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SPATIAL-TEMPORAL VARIATION OF GROUNDWATER RECHARGE FROM PRECIPITATION IN THE STONY ATHI SUB-CATCHMENT, KENYA

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Abstract

Purpose: Groundwater recharge is an important process for sustainable groundwater development and its quantification is a prerequisite for efficient management of groundwater resources. The purpose of this study was to evaluate the scale and spatial-temporal variation of groundwater recharge from precipitation in the semi-arid Stony Athi sub-catchment.

Methodology: A descriptive case study approach was used for the evaluation. WetSpass-M, a GIS physically based, spatially distributed watershed model was applied. The model integrates biophysical and climatic characteristics of a watershed to simulate the long term mean groundwater recharge. Grid maps of the sub-catchment characteristics were prepared from primary and secondary data using ArcMap. The model was applied for four periods, namely, 1984, 1995, 2005 and 2017. Besides the average groundwater recharge, other outputs of the model include surface run-off and actual evapotranspiration. The study was carried out between January and December 2018.

Findings: Land cover in the Stony Athi sub-catchment is comprised of built-up area, agricultural land, grassland, shrub-land, mixed forest and bare land. Topography ranges from 1493 m to 2,082 m above sea level with a slope of between 0% and 30%. Soil types include sandy loam, loam, sandy clay loam, sandy loam and clay. The mean annual precipitation is about 634 mm while the potential evapotranspiration is about 1,490 mm. Annual temperature averages 19.0°C with a mean maximum of 25°C and a mean minimum of 12.7°C. The results of the simulation indicated that the long-term temporal and spatial average annual rainfall of 634 mm is distributed as 88 mm (14%) recharge, 77 mm (12%) surface runoff while 475 mm (75%) is lost through evapotranspiration.

Unique contribution to theory, practice and policy: This study demonstrate the importance of physically-based spatially-distributed hydrological models in estimating the water balance. The study provides a theoretical basis for scientific, rational resource allocation and utilization as well as creating awareness of the need to enhance groundwater governance. Results from this study can be used as an input for building an integrated groundwater modelling and for evaluation of potential sites for managed artificial recharge through harvesting runoff to improve groundwater storage.

Key Words: *Groundwater recharge; WetSpass-M; Stony Athi*

1.0 INTRODUCTION

Groundwater recharge is an important factor that determines the groundwater development potential of an area (Mohan *et al*., 2018). The process of groundwater recharge is governed by many factors such as land use and land cover, topography, soil conditions, climate and the spatial patterns of interactions of these factors (Saghravani *et al*., 2013; Zomlot *et al.*, 2015; Zarei *et al.*, 2016). In a water catchment, a strong dynamic interaction exists between land characteristics and the natural water systems, which can significantly impact water quantity and quality for various human uses and ecosystem health (Klemas & Pieterse, 2015; Pulido-Velazquez *et al.,* 2015). Mohan *et al*., (2018) showed that meteorological factors, especially precipitation and potential evapotranspiration as well vegetative cover have the most predictive power for groundwater recharge. Vegetated surfaces intercept rainfall and delay flow on the surface, thereby promoting infiltration. Forest soils retain water such that it is slowly released to groundwater or flow to streams and rivers over days, weeks and months. Open, grassy surfaces likewise capture and slow the flow of water; hence retain soil moisture, thereby promoting infiltration. In contrast, pavement and compacted or indurated soils impede infiltration and increase surface runoff, which consequently contribute to flooding and may contaminate surface waters (Klemas & Pieterse, 2015; Owuor *et al*., 2016).

The spatial-temporal variability of climatic conditions and land use/land cover as well as the spatial heterogeneity of physical characteristics of a watershed imply that groundwater recharge also varies spatially and temporally (Zomlot et al., 2015). Understanding the spatial and temporal variations of the water balance components in a region is indispensable for efficient and sustainable management of groundwater resources (Gebremeskel & Kebede, 2017). With the advent of Geographic Information System (GIS), physically-based hydrologic modeling has become important in contemporary hydrology for assessing the water balance at a spatial scale in a cost effective way. The spatial variation in recharge due to distributed land use and land cover, soil texture, topography, and climatic conditions are important parameters which should be accounted for in recharge estimation (Rwanga, 2013; Rwanga & Ndambuki, 2017). In the present study, the long-term monthly average climatic time-series data was used in combination with biophysical characteristics of the Stony Athi sub-catchment to simulate the distributed water balance components for the years 1984, 1995, 2005 and 2017 using WetSpass-M model, integrated in GIS ArcMap.

1.1 Statement of the Problem

Migration occasioned by employment opportunities and availability of land for settlement, coupled with changes in land tenure and land policy has led to expansion of settlements, agricultural activities and urban development in the Stony Athi sub-catchment. This has resulted to increased water demand due to the increased population and changes of sedentary lifestyles (Morara *et al*., 2014; Said *et al*., 2016). Like other parts of the world, arid and semi-arid areas in Kenya are characterized by low rainfall amounts with erratic and unreliable timing associated with recurring droughts (Bobadoye *et al*., 2014). Therefore, groundwater is the main source of water for the populace and is key to economic development. According to the Kajiado County Integrated Development plan 2018-2022 report, the main sources of water in the rural areas are water pans, dams and protected springs with the most reliable source being boreholes (CIDP, 2018). Presently, utilization of groundwater in the sub-catchment is going on with limited knowledge of its potential.

Groundwater occurrence in the area is highly spatially variable and the percentage of precipitation that undergoes recharge is unknown. It is against this background that the present study was carried out with the aim of addressing this knowledge gap for optimal and sustainable utilization of the groundwater resource as well as its protection against pollution.

2.0 LITERATURE REVIEW

Groundwater is an important source of water for human use globally because of its capacity to buffer short-term climatic variability; its comparatively good quality; and the affordability of infrastructure for groundwater abstraction, compared to surface water (Wang *et al*., 2010). Groundwater replenishment is facilitated by rainfall through the process of recharge, quantification of which is a fundamental part of groundwater resources evaluation (Herrmann *et al.*, 2015, von Freyberg *et al.*, 2015). In semi-arid and arid areas where groundwater is often the major water resource, and is likely to be prone to depletion under projected future climate trends, groundwater recharge estimation is even more important (Wang *et al.*, 2010). A host of methods are available for quantification of groundwater recharge, which include direct measurements, Darcian approaches, water-balance methods, tracer techniques, empirical relationships, and groundwater model methods. Selection of any one method depends on available data, local geographic and topographic conditions as well as the spatial and temporal scale required (Islam *et al*., 2015; Ali & Mubarak, 2017). However, estimating recharge has long been one of the most difficult challenges in hydrological science because recharge rates vary widely in space and time. Application of physically distributed modelling techniques has been an area of significant scientific advancement in recent years, driven by technological advances in GIS that has rendered analysis of water resources cost-effective. The techniques are useful tools for assessing the spatial distribution of groundwater recharge brought about by heterogeneity of the various controlling physical factors as well as temporal distribution due to changes in land use / land cover and climatic conditions.

In Kenya, investigations of groundwater recharge is still highly fragmented. There is a gap in information on the scale, temporal and spatial distribution of groundwater recharge across much of the country. To reduce this gap, the present study applied the WetSpass-M model, a useful tool for simulating spatially distributed recharge, surface runoff, and evapotranspiration for monthly averaged climatic conditions as presented by Abdollahi *et al*., (2017). The model and its precursor version WetSpass, has been shown to help better characterize water balance and is applicable in a variety of geographical areas in the world with different environments (Abdollahi *et al*., 2018; Salem *et al*., 2019). It has been widely used for various hydrological studies by different authors, for example, Al-Kuisi & El-Naqa, (2013) used WetSpass to estimate groundwater recharge in Jafr basin, Jordan while Albhaisi *et al.*, (2013) used the model to determine land use changes in upper Berg catchment, South Africa and to predict the impact of these land use changes on groundwater recharge; Aish, (2014) also used the model to estimate the water balance components in the Gaza Strip, Palestine while Zarei *et al*., (2016) applied WetSpass-M to assess the groundwater recharge, surface runoff and evapotranspiration in the Mashhad basin in Iran; Arefaine *et al*., (2012), Gebreyohannes *et al.*, (2013), Gebremeskel & Kebede, (2017) and Meresa *et al*., (2019) used WetSpass to assess the water balance in Illala catchment, Geba basin, Werii and Birki watersheds in Ethiopia, respectively; Zhang *et al*., (2017) applied the model to evaluate the urbanization effects on the water balance on a regional scale in Beijing, China; Graf & Przybyłek (2018) used the same method to identify factors controlling recharge of shallow groundwater in Poznań Upland, Poland. Ashaolu *et al*., (2020) applied the model to evaluate its performance in estimating groundwater recharge for data poor regions in a Basement Complex Nigeria. Other authors who have applied the model include Abdollahi *et al.*, (2012), Rwanga, (2013), Zomlot *et al.*, (2015), Abdollahi *et al.*, (2017), Armanuos *et al*., (2016), Melki *et al*., (2017) and Salem *et al*., (2019). In Kenya no study using this model has been reported and this research is the first one to assess the spatial and temporal distribution of groundwater recharge.

3.0 MATERIALS AND METHODOLOGY

3.1 Location of the Study Area

The map in Figure 1 shows the Stony Athi sub-catchment, the general drainage pattern and the major towns as well as its location in the Republic of Kenya.

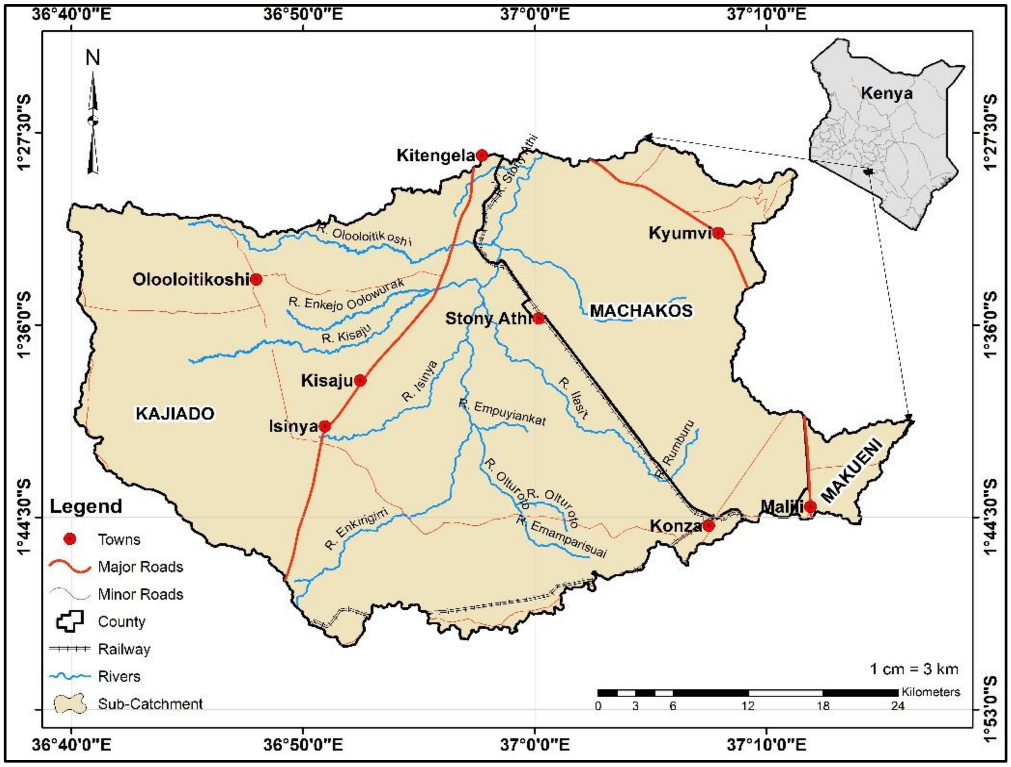

Figure 1: Map of Stony Athi Sub-catchment with inset showing its location in Kenya

The sub-catchment is bounded by latitudes 1°28'S and 1°50'S and longitudes 36°40'E and 37°15'E covering an area of about 1,745 sq.km. The larger part of the sub-catchment (71%) lies in Kajiado County, 27% in Machakos County and 2% in Makueni County. It is part of the head-waters of the Athi River, which is the second largest river in Kenya. The sub-catchment lies in the semi-arid Athi-Kapiti plains which gently slopes from west to east with relief ranging from 2,082m to 1493 m above sea level with a mean of 1787 m. Isinya aquifer is the main groundwater reservoir.

3.2 WetSpass-M Model

WetSpass-M stands for **W**ater and **E**nergy **T**ransfer between **S**oil, **P**lants and **A**tmosphere under quasi-**S**teady **S**tate (Abdollahi *et al.*, 2017) while M stands for monthly simulation. WetSpass was developed to estimate the long-term average, distributed water balance components at a seasonal scale (Batelaan & De Smedt, 2001). WetSpass-M is a downscaled model from the seasonal temporal resolution to a monthly scale. It calculates the monthly actual evapotranspiration as a sum of the evaporation of water intercepted by vegetation, the transpiration of the vegetative cover and the evaporation from bare soil between the vegetation. The model uses the runoff coefficient method for the estimation of surface runoff, which is a function of the vegetation type, soil texture and slope (Al-Kuisi & El-Naqa, 2013). Groundwater recharge is the residual component of the water balance obtained by subtracting the sum of surface runoff and actual evapotranspiration from precipitation. Since the model is a distributed one, the water balance computation is performed at a raster cell level. Each raster hydrological component is obtained by summing up independent components for the vegetated, bare soil, open-water, and impervious fraction of a raster cell to obtain the water balance from each cell (Batelaan & De Smedt, 2001; Abdollahi *et al.*, 2012). Thus, the water balance components of a raster cell for a given time period are as follows:

$$ETraster = avETv+asEs+aoEo+aiEi$$

$$Sraster = avSv+asSs+aoSo+aiSi$$

$$Rraster = avRv+asRs+aoRo+aiRi$$

Where; ET_{raster}, S_{raster} and R_{raster} represent evapotranspiration, surface runoff, and recharge. Subscripts relate to a raster cell's vegetation (v), bare soil (s), open water (o) and impervious area (i) while av, as, ao, and ai are the fractions of each land cover in a raster cell. The monthly water balance per a grid cell can be represented as follows:

$$Pm = SRm + ETm + Rm$$

Where; Pm is the monthly precipitation, SRm is the monthly surface runoff, ETm is the monthly evapotranspiration, and Rm is monthly groundwater recharge.

3.3 Input Data for WetSpass-M Model

The WetSpass-M model requires two types of input data namely, GIS grid maps and parameter tables. The GIS grid maps are prepared from climatic data (rainfall, air temperature, potential evapotranspiration, and wind speed) as well as biophysical characteristics including topography, slope, soil type and groundwater depth (Abdollahi *et al.*, 2017). In the present study, land use and land cover data was obtained from satellite images of multi-temporal images for the years 1984, 1995, 2005 and 2017 downloaded from the USGS Earth Explorer website https://earthexplorer.usgs.gov/. The data was then processed and classified as described by Young *et al*., (2017). The classification accuracy was verified by ground truth data in form of ground reference points collected using a hand held Geographical Positioning System (GPS) set. Climatic data used in the study was obtained from the Kenya Meteorological Department for four different stations located within and surrounding the sub-catchment. Additional data for five other stations was downloaded from https://en.climate-data.org website Elevation data was obtained from Shuttle Radar Topography Mission *(*SRTM*)* dataset in form of Digital Elevation Model (DEM), which was then used to generate a slope map. The soil grid map was generated from the exploratory soil and agro-climatic zone map of Kenya (Sombroek *et al.*, 1982) on a scale of 1:1,000,000, the Harmonized World Soil Data (HWSD) base (Karim & Saeid, 2019) and analyses of 67 soil samples collected randomly within the sub-catchment and tested in the laboratory using the hydrometer test to determine the United States Department of Agriculture (USDA) soil texture classification. Groundwater depth data was obtained from the Water Resources Authority. Interpolation of the vector data was done using the inverse direct weighting (IDW) interpolation tool in ArcMap. All the maps were normalized to achieve a uniform 30-meter resolution and then converted to ASCII files for use in the WetSpass-M software.

WetSpass-M requires all the grid maps to have the same number of columns and rows, number of bands, cell size, extent and spatial reference (Rwanga, 2013). All inputs for the model were therefore resampled based on the DEM with total number of 2192 x 1347 raster cells and a cell size of 30 x 30 m. The land use and land cover and soil data were supported by attribute look-up tables in the simulation process (Abdollahi *et al.*, 2012). Based on the soil texture map, physical parameters namely, saturated hydraulic conductivity, soil porosity, field capacity, residual moisture, pore distribution index, plant wilting point and initial moisture were created by means of an attribute lookup table. On the other hand, root depth, vegetation fraction, interception capacity and the leaf area index (LAI) were assigned for each cell based on the land cover map (Albhaisi *et al.*, 2013).

3.3.1 Land Use and Land Cover

The land use and land cover thematic maps for the years 1984, 1995, 2005 and 2017 for the Stony Athi sub-catchment are presented in Figure 2 while the area and percentage of each land use/land cover category are shown in Table 1.

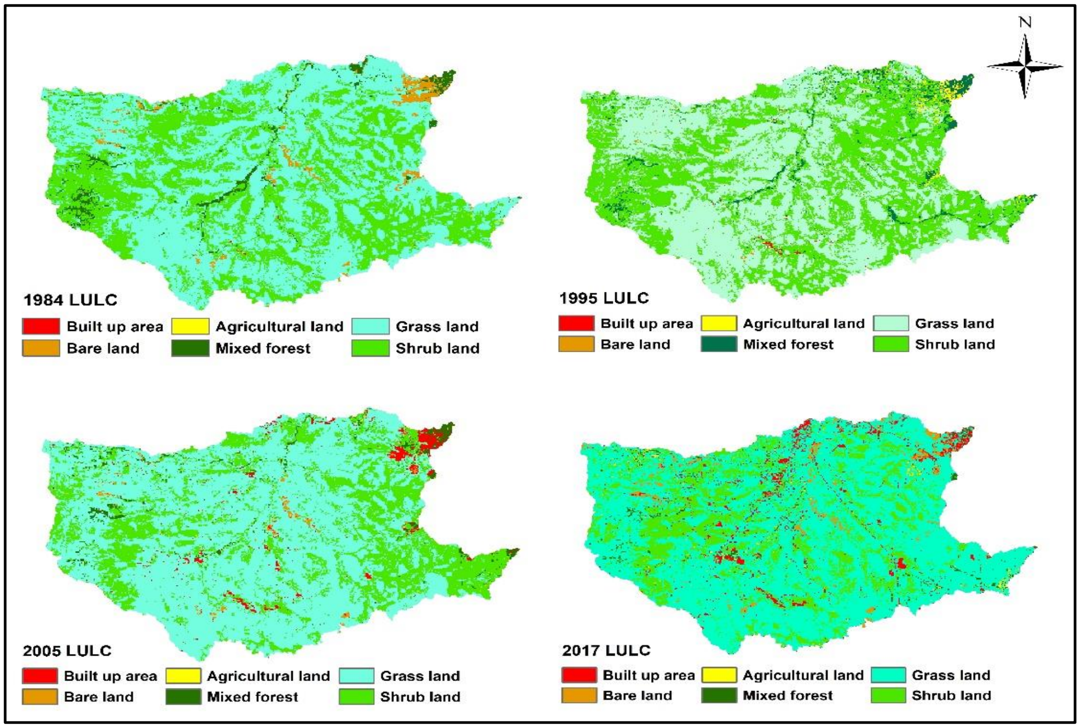

Figure 2: Land use and land cover thematic maps of Stony Athi Sub-catchment

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Table 1: LULC area and percentages in Stony Athi Sub-catchment - 1984 to 2017

	1984		1995		2005		2017	
Land use and land cover Class	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**
Built-up area	0.64	0.04	4.1	0.2	33.4	2.0	59.5	3.4
Agricultural land	1.04	0.06	6.2	0.4	3.7	0.2	11.6	0.7
Grassland	1016.4	58.2	910.0	52.1	1175.5	67.4	1250.0	71.6
Shrub land	647.7	37.1	765.7	44.0	486.2	28.0	368.0	21.1
Mixed forest	44.0	2.5	57.5	3.3	34.0	2.0	23.7	1.4
Bare land	35.8	2.1	2.08	0.1	12.6	0.7	32.6	2.0
Total	**1,745**	**100**	**1,745**	**100**	**1,745**	**100**	**1,745**	**100**

Six land use and land cover types were identified, namely; built-up area, agricultural land, grassland, shrub-land, mixed forest and bare land (Mathenge *et al*., 2019). In 1984, out of the total area of 1,745 km^2 of the Stony Athi sub-catchment, built-up area occupied 0.64 km^2 while agricultural land was 4.1 km^2; grassland, 1,016.4 km^2; shrub land, 647.7 km^2; mixed forest, 44.0 km^2; and bare land, 35.8 km^2. By 2017 built-up area occupied 59.5 km^2; agricultural land, 11.6 km^2; grassland, 1,250 km^2; shrub land, 368 km^2; mixed forest, 23.7 km^2; and bare land, 32.6 km^2. Significant changes were observed in all the land use and land cover classes with an increase in built-up areas (0.04% in 1984 - 3.4% in 2017), agricultural land (0.06% in 1984 - 0.7% in 2017), savannah grasslands (58.2% in 1984 - 71.6% in 2017), but a decrease in savannah shrubs (37.1% in 1984 - 21.1% in 2017) and mixed forest (2.5% in 1984 - 1.4% in 2017). Marginal changes were detected in bare grounds (2.1% in 1984 - 2.0% in 2017).

3.3.2 Climatic Characteristics

Figure 3 shows the distribution of the annual climatic parameters of rainfall, potential evapotranspiration and temperature of the Stony Athi sub-catchment.

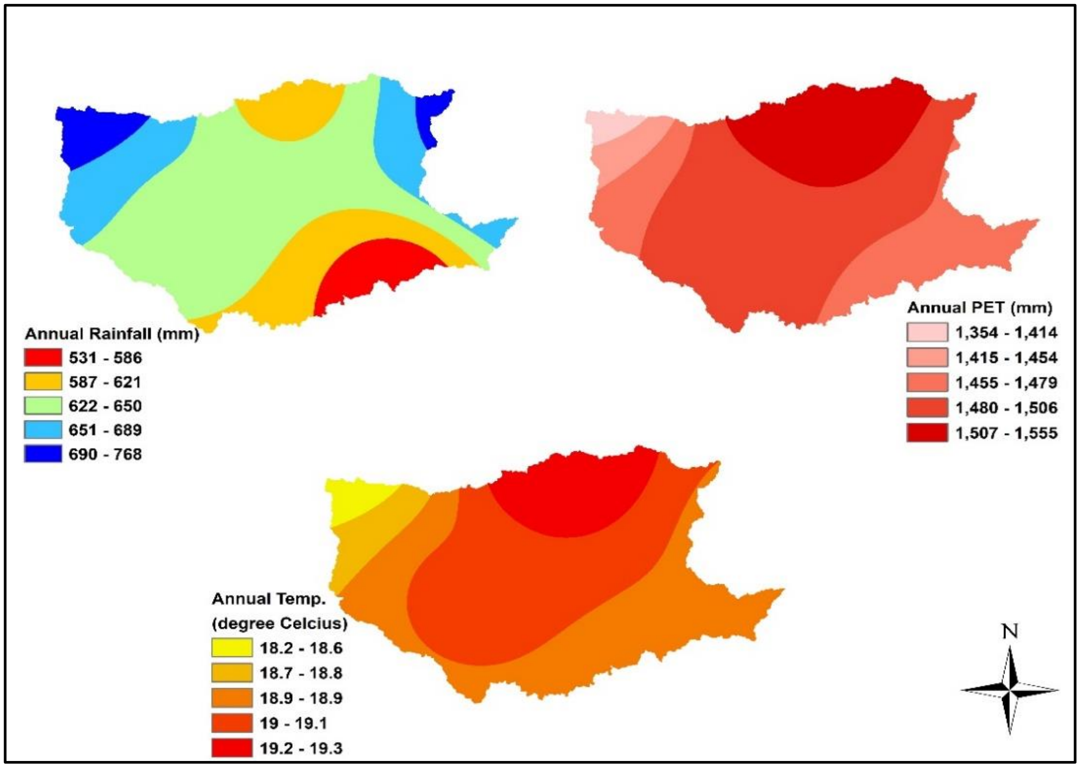

Figure 3: Annual climatic parameters: rainfall, potential evapotranspiration and temperature

Overall, the climate of the area is semi-arid with average annual rainfall ranging between 531 mm and 768 mm with a mean of 634 mm and a standard deviation of 33 mm. The annual potential evapotranspiration (PET) ranges between 1354 mm and 1555 mm with an average value of 1490 mm and a standard deviation of 25 mm while annual temperatures average 19.0 °C with a mean maximum of 25 °C and a mean minimum of 12.7 °C. Wind speed varies from 2.8 m/s to 4.5 m/s, with an average value of 3.7 m/s. The monthly climatic data for the sub-catchment is presented in Table 2 and Figures 4 & 5.

Table 2: Monthly climatic data for the Stony Athi sub-catchment

Month	Average rainfall (mm)	Potential Evapotranspiration (mm)	Temp $_{Max}$ (^{0}C)	Temp $_{Min}$ (^{0}C)	Temp $_{Ave}$ (^{0}C)	Wind speed (m/s)
January	41.6	134	26.3	12.7	19.4	4.4
February	39.8	146	27.4	12.9	20.2	4.5
March	77.6	151	27.0	14.2	20.5	4.3
April	137.9	139	25.4	14.5	20.0	3.6
May	77.3	122	24.3	13.7	19.0	2.9
June	15.1	99	23.4	11.6	17.4	2.8
July	4.7	88	22.3	10.8	16.5	2.8
August	6.7	94	22.9	11.0	16.9	3.0
September	8.7	119	25.2	11.5	18.4	3.4
October	38.7	140	26.3	13.0	19.7	4.1
November	113.1	129	24.7	13.8	19.3	4.2
December	72.3	128	24.8	13.0	18.9	4.5
Annual	**633.5**	**1489**	**25**	**12.7**	**19.0**	**3.7**

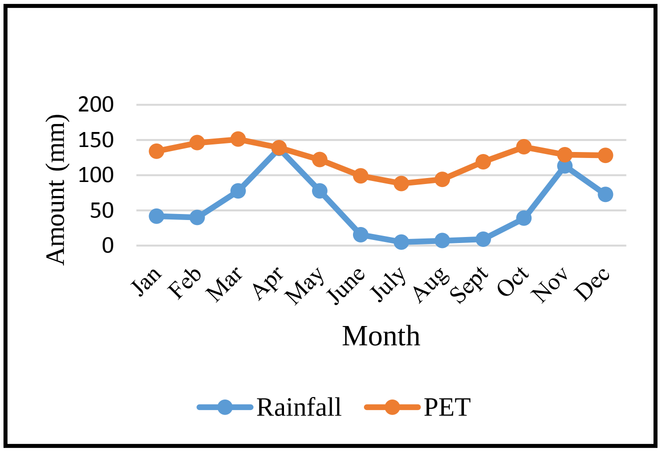

Figure 4: Monthly average precipitation and potential evapotranspiration

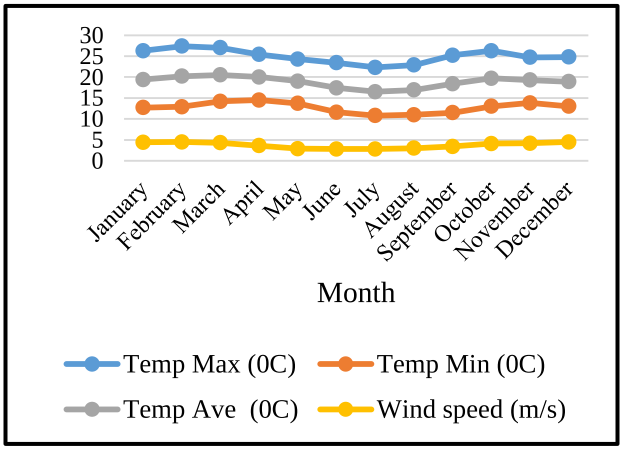

Figure 5: Monthly temperature and wind speed

The rainfall pattern shows a bimodal trend, depicting two rainy seasons; the first rainy season from March to May with a peak in April while the second rainy season is from October to December with rainfall amounts less than that of the first rainy season. The least amount of rainfall occurs in July, August and September with values of 4.7 mm, 6.7 mm and 8.7 mm, respectively, while the highest occurs in April and November with average amounts of 137.9 mm and 113.1 mm, respectively. The average monthly rainfall is about 53 mm, which fairly agrees with Bobadoye et al., (2014) who gave 51.01 mm as the average rainfall at Isinya meteorological station, which is centrally located in the Stony Athi sub-catchment. The highest potential evapotranspiration was recorded for the month of March followed by February with 151 mm and 146 mm, respectively, while the lowest values were 88 mm and 94 mm for the months of July and August, respectively.

The highest temperatures have been recorded in February while July has the lowest temperature in the year with values of 27.4°C and 10.8°C, respectively. The mean annual temperature is 19.0°C Wind speed varies from 2.8 in June and July to 4.5 m/s December to February.

3.3.3 Physical Characteristics

The distribution of the physical characteristics of the Stony Athi sub-catchment namely, the digital elevation model (DEM), slope, soil type and groundwater depth is presented in Figure 6.

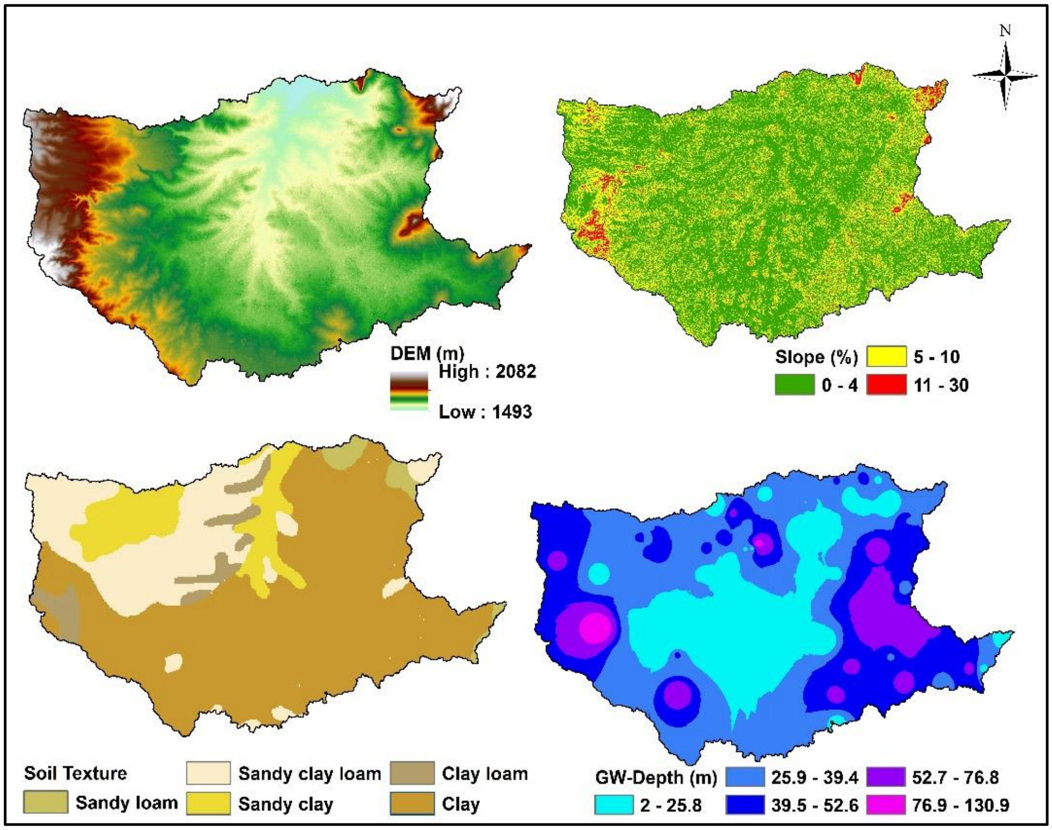

Figure 6: Stony Athi sub-catchment physical characteristics – DEM, slope, soil and groundwater depth

Topography and Slope

DEM data indicates that the maximum elevation is 2082 m in the western part and the minimum is 1493 m in the north and eastern areas with a mean of 1787 m. The surface topography of the study area indicates a mild gradient from west to east. The slope was categorized as class 1 (0- 4%), class 2 (5 – 10%) and class 3 (11 – 30%). The slope dictates the amount and rate of surface runoff and the water that is infiltrated. The steeper the slope the greater the velocity of the flow and hence the lower will be the recharge. Moderately gentle slopes indicate that slopes have a lower gradient, favouring infiltration and thus enhance the groundwater recharge potentiality. The slope of the study area can be described as low to moderate.

Soil Texture

Soil type classes were translated into USDA soil texture classes, using the percentages of coarse and fine particle size fractions in the topsoil as presented in Table 3.

Table 3: Soil texture and their respective hydraulic conductivities (*after Saxton & Rawls, 2006)*

Soil texture	Area covered (Km^2)	Percentage covered (%)	Hydraulic conductivity (m/s)
Sandy loam	36.9	2.2	1.4×10^{-5}
Sandy clay loam	338.8	20.5	3.1×10^{-6}
Sandy clay	177.3	10.7	1.2×10^{-6}
Clay loam	73.1	4.4	3.9×10^{-7}
Clay	1,027.4	62.1	3.0×10^{-7}

The study area is composed of sandy loam (2.2%), sandy clay loam (20.5%), sandy clay (4.4%), clay loam (10.7%) and clay (62.1%). The area is therefore dominated by clay soils covering an area of 1027.4 km^2 followed by sandy clay loam (338.8 km^2) and sandy clay (177.3 km^2). Clay loam (73.1 km^2) and sandy loam (36.9 km^2) cover relatively smaller portions of the sub-catchment. Sandy loam has the highest hydraulic conductivity while clay has the lowest. Thus more recharge is expected in sandy loam as compared to clay soils.

Groundwater Depth

Maps of groundwater depth are needed for the WetSpass-M model simulations. However, if the depth to groundwater is more than the root depth, the groundwater depth map is of little significance for the WetSpass-M simulation (Gebreyohannes *et al.*, 2013). In the present study, the groundwater depth was found to be in the range of 18-130 m below the surface due to the semi-arid climatic conditions of the area.

4.0 RESULTS

The objective of this study was to assess the spatial-temporal variation of the groundwater recharge from precipitation in the Stony Athi sub-catchment, using WetSpass-M model, which derives the actual evapotranspiration as a sum of the evaporation of water intercepted by vegetation, the transpiration of the vegetative cover and the evaporation from the bare soil between the vegetation. Surface runoff is derived by a rationale method based on actual surface runoff and soil moisture coefficients while groundwater recharge is the residual component obtained by subtracting the sum of surface runoff and actual evapotranspiration from rainfall (Batelaan & Woldeamlak, 2007).

The major outputs of the WetSpass-M model simulation are digital maps, which show the spatial distribution as well as numerical values of the water balance components. The digital maps are raster maps, in which every pixel represents the magnitude of the respective water balance component. Thus the simulated values of the water balance components in the sub-catchment are unique averaged values produced from each cell. The resulting average monthly water balance

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values from the simulation are presented in Table 4 while Figure 7 shows the percentage ratio of the hydrological components to precipitation.

Table 4: Monthly Water balance components for the Stony Athi sub-catchment (1984 – 2017)

Month	Average Rainfall (mm)	AET (mm)	% of Rainfall	Surface Runoff (mm)	% of Rainfall	Recharge (mm)	% of Rainfall
January	41.6	30.8	74	1.45	3	9.40	23
February	39.8	27.9	70	1.65	4	10.3	26
March	77.6	53.4	69	13.3	17	11.2	14
April	137.9	109.3	79	24.9	18	7.53	5
May	77.3	60.5	78	9.41	12	7.82	10
June	15.1	10.5	70	0.21	1	4.42	29
July	4.7	2.8	60	0.05	1	1.83	39
August	6.7	4.2	63	0.06	1	2.43	36
September	8.7	4.6	53	0.19	2	3.93	45
October	38.7	28.2	73	1.14	3	9.38	24
November	113.1	89.9	79	14.6	13	10.2	9
December	72.3	53.3	74	9.67	13	9.60	13
Annual	**633.5**	**475.4**	**75**	**76.6**	**12.0**	**87.9**	**13.8**

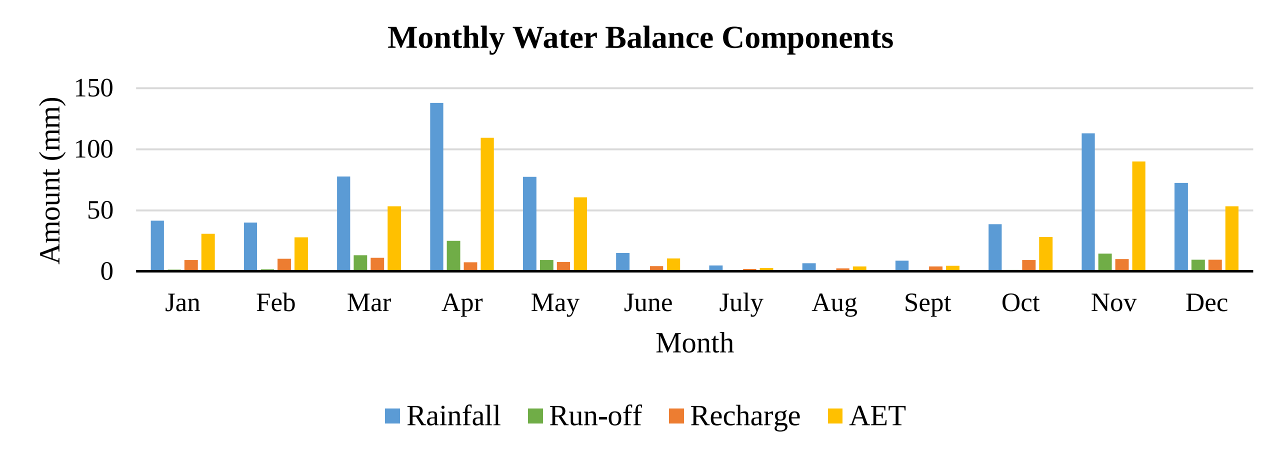

Figure 7: Average monthly water balance components in the Stony Athi sub-catchment for four temporal periods (1984 – 2017)

Actual evapotranspiration ranges between 2.8 mm to 109 mm in the months of July and April, respectively. Surface runoff is lowest in July and August, which are the months with the lowest rainfall while the highest is recorded in April, which coincide with the month with the highest rainfall. The monthly groundwater recharge varies from 1.8 mm in July to 11.7 mm in March and 10.3 mm in October, which correspond to the start of the long and short rains respectively. The lumped annual water balance components were derived from the monthly averages using the raster calculator tool in ArcMap as shown in Table 5 and Figure 8 for the four different temporal periods under different land use and land cover scenarios.

Table 5: Average water balance components in Stony Athi Sub-catchment - 1984 to 2017

Component	1984 Amount (mm)	1984 % (ppt)	1995 Amount (mm)	1995 % (ppt)	2005 Amount (mm)	2005 % (ppt)	2017 Amount (mm)	2017 % (ppt)
Actual Evapotranspiration								
Range	190-608		142-567		148-608		143-571	
Mean	478	75.3	476	75.1	475	74.9	472	74.4
Std, Dev.	39		42		44		54	
Surface run-off								
Range	25-420		24-488		25-512		24-512	
Mean	74	11.7	71	11.2	77	12.1	85	13.4
Std, Dev.	40		25		55		72	
Recharge								
Range	0-325		0-325		0-325		0-325	
Mean	88	13.8	91	14.3	87	13.7	84	13.2
Std, Dev.	38		37		35		34	

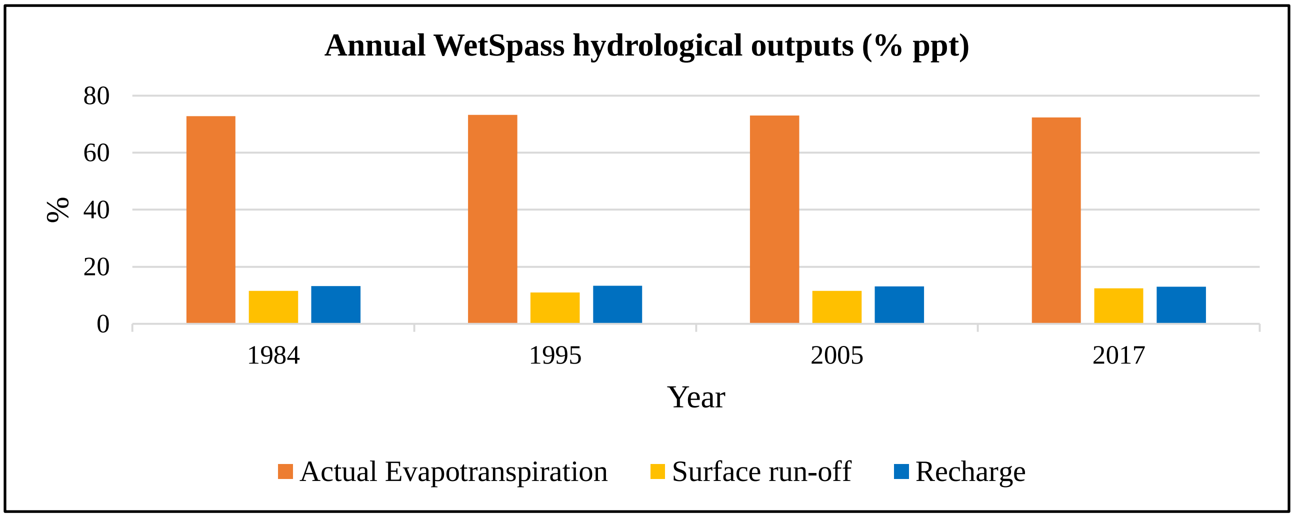

Figure 8: Annual water balance components in the Stony Athi sub-catchment for four temporal periods (1984 - 2017)

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On a temporal scale, actual evapotranspiration ranges from 478 mm in 1984 to 472 mm in 2017 while surface run-off shows an increase from 74 mm in 1984 to 85 mm in 2017. Annual recharge ranges from 0 mm to 325 mm with means of 88 mm, 91 mm, 87 mm and 84 mm for the years 1984, 1995, 2005 and 2017, respectively. These values show that 14% of the average annual precipitation (634 mm) goes to recharge, 12% is surface run-off while 75% is lost through evapotranspiration. Evapotranspiration is the major process by which water is lost in the study area. Both recharge and evapotranspiration indicated decreasing trends while run-off increased over the period. The spatial variability of the water balance components distribution maps for Stony Athi sub-catchment, are presented in Figure 9.

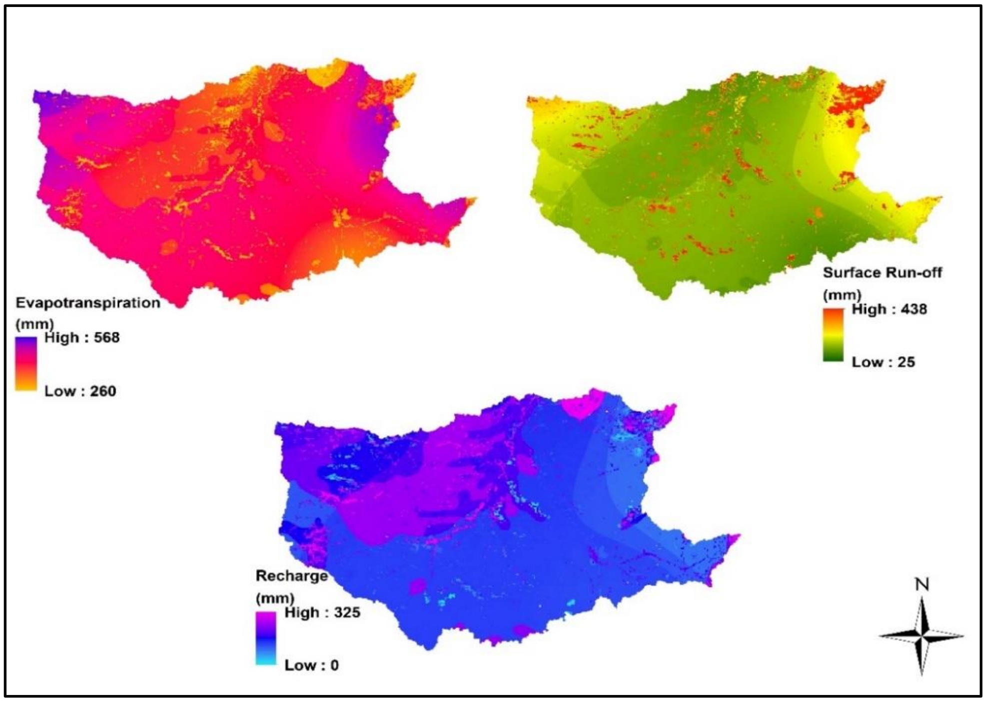

Figure 9: Annual spatial distribution of the water balance components

The annual actual evapotranspiration varies from 260 mm to 568 mm while surface run-off ranges from 25 mm to 438 mm. The annual groundwater recharge shows a large spatial variation with values ranging between a minimum of 0 mm and a maximum of 325 mm with a mean of 87.9 and a standard deviation of 30.5 mm. Table 6 shows the mean annual groundwater recharge for different combinations of land use land cover and soil texture.

Table 6: Mean annual recharge (mm) for different combinations of LULC and soil texture

Soil texture / LULC	Sandy loam	Sandy clay loam	Clay loam	Sandy clay	Clay
Built-up area	49	46	44	45	35
Bare land	84	73	59	52	36
Agricultural land	136	130	107	102	67
Mixed forest	197	181	171	170	138
Grassland	146	125	114	101	69
Shrub land	172	127	105	100	73

The highest recharge occurs on sandy loam soils with forest cover at 197 mm per year while the lowest values are observed on clay soil in built up areas at 35 mm per year. Agricultural and grassland show relatively similar recharge values for the same soil textures. Shrub land show relatively higher values than grassland, but less than mixed forest while bare land exhibit relatively higher values compared to the built up areas. As expected sandy loam has the highest recharge while clay has the lowest.

5.0 DISCUSSION

Water balance is a representation of the net result of the inflow and outflow of a system. Precipitation is the main inflow component while evapotranspiration, groundwater recharge and surface runoff are the most significant outflow components (Aish, 2014; Zarei *et al.*, 2016). The water balance components for the Stony Athi sub-catchment for the period 1984-2017 has shown variation, both spatially and temporally. On a temporal scale the mean annual recharge decreased from 88 mm in 1984 to 84 mm in 2017, which can be attributed to the fact that rangelands (mixed forest, shrubs and grass land) in the sub-catchment have been lost over time and converted to agricultural and built-up areas. Rangeland coverage as of 1984 was 98% while this has progressively reduced to 94% by the year 2017. On the other hand, agricultural and built-up areas has increased from 0.1% to 4% of the total area. These land use / land cover changes have also contributed to a decrease in actual evapotranspiration and an increase in surface run-off. However, there is a wide spatial variation of the water balance components as well as the observed monthly values.

WetSpass calculates the actual evapotranspiration per pixel as a sum of the evaporation of water intercepted by vegetation, the transpiration of the vegetative cover and the evaporation from bare soil between the vegetation (Batelaan & Woldeamlak, 2007; Al-Kuisi & El-Naqa, 2013; Abdollahi *et al*., 2017). The simulated actual evapotranspiration mean monthly spatial values range between 21 mm and 47 mm with a mean of 39 mm and a standard deviation of 3 mm while annual amounts vary between 260 mm and 568 mm with a mean of 475 mm and a standard deviation of 36 mm. This represents 75% of the annual precipitation. A high actual evapotranspiration is observed in the north-western parts of the sub-catchment because of the higher rainfall, while the central and south-eastern areas which receive less precipitation have lower evapotranspiration.

The model uses the runoff coefficient method for the estimation of surface run-off, which is a function of the vegetation type, soil texture and slope (Batelaan & Woldeamlak, 2007; Al-Kuisi & El-Naqa, 2013; Abdollahi *et al*., 2017). The monthly surface run-off varies from a minimum of 2 mm to a maximum of 36 mm, with an average value of 6 mm and a standard deviation of 3 mm. Annual surface run-off values show a large spatial variation, which range from 25 mm to 438 mm with a mean of 77 mm and a standard deviation of 37 mm. Surface run-off in the sub-catchment constitutes about 12% of the annual mean rainfall. In most of the north-western parts, there is less surface runoff, associated with the sandy clay loam and sandy loam soils, which have higher infiltration rates and therefore hinder high surface run-off. It is important to note that regardless of the land use / land cover type, areas with clay soil and clay loam tend to generate high amount of surface runoff, while places with loamy sand and sandy loam soils generate lower surface runoff (Ashaolu *et al*., 2020).

Groundwater recharge is calculated as the residual hydrological component in the simulation process by subtracting the sum of surface runoff and actual evapotranspiration from rainfall (Batelaan & Woldeamlak, 2007; Al-Kuisi & El-Naqa, 2013; Abdollahi *et al*., 2017. The monthly recharge varies from 0 mm to 27 mm, with an average of 7 mm and a standard deviation of 3 mm. Though the peak rainfall occurs in the month of April, the highest recharge was observed in March while July has the lowest. This can be attributed to the textural properties of clayey soils, the major soil type covering a large percentage of the area, which absorb water at the onset of the long rains and become saturated as rainfall increases, thus resulting to a decreased infiltration capacity during the peak rainfall month. The minimum, maximum and mean values of annual groundwater recharge values are 0 mm, 325 mm and 88 mm respectively. The average recharge constitutes 14% of the average annual rainfall. The digital maps appear to indicate that surface recharge is highly controlled by the soil texture, rather than the effect of land use/land cover type or slope.

The spatial distribution of groundwater recharge depends on topography, slope, soil type, land cover/land-use, and climatological conditions. Moreover, recharge has a spatial complex pattern, depending to a large extent on the soil texture and land cover (Batelaan & Woldeamlak, 2007). The recharge digital map appears to indicate that the spatial variation of recharge is strongly controlled by these two factors. The highest recharge was observed on sandy loam soils with forest cover at 197 mm per year, which was attributed to the fact that vegetation intercepts and slows down surface run-off in forested areas and hence allows more infiltration by the relatively high permeable sandy loam soils to recharge the groundwater system. On the other hand, the lowest values are on clay soil in built up areas at 36 mm per year due to the higher percentage of impervious surfaces in built up areas with low permeability clay soils, which inhibit infiltration, but increase surface run-off. Agricultural and grassland show relatively similar recharge values for the same soil textures. Generally, areas located in the central and south-eastern parts have lower annual recharge due to the heavy presence of clay soils while areas in the north-western parts show relatively high recharge due to more loamy and sandy soils.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The WetSpass-M model, a spatially distributed water balance model, was applied to estimate the spatial-temporal distribution of the long-term average water balance in the Stony Athi sub-catchment, with emphasis on groundwater recharge. Simulated results showed that the long-term mean annual rainfall of 634 mm is distributed as follows: 14% recharge; 12% surface run-off and 75% evapotranspiration. The temporal mean annual recharge varied from 88 mm in 1984, 91 mm in 1995, 87 mm in 2005 and 84 mm in 2017; an average of 87.9 mm/year. Surface run-off varies from 74 mm in 1984 to 85 mm in 2017 with an annual average of 76.6 mm while actual evapotranspiration ranges from 478 mm and 472 mm with an average of 475.4 mm per year. These results indicate a decrease in recharge and actual evapotranspiration, but an increase in surface run-off. This can be attributed to changes in land use and land cover; an increase in built up areas, which increases impervious areas, thus inhibiting infiltration and increasing run-off. The decreased evapotranspiration can be attributed to the decreased forest and shrubs cover. The total annual groundwater recharge within the sub-catchment is about 153M m^3 while the total annual run-off is about 134M m^3. This study has demonstrated the importance of physically-based spatially-distributed hydrological models in estimating the water balance in a region. The quantification of groundwater recharge has provided a new insight of the water balance conditions in the Stony Athi sub-catchment, which will assist water managers and land planners to allocate groundwater resources in a more sustainable manner and a better strategic land use planning, respectively. The study also provides a theoretical basis for the scientific, rational resource allocation, utilization and awareness creation of the need to enhance groundwater governance.

6.2 Recommendations

This study recommends an improvement of meteorological and hydrological data collection as well as groundwater abstraction monitoring, not only in the Stony Athi sub-catchment, but also across the country. Results from this study can be used as an input for building an integrated groundwater modelling and for evaluation of potential sites for managed artificial recharge through harvesting runoff during the rainy season to improve groundwater storage. Based on this study, the County Government should institute water management and governance policies in order to develop and implement a framework for sustainable surface and groundwater resource use in the county.

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