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Groundwater recharge modelling using SWAT analysis for groundwater reserve quantification of Ka watershed catchment area part of Sokoto-Rima Basin, North West Nigeria

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Abstract

Recharge plays a vmajor role in water resources management. However, measuring its spatiotemporal dispersion at the catchment region is an extremely difficult undertaking. This study used the Soil and Water Assessment Tool (SWAT) model and the Geography Information System (GIS) technique to estimate the recharge, spatial distribution, and potential recharge zones of groundwater at different scales in the Ka watershed catchment area. With the use of soil, land use, climate, and discharge data, as well as a digital elevation model, the SWAT model was established using data sets that span from (1996 – 2017), calibrated (2002 – 2017), and validated (2002–2017). The seven influencing groundwater recharge parameters that were integrated: rainfall, evapotranspiration, land cover/use, drainage, soil, hydraulic conductivity data, and runoff were utilized in mapping the recharge zones. The calibration and validation results are in good agreement with the field measured data, during the simulation exercise. Water balance analysis revealed groundwater recharge rate that ranges from 196.64 to 339.80 mm/annum with mean value of 269.08 as sole input into groundwater system which accounts for 28% of the input within this basin, while the basin receives mean precipitation of 972.83 mm/annum. The groundwater reserve of Ka watershed is estimated at 21,035,746.20 m^3. This available groundwater potential is sufficient for both irrigational use and domestic usage based on the fact that the area is sparsely populated and entirely depend on agricultural produce for survival.

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Keywords: Soil and Water Assessment Tool (SWAT), Groundwater recharge, Water budget, Hydrological response unit, Ka-river watershed

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1. Introduction

The effects of climate change on the groundwater aquifers are attracting more attention in recent research [1–8]. Hydrological systems and regional climates are anticipated to be impacted by the anticipated worldwide changes in precipitation and temperature. Groundwater levels are anticipated to fluctuate in response to alterations in the recharging of adjacent groundwater aquifers [9].

Therefore, developing policies for water resources and making decisions about planning and management in the area require a deep understanding of the hydrological processes taking place in basins [10–15]. This means that assessing the effects of changes to land use, vegetation, groundwater use, and river basin operation on the efficacy of planning, management, and policies connected to water resources requires modeling the key elements of the hydrological cycle [16–22].

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The system of water resources as a whole is impacted by its usage. Watershed system characteristics such as pollutant discharge, water supply, water recharge-discharge, and water ecology are influenced by surface water runoff and baseflow components of groundwater interactions [23–26]. Therefore, when developing an integrated water resource management plan, an assessment of a watershed's surface and groundwater resources should be considered holistically. Establishing and managing sustainable water resources requires an assessment of surface-groundwater interactions at the basin scale [27, 28].

Generally, groundwater is necessary for life flouring. Particularly in arid and semi-arid regions, recharge is essential for the development of water resources [29]. The amount of water recharge as measured by surface and subsurface water balance studies determines the productivity of aquifers. One of the main human-caused factors affecting recharging of groundwater resources is changes in land use and land cover (LULC) [30–36].

Environmental problems like biodiversity loss, biomass pollution, and climate change have been brought on by these developments. To ensure the sustainable development of water resources, a great deal of research is being done on tracking and reducing the effects of land-use change [37–40]. Sokoto-Rima hydrology catchment area is witnessing substantial agricultural and demographic expansion, which is raising demand for groundwater supplies. Accurate simulation and monitoring are becoming more and more important for managing groundwater resources successfully [41].

In particular, in the context of anthropogenic activities and climate change, which can cause significant changes in the hydrological system, a hydrological model was developed to resolve and address the practical issues related to water resources management and to better understand the dynamics of hydrological fluxes. Hydrologic models usually incorporate several parameters in order to represent the hydrologic processes and account for geographical variations caused by factors like land use, soil type, and climate [42–46].

To ascertain the amount of groundwater recharge, several methods have been developed, such as the point measurement with lysimeters, the water table fluctuation method, the Darcy method, and the water balance approach on the basin. However, it's unclear if the spatiotemporal variability of the factors controlling groundwater recharge is taken into account by the methods used to measure it currently [47–52].

Large-scale simulation models that use global data sets are essential because without sufficient data, such as large-scale groundwater dynamics observations and aquifer characteristics, experimental methods could not be practical [52–56].

Since recharge is the main source of water entering aquifers, quantifying it is essential for the sustainable management of surface and groundwater resources [57].

Large-scale continental and global groundwater recharge simulation models have currently been constructed [58]. Given the input climate conditions, many of the hydrological models currently in use can mimic watersheds that are changing quickly. Precipitation events have minimal direct effect on the hydrograph's structure (such as peak flow) in rivers where baseflow predominates. Consequently, the model's performance may degrade when simulations are conducted on rivers that are mostly dominated by baseflow [59].

In agricultural watersheds with varying soil, land use, and management circumstances, SWAT is a long-term, distributed-parameter model that forecasts how land management practices will impact hydrology and water quality [60]. The foundation of SWAT consists of hydrological response units (HRUs), which are sub-basins with unique soil, land use, and management features. Based on factors such as weather, soil characteristics, geography, vegetation, and land management, each HRU's runoff, sediment, and nutrient loadings are estimated separately. The sum of these values then yields the overall loading from the sub-basin [61].

SWAT offers a dependable technique that makes it suitable for assessments in integrated hydrological modeling, based on the soil water balance at the watershed scale [62]. The SWAT model is frequently used to evaluate the long-term effects of hydrological changes and has been effectively applied to a variety of river basins.Unfortunately, the majority of these earlier research used significant input parameters, including runoff and precipitation, to examine possible effects on a single parameter (e.g., total streamflow, evapotranspiration, groundwater recharge) [63]. As a result, they are unsuitable for evaluating specific model components. Many important hydrological components have not gotten much attention in research investigations.

Using SWAT modeling at the watershed scale, this study intends to examine the effects of surface and groundwater interactions on groundwater recharge and water balance in the Ka River basin of the Sokoto-Rima hydrological basin.

2. Materials and methods

The Ka watershed area is located south-west of river within Sokoto-Rima hydrological basin with a latitude of 5°0'00"E to 6°50'0"E and Longitude 11°10'0"N to 11°50'0"N with total area coverage of 7,970,940 m^2. Its tributaries drain from North-East highlands and discharge into river Sokoto river at western part of the study region. The Ka River basin within the study area has twenty-five (25) subbasins with 127 hydrological response units (HRU) (Figure 1). HRUs are the smallest segments of a watershed, encompassing different LULC, soil, and landscape properties among sub-basins. Flow is computed for each piece of the watershed separately. The watershed is divided into multiple sub-basins or sub-watersheds by the model. The use of sub-basins in a simulation is particularly helpful when different sections of the watershed are dominated by land uses or soils with qualities that differ enough to effect hydrology.

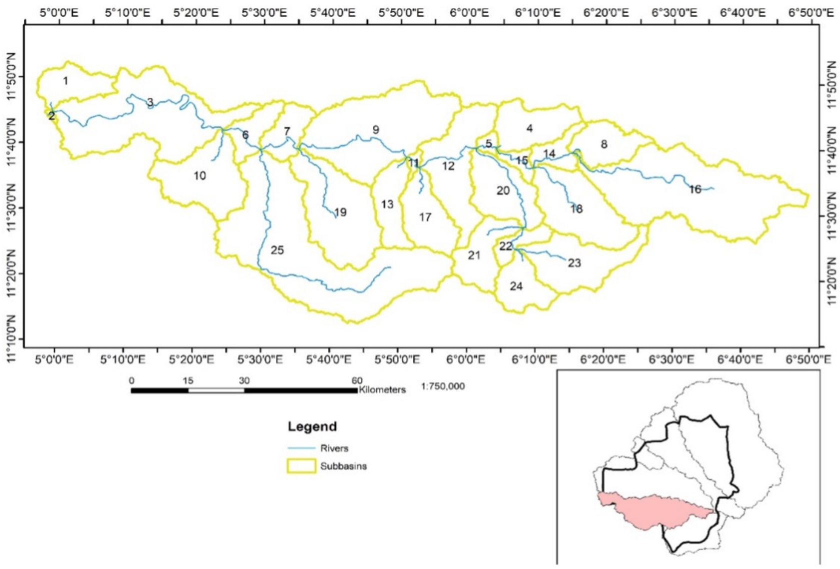

Figure 1: Ka river watershed/subbasins.

Table 1: Water balance of the river Ka watershed.

Parameters	Minimum	Maximum	Sum	Mean	Std. deviation
Groundwater Recharge	196.64	339.8	6726.99	269.08	34.63
Precipitation	853.96	1026.54	24320.76	972.83	65.45
Evapotranspiration	426.11	540.47	12886.05	515.44	27.82
Runoff	102.12	167.5	3479.74	139.19	24.41

Ka watershed has an installed instrumented river gauge for streamflow measurement weather station, coordinated by Sokoto-Rima Basin Authority.

The entire watershed is underlain by crystalline lithological units, such as mica schist, quartzite and intrusive granites. Its aquiferous unit are structurally controlled by tectonic episodes that occur within the region as reported in the work of Shuaibu [64].

Using hydrological equation (1), the model simulates variables that affect aquifer recharge, including precipitation, evapotranspiration, surface runoff, landuse/cover, soil map, and slope (Figure 2). The climatic data were processed using the weather generator model, then packaged in the proper manner and transferred to the SWAT model database to finish the setup of the SWAT model. Data from six weather stations were cleaned up and included into the model. The simulation was run for 15 years, from 2002 to 2017, and data from 2002 to 2017 were used for validation.

$$SW(t) = SW_0 + \sum (R_{annual} - Q_{surface} - W_{seepage} - E_a - Q_{qw}). \quad (1)$$

In the provided context, $SW(t)$: This variable represents the soil moisture content at a specific time 't' (measured in millimeters - mm). SW_0: Denotes the initial or base soil moisture level (also measured in millimeters - mm) at the beginning of the considered time period. 't': Represents time, typically measured in days, indicating the duration over which changes in soil moisture content or hydrological processes occur. R_{annual}: Signifies the volume of rainfall occurring over a specific period (typically annual rainfall) measured in millimeters (mm). It characterizes the total amount of precipitation received within a year. $Q_{surface}$: Represents surface runoff, denoting the portion of rainfall or water that does not infiltrate the soil but instead flows over the land surface. It's measured in millimeters (mm) and contributes to streamflow. E_a: Stands for evapotranspiration, encompassing both evaporation and plant transpiration. It represents the process by which water is released into the atmosphere from soil surfaces and through plant leaves. It is measured in millimeters (mm). $W_{seepage}$: Indicates water seepage from the soil into deeper layers or possibly downward movement within the soil profile. These variable measures the amount of water percolating below the surface and is measured in millimeters (mm). Q_{gw}: Represents groundwater recharge, denoting the process by which water infiltrates the soil and replenishes underground aquifers. It signifies the amount of water that contributes to the renewal of groundwater resources and is measured in millimeters (mm). ArcSWAT version 2012 was used for the integration and simulation of the hydrologic parameters (Figure 2). The set-up process is well described and presented in the work of Refs. [65–67].

For the calibration and simulation in SWAT-Cup, semi-automated sequential uncertainty fitting (SUFI-2) was utilized in monthly time increments [68]. Seven sensitive parameters were chosen for the Sufi-2 algorithm using sensitivity analysis techniques. The

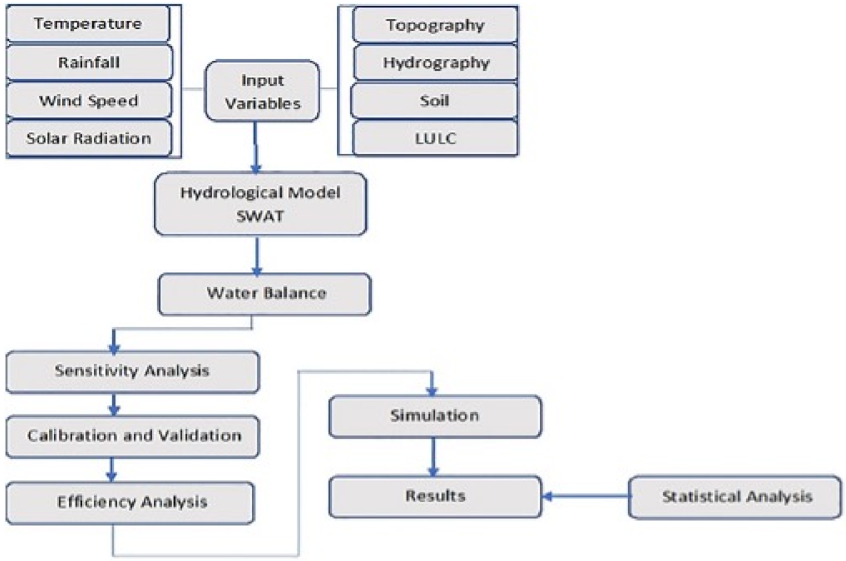

Figure 2: SWAT model set-up flowchart.

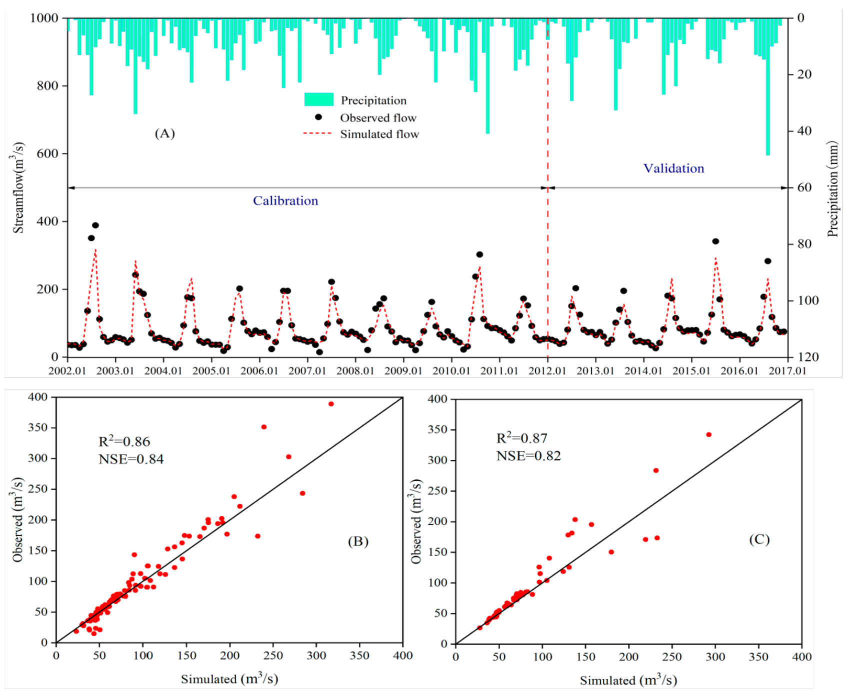

Figure 3: Simulated and observed streamflow compared to calibration and validation periods (A), with coefficient of determination (B, C).

effectiveness of the calibration and validation procedure was assessed using two indicators, namely the Nash-Sutcliffe Coefficient of efficacy (NSE) and the R^2 indicator, which were employed in the work of Bieger *et al.* [68, 69], Bruner *et al.* [70].

The results of the measurement were utilized for the simulation hydrological parameters and served as reference point for the entire evaluation exercise. Standard value of NSE range between - ∞ to 1, and value close to 1 or equal to 1 indicate high model accuracy. Whereas, R^2 values range between 0 to 1, it is used to established statistical relationship between simulated and field data (observed), values to close to 1 shows strong relationship and an excellent fitting.

3. Results and discussion

The calibration and validation exercises demonstrated that the observed field values closely align with the simulation results derived from the SWAT model. During the model calibration process, the Nash-Sutcliffe Efficiency (NSE) coefficient was 0.8, and

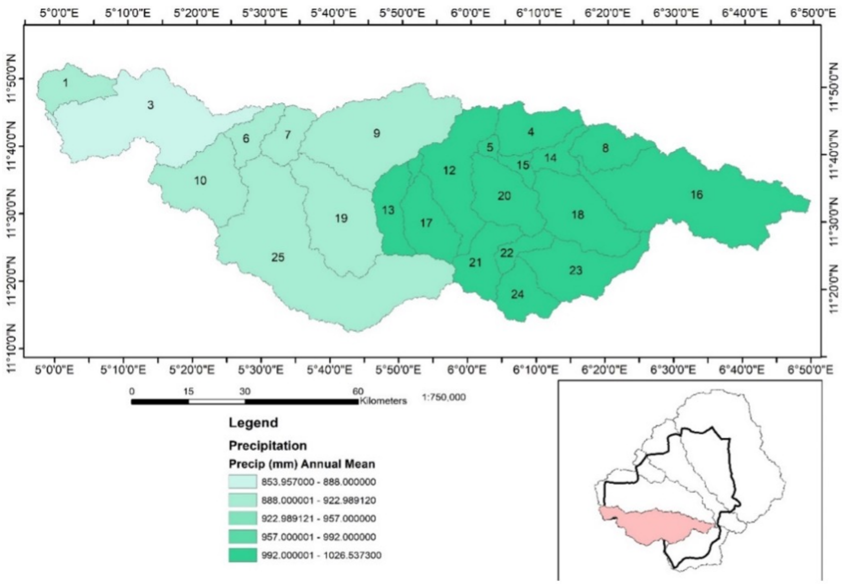

Figure 4: Precipitation distribution of Ka river watershed.

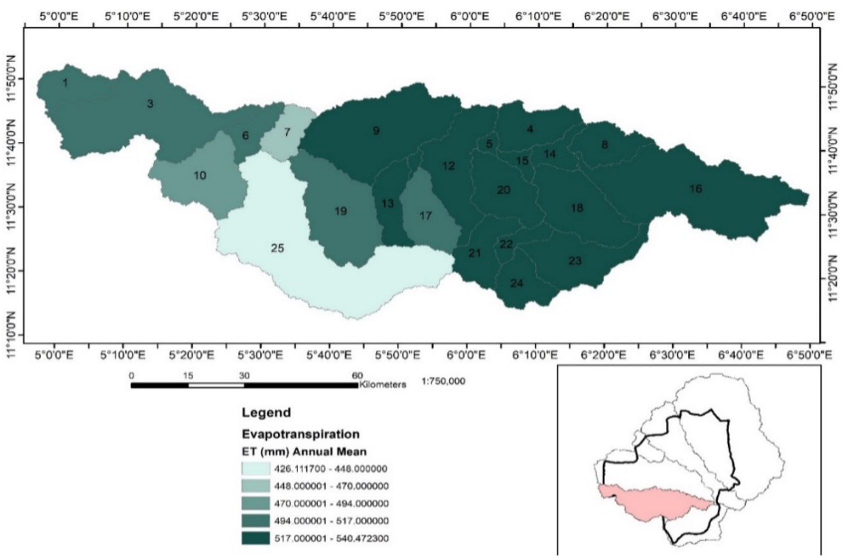

Figure 5: Evapotranspiration distribution of Ka river watershed.

the coefficient of determination (R^2) was approximately 0.9, indicating a strong relationship between simulated and observed data (Figure 3). These results underscore the model's robustness and reliability in simulating the hydrological processes within the Ka River watershed, as supported by similar applications of SWAT for hydrological assessments in various basins [2, 19, 37].

The output of the input hydrologic data for the SWAT model are presented in Figures 4, 5, 6, 7 and 8 respectively.

Precipitation acts as the primary source of water for infiltration into the groundwater system. Variations in precipitation directly affect recharge rates. In Ka watershed, understanding the distribution of precipitation (as illustrated in Figure 4) helps identify areas of high recharge potential. A region with high rainfall intensity is more likely to contribute significantly to groundwater replenishment as reported in the work of Pascual-Ferrer *et al.* [37].

Evapotranspiration represents water loss through evaporation and plant transpiration. Higher evapotranspiration reduces the amount of water available for infiltration. The distribution (Figure 5) informs the net recharge potential, helping determine areas where actual infiltration is likely diminished due to high water loss according to Dolottier *et al.* [52].

Land Use and Land Cover (LULC) determines surface characteristics such as permeability, runoff potential, and vegetation cover as reported by Guzman *et al*. [37]. Agricultural areas, as noted in the Ka watershed, can significantly alter recharge rates. Over 80% of the Ka watershed is agricultural land, likely impacting infiltration positively in areas where soils are permeable or negatively if extensive compaction has occurred due to farming practices.

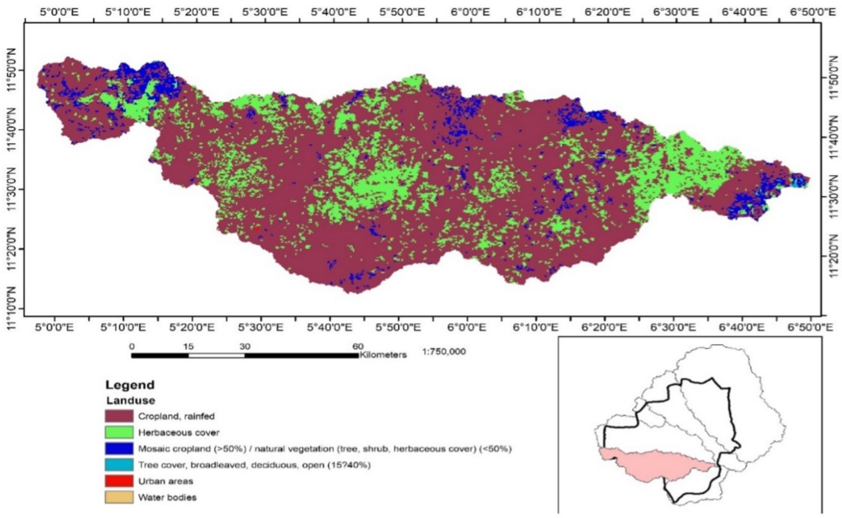

Figure 6: Landuse map of the Ka river watershed.

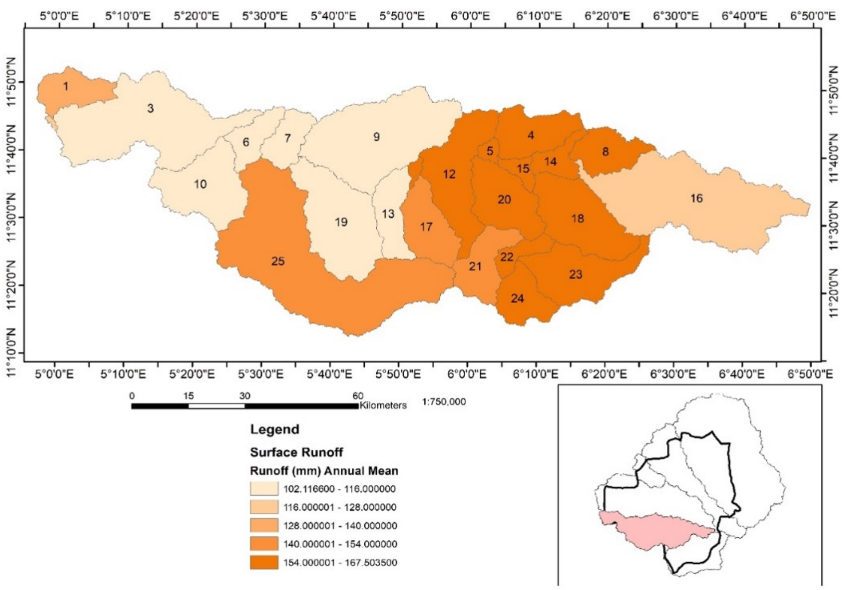

Figure 7: Runoff distribution of the Ka river watershed.

Runoff patterns dictate how much water flows to streams rather than infiltrating into the subsurface. Understanding runoff distribution (Figure 7) can reveal how surface water is redirected and its implications on recharge zones according to Ware *et al.* [50].

Soil texture and composition control infiltration rates. Sandy soils generally allow higher infiltration, whereas clayey soils impede water flow according to Jin *et al.* [14]. The soil map (Figure 8) of the Ka watershed identifies zones with varying recharge potential based on soil types. Areas with sandy or loamy soils likely contribute more to groundwater recharge. This is similar to the result obtained by Shuaibu and Murana [71] in the same climate region.

3.1. Water resources availability

The average groundwater recharge distribution for the entire simulated period (2002–2017) is shown in Figure 9. The groundwater recharge in the watershed is seen to be significantly distributed both spatially and temporally in the Figure 9.

Precipitation serves as the primary water source for infiltration, with significant spatial and temporal variations across the watershed. The mean annual precipitation was 972.83 mm, contributing to a groundwater recharge rate ranging from 196.64 to 339.80 mm/annum, with a mean value of 269.08 mm (Table 1). This recharge accounted for 28% of the total input, a finding consistent with recharge studies in semi-arid regions [15], [29], [45]. Evapotranspiration accounted for 53% of the water loss, while surface

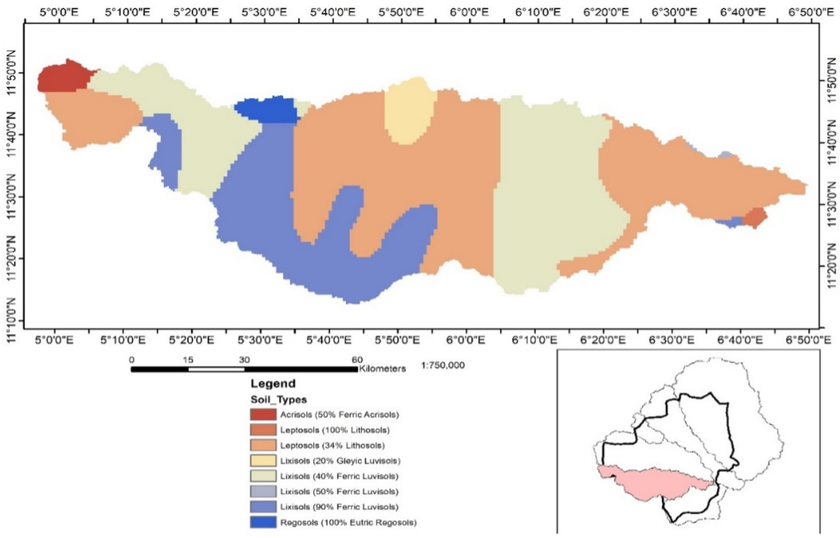

Figure 8: Soil map of the Ka watershed.

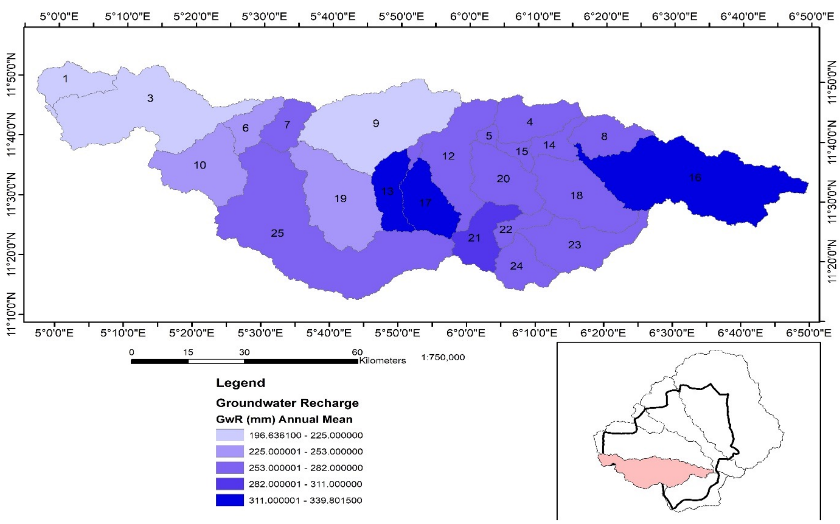

Figure 9: Groundwater recharge distribution of Ka river watershed.

runoff contributed 14.31%. These proportions align with findings from other hydrological studies emphasizing evapotranspiration's dominance in water loss pathways [51, 60].

The estimated groundwater reserve for the Ka watershed, calculated as the product of the watershed area (7,819,980 m^3) and average recharge (2.69 m), amounts to 21,035,746.20 m^3. This volume is sufficient for both domestic and irrigation purposes, affirming the importance of sustainable groundwater management in the region. Similar conclusions have been drawn in studies focusing on integrated water management in semi-arid regions [12, 40, 41].

The spatial distribution of groundwater recharge revealed significant variability influenced by precipitation, land use, and soil type (Figure 9). Regions with sandy or loamy soils showed higher infiltration potential, consistent with previous studies highlighting soil texture's critical role in recharge dynamics [10, 36]. Agricultural practices, which dominate over 80% of the Ka watershed, may enhance recharge in permeable soils but reduce it in compacted areas due to land-use changes, as observed in other studies [22, 33, 53].

The results of the hydrologic SWAT model often show that evapotranspiration is responsible for over half of the annual precipitation in the water catchments. The unsaturated zone, the shallow unconfined aquifer, and the deep aquifer are the percolation portion, and the remaining components discharge (surface runoff, lateral flow, and return flow) are considered as discharge components. When examining only the ratio of these components, the surface runoff component of the total discharge is greater than sixteen percent.

Nevertheless, substantial surface runoff volumes are produced by saturated soils even during the heaviest rainy season, which falls in August and September. This usually leads to flooding in some catchment regions.

In the event that rainfall decreases and some late crops that still require water are impacted, there is a higher likelihood of

Table 2: General model parameter.

Parameters	Definition	Range	SWAT default	Final Value
CN2.mgt	Initial SCS CN II value	30 - 99		68.3 - 98
ALPHA_BF.gw	Baseflow alpha factor [days]	0 - 3.5	0.048	0.035
GW_DELAY.gw	Groundwater delay [days]	0 - 600	32	32
REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur [mm]	0 - 800	760	742
RCHRG_DP.gw	Deep aquifer percolation fraction	0 - 1.3	0.06	0.074
GW_SPYLD.gw	Specific yield of the shallow aquifer [m3/m3]	0 - 0.5	0.004	0.0037
GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur [mm]	0 - 600	800	1078
SURLAG.hru	Surface runoff lag time in the HRU (days)	0.06 - 28	7.8	0.9
ESCO.hru	Soil evaporation compensation factor	0 - 1	0.95	0.4
EPCO.hru	Plant uptake compensation factor	0 - 1	1	0.8
HRU_SLP	Average slope steepness [m/m]	0 - 180	0.018	0.05

depending on runoff for capturing and storing it in ponds or reservoirs for use during the dry season or extracting what is stored in the soil for supplemental irrigation. It is estimated that 28% of the precipitation, or 120 mm/year on average, seeps into groundwater, which is made up of the deep aquifer, the shallow unconfined aquifer, and the unsaturated zone. Five percent of the water is lost during this percolation process as the return flows, feeding the watershed outlets. The shallow aquifer, which is easily accessible and unsaturated, contains around 3.5% of the recharge from the deep aquifer (Table 2).

While the SWAT model is highly effective in simulating hydrological processes, its accuracy can be influenced by baseflow-dominated rivers, as noted by Healy and Cook [59]. The interplay of surface runoff and shallow aquifer recharge during peak rainfall periods also highlights the need for targeted interventions to mitigate flood risks and enhance water storage during dry seasons [60, 66].

4. Conclusion

This study effectively quantified groundwater recharge and reserves within the Ka watershed catchment area, employing the SWAT model for a detailed hydrological assessment. Calibration and validation results, with NSE and R^2 values of 0.8 and 0.9 respectively, demonstrate the model's robustness in simulating the hydrological processes of the region. Findings revealed that 28% of annual precipitation contributes to groundwater recharge, with an estimated reserve of 21,035,746.20 m^3. This resource, distributed across shallow unconfined aquifers and deep aquifers, is sufficient to support both domestic and agricultural water demands in the sparsely populated, agriculture-dependent watershed.

The spatial variability of recharge, influenced by soil texture, land use, and precipitation, highlights the critical need for targeted water resource management strategies to enhance sustainability. Surface runoff and evapotranspiration account for significant portions of water loss, underscoring the potential benefits of improved water conservation practices. Additionally, the study underscores the utility of SWAT modeling in integrated water resource management, offering valuable insights for decision-making in similar semi-arid regions experiencing climatic and anthropogenic pressures. Future research could explore integrating additional data sources to enhance predictive capabilities and mitigate potential flood risks during peak rainy seasons.

Data availability

All datasets employed in this research are readily available from the corresponding author and can be accessed by interested researchers in this field, promoting transparency, reproducibility, and further scientific inquiry.

Acknowledgment

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