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Runoff Estimation for an Urban Area using SCS-CN Method, Remote Sensing and Geographic Information Systems Approach: A Case Study of Mavoko Municipality, Kenya

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Abstract: Over the last few years, Mavoko Municipality which borders Nairobi city in Kenya has experienced widespread land use \ land cover change which has altered the hydrological patterns of this watershed leading to occurrence of widespread flooding after rainfall events.

This study used the Soil Conservation Service Curve Number (SCS-CN) method integrated with remote sensing and Geographic Information Systems (GIS) techniques to estimate urban runoff and to study the impact of the land use\land cover changes on surface runoff rates between 1989 and 2018.

Precipitation data was from two rainfall stations i.e. Mua Hills rainfall station and the Jomo Kenyatta International Airport (JKIA) rainfall station. A Digital Elevation Model (DEM) was used to determine the Drainage network. Historical land use/land cover changes were mapped between 1989 and 2018 and combined with SCS-CN model to estimate depth and volume of runoff from the watershed.

Built-up areas that are largely impervious increased from 24.6% in 1989 to 37.0% in 2018 while the more pervious land under grasslands, open spaces and barren land decreased from 65.5% in 1989 to 44.5% in 2018.

69% of the annual precipitation in 1989 was converted into runoff while in 2018 76% of the annual precipitation was converted in runoff. The result was consistent with the land use/land cover changes and modelling results which showed that 68% of the area experienced increased runoff, 23% no change and 9% a decrease in runoff.

Correlation between potential maximum storage and the runoff volumes increased from 0.56 in 1989 to 0.59 in 2004 and 0.77 in 2018. The observed correlation between potential maximum storage and the runoff volumes indicates that the SCS-CN Method, Remote Sensing and Geographic Information Systems Approach can be a useful tool for runoff estimation.

Keywords— Precipitation, Runoff volume, SCS-CN, Land Use \ Land cover change, DEM

I. INTRODUCTION

Across the world there is an acute shortage of the availability surface runoff data from urban areas [1]. Additionally, there exists a knowledge gap on the hydrological catchment response to urbanization and land use \ land cover change in many cities [2].

Mavoko Municipality is one of the urban areas in Kenya which has experienced rapid land cover changes due to population pressure and land use\land cover changes [3]. These changes have resulted in increased impervious areas which in turn have led to decreased evapotranspiration rates, reduction in surface retention volumes and presence of barriers in natural water courses.

A knowledge gap exists in the rainfall- runoff patterns of Mavoko municipality. Over the years lack of sufficient runoff data has not been given the importance it requires. The common practice to address this issue, has habitually been oversizing and/or expanding the existing storm drainage infrastructures which has only served to delay the problem but has not provided a sustainable long-term solution.

This study sought to determine the depth and volume of surface runoff for Mavoko Municipality urban watershed based on the SCS-CN method, geographic information systems (GIS) and remote sensing techniques. It further sought to evaluate land use\land cover changes for the last 30 years and further evaluate the impact of land use\ land cover changes on depth and volume of surface runoff. To achieve this, a simple hydrological model was used.

Among all hydrologic models, the SCS-CN method stands out as the most widely used empirical model for computing the depth and volume of surface runoff [4]. The SCS-CN was developed by Ogrosky and Mockus in 1957 though it has undergone major advances since then [5]. This method not only considers climatic factors but also watershed characteristics such as soil type, slope of the land, hydrological soil condition (HSC), antecedent moisture content (AMC) and land use\ land cover types [6].

This study applied remote sensing technology and GIS technology as tools to estimate equation coefficients and model parameters which were then used in the SCS-CN model [7].

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II. METHODOLOGY

A. Description of Study Area

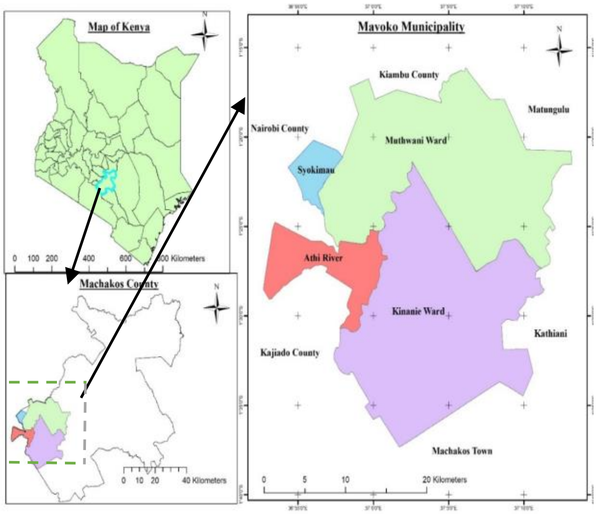

Figure 1: Location of Study Area

Mavoko Municipality lies within the Athi Catchment Basin and covers an area of 820 Km². Its population was enumerated in the 2019 national population census as 322,499 (Kenya National Bureau of Statistics, 2019). It is among the urban areas having the fastest urban growth rates in the Nairobi Metropolitan Region (NMR). Its population is projected to grow to 593,182 by 2030.

The Mavoko Municipality Catchment Basin is drained by Athi River and Mto wa Mawe rivers. This watershed experiences tropical savannah climate with an average annual rainfall of 712.89 mm with maximum and minimum temperatures ranging between 11 °C and 28 °C.

Mavoko Municipality has a high prevalence of clay soils formed on Pliocene and Miocene rock types and which comprise 60% of clayey soils [3].

B. Data Availability and Data sources

Digital Elevation Model (DEM) for the study area was obtained from the United States Geological Survey (USGS). Precipitation data for 1989 to 2018 for the watershed was obtained from the Kenya Meteorological Department (MET). Land use\land cover data was obtained from the Regional Centre for Mapping of Resources for Development (RCMRD) Kenya with a resolution of 30 m. Soil data was obtained from the Survey of Kenya.

C. Methodology

This study evaluated surface runoff changes, land use\land cover changes and the impact of land use/land cover changes on surface runoff rates for Mavoko Municipality. The study applied the SCS-CN method integrated with remote sensing and GIS techniques for estimation of urban runoff for 1989, 2004 and 2018 following the methodology depicted in Figure 2.

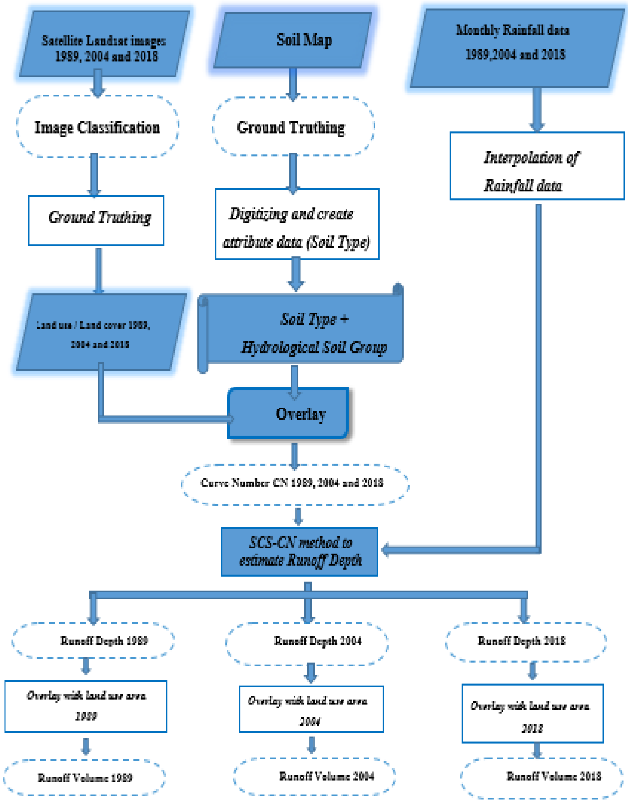

Figure 2: Methodology flowchart

Digital Elevation Map (DEM) was used to represent the landform of study area and the drainage network [8]. It enabled identification and location of all streams in the area, boundaries of the study area and preparation of the contour map of the area.

The procedure adopted in the methodology of this study involved creation of the following items which were used as inputs into the SCS-CN method;

1. Soil map,
2. Hydrological soil Group Map,
3. Precipitation maps (P) for 1989,2004 and 2018.
4. Land use/ land cover maps for 1989,2004 and 2018.

The created layers were processed using ArcGIS hydro tools integrated with the SCS-CN method to compute direct runoff depth.

1) Soil Conservation Service – Curve Number(SCS-CN) Method

a) Curve Number

The land use\ land cover image for 1989 was overlaid with the HSG map for 1989 and then re-coded and Curve Number values calibrated using the SCS table (USDA 1972) [9]. From the above process, a Curve Number image for 1989 was created. Curve Number maps for 2004 and 2018 were also developed using the above process.

b) Potential Maximum storage

The potential maximum storage (S) was computed for each pixel using map algebra GIS functions with the Curve Number map for 1989 being used as input (Equation 1)

$$S = \frac{25400}{CN} - 254 \quad (1)$$

Where CN is the Curve Number
S is the Potential maximum storage

A layer of potential maximum storage was then created for 1989. Potential maximum storage layers for 2004 and 2018 were also developed simmilarly.

c) Surface Runoff depth

The potential maximum storage layer for 1989 was overlaid with the precipitation layer for 1989 using map algebra GIS functions. (Equation 2)

$$Q = (P - 0.2S)^2)/(P + 0.8S) \quad (2)$$

Where P is the precipitation for 1989 in millimetres
S is the potential maximum storage for 1989
Q is the runoff depth for 1989 in millimetres

The new image created was the runoff depth image for 1989. Runoff depth maps for 2004 and 2018 were also developed using the above process.

d) Surface Runoff Volume

The runoff volume for the study area in 1989 was calculated using runoff depth layer and map algebra GIS functions. (Equation 3)

$$V = (A \ x \ (10)^6) \ x \ (Q/1000) \quad (3)$$

Where V is the runoff volume in cubic metres for 1989
Q is the runoff depth for 1989 in millimetres
A is the catchment area experiencing the respective runoff depth value in square metres

The new image created was the runoff volume map for 1989. Runoff volume maps for 2004 and 2018 were also developed similarly.

e) Surface Runoff Volume changes

The raster layer of runoff volume values in 2018 was divided by the raster layer of runoff volume values for 1989.The resulting image was classified to show areas whose runoff increased, decreased or remained the same over the 30 years.

2) Impact of land use \ Land cover change on Surface Runoff

According to the SCS-CN model, an urban area with a high degree of built up area i.e. large impervious areas has a low average value of potential maximum storage while an urban area with a low degree of built up area i.e. small impervious areas has a high average value of potential maximum storage. Therefore, the effect of land use\land cover change on surface runoff was studied by relating the two variables ie the potential maximum storage and the runoff volumes for the specific years.

III. RESULTS AND DISCUSSIONS

a) Soil Types and Hydrological soil Conditions in study area

The study area had four soil types namely, loamy, sandy, clayey and very clayey soils that were distributed as shown as shown in Figure 3. Sandy soils were observed in Kinanie ward and Loamy soils were observed in Muthwani ward and some sections of Athi River ward. Clayey and very clayey soils were observed in Muthwani and Kinanie wards and sections of Syokimau and Athi River wards.

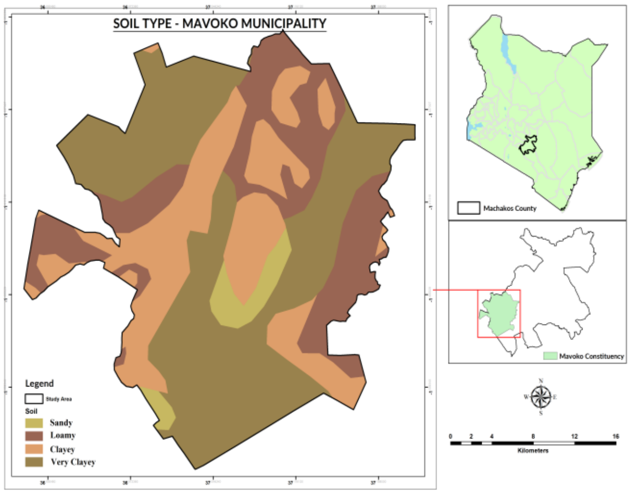

Fig 3: Soil Map for the Study area

The soil map of the study area was analyzed as per the United States Department of Agriculture (USDA) soil classification table categorized into four Hydrological Soil Groups (HSG).

Sandy soils were categorized into HSG A which has of low runoff potential and high infiltration capability. Loamy soils were classified into HSG B which has moderate infiltration rates and moderate runoff potential. Clayey soils were classified into HSG C which has low infiltration rate and high downward moment of water according to USDA soil classification table. Very Clayey soils were classified into HSG D which has remarkably high runoff potential and very low infiltration rates of water.

Hydrological soil Group A was observed in Kinanie and Muthwani wards respectively. Hydrological soil group B was observed in Muthwani ward and some sections of Athi River ward. Hydrological soil Groups C and D were observed in Muthwani and Kinanie wards and sections of Syokimau and Athi River wards. The four hydrological soil conditions are shown in Figure 4.

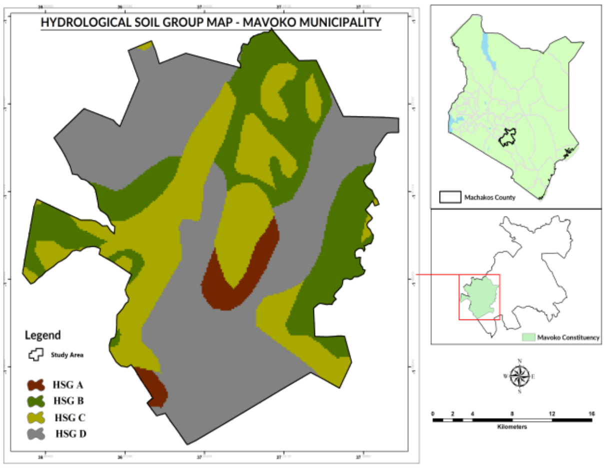

Fig 4: Hydrological Soil Group map of the Study area

b) Land use and Land cover changes in study area

The percentage of built up areas increased from 24.6% in 1989 to 26.8 % in 2004 and to 37% in 2018. The percentage of grasslands, open spaces and barren land decreased from 65.5% in 1989 to 47.6% in 2004 and finally decreased to 44.5% in 2018 (Figure 5).

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A keen study of the land use\land cover map for the study area indicates that areas that were classified as grassland and open spaces in 1989 had been transformed into built-up area, agricultural land or forest land in 2018.

The area under forest cover increased from 0.4% in 1989 to 1.9% in 2004 and to 2.9% in 2018 which was attributed to agroforestry and tree planting in homes and reforestation initiatives by Cement processing companies in the area.

A keen study of the land use/ land cover maps for 2004 and 2018 shows that big tracts of land which had been initially been under agricultural land use were transformed into built up area (Figure 5).

The area under agricultural land increased from 3.2% in 1989 to 5.8% in 2004. This was due to setting up of extensive horticultural farms along Athi River and increased farming activities among the local inhabitants of the study area. The area decreased from 5.8% in 2004 to 5.1 % in 2018 due to urbanization.

The area under rivers and water bodies increased from 6.3% in 1989 to 17.9% in 2004. This was due to massive land reclamation activities by cement processing companies which converted their clay borrow pits into Man-made lakes.

The area under rivers and water bodies then decreased from 17.9% in 2004 to 10.5 % in 2018 (Figure 5). This was due to encroachment of riparian lands and that the originally reclaimed lands by most Cement processing companies were now being converted into settlement schemes.

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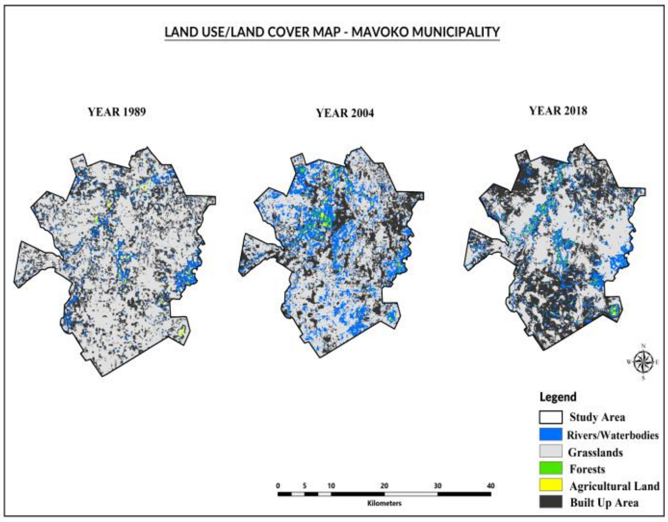

Fig 5: Land use\ land cover maps for in 1989, 2004 and 2018

The Curve Number map for 1989 indicated that CN value 86 was observed to be the most dominant CN value in the urban watershed. This was attributed to the fact that 65.5% of the watershed was covered by grasslands and open spaces which have a CN value of 86 (Figure 6).

In the Curve Number map for 2004, CN value 86 and CN value 100 were dominant. The observation was attributed to 47.6% coverage of the watershed by grasslands and open spaces which have a CN value of 86 and 17.9% of the watershed being covered by rivers and waterbodies whose Curve Number values is 100 (Figure 6).

In the Curve Number map for 2018, CN value 86 and CN value 98 were observed as the most dominant CN values. The observation was attributed to 42.5% coverage of the watershed by grasslands and open spaces, which have a CN value of 86, and 37% coverage of the watershed by built-up areas whose Curve Number value is 98 (Figure 6)

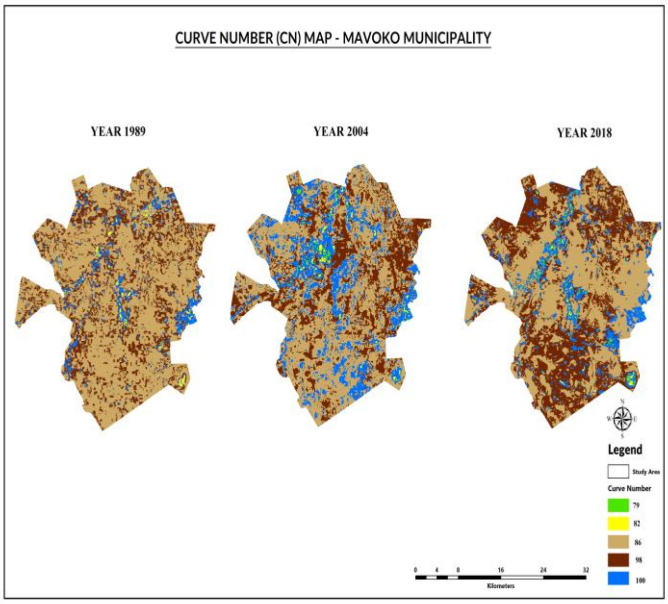

Fig 6: Curve Number maps for the Study area in 1989, 2004 and 2018.

c) Rainfall patterns

This study focused on the rainfall patterns of 3 years; namely, 1989, 2004 and 2018. Figure 7 shows the precipitation map for 1989 for the two rainfall stations, Mua Hills and the Jomo Kenyatta International Airport (JKIA) that were used in the study. Year 2018 had the highest precipitation of the 3 years while 2004 had the lowest with an annual rainfall.

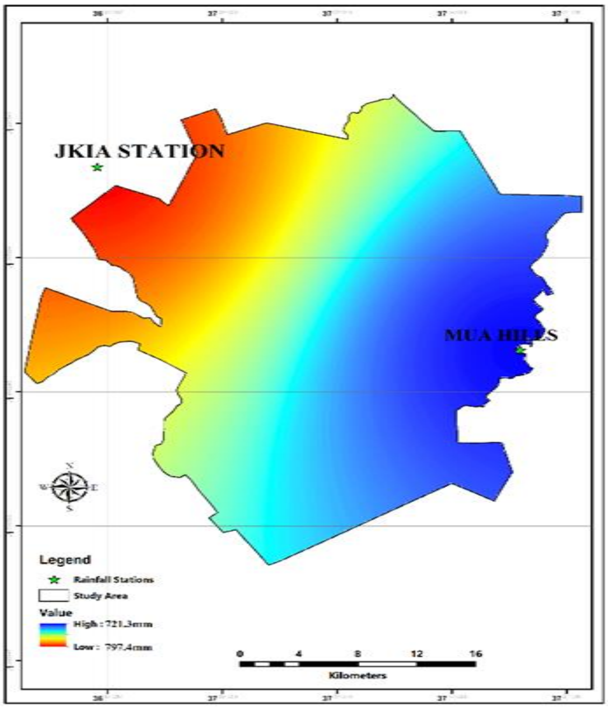

Fig 7: Precipitation map for the study area in 1989

d) Modelled runoff depths and Volumes

The annual runoff depth observed from SCS-CN method, GIS and remote sensing techniques for 1989, 2004 and 2018 was 525.8, 474.2 and 590.5 mm respectively (Figure 8).

In 1989, 69 percent of the rainfall was converted into runoff. In 2004, 72 percent of the annual precipitation was converted into runoff while in the year 2018, 76 percent of the annual precipitation was converted into runoff (Figure 8).

Figure 8 shows that the rainfall-runoff potential has been increasing throughout the 30 years' period. This observation can be attributed to land use/land cover changes such as increase in built up areas, which had increased the impervious surfaces. It can also be attributed to decrease in pervious surfaces such as open spaces barren lands and grasslands.

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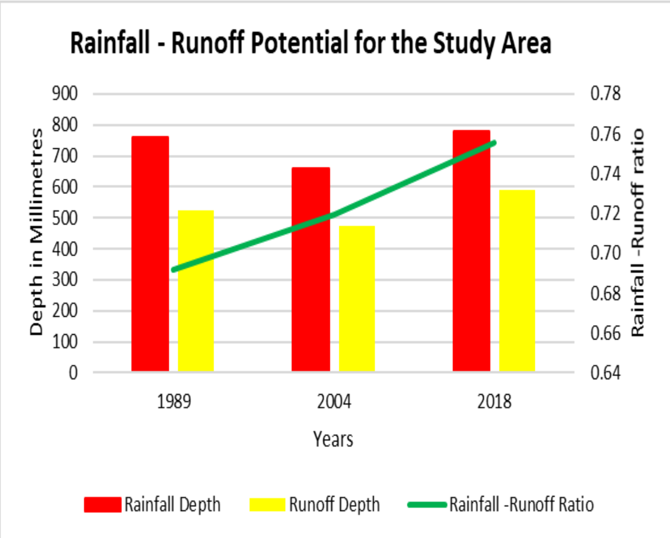

Fig 8: Rainfall – Runoff Ratio for the study area in 1989, 2004 and 2018

Fig. 9 shows that runoff volume in Mavoko Municipality was predominantly (over 96%) from built-up areas and grasslands and open spaces. Forest and agricultural land contributing the remaining 4%.

The relative contribution of the two dominant land use areas built-up areas and grasslands and open spaces changed significantly over the study period. Runoff from grasslands and open spaces decreased by 26.9% between 1989 and 2018. On the other hand, runoff from built-up areas increased by 18% to account for 48% of the total runoff.

The observed trend in runoff volumes indicate that built-up areas in the future, built-up areas will be the predominant contributor to surface run-off. Because built-up areas have greater runoff than other land uses, designs for drainage systems should factor in the increased runoff in the design life of the systems.

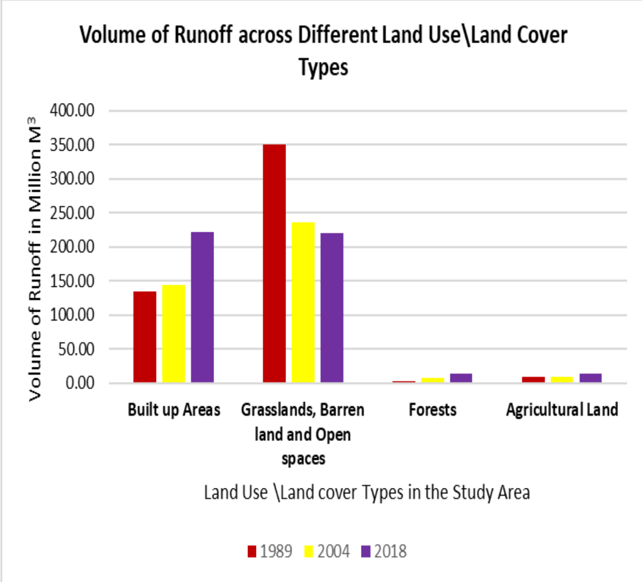

Fig 9: Runoff volume changes from different land use \ land cover types in the study area in 1989, 2004 and 2018

e) Spatial Runoff changes

In order to illustrate the change in runoff production over the 30 years, the raster layer of runoff depth values for 2018 was divided with the layer of runoff depth values for 1989. The obtained results were classified into three categories; namely, less than one representing decrease in runoff volume, no change which represents the same or unchanged runoff and greater than one which represents increased runoff (Figure 10).

Areas in the first category with decreased runoff are mainly previous pasture land, which was subdivided and converted to agroforestry and farming land or otherwise fenced off allowing growth of vegetation. The second category with no change in runoff depth includes areas that have retained their land use. The third category with increased runoff indicates land use to that with more impervious surfaces such as built-up areas. The result shows that overall 68% of the study area experienced an increase in runoff volume, 23% no change and 9% a decrease.

When the 2004 runoff image was subtracted from that of 2018, the resulting image of change indicated that the annual runoff depth had increased by 121 mm of which only 114 mm could be accounted for by the difference in precipitation; the remaining difference was attributed to changes in land use and land cover.

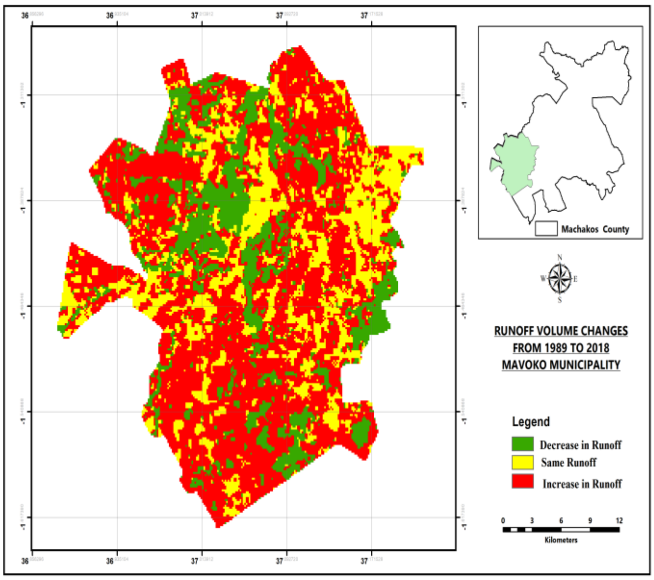

Fig 10 : Runoff depth changes from 1989 to 2018

The correlation value "r" between impervious area and potential maximum storage for the study area was 0.56 for 1989, 0.59 for 2004 and 0.77 for 2018. The increase in correlation value over the 30 years indicated the effect of land use/land cover changes on the surface runoff.

IV. CONCLUSIONS

This study evaluated the long term effects of land use\land cover changes on surface runoff in the Mavoko Municipality. Land use changes for over a 30year period from 1989 to 2018 were studied and the runoff changes analysed.

This study showed an increase in built up areas and forests. The built-up area expanded from 202 km^2 to 303 km^2 i.e. to 37% of the total area over the 30 years' period. There was a corresponding reduction in agricultural land, barren lands, grasslands and open spaces.

There was a strong relationship between increase in impervious surface and increase in runoff volume. It was observed that land use\land cover changes had impacted positively on surface runoff leading to an increasing trend in surface runoff rates for the study area

Remote sensing and Geographical information systems were observed to be efficient tools for the preparation of most input data required by the SCS curve number model.

Suggestions for further work

This study has demonstrated the use of the SCS-CN method, GIS and Remote Sensing in runoff estimation for urban areas. Future studies on should focus on Flood hazard zone mapping to complement this research work.

Conflict of interest: The author declares that he has no any conflict of interest.

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