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# Estimating Groundwater Recharge Rates and Identifying Groundwater Recharge Zones in Kakia and Esamburbur Sub-Catchment Narok, Kenya

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**Abstract**

Groundwater recharge has become a significant practice for sustainable groundwater development and efficient water resource management. Many countries in Africa including Kenya are currently experiencing water scarcity. Kakia and Esamburmbur sub-catchment, Narok County in southwest Kenya suffers water shortage during the dry season and surface water sources dry up. Identifying groundwater recharge zones and estimating groundwater recharge rates in Kakia and Esamburmbur sub-catchment will help water-resource authorities and policymakers to properly plan and develop groundwater resources in the sub-catchment. A geophysical survey was executed using the PQWTs-500 equipment to map the sub-surface condition of the study area in order to determine the suitable recharge zones. Five profile lines were generated of 20.9 km in total with 104 points at 200 m intervals. Soil and Water Assessment Tool plus (SWAT+) model was used to estimate groundwater recharge rates in the sub-catchment. The SWAT+ model was calibrated and validated with seventeen years (2003 – 2019) of monthly satellite soil moisture data. Model performance values obtained for calibration and validation were coefficient of determination ($R^2$) 0.51 and 0.59, Nash-Sutcliffe efficiency (NSE) 0.17 and 0.20, and percent bias (PBIAS) 33.8% and 28.5% respectively. The geophysical survey results showed that the south-central and southeast zones of the sub-catchment are potentially good groundwater recharge zones and therefore suitable for managed aquifer recharge structures to augment the groundwater resources. Additionally, the SWAT+ simulation showed that the long-term average groundwater recharge rate ranges from 0 to 175 mm per year. It was also observed that the highest groundwater recharge occurs in April, May and, June.

**Keywords** Groundwater recharge, Kakia and Esamburmbur, Recharge zones, SWAT+

## 1. Introduction

Globally, about 62% of the world population are expected to live in nations with water scarcity by 2025 [1]. Water scarcity has become a global challenge as a result of urbanization, population growth, and climate change. Groundwater is the world's biggest source of freshwater, contributing to 30% of all freshwater bodies [2]. Due to lack of sufficient and regular water supply by service providers in Kenya, people have shifted to groundwater sources both in urban and rural areas [3]. Groundwater sources are more protected from pollution than surface water resources. Additionally, the usage of groundwater is not restricted by seasonal and inter-annual flow fluctuations [4]. However, over-developing of groundwater sources can result in aquifer depletion.

Aquifer depletion due to over-extraction of groundwater has been reported in many cities such as Nairobi in Kenya, Addis Ababa in Ethiopia, and Dar es Salaam in Tanzania [3]. A study conducted in India established that the majority of the aquifers had been depleted. This was attributed to higher extraction of groundwater compared to the net recharge [5]. In order to meet the growing demand for freshwater, it is essential to replenish groundwater [2]. Recharging of groundwater has become a possible way to address the issue of water table depletion. Artificial recharge systems are designed to allow surface water to infiltrate into the ground thus augmenting groundwater resources [6].

Groundwater is largely unutilized in Kakia and Esamburmbur sub-catchment, where the primary source of water is surface water. In the dry season, Narok town including the study area experiences a shortage of water as reported in the Narok County Integrated Development Plan [7]. Further, according to the report, inadequate recharge sources coupled with catchments degradation, low flow in rivers and springs have been reported [7]. Therefore, this study provides information that could be used in improving sustainable water resource management in Narok County. This can be done by estimating groundwater recharge rates and identifying suitable zones for managed aquifer recharge. Estimation of groundwater recharge rate is one of the primary steps in determining the sustainability of an aquifer for potential water uses [4].

Groundwater recharge varies spatially and temporally due to variations in climatic conditions, land use, soil characteristics, and aquifer parameters. The significance of groundwater recharge variability has become increasingly important during the last decade. This has been exacerbated by the growing concerns over the human activities on groundwater resources [8]. Groundwater recharge zones are areas where surface water can infiltrate and percolate through the soil [1]. Studies have established that implementation of Managed Aquifer Recharge (MAR) could be part of sustainable water management [9]. The primary goal of MAR is to enhance groundwater storage, to address the temporal imbalance between local water demand and availability by ensuring a reliable water supply throughout the year [10]. The first step during implementation of managed aquifer recharge is the identification of suitable groundwater recharge zones [11].

SWAT is a basin-scale, physically based, semi-distributed hydrologic model that was designed to estimate the long-term impact of land management techniques on water and sediment. SWAT model applications include runoff, sediment yield, actual evapotranspiration, and recharge estimation at a catchment scale [12]. Geophysics provides the ability to investigate subsurface structures using a variety of physical characteristics. The ability of a hydrological unit to store groundwater is controlled by the geological properties of a formation, which vary significantly from place to place within lithological units. Groundwater and electric currents are understood to flow from higher to lower potential areas, and their flow rates are influenced by the potential gradient. Groundwater flow rate is determined by the formation's hydraulic permeability, whereas electric current flow is controlled by the formation's electrical conductivity [13].

## 2. Materials and Methods

### 2.1. Study Area

The study was conducted in Kakia and Esamburmbur sub-catchment in Narok County, located in southwest Kenya (Figure 1). The area borders Kajiado, Nakuru, Kisii, Migori, and Nyamira counties, respectively. The study area is about 46.2 $km^2$ in size, with an average elevation varying from 1828 m to 2124 m. There are two rainy seasons: the long-rain season is usually between March and May while the short rain is from September to December [14]. The annual average rainfall in the area is about 750 mm, while the average temperature ranging from 8 $^0$C to 28 $^0$C. The hydrological soil group in the study area is group C, where the dominant soil texture is clay loam [14], [15]. Soils in this group have moderately high runoff potential and low infiltration rates (5 to 10 mm/h) [16]. Additionally, the soils have low bulk densities (1.4 to 1.5 g/$cm^3$) and typically have between 20 and 40 percent of clay [16]. Clay loam is the dominant soil texture. The main permanent river which passes through Narok town is the Enkare Narok River. Kakia and Esamburmbur are seasonal streams that have a tendency to overflow their banks during the rainy seasons. In the dry seasons, Narok county experiences a shortage of water [7]. Mostly, the catchment comprises of agricultural land with maize and wheat being the dominant crops [17].

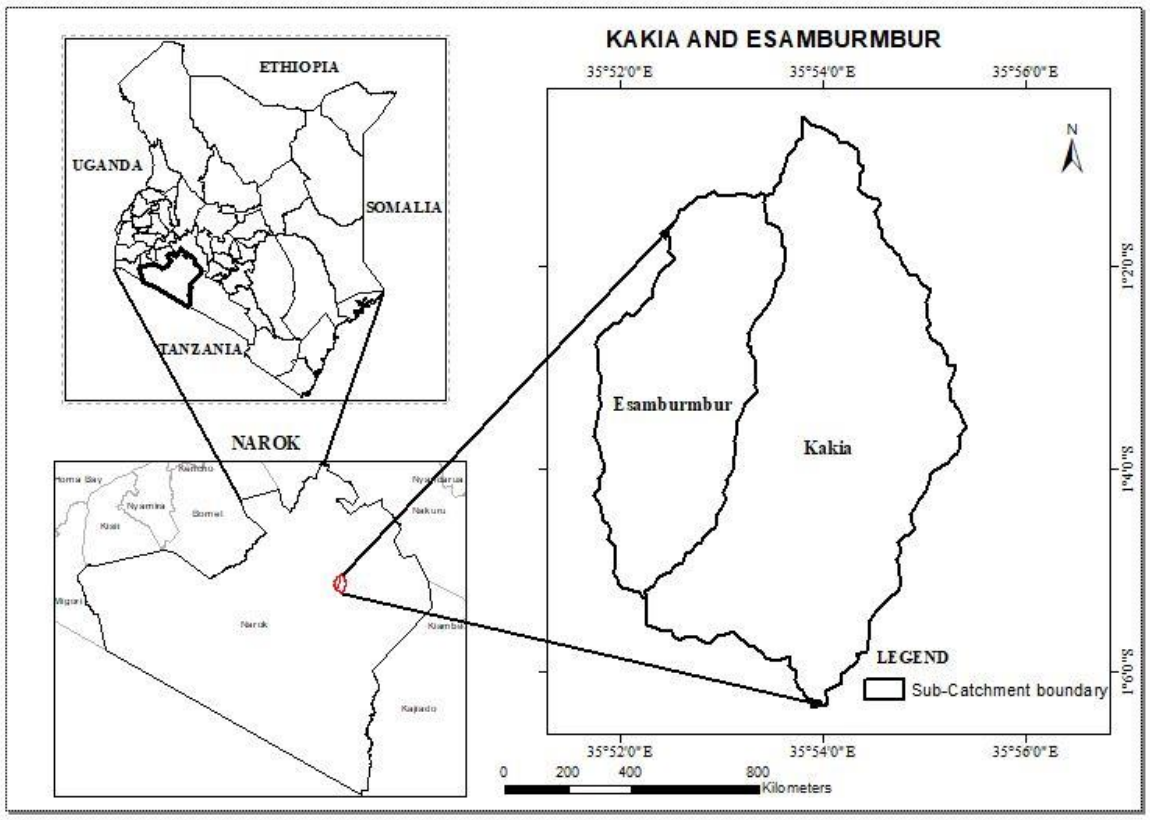



**Fig. 1**: Location of the study area

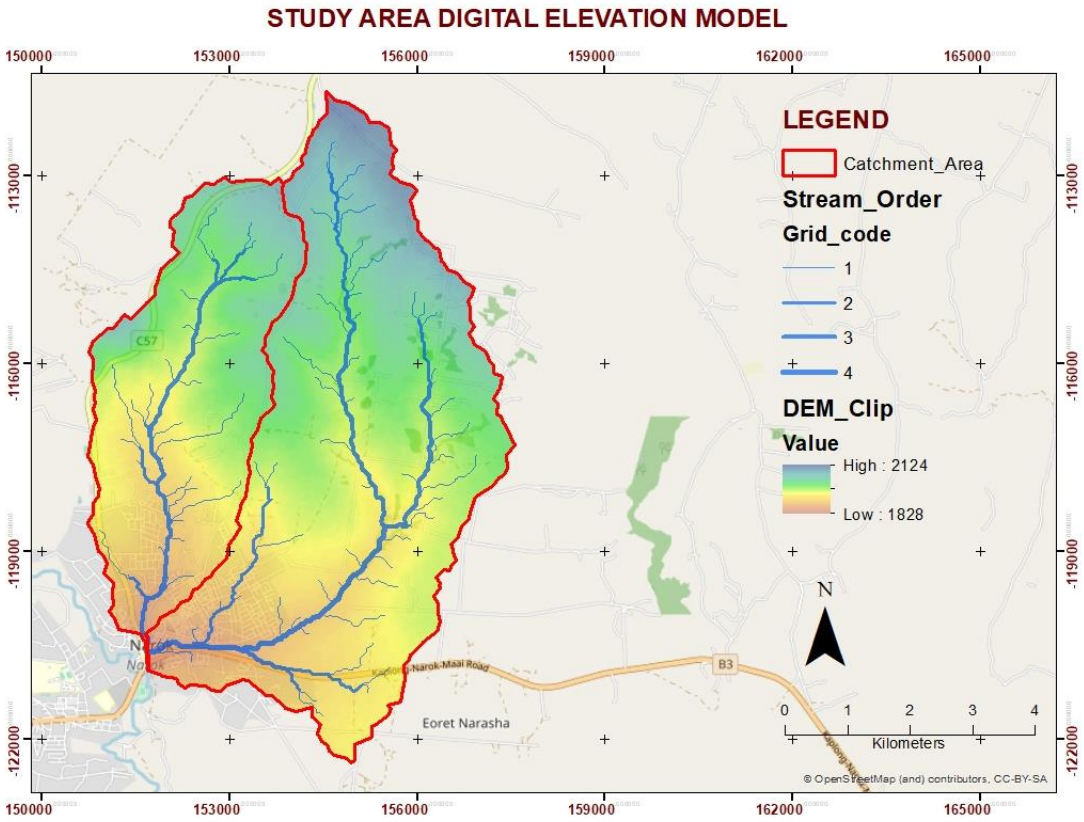



**Fig. 2:** Digital Elevation Map of Kakia and Esamburmbur

## 2.2. Data acquisition and preparation

### *2.2.1. Geophysical survey*

The geophysical survey was conducted to understand the sub-surface condition of the area in order to determine the suitable recharge zones in the sub-catchment. Geophysics provides the ability to investigate the structures and composition of the sub-surface using a variety of physical characteristics [13]. For instance, groundwater recharge is expected to be higher in regions characterized by weathered or fractured rocks. The geophysical data was collected to identify groundwater recharge zones in Kakia and Esamburmbur sub-catchments. Data collection was undertaken during the month of April 2021. PQWT-s500 equipment was used during the survey. Basically, this machine is capable of probing a maximum depth of 500 meters. Five profile lines measuring 20.9 km in total with 104 points of 200 m interval were generated as shown in Figure 3. The PQWTs equipment uses potential difference method which measures naturally occurring electrical potentials in the earth [18]. The survey was done using two non-polarizable electrodes with a spacing of 10 m apart. The rods were driven in the ground, with one electric wire running from each electrode to the equipment. The gauge on the equipment registers the voltage difference and then stores the values in its memory.

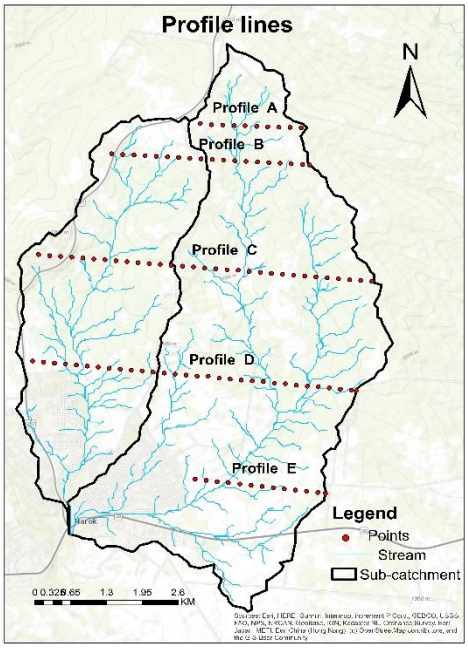



**Fig. 3**: Showing the study area with geophysical profiles

Profile line A, (Fig. 3) comprises of 10 points, with an interval of 200 m. The first point is placed 821919 E, 9886881 N, at an elevation of 2090 m above sea level and the last point of the profile is placed at 823752 E, 9886796 N at an elevation of 2139 m. The total profile length is 2,000 m. While profile B has 19 points, with an interval of 200 m. The first point is placed 820309 E, 9886307 N, at an elevation of 2051 m above sea level and the last point of the profile is placed at 823903 E, 9886094 N at an elevation of 2124 m. The total profile length is 3,800 m. Also, profile C contains 31 points, with an interval of 200 m. The first point is placed 818981 E, 9884399 N, at an elevation of 2061 m above sea level and the last point of the profile is placed at 825037 E, 9883892 N at an elevation of 2071 m. The total profile length is 6,200 m. Profile D has 31 points, with an interval of 200 m. The first point is placed 818872 E, 9882385 N, at an elevation of 1974 m above sea level and the last point of the profile is placed at 824752 E, 9881826 N at an elevation of 2007 m. The total profile length is 6,200 m. And profile E, contains 13 points, with an interval of 200 m. The first point is placed 821825 E, 9880156 N, at an elevation of 1942 m above sea level and the last point is placed at 824192 E, 9879885 N at an elevation of 1999 m. The total profile length is 2,600 m, with an interval of 200 m. Each of the five profiles has a depth of study of up to 500 meters.

### *2.2.2. QSWAT+ data preparation*

The input data required for running SWAT+ includes Digital Elevation Model (DEM), soils, land cover, (Fig. 4) weather data (precipitation, temperature, humidity, and wind speed) and, soil moisture data for calibration and validation. A DEM of 12.5 m resolution of Enkare Narok River Catchment was obtained from Alos Palsar website at (https://search.asf.alaska.edu/). The soil data was obtained from the Kenya soil and terrain (KENSOTER) database at a scale of 1:1 m, from International Soil Reference and Information Center (ISRIC) website (https://www.isric.org/explore/soter). The KENSOTER shapefile was uploaded to QGIS 3.10. Thereafter, the Kakia and Esamburmbur sub-catchment was clipped using a clipping tool in the spatial analysis tool. Then soil groups in the study area were identified and classified in the attribute table. The land cover map of the study area was extracted from a 20 m resolution Kenya land cover map downloaded from the ESA (European Space Agency) CCI (Climate Change Initiative) Website. http://2016africalandcover20m.esrin.esa.int/download.php. The map is based on Sentinel-2A observations from December 2015 to December 2016. Daily precipitation data from 1986 to 2020 were collected from Narok

meteorological station. Maximum and minimum temperature, humidity, and wind speed were obtained from NASA power data access https://power.larc.nasa.gov/data-access-viewer/. Soil moisture data was obtained from the European Space Agency climate change initiative, https://www.esa-soilmoisture-cci.org/data. This data provided daily surface moisture at a 0.25º spatial resolution. The study area covered a single grid cell, and the data from that grid cell was extracted for model calibration. Since the land cover and topography of the study area are relatively uniform, this data was considered adequate for model calibration. Soil moisture data was then used to calibrate the model. This was because both Kakia and Esamburmbur streams are not gauged. The QSWAT+ input data is summarized in Table 1.

### 2.3. Voxler model

To improve the visualization of the sub-surface features, three-dimensional model (3D) was generated using the Voxler 4 software. Voxler is an extensive 3D software modeling tool that is capable of visualizing both single-component and multi-component data. Voxler 4 version with advanced tools and updated interpolation algorithms is used for this model. The data received from the PQWT-s 500 equipment is in form of singular data and does not include coordinates for each point measured. The data was reprogrammed and populated together, in order to enable the modeling software Voxler 4, to read the data and model appropriately. The coordinates were encrypted with the populated data for each site to produce a coordinated block. Then a volume render was generated and interpolated.

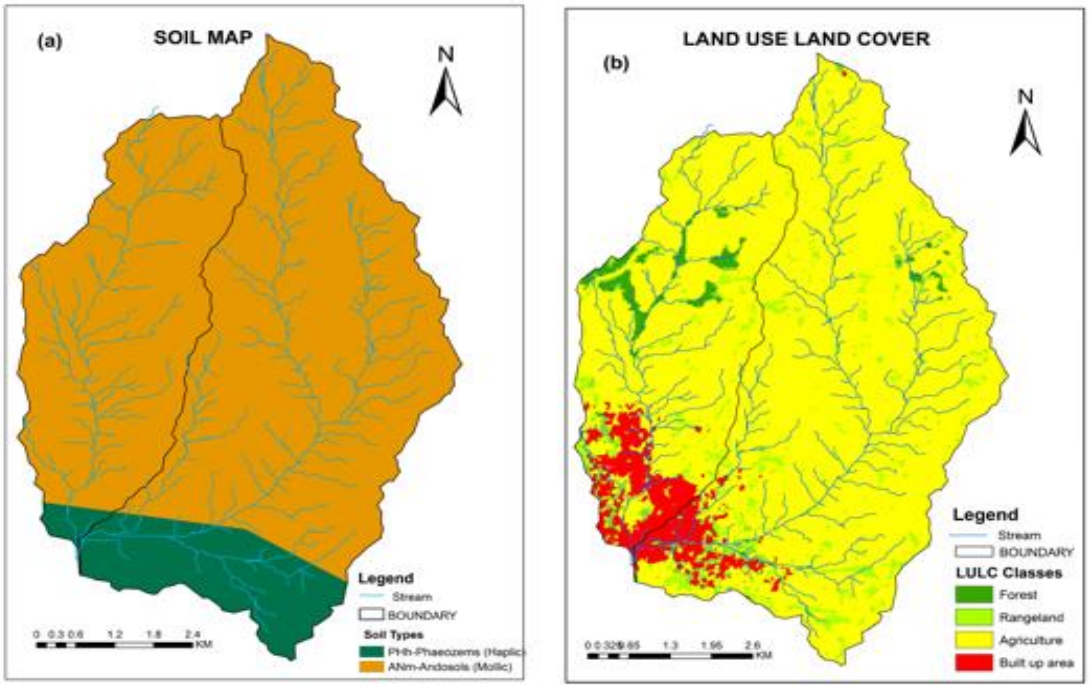



**Fig. 4**: (a) Soils map (b) Land use land cover map

**Table 1:** Data used for SWAT + set model up

| Datasets | Details | Sources |
|---|---|---|
| Digital Elevation Model | 12.5 m resolution | ALOS PALSAR |
| Soil map | Scale 1:1 M | ISRIC |
| Land use map (2016) | 20 m resolution | Sentinel 2A (ESA) |
| Meteorological data (Tmax, Tmin, Rainfall, humidity, and wind speed) | Daily (1986-2020) | KMD, NASA Power |
| Soil Moisture data | Daily (2003-2019) | ESA CCI |

### 2.4. QSWAT+ Model

Soil, and Water Assessment Tool plus (SWAT+) is an entirely restructured version of the Soil and Water Assessment Tool (SWAT) watershed modeling code [19], [20]. SWAT+ model was used to delineate the spatial distribution of groundwater recharge rate. The input data required for training SWAT+ include Digital Elevation Model (DEM), (Fig.2), land use, soils (Fig.4) and weather data (precipitation, temperature, humidity, and wind speed). While, soil moisture data is required for calibration and validation of the SWAT+ model.

SWAT plus was constructed using the QSWAT+ interface. The sub-catchment was delineated by taking the sub-catchment outlet as the confluence of Kakia-Esamburmbur streams and Enkare Narok River. Land use, soils maps, and their respective lookup tables were then uploaded to the QSWAT+ interface. The sub-catchment was delineated and sub-divided into 71 sub-basins and 103 Hydrologic Response Units (HRUs). QSWAT+ editor was then used to import the weather data obtained from the Narok Meteorological station and NASA Power**,** execute the model, and export outputs.

### 2.5 Calibration and Validation

In a large number of regions, hydrological model calibration is challenging due to lack of streamflow observations and other ground data [21]. Soil moisture data obtained through remote sensing have a high temporal resolution and large spatial range. In recent years, researchers have adopted the use of satellite soil moisture for hydrological model calibration [21]–[25]. In this study, the obtained soil moisture data (2003 to 2019) was divided into two periods, one period was used for model calibration, while the other period was used for model validation. Calibration was done with the soil moisture data for the period between January 2003 to December 2010, and validation was done with data for the period between January 2011 to December 2019. The data obtained for January 1999 to December 2002 was used as warm-up period. The values of CN were changed depending on the type of land use whereas the values of the soil available water capacity (SOL_AWC) were changed depending on soil type and different layers of each soil. The calibrated parameters values are presented in Table 2.

SWAT+ performance in the sub-catchment was evaluated using three statistical performance indices as recommended by [26]. Those indices are coefficient of determination ($R^2$), Nash Sutcliffe efficiency (NSE) and percent bias (PBIAS) given below in Equations (1), (2), and (3).

$$R^2 = \left[\frac{\sum_{i=1}^{n}(0_i - \bar{0})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(0_i - \bar{0})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad (1)$$

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

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n}(O_i)}\right] \quad (3)$$

Where, $O_i$ is the ith observed value, $P_i$ is the ith simulated value, $\tilde{O}$ is the mean of observed data, P is mean of the simulated, and n is the total number of observation.

**Table 2:** SWAT+ parameters adjusted during the calibration process

| Parameter Name | Description | Default ranges | Calibrated value |
|---|---|---|---|
| CN2 | Initial SCS runoff curve number for moisture condition II | 25-98 | Varying |
| SOL_AWC | Available water capacity of the soil layer | 0.01 - 1 | Varying |
| ALPHA_BF | Base flow alpha-factor (days) | 0 - 1 | 0.3 |

## 3. Results and Discussion

### 3.1. Two Dimensional Model

PQWTs-500 automatically processed 2-D figures were analyzed to demonstrate the suitable recharge zones in Kakia and Esamburmbur. Hydrogeologically, a compact rock neither fractured nor weathered has no ability to transmit or store groundwater. So, whenever there is a loose or less compacted area or when there is a crack or fracture between the compact rocks, there is a high possibility of groundwater recharge. Blue, light blue, and light yellow colors indicate the presence of low potential difference value materials like water, soft mud, and some metal minerals. The yellow color shows the presence of a middle potential difference value material like rocks. While red color indicates the presence of high potential difference value materials like high density hard rock formation. Profile A, (Fig. 5) shows a compact zone to the Western side and very deep fracture at the center and biased to the East beginning from point 4 to point 9. Profile B (Fig. 6) indicates the accuracy of a major weak zone to the East from point 10 to the last point of the profile. It has a deep depth and a slightly buried weak zone to the west between points 5 to point 10 which becomes even more pronounced in profile C. In Profile C (Fig. 7), the Eastern weak zone becomes more apparent from point 18 extending up to point 31 with an endless depth. In the Western part of the profile, a less dense zone is partly sandwiched between high compacted layers and begins at point 7 to point 9. The Western fracture zone fades off as can be seen in profile D (Fig. 8), while the Eastern weak zone grows wider from point 13 to point 31 with a depth of noticeably 500 m and possibly deeper. Profile E (Fig. 9) which is in the Southeastern part of the study area, the Eastern fracture is apparently seen horizontally from the first point to the last point of the profile with around 100 m maximum depth at the weak zone. Most of the groundwater flow/recharge water flows out of the sub-catchment to the Southeastern direction.

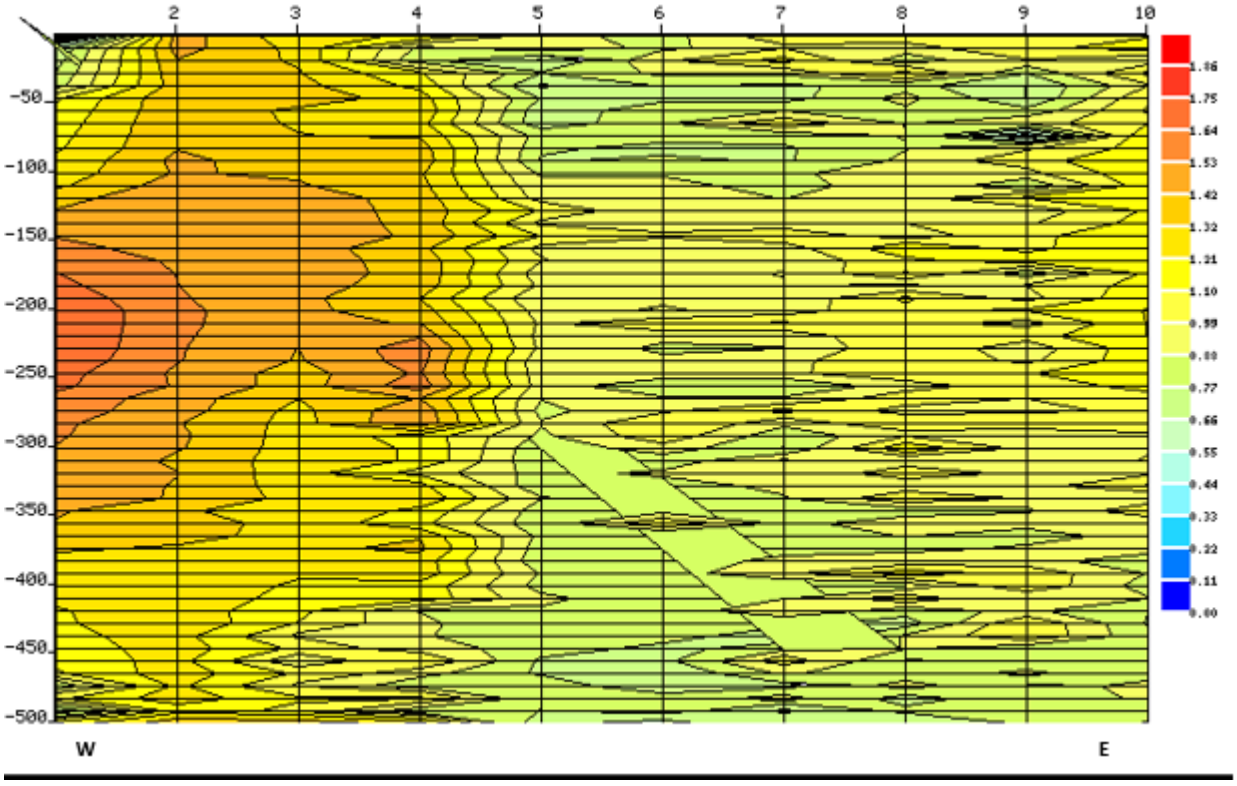



**Fig. 5.** Profile A, 2D Geophysical Survey Profile Showing the Different Colors of Potential Difference of Subsurface Features

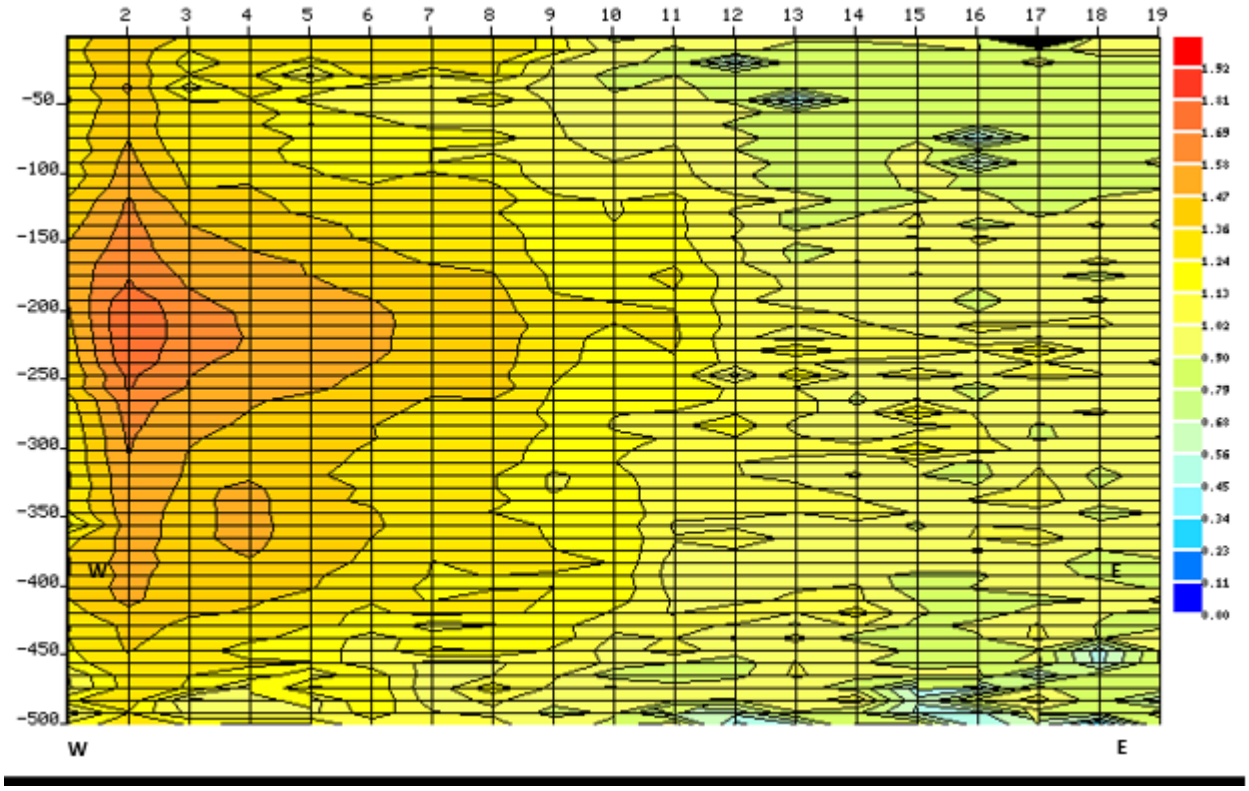



**Fig. 6**: Profile B, 2D Geophysical Survey Profile Showing the Different Colors of Potential Difference of Subsurface Features

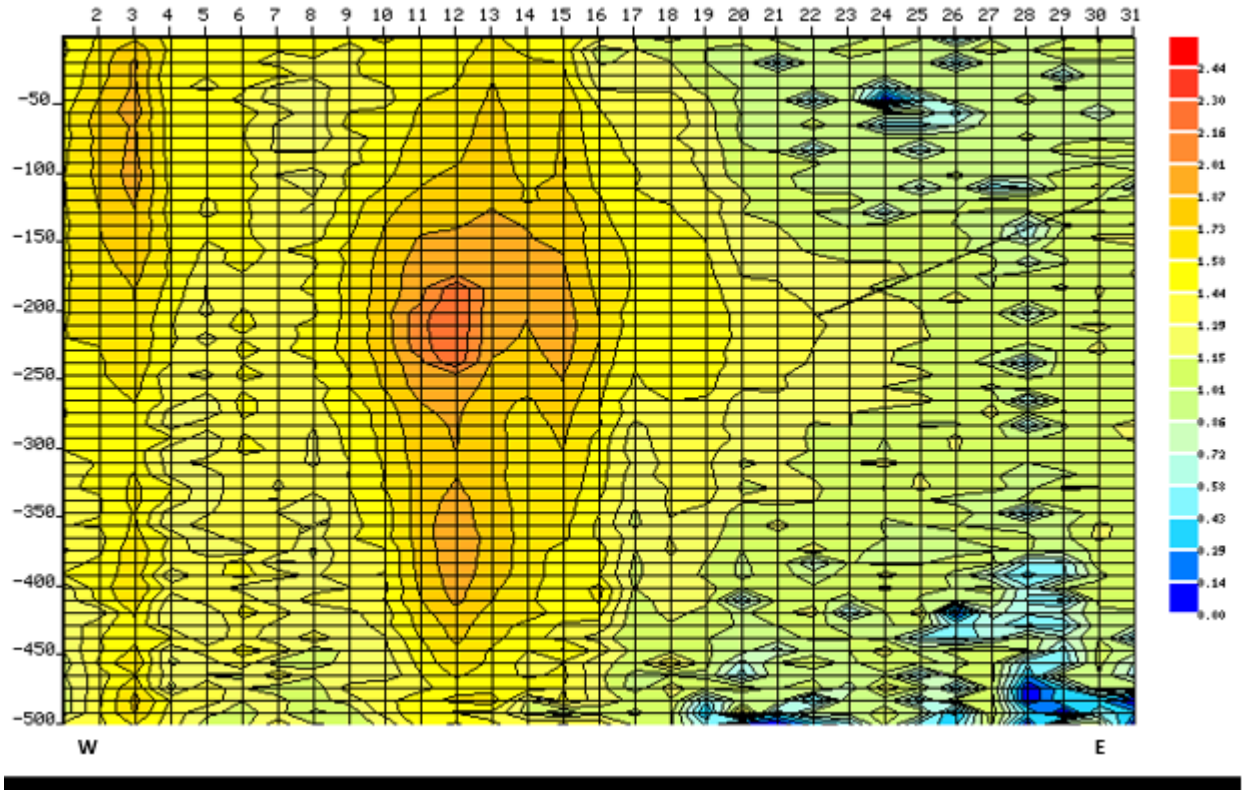



**Fig. 7.** Profile C, 2D Geophysical Survey Profile Showing the Different Colors of Potential Difference of Subsurface Feature

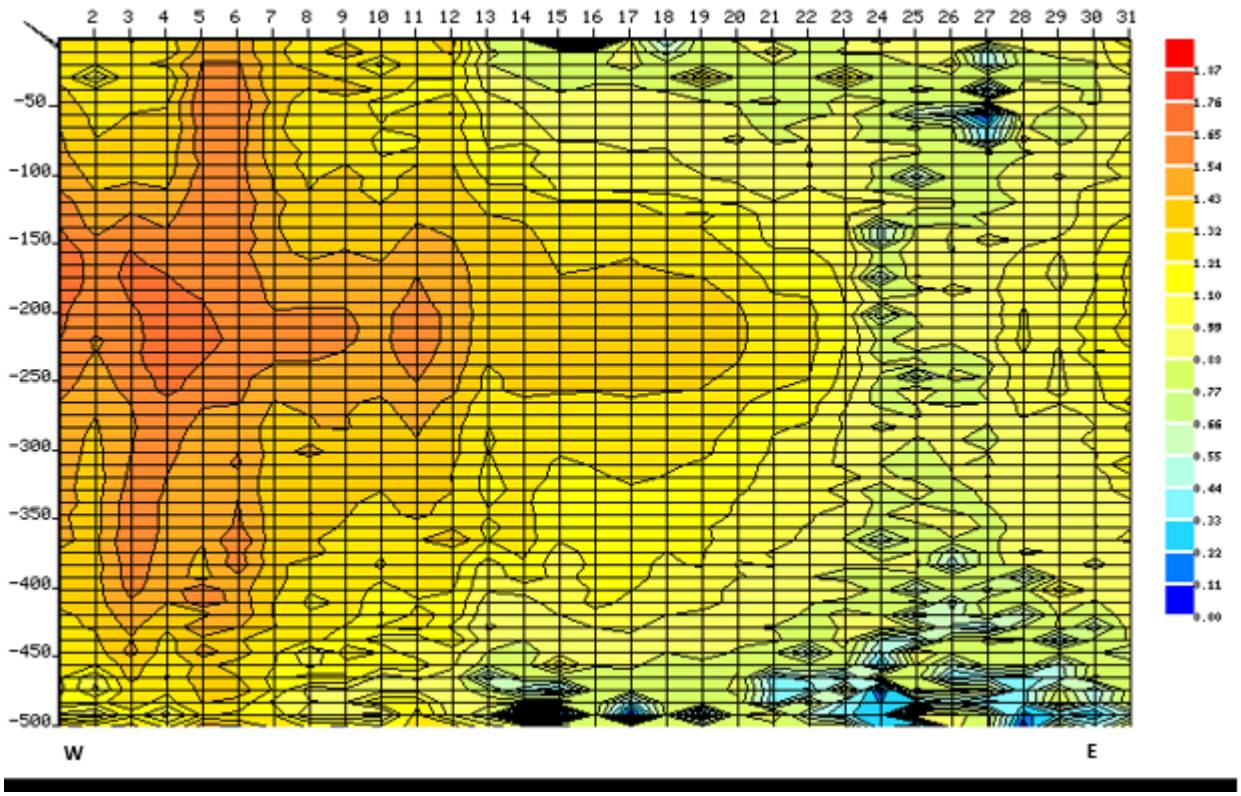



**Fig. 8**: Profile D, 2D Geophysical Survey Profile Showing the Different Colors of Potential Difference of Subsurface Feature

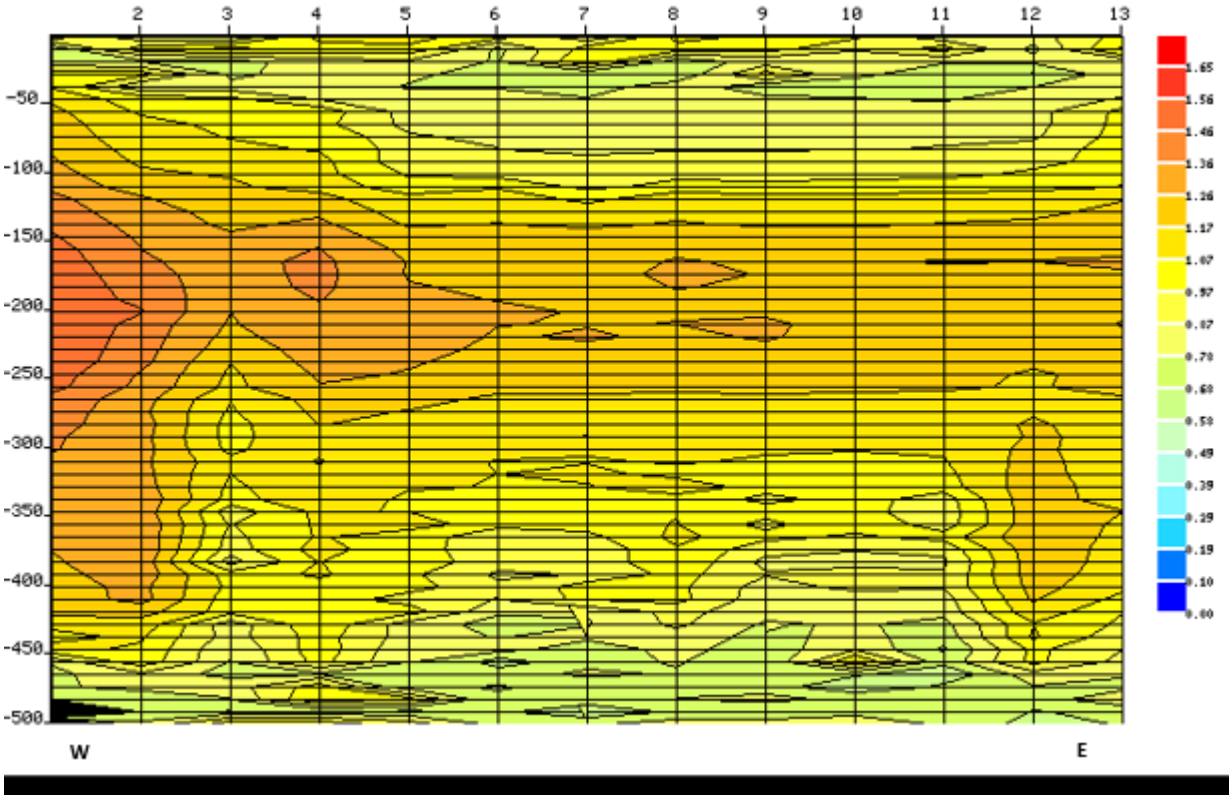



**Fig. 9**: Profile E, 2D Geophysical Survey Profile Showing the Different Colors of Potential Difference of Subsurface Feature

### 3.2. Three-Dimensional Model

The Voxler 4 generated 3D figures shows the subsurface structures. The X-axis represents the Eastern direction and Y-axis pointing to the North and the blocky Volrender gives a rough indication of the loose zones around the study area. Loose zones usually have a porous arrangement that allows water to flow. Different coloring has been used to represent a range of various potential difference values with blue color representing the highest and red representing the lowest groundwater flow zones. This means that the blue marked zones are loosely packed with increasing groundwater flow and the red zones indicated reduced groundwater flow which consists of very compact rocks. The subsurface structure of the eastern part of the study area (Kakia), which is less compacted is shown in Fig. 10. The area represents a high groundwater recharge zone as compared to the Western part (Esamburmbur) of the study area.

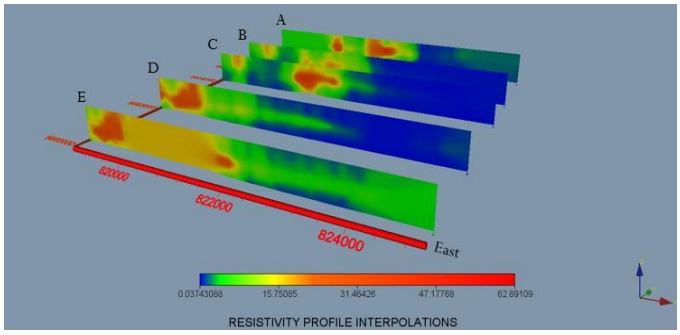



**Fig. 10**: Individual Profile Interpolations Showing the Different Colors of Potential Difference of Subsurface Feature

According to a study conducted by [27] in Wasi El Tarfa, Egypt, low resistivity values observed in the western part of the area indicate the presence of a high density of fractured and porous zones, which are considered major recharge sites. High resistivity values were dominant along the eastern areas of the study area. This could mainly be attributed to the presence of highly cemented rocks or sandstone with low porosity and therefore less recharge potentiality. From geo-electrical data analysis by [28],it was found that the low resistivity values near the surface layer are potential high groundwater recharge areas. Despite SWAT+ and the PQWT-s 500 models operating with different depths, the spatial distribution of annual average groundwater recharge developed in QSWAT plus and the 3-D model showed that the weak zone and the high recharge areas are in the Eastern part of the Kakia sub- catchment. However, the weak zones are shown to cover much larger extent than they appear in the average annual recharge map.

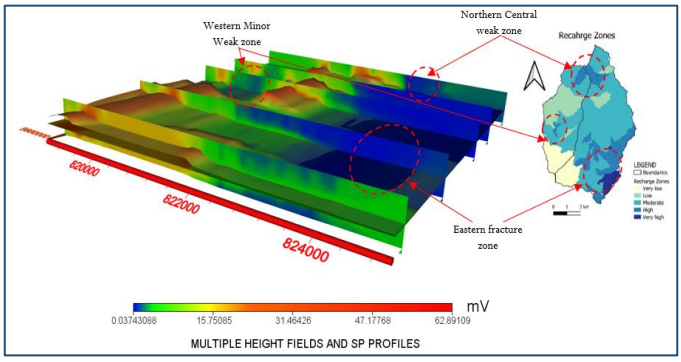



**Fig. 11**: Three-dimensional model compared to the Long-term annual average groundwater recharge

The good groundwater recharge zones are suitable for managed aquifer recharge (MAR) structures to augment the groundwater resources. Percolation ponds, ditches, and furrows, check dams, and bore-wells are examples of MAR structures that augment groundwater resources. Percolation ponds, ditch, and furrow are appropriate in flat and gentle slope areas. Ditches can be recharged in shallow aquifers with a high percolation rate. On the other hand, bore-wells are suitable in deep aquifer areas, whereas, check dams can be put within the streams.

### 3.3. Model Performance

The monthly calibration and validation hydrographs (Fig. 12 and Fig. 13) show a good fit between the observed and simulated soil moisture data. The statistical results for calibration (Jan 2003 – Dec 2010) and validation (Jan 2011– Dec 2019) periods indicates that $R^2$ values during calibration and validation periods were 0.51 and 0.59, respectively. According to [26] $R^2$ values equal or greater than 0.5 are satisfactory. NSE values of 0.17 and 0.20 were obtained for calibration and validation periods respectively. According to [29] NSE values less than 0.36 are considered not satisfactory. The low value of NSE indicates that the mean observed value is a better predictor than the simulated value [26]. This may be attributed to the underestimation of the high peaks. As it can be seen in the Fig.12 and Fig.13, the model underestimated the soil moisture, for instance in 2007, 2008, 2010, and 2019. The PBIAS values obtained for calibration and validation were 33.8% and 28.5%, respectively.

According to [29] PBIAS values between ± 20% and ± 40 were considered satisfactory. Hence in this study the PBIAS results of calibration and validation were considered satisfactory.

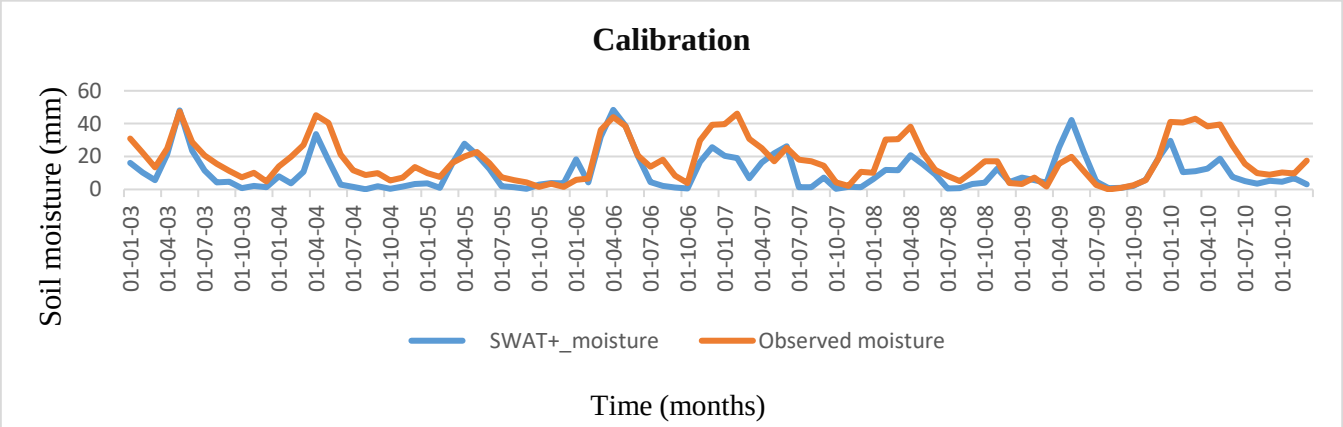



**Fig.12:** Calibration of Monthly Averages of Entire Study Area ESA Satellite Soil Moisture Data and Monthly SWAT+ Simulated Soil Moisture Data from January 2003 to December 2010

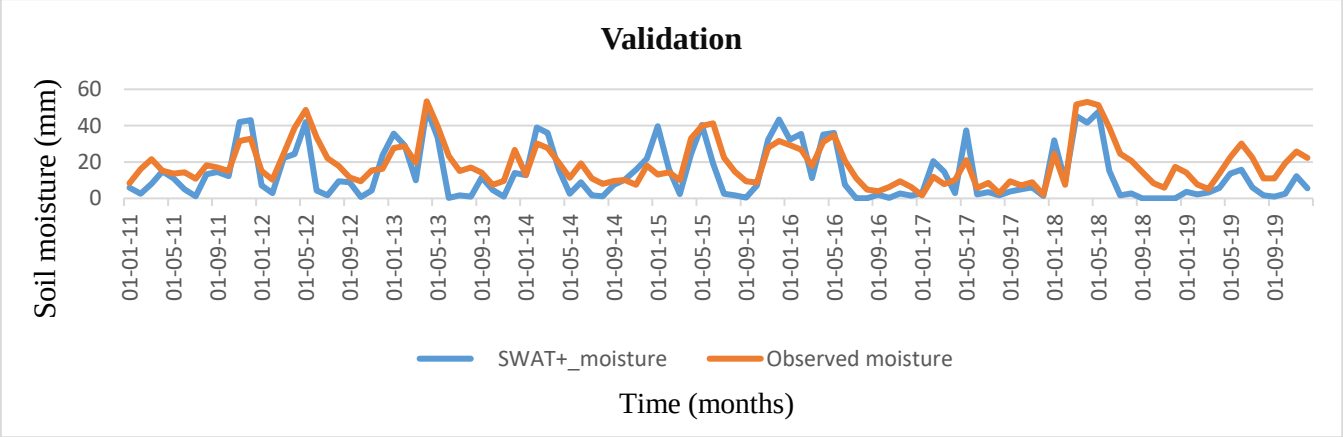



**Fig. 13:** Validation of Monthly Averages of Entire Study Area ESA Satellite Soil Moisture Data and Monthly SWAT+ Simulated Soil Moisture Data from January 2011 to December 2019

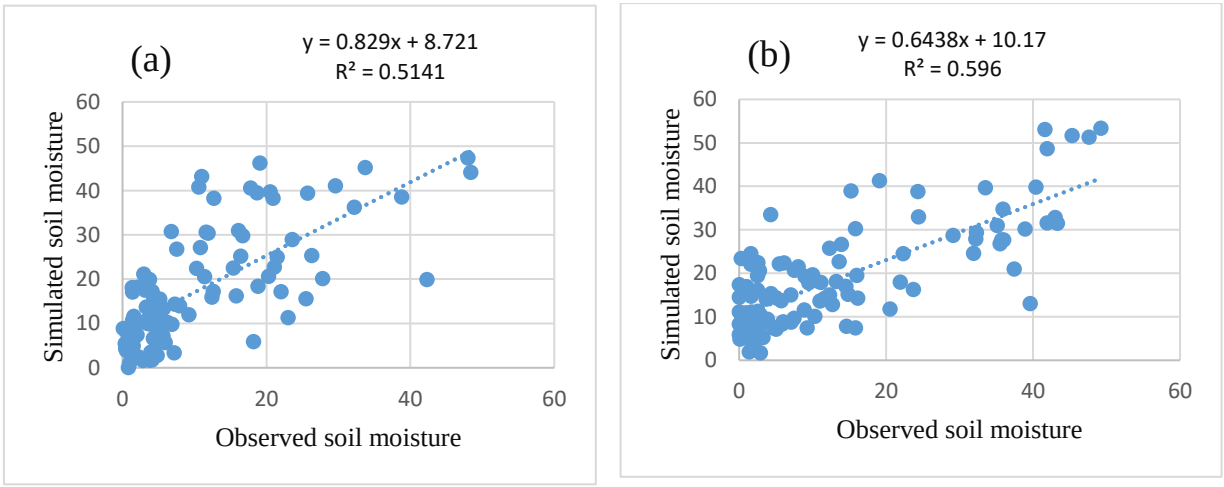



**Fig. 14:** Scatter plot of monthly soil moisture for (a) calibration period and (b) validation period

### 3.4. Estimating groundwater recharge rates

The QSWAT Plus model was run for a period of thirty years, from 1991 to 2020, in order to estimate groundwater recharge rates of Kakia and Esamburmbur sub-catchments. Figure 15 shows the distributed average annual groundwater recharge rates over the entire simulation period. The figure shows considerable spatial and temporal variation for long-term average groundwater recharge rates in the Kakia and Esamburmbur sub-catchment. It was assumed that the study area receives an equal amount of precipitation. However, this spatial pattern appears to be controlled significantly by land cover and slope. Slopes with steeper gradients have more runoff, whereas topographical depressions have more recharge.

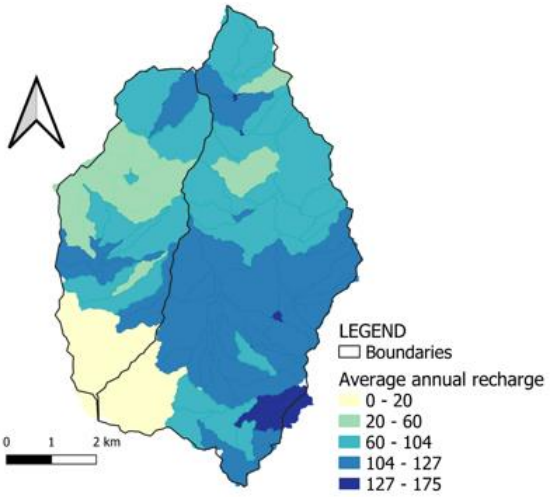



**Fig. 15:** Long-term average groundwater recharge (1991-2020) mm/year

The long-term average groundwater recharge rate ranges from 0 to 175 mm per year. The highest groundwater recharge in the sub-catchment was observed in the Southeastern portion of the study area and a small patch of the North. While most of the middle part of the area in both Kakia and Esamburmbur receive the high and moderate recharge. The lowest rate of recharge occurs in Narok town, the Southwest portion of the sub-catchment (Fig. 15). This can be attributed to the impervious surface in most parts of the town. Impervious surface minimizes the amount of water that infiltrates into the ground, hence low recharge rate. The low recharge rates at the upstream can be attributed to the steep slope at the upstream which tends to encourage runoff. Thus, minimal water infiltrates into the soil compared to lesser steep areas within the catchment. On comparing the recharge distribution within the simulated period, it was observed that recharge in the year 1998 was the highest, and accounted for 9.8% recharge. Lowest recharge was observed in the year 2009, and accounted for only 0.06% (Figure 16).

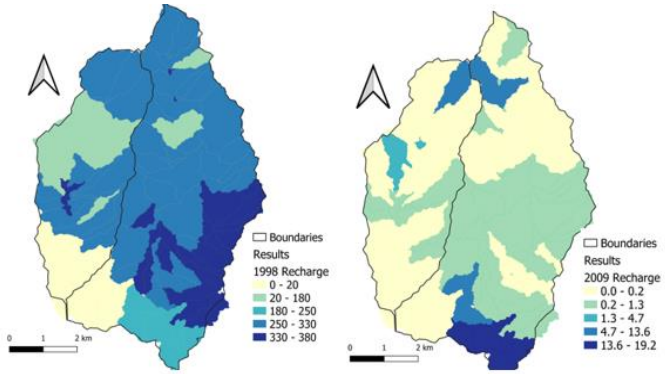



**Fig. 16:** Groundwater recharge of 1998 and 2009

The annual variations in the distribution of the groundwater recharge were due to the variability of the annual rainfall. About 29% of the annual precipitation in 1998 was recharged, while in 2009, 0.28% of the annual precipitation was recharged (Fig. 17). The results show that the highest groundwater recharge occurs in the months of April, May, and June. This is due to the long rainy season between March and May within the sub-catchments. In a similar study, it was found that groundwater recharge in Nairobi and the south coast aquifers are dominant in the months of March, April, May and, November [8].

The results show that about 12.6 % of the total annual precipitation in the simulated period (1991-2020) becomes available for groundwater recharge (Fig. 16). Similarly, [30] Estimated groundwater recharge of the Stony Athi sub-catchment, Kenya. They found that annual recharge ranged from 0 to 325 mm, and 14% of the average annual precipitation gets recharged. In a similar study done in the Raya basin in Ethiopia, it was reported that the mean annual groundwater recharge accounts for 8% of the precipitation [31].

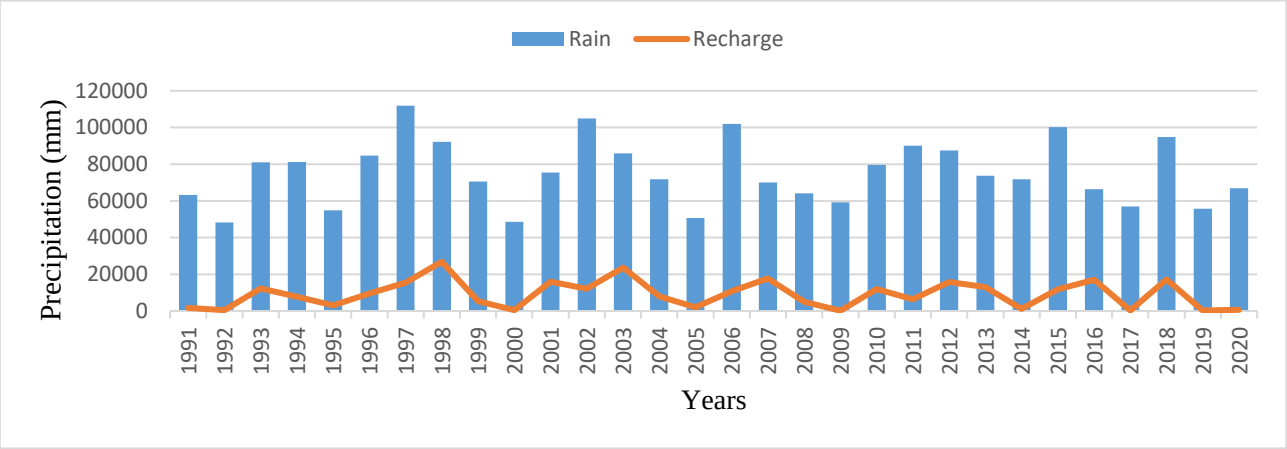



**Fig 17:** Annual Precipitation and recharge of the sub-catchment (1991-2020)

**Table 3:** Annual water balance components in Kakia and Esamburmbur catchment (1991-2020)

| Year | Precioitation | Runoff | AET | Water yield | Recharge |
|---|---|---|---|---|---|
| Long-term averages (1991- 2020) | 744 mm | 51.8 mm | 598 mm | 96 mm | 88.66 mm |

In Table 3, the water balance components of the Kakia and Esamburmbur sub-catchments in the simulated period (1991- 2020) are presented. The result shows that the average annual precipitation, which is about 744 mm, contributed to 12% recharge to the groundwater, 6.9% surface runoff, while actual evapotranspiration dominates the water balance, with a percentage of 80% of the average annual precipitation.

## 4. Conclusion

The purpose of this study was to estimate groundwater recharge rates and identifying groundwater recharge zones in Kakia and Esamburmbur sub-catchment. A geophysical survey was executed using the PQWTs-500 equipment to determine the suitable recharge zones. The geophysical survey results showed that the south-central and southeast zones of the sub-catchment are potentially good groundwater recharge zones. Groundwater recharge rates were simulated for a period of 30 years (1991-2020) using QSWAT+. The results show that the Southeastern part of Kakia has the highest recharge rates, hence the most suitable zone for recharge. The dominant soil type in the southeastern part of kakia is Andosols. These soils are porous with low bulk density, excellent water holding capacity, high infiltration rate, and high saturated hydraulic conductivity. The urban areas had the least recharge rate, as it is characterized by partial or full impervious surface. Also, some parts in Southwest and East-central in Esamburmbur experience very low and low recharge, respectively. This spatial pattern appears to be controlled significantly by the sub-catchment land use type and slope. Recharge was found to be higher in gentle slope and lower in steep slopes. Additionally, agricultural area, which is the most dominant land use type, had a high amount of recharge. Therefore, there is need for adoption of managed aquifer recharge structures, which would significantly improve recharge, and thus increased availability of water to the locals even during the dry seasons. Some of the managed aquifer recharge structures include percolation ponds, ditch and furrow, check dams, and bore-wells.

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## Conflict of interest

The authors declare no conflict of interest.

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