropland will reduce surface runoff while increasing cropland and settlement increases runoff significantly.

4.2.2 Runoff harvesting spots

Regions in the study area have experienced negative land cover change including loss of forests and shrubland for cropland and settlement. The areas with the highest recorded areas of conversion also recorded the highest runoff values. The high values of runoff generated per year in the subbasins will provide an opportunity for runoff harvesting where other conditions such as soil and terrain allow. Sub-basins 31, 44, 14 recorded the greatest increase in runoff depth of 83.57. 74.83 and 73.25 mm/year. Sub-basins 6, 8 and 16 recorded increased surface runoff depths of 60.6mm/year each. In Sub-basin 31 and 44 which lie in semi-arid regions of the study area, runoff water can be used for agriculture especially due to scarcity of rainfall in the area.

5. Conclusions

Land cover change was evaluated using remotely sensed images of land cover. The study took into account simulations of SWAT hydrological model only and did not consider other possible models. The limitations to this study were cloud interference on the satellite images for some years, lack of comprehensive evenly distributed comprehensive data for rainfall and especially river flow data.

The simulation results for surface runoff between 1990 and 2013 have been presented for the whole study area and in specific land cover AOCs. Overall, the key changes in land cover observed in the study area between 1990 and 2013 were decreased forests and shrubland; and increased cropland and grasslands. It is notable that the chief potential drivers of these changes in the study area were growth of population and urbanization and climate change. Moreover, uncontrolled land uses due to weak policy framework for resource management has resulted in land cover changes in most parts of the study area. The simulated runoff results observed in the AOCs included reduction of forest cover and shrubland which recorded decreased runoff while reduction of grassland and cropland led to increased runoff in some areas. It was also noted that conversion of shrubland to forests had no significant impact on the changes in runoff quantities. Therefore, land cover changes driven by human factors have impact on surface runoff. Further research should be conducted to further identify and map land cover change for vegetation species in the AOCs and assess suitability for runoff harvesting in the AOCs, in order to advise on strategies to manage negative changes by implementing positive land cover conversions and promote sustainable water resource exploitation.

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