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Spatial and temporal estimation of groundwater recharge in Kabago watershed using the soil and water assessment tool (SWAT) hydrological model: implications for sustainable water resource management in Northwestern Nigeria

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ABSTRACT

Assessing groundwater recharge is essential for managing water resources sustainably, especially in semi-arid regions. In order to assess groundwater reserves for residential and agricultural use, this study examines the spatial and temporal distribution of recharge in the Kabago watershed in Southern Zamfara State, Nigeria. The watershed, which is roughly 5.97 km^2 in size and is composed of migmatite, gneiss, schist, and granitic rocks, has a Sudan savannah climate with high evapotranspiration and little annual rainfall (1164 mm). Hydrological processes during a 21-year period (1990–2010) were simulated using the Soil and Water Assessment Tool (SWAT 2012) linked with ArcGIS. SUFI-2 in SWAT-CUP was used for calibration and validation utilizing streamflow data from the Maru gauging station. With NSE values of 0.85 and 0.75, R^2 values of 0.85 and 0.75, PBIAS of 2.5% and −1.3%, and RSR values of 0.43 and 0.52 for calibration and validation, respectively, the model performed satisfactorily. Soil water capacity, groundwater delay, baseflow coefficient, and surface runoff factors were among the sensitive characteristics. The results indicated that model-derived potential recharge values, which represent roughly 49% of annual precipitation, ranged from 379.93 to 678.88 mm/year with an average of 545.69 mm/year. Runoff and evapotranspiration were responsible for 15.35% and 33.24% of the water loss, respectively. Recharge variability was largely influenced by rainfall distribution, soil type, slope, and land use, with agricultural land promoting infiltration. Overall, the Kabago watershed functions as a significant recharge zone, though high evapotranspiration highlights vulnerability to land use and climate change. These findings provide a sound basis for groundwater management and policy in Zamfara and comparable semi-arid regions.

1. INTRODUCTION

Groundwater is an extremely important resource upon which survival of life on Earth depends. The focus on groundwater is im-

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portant particularly in Sub-Saharan Africa, where drought, population growth, and climate change impact water resources. In arid and semi-arid regions, replenishment is more crucial for the expansion of water resources [1, 2]. The amount of water that recharges the vadose zone makes up the surface and subsurface water balance components of the aquifers. The most important human factors impacting groundwater resource change are changes in land use and land cover (LULC), as they affect groundwater recharge [3].

Watersheds integrating urban and agricultural land use must prioritize sustainable development and management due to climate change, the increasing demand for water supplies, and inadequate management of water resources [1–4]. Understanding the hydrological water cycle and its kinship system in detail is essential for controlling and preserving the watershed's water resources [5, 6]. It affects water quality, water supply, and watershed recharge-discharge [6, 7]. Furthermore, it's critical to estimate water balance components using an appropriate method [5, 6, 9]. Therefore, evaluating the groundwater recharge of the studied watershed is the main focus of this article.

Addressing water resource concerns, such as the effects of urbanization, various management options, and future climate oscillation on streamflow and water quality, requires a detailed understanding and accurate modeling of Earth surface processes at the watershed scale [10]. Understanding watershed dynamics requires a thorough understanding of weather conditions as well as measurements of runoff, water stage, erosion, soil moisture, and water quality.

Experimental catchments are meticulously designed and closely monitored to generate databases of long-term historical hydrological data that support the study of the processes causing surface runoff [11]. Furthermore, experimental catchments can serve as satellite sensor validation sites and aid in the creation and verification of many watershed models [12].

Prior research employed a variety of methods to estimate groundwater recharge, including numerical methods [13–15], physical methods [10–12], and tracer methods [2, 16, 17]. Every technique has limitations when it comes to evaluating recharging [11]. Researchers are increasingly using the numerical method, which analyzes either surface or aquifer conditions, or both, to assess groundwater recharge [18, 19].

The Soil and Water Assessment Tool (SWAT) is routinely used to simulate surface water flow, whereas the Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW) is frequently used to assess unconfined groundwater flow. The quantity and quality of surface and groundwater at various watershed sizes have been evaluated using SWAT [20, 21]. It also predicts how a chosen watershed will be affected by land use/cover and climate change [22–25]. The SWAT model has been used for multi-scenario environmental investigations and at a variety of scales in hydrological watersheds [26–28].

For instance, water resource sustainability [29], water balance analysis [28], and water quality assessment [30] were all conducted in South Korean watersheds using the SWAT model. Although the SWAT model emphasizes surface processes, its lumped structure makes it insufficient for simulating groundwater movement [31].

A more sophisticated groundwater storage module [32], a modified code [33], or the substitution of the grid cell aquifer for the non-shallow aquifer [34–37] are some of the methods used to solve the inadequacies of the original SWAT groundwater module. But its ability to replicate groundwater flow properly is limited due to its semi-distribution technique.

The SWAT application describes [38] itself as a continuous-time, semi-distributed, process-based model. The model has been adjusted to employ sub-daily time step computations instead of the daily time step [39]. SWAT was established to evaluate how management practices might affect the yields of water, sediment, and agricultural chemicals over the long term in large river basins. The weather, hydrology, soil properties, land use, crop growth, nutrients, sediments, pesticides, bacteria, and diseases are the main components of SWAT. A watershed is divided into multiple subbasins in SWAT, which are further divided into hydrologic response units (HRUs) based on unique soil, slope, and land use characteristics.

With the use of HRUs, the model can take into consideration how evapotranspiration varies depending on the kind of soil and plant. As per Gumuła-Kawecka *et al.* [40], the hydrology simulation of a watershed can be separated into two stages: the land phase, which determines the loadings of water, sediment, nutrients, and pesticides to the main channel, and the routing phase, which entails transporting the loadings to the outlets via the subbasin streams.

A variety of hydrological processes, including canopy storage, surface runoff, precipitation partitioning, infiltration, water redistribution within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers, are simulated differently by each HRU [41]. SWAT uses a single plant growth model to recreate different types of vegetation and differentiate between annual and perennial plants. The plant growth model estimates transpiration, biomass/yield generation, and the amount of water and nutrients taken out of the root zone.

In order to establish the groundwater reserve in the region for household and agricultural uses, this study aims to utilize the SWAT hydrological model with the addition of geological parameters to determine the geographical and temporal distribution of the recharge rate of the Kabago watershed.

2. MATERIAL AND METHODS

2.1. STUDY AREA

River Kabago watersheds lie within latitude 10° 50″ 0′N to 11° 30″ 0′N and longitude 6° 10″ 0′E to 7° 0″ 0′E of Southern part of Zamfara State, Nigeria with an estimated area coverage of 5,970,940 m^2. The Kabago river basin has thirty-five (35) subbasins with 150 hydrological response units (Figure 1).

The average daily temperature is extremely high, with a minimum of 16°C during the mild months of January and December and a maximum of 38°C and a minimum of 24°C during the hottest months of April to June. All year long, the average daily low is 21°C, while the average high temperature is 36°C. It doesn't rain much. After 35 years, the average yearly rainfall is roughly 1164 mm. May through September sees the most rain, and October through April sees the least amount of precipitation. High levels of evaporation occur from July (80 mm) to April and

May (210 mm) [20].

Thirty percent of the catchment's monthly average precipitation falls within a monthly average evaporation range of roughly 140 mm [42]. The maximum evaporation occurs during the warmer months of April through May. Only during the rainy months of June through September does the relative humidity rise from its low levels throughout the year. Usually found in Sudan savannah, the vegetation is distinguished by thorny, stunted plants that are always of the acacia variety.

Gneiss (banded gneiss), granite-gneiss, mica schists, quartzite, and granite varieties (fine-grained biotite granite, medium-grained biotite and hornblende granite, biotite hornblende granodiorite, porphyritic biotite and hornblende granite) comprise the primary lithological units in the study area. Minor rock types include quartz veins, pegmatites, quartzo-feldspathic intrusions, and a number of other rocks. Within the studied area, there were both brittle (joints and faults) and ductile (foliations and folds) structural features [43].

2.2. ANALYTICAL TECHNIQUES

Hydrologic response units (HRU) are the foundation of SWAT, a large-area hydrologic/water quality model [44–47]. SWAT replicates nutrient cycle, erosion, and water movement in soil and groundwater [48]. SWAT comes in several versions with various interfaces; in this case, version 2012 with the ArcGIS interface (ArcSWAT) was used.

The smallest portion of a watershed that reflects a range of LULC, soil, and landscape characteristics is the HRU within the subbasins. Flow is calculated separately for each watershed segment. According to [49–53], the general equation for the SWAT model is as follows:

$$SW(t) = SW_0 + \sum_{i=1}^{t} \left(R_{annual} - Q_{surf} - W_{seep} - ET - Q_{gw} \right). \quad (1)$$

W_{seep} is the seepage (mm/day), Q_{gw} is the flow from the aquifer, Q_{surf} is the surface runoff (mm/day), ET is the evapotranspiration (mm/day), SW_0 and SW_t are the starting and final soil water levels (mm/day), and t is the time in days.

The 21-year SWAT simulation, which included a two-year warm-up, ran from 1990 to 2010. The first 11 years were used for calibration, while the remaining data was used to evaluate the model after the warmup period. Streamflow data obtained at the Maru gauging station was used to calibrate and validate the SWAT model. The calibration and validation were performed on monthly time steps using SWAT-CUP's semi-automated sequence uncertainty fitting version 2 (SUFI-2).

The SUFI-2 algorithm was applied for global sensitivity analysis, through which twelve key parameters were identified as most influential. These include "soil-related factors (SOL_K, SOL_BD, and SOL_AWC)", "groundwater parameters (GW_DELSY, ALPHA_BF, GWQMN, and GW_REVAP)", a "lateral flow parameter (HRU_SLP), surface runoff variables (SURLAG and CN2), an evaporation factor (ESCO)", and the main "channel hydraulic conductivity (CH_K2)". Then, by contrasting the measured and modeled flow data, these parameters were adjusted. The definition and the minimum and maximum values for the calibration are listed in Table 1.

Table 1. Flow parameter and calibration range definition.

Parameters	Meaning	Range
v__CN2.mgt	The number of runoff curves by Soil Conservation Service (SCS)	-0.2 – 0.6
n__GW_DELAY.gw	Delay_Groundwater (days)	0 – 600
n__GWQMN.gw	The shallow aquifer's minimum water depth (mm H_2O) needed to start a return flow	0 – 7000
n__GW_REVAP.gw	An indicator of the water's readiness to flow from the shallow aquifer to the root zone	0.03 – 0.5
n__ALPHA_BF.gw	Recession coefficient of the baseflow	0 – 1.5
n__ESCO.hru	A coefficient to adjust the soil evaporation demand	0 – 1.2
n__CH_K2.rte	Main channel hydraulic conductivity (mm/hr)	0.03 – 160
n__SOL_AWC.sol	Soil water capacity measure (mm H2O/mm soil)	0.5 – 0.6
n__SOL_K.sol	Hydraulic conductivity at Saturation (mm/hr)	-0.4 – 0.6
n__SURLAG.bsn	Surface runoff coefficient lag	0.06 – 25
v__HRU_SLP.hru	Mean_slope steepness (m/m)	0 – 0.7
v__SOL_BD.sol	Bulk density of Moisture content (Mg/m^3)	-0.4 – 0.7

Note: The value of v__parameter is multiplied by (1+ a provided value); the value of n__parameter is substituted.

RSR (standardize root mean square error), percentage bias (PBIAS), the coefficient of determination (R^2), and the Nash–Sutcliffe coefficient of efficiency (NSE) are four commonly used indicators that were used to evaluate the calibration and validation performance.

Among the time-series and spatial data needed by the SWAT model are solar radiation, rainfall, wind speed, temperature, and relative humidity. Various offices (NIHSA, NiMET and Bakolori Irrigation Programme) and publicly accessible websites were the main sources of the data.

The Nigeria Hydrological Service Agency (NIHSA) provided the streamflow data, the Nigeria Meteorological Agency (NiMET) provided the precipitation data, and the Nigeria Geological Survey Agency provided the lithological map of the region. In contrast, information on land use, soil, and geomorphology was sourced from the USGS and NASA databases. Both a LULC and a DEM with a spatial resolution of 30 m were downloaded. The ArcGIS interface was mostly used to process the topographic characteristics produced from the DEM. Prior to being included in the modeling, all of the maps were re-projected to UTM zone 32N.

The SWAT model's primary inputs include soil, weather, LULC, and DEM data (Figure 2). Importing grid-based spatial data, defining the HRU, defining the watershed, and creating subbasins are the initial steps in configuring the model. The SWAT model uses DEM to identify the watershed and create subbasins

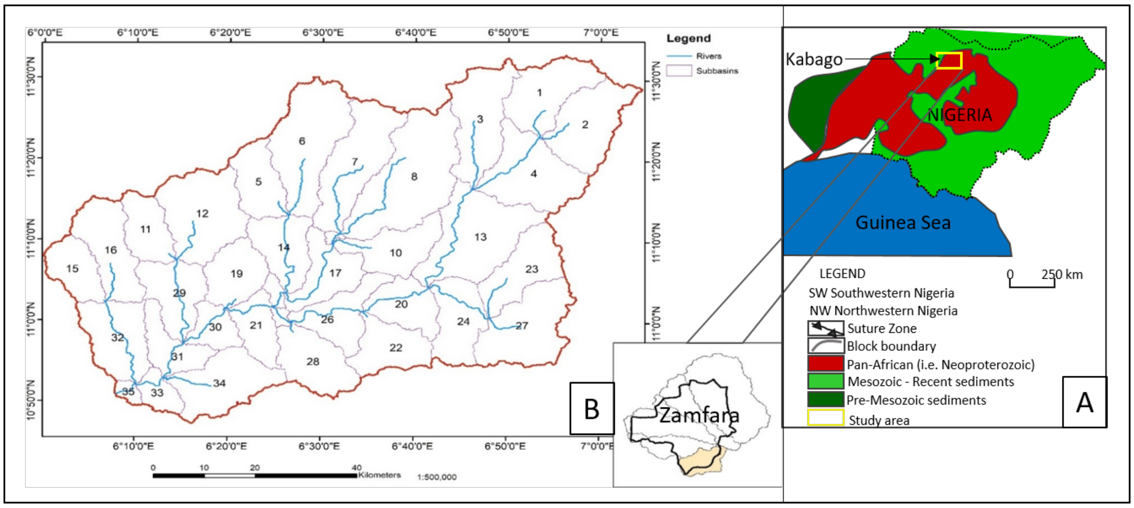

Figure 1. (A) Geological map of Nigeria (B) River Kabago watershed/subbasins within the study area.

and stream networks. Every HRU has unique soil and LULC characteristics. The watershed was separated into 35 subbasins, which were further subdivided into 150 HRUs. The recharge change is the primary indicator of LULC's impact on groundwater and surface water [42]. Over 80% of the Kabago watershed is covered by agriculture, with seven different land-cover classifications.

Six major soil groups are shown in the classification. Clay is the predominant soil type in the region. The weather generator model WXGEN was used to process the climatic data, prepare it in the necessary format, and add it to the SWAT model database in order to finish the SWAT model setup. Data from six weather stations was processed and added to the model.

2.2.1. Conceptual limitations of SWAT for groundwater estimation

SWAT are widely applied for simulating watershed hydrology and assessing groundwater recharge at basin scales [6]. Despite its robustness and popularity, SWAT embodies several conceptual simplifications that constrain its ability to accurately represent groundwater processes, particularly in semi-arid and basement complex terrains. These limitations arise mainly from the model's structural assumptions, scale dependency, and simplified representation of subsurface flow dynamics [11].

SWAT conceptualizes groundwater using a lumped two-reservoir system, comprising a shallow unconfined aquifer and a deep confined aquifer. Recharge from the soil profile enters the shallow aquifer, while percolation to the deep aquifer is treated as a fixed fraction [12]. This conceptualization assumes vertical flow dominance and neglects complex groundwater flow pathways such as lateral flow through fractured basement rocks, which are common in semi-arid regions like northwestern Nigeria [54]. Consequently, groundwater–surface water interactions are oversimplified, potentially leading to misrepresentation of baseflow contributions to streams.

Furthermore, SWAT does not explicitly represent aquifer thickness, hydraulic gradients, transmissivity, or spatial heterogeneity [42]. Groundwater parameters such as the baseflow recession constant and groundwater delay time are treated as lumped calibration variables rather than physically measurable properties. In heterogeneous hydrogeological environments, where groundwater storage and movement are controlled by localized fractures and weathered zones, this assumption limits the model's realism and predictive reliability [32].

In addition, groundwater flow in SWAT is not governed by Darcy-based flow equations. Instead, groundwater discharge is simulated using empirical relationships that approximate baseflow recession [20]. As a result, SWAT cannot dynamically simulate changes in groundwater heads, inter-aquifer flow, or spatial redistribution of groundwater. This limitation restricts the model's ability to evaluate groundwater abstraction impacts, aquifer depletion, or long-term groundwater sustainability under changing climatic conditions [54].

It operates on HRUs, which are non-spatial entities defined by land use, soil, and slope combinations. While effective for surface processes, HRUs lack lateral connectivity, causing groundwater recharge and storage to be spatially disconnected from real aquifer systems. This conceptual limitation is critical when estimating groundwater recharge distribution, as recharge simulated at the HRU level may not correspond to actual recharge zones or groundwater flow paths within the watershed [44].

In a nutshell, groundwater parameters in SWAT are often calibrated against streamflow rather than direct groundwater observations such as water table depth or piezometric levels [45]. This calibration strategy can produce acceptable streamflow simulations while masking inaccuracies in groundwater storage and recharge estimation [26]. Consequently, the model may perform well statistically but remain conceptually weak in representing actual groundwater dynamics.

3. RESULTS AND DISCUSSION

Figure 3 compares the actual and calculated streamflow in a monthly time step from 1992 to 2010. Peaks and lows of the two lines reflecting observed and calculated streamflow are fairly similar, except for 1997 and 2002 and the year following. The flow pattern during the two drought years in the area was not replicated by the model in comparison to the other years in the simulated period. After a sudden shift from the previous year's

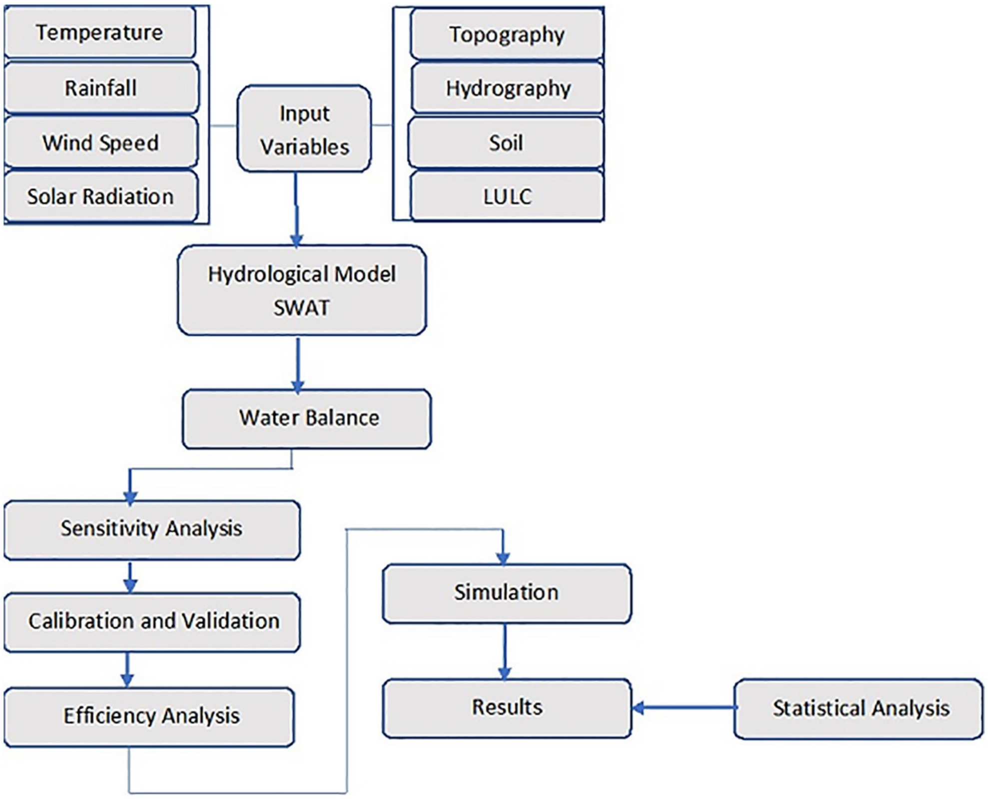

Figure 2. SWAT model set-up.

Table 2. Statistics of validation and calibration outcomes.

Parameter	Calibration	Validation
NSE	0.85	0.75
R^2	0.85	0.75
PBIAS	2.5	-1.3
RSR	0.43	0.52

regular flow to low flow, the flow resumed its normal flow the subsequent year.

Aside from the drought periods previously stated, the region had irregular precipitation in 1994, 2004, 2008, and 2010 as a result of the occurrence of lengthy and brief rainy seasons. The region's wettest months are typically half of June through August, however extended rainy seasons with a moderate peak were noted in 1994 and 2010. The precipitation record also reveals that 2004 and 2008 had a lot of rain. The model performance statistics during the calibrated validation period are displayed in Table 2. Every parameter that has been tabulated falls within the suggested range [43].

In contrast to the calibration period, the majority of parameters exhibit lower performance values in the validation. For example, the NSE, which was 0.85 in the calibration, dropped to 0.75 in the validation. The validation period began during the region's 2002 drought, which is most likely the cause.

Figures 4 shows how recharging fluctuates over time in the Kabago watershed. Figure 4 displays the average monthly recharge, evapotranspiration (ET), and surface runoff. It is clear that the primary components of the water balance and recharge are seasonal. The years 1997, 2002, and 2005 had the lowest recharge levels across the whole period.

Variations in rainfall throughout the watershed are depicted in Figure 5. Since rainfall is the main input influencing the hydrological cycle, variability in recharge and runoff can be explained by spatial heterogeneity in precipitation. Higher potential recharge zones are found in areas with more precipitation.

Evapotranspiration (ET) Distribution in Figure 6 draws attention to regional variations in water loss from plant transpiration and evaporation. About 33.24% of the input is lost as a result of ET, and the map identifies regions where temperature and vegetation cover increase ET rates.

Surface runoff is a function of slope, rainfall intensity, and land cover (Figure 7). Runoff tends to be higher in areas with steep slopes, compact soils, or urban surfaces, which helps explain the estimated 15.35% basin loss.

Figure 8, reveals the extent of agricultural, forested, and built-up land. Critical for interpreting how human activities affect infiltration, runoff, and recharge. Agricultural dominance, for example, enhances infiltration compared to urbanized land. Similarly, Figure 9 shows the distribution of different soil types (clay, sandy loam, etc.). Soil texture controls infiltration and storage capacity: sandy soils promote recharge, while clay-rich soils restrict infiltration and increase runoff.

The maps collectively provide a spatially explicit view of how climate (rainfall), land cover, and soil control the water balance. They reinforce the idea that recharge is not uniform across the basin but influenced by heterogeneous environmental factors.

The groundwater model result for the Kabago watershed is

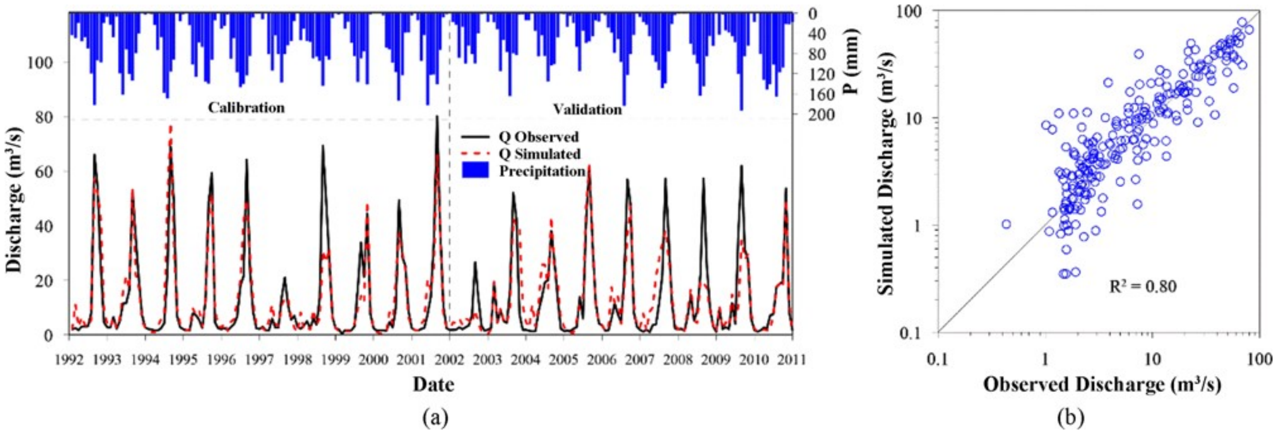

Figure 3. Streamflow, both observed and simulated, from 1992 to 2010: seasonal variability (a), scatter plot (b).

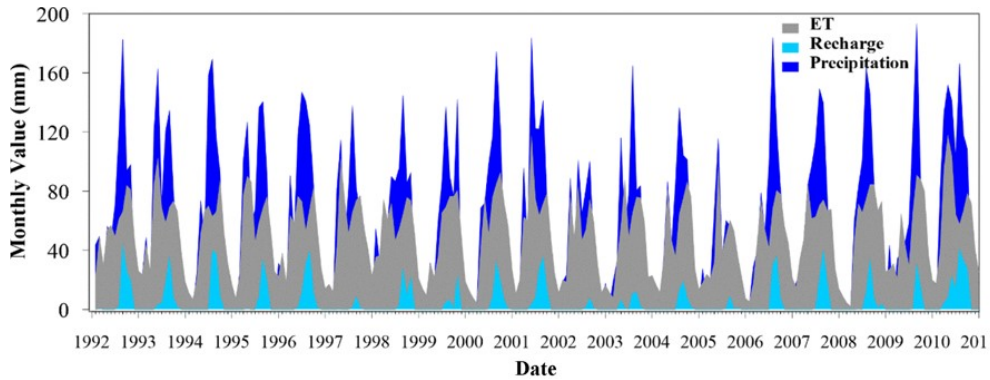

Figure 4. Surface runoff, ET, and monthly average recharge.

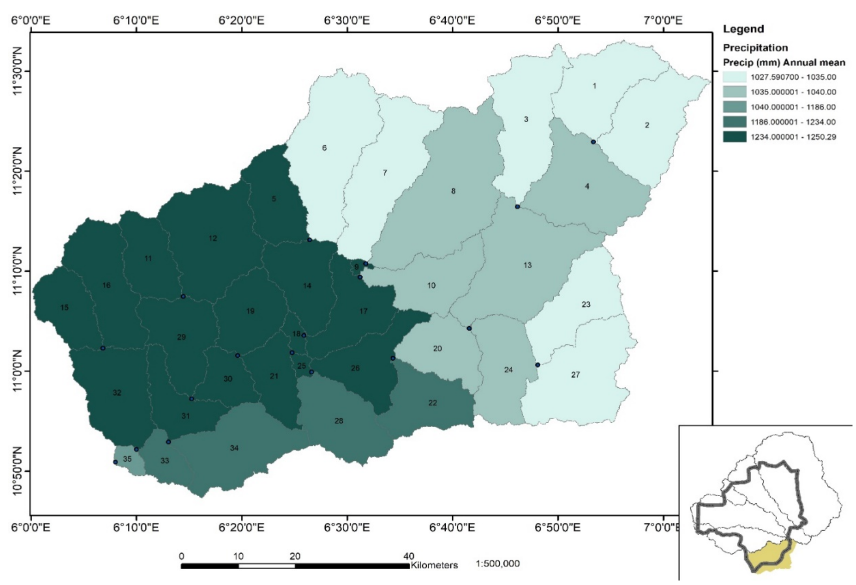

Figure 5. Precipitation distributions for River Kabago watershed.

presented in Table 3 and Figure 10. The model-derived potential recharge value range between 37.93 to 678.88 mm/annum with mean value of 545.69, this account for 49% of the total input into the groundwater system, highlighting how local geology, land cover, and rainfall interplay to regulate subsurface water replenishment. The potential recharge range is bounded by SUFI-2 uncertainty envelopes. While the average precipitation received by the basin is 1164 mm/annum. Whereas evapotranspiration and runoff contribute 33.24% and 15.35% of the total water loss from the basin with average values of 386.93 and 178.65 mm/annum respectively.

The balance demonstrates that nearly half of the rainfall con-

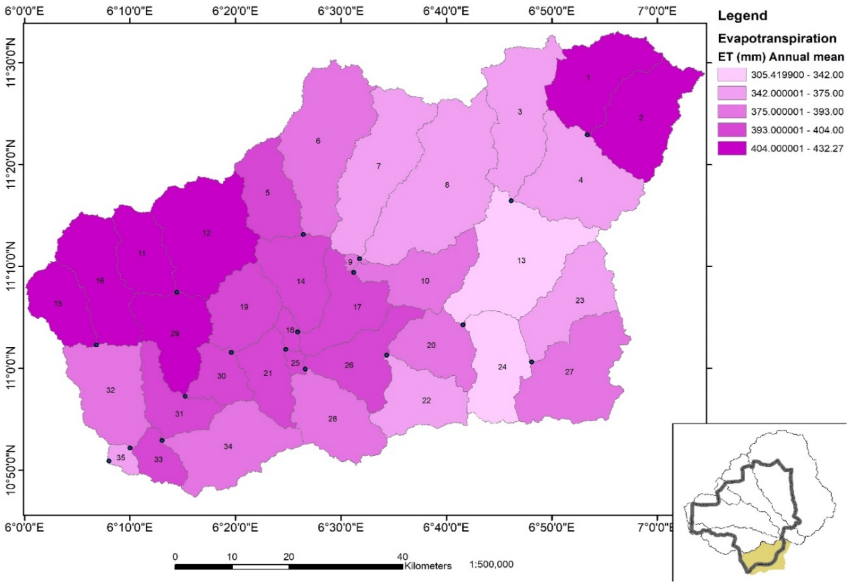

Figure 6. Evapotranspiration distribution for River Kabago watershed.

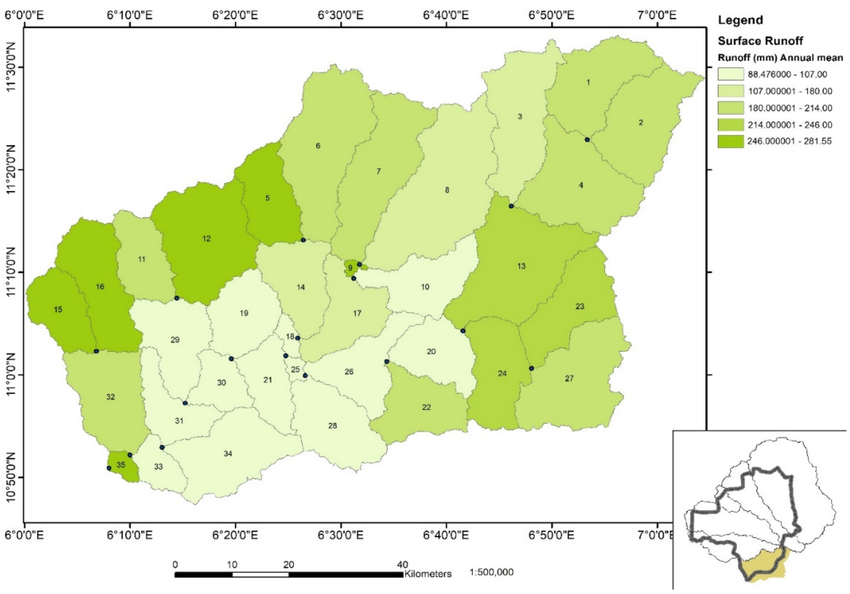

Figure 7. Surface runoff distribution for River Kabago watershed.

Table 3. Water budget for Kabago watershed (mm/annum).

Parameters	Minimum	Maximum	Mean	Std. Deviation
Potential Recharge	379.93	678.88	545.69	110.18
Precipitation	1027.59	1250.29	1164.27	101.88
Evapotranspiration	305.42	432.27	386.93	26.09
Runoff	88.48	281.55	178.65	67.15

tributes to aquifer replenishment, making the watershed an important recharge zone. However, the high ET fraction also shows vulnerability to land use change (e.g., deforestation or irrigation expansion). The relatively low runoff percentage suggests limited flooding risk but underscores groundwater reliance.

The annual recharge flux potential for the entire watershed is estimated as the product of average recharge amount received by the watershed and its total area coverage which is 5.46 m $\times$ 5,970,940 m^2 = 32,601,332.40 m^3. The actual exploitable groundwater storage depends on transmissivity, storativity, abstraction, and discharge losses of the groundwater system [42]. The estimated value represent an upper-bound, theoretical estimate of groundwater system.

The Kabago watershed exhibits mean annual recharge of ~545.69 mm/year, representing ~49% of annual rainfall. This proportion is remarkably high when compared to most semi-arid basins in northern Nigeria. Studies across the Sokoto–Rima Basin, Zamfara, Katsina, Kano, and parts of Kaduna typically report recharge fractions ranging between 10–35% of annual precipitation [54], depending on lithology, soil texture, and land use. For instance, SWAT-based assessments in neighbouring catchments of northwestern Nigeria commonly yield recharge values between 120–400 mm/year, even under similar rainfall regimes

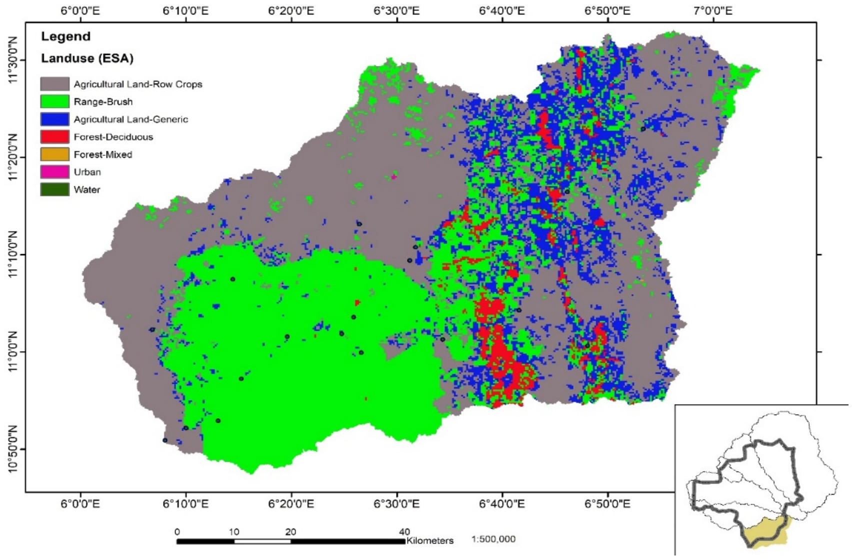

Figure 8. Landuse map for the Kabago watershed.

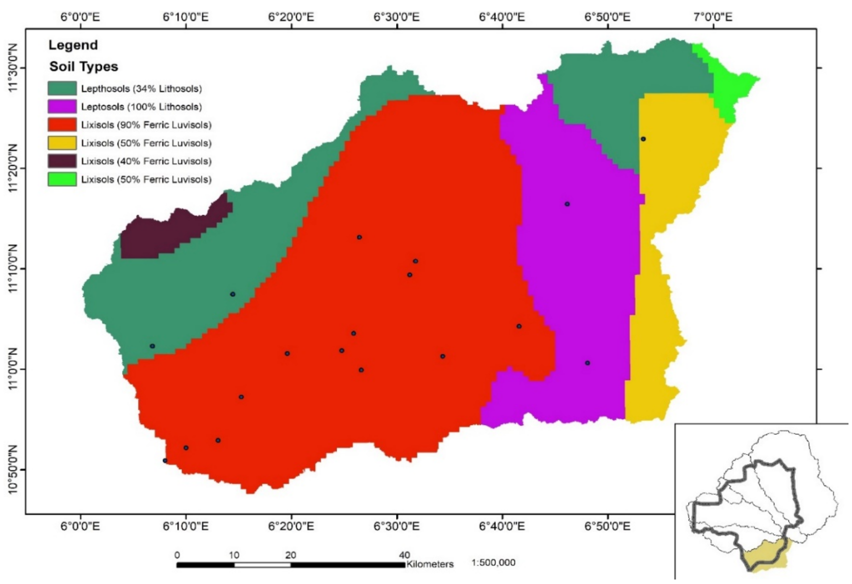

Figure 9. Soil type distribution map of the Kabago watershed.

(∼900–1200 mm/year) [6, 20].

However, the higher recharge fraction in Kabago therefore indicates, favorable basement rock fracturing (gneiss, migmatite, schist), extensive agricultural land cover, which enhances infiltration, relatively low runoff losses (15.35%) compared to other basins. In contrast, semi-arid catchments dominated by urban expansion or compacted lateritic soils (e.g., parts of Kano and Zaria) show lower recharge due to increased runoff and reduced infiltration.

Evapotranspiration (ET) accounts for 33.24% of annual rainfall (≈387 mm/year) in Kabago. This value is consistent with semi-arid northern Nigeria, where ET typically ranges between 30–55% of precipitation. However, some basins in the Sudan–Sahel transition zone report higher ET dominance (up to 50–60%), often attributed to; Sparse vegetation cover, Sandy soils with shallow moisture retention, longer dry seasons. Kabago's relatively moderate ET fraction suggests that soil moisture retention and vegetation cover (particularly cropland) partially buffer evaporative losses, allowing more water to percolate into the subsurface.

Surface runoff in Kabago constitutes only 15.35% of the annual water balance, which is lower than many semi-arid Nigerian watersheds, where runoff commonly exceeds 20–35%, especially in, steeper terrains, areas with shallow soils and urban or degraded catchments. This lower runoff aligns with, gentle slopes across much of the watershed, agricultural dominance (>80% land use), soil textures that favour infiltration over Huttonian overland flow.

4. CONCLUSION

In order to evaluate the groundwater recharge dynamics of the Kabago watershed in Zamfara State, Nigeria, this study used the SWAT hydrological model, which was calibrated and verified us-

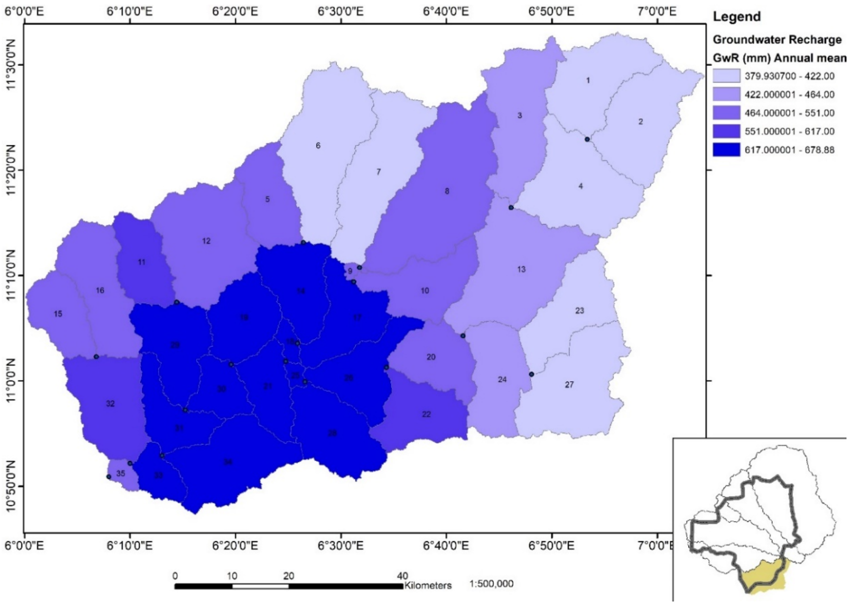

Figure 10. Potential recharge distribution for Kabago watershed.

ing observed streamflow. According to model results, potential recharge or percolation in the watershed represents 49% of total precipitation input and ranges from 379.93 to 678.88 mm/year, with an average of 545.69 mm/year. With respective contributions of 33.24% and 15.35%, evapotranspiration and runoff were also important elements of the water balance. These findings underscore the Kabago watershed as a critical recharge zone, where local climate, land use/land cover, soil characteristics, and topography jointly regulate subsurface water replenishment.

The research demonstrates that despite semi-arid conditions and irregular rainfall patterns, a substantial portion of precipitation infiltrates and sustains aquifer reserves. However, the high contribution of evapotranspiration highlights the system's vulnerability to climate variability and land-use changes such as deforestation, agricultural expansion, and urbanization. Similarly, spatial heterogeneity in recharge emphasizes the need for location-specific water resource management strategies. The identification of recharge hotspots provides a scientific basis for siting boreholes and wells more effectively, reducing the risk of groundwater failure. This is particularly important for sustaining agricultural productivity and meeting domestic water demand in Zamfara State, where reliance on groundwater is high. With recharge strongly influenced by rainfall variability, the study highlights the need for adaptive water management policies that incorporate climate projections. Enhancing water storage infrastructure, promoting rainwater harvesting, and maintaining vegetation cover will be essential in mitigating the impacts of prolonged droughts.

DATA AVAILABILITY STATEMENT

All data sets 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.

References

[1] R. A. Aslam, S. Shrestha, M. N. Usman, S. N. Khan, S. Ali, M. S. Sharif, M. W. Sarwar, N. Saddique, A. Sarwar & M. U. Ali, "Integrated SWAT-MODFLOW modeling-based groundwater adaptation policy guidelines for Lahore, Pakistan under Projected Climate Change, and Human Development Scenarios", Atmosphere **13** (2022) 2001. https://doi.org/10.3390/atmos13122001.

[2] A. Arshad, A. Mirchi, M. Samimi & B. Ahmad, "Combining downscaled-grace data with SWAT to improve the estimation of groundwater storage and depletion variations in the irrigated Indus Basin (IIB)", Sci. Total Environ. **838** (2022) 156044. https://doi.org/10.1016/j.scitotenv.2022.156044.

[3] L. Locatelli, O. Mark, P. S. Mikkelsen, K. Arnbjerg-Nielsen, A. Deletic, M. Roldin & P. J. Binning, "Hydrologic impact of urbanization with extensive stormwater infiltration", J. Hydrol. **544** (2017) 524. https://doi.org/10.1016/j.jhydrol.2016.11.030.

[4] O. V. Barron, M. J. Donn & A. D. Barr, "Urbanization and shallow groundwater: predicting changes in catchment hydrological responses", Water Resour. Manag. **27** (2013) 95. https://doi.org/10.1016/j.jhydrol.2012.04.027.

[5] H. Desta & B. Lemma, "SWAT based hydrological assessment and characterization of Lake Ziway sub-watersheds, Ethiopia", J. Hydrol. Reg. Stud. **13** (2017) 122. https://doi.org/10.1016/j.ejrh.2017.08.002.

[6] A. M. Shuaibu & K. A. Murana, "SWAT hydrological model of Zamfara watershed of Sokoto-Rima River catchment, North West Nigeria", Niger. J. Technol. **43** (2024) 411. https://www.ajol.info/index.php/njt/article/view/288061.

[7] B. Berehanu, T. Ayenew & T. Azagegn, "Challenges of groundwater flow model calibration using MODFLOW in Ethiopia: With particular emphasis to the Upper Awash River Basin", J. Geosci. Environ. Prot. **5** (2017) 50. https://doi.org/10.4236/gep.2017.53005.

[8] H. C. Nair, D. Padmalal, A. Joseph & P. G. Vinod, "Delineation of groundwater potential zones in river basins using geospatial tools — An example from Southern Western Ghats, Kerala, India", J. Geovis. Spat. Anal. **1** (2017) 5. https://doi.org/10.1007/s41651-017-0003-5.

[9] E. Mosase, L. Ahiablame, S. Park & R. Bailey, "Modelling potential groundwater recharge in the Limpopo River Basin with SWAT-MODFLOW", Groundw. Sustain. Dev. **9** (2019) 100260. https://doi.org/10.1016/j.gsd.2019.100260.

[10] M. Sophocleous & S. P. Perkins, "Methodology and application of combined watershed and groundwater models in Kansas", J. Hydrol. **236** (2000) 185. https://doi.org/10.1016/S0022-1694(00)00293-6.

[11] D. Chunn, M. Faramarzi, B. Smerdon & D. Alessi, "Application of an integrated SWAT–MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater–surface water interactions in West-Central Alberta", Water **11** (2019) 110. https://doi.org/10.3390/

w11010110.

[12] M. Zambrano-Bigiarini & R. A. Rojas, "Model-independent particle swarm optimisation software for model calibration", Environ. Model. Softw. **43** (2013) 5. https://doi.org/10.1016/j.envsoft.2013.01.004.

[13] L. Yuan, T. Sinshaw & K. J. Forshay, "Review of watershed-scale water quality and nonpoint source pollution models", Geosciences **10** (2020) 25. https://doi.org/10.3390/geosciences10010025.

[14] V. Hung Vu & B. J. Merkel, "Estimating groundwater recharge for Hanoi, Vietnam", Sci. Total Environ. **651** (2019) 1047. https://doi.org/10.1016/j.scitotenv.2018.09.225.

[15] C. Simsek, A. C. Demirkesen, A. Baba, A. Kumanlıoglu, S. Durukan, N. Aksoy, Z. Demirkıran, A. Hasözbek, A. Murathan & G. Tayfur, "Estimation groundwater total recharge and discharge using GIS-integrated water level fluctuation method: A case study from the Alasehir Alluvial aquifer Western Anatolia, Turkey", Arab. J. Geosci. **13** (2020) 143. https://doi.org/10.1007/s12517-020-5062-0.

[16] H. Delottier, A. Pryet, J. M. Lemieux & A. Dupuy, "Estimating groundwater recharge uncertainty from joint application of an aquifer test and the water-table fluctuation method", Hydrogeol. J. **26** (2018) 2495. https://doi.org/10.1007/s10040-018-1790-6.

[17] I. M. Chung, Y. J. Kim & N. W. Kim, "Estimating the temporal distribution of groundwater recharge by using the transient water table fluctuation method and watershed hydrologic model", Appl. Eng. Agric. **37** (2021) 95. https://doi.org/10.13031/aea.13376.

[18] E. Park, "Delineation of recharge rate from a hybrid water table fluctuation method", Water Resour. Res. **48** (2012) 109. https://doi.org/10.1029/2011WR011696.

[19] A. Gumuła-Kawecka, B. Jaworska-Szulc, A. Szymkiewicz, W. Gorczewska-Langner, M. Pruszkowska-Caceres, R. Angulo Jaramillo & J. Simunek, "Estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modeling and water table fluctuation method", J. Hydrol. **605** (2022) 127283. https://doi.org/10.1016/j.jhydrol.2021.127283.

[20] A. M. Shuaibu, K. O. Musa & I. M. Okiyi, "Groundwater recharge modelling using SWAT analysis for groundwater reserve quantification of Ka watershed catchment area part of Sokoto-Rima Basin, North West Nigeria", Afr. Sci. Rep. **4** (2025) 255. https://doi.org/10.46481/asr.2025.4.1.255.

[21] A. R. Cobb & C. F. Harvey, "Scalar simulation and parameterization of water table dynamics in tropical peatlands", Water Resour. Res. **55** (2019) 9351. https://doi.org/10.1029/2019WR025411.

[22] F. Hussain, R. S. Wu & D. S. Shih, "Water table response to rainfall and groundwater simulation using physics-based numerical model: WASH123D", J. Hydrol. Reg. Stud. **39** (2022) 100988. https://doi.org/10.1016/j.ejrh.2022.100988.

[23] M. Faramarzi, R. Srinivasan, M. Iravani, K. D. Bladon, K. C. Abbaspour, A. J. B. Zehnder & G. G. Goss, "Setting up a hydrological model of alberta: data discrimination analyses prior to calibration", Environ. Model. Softw. **74** (2015) 48. https://doi.org/10.1016/j.envsoft.2015.09.006.

[24] K. C. Abbaspour, "SWAT-CUP SWAT calibration and uncertainty programs", Arch. Orthop. Trauma Surg. **130** (2010) 965. https://doi.org/10.13031/2013.23153.

[25] D. N. Moriasi, J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel & T. L. Veith, *Model evaluation guidelines for systematic quantification of accuracy in watershed simulations*, ASABE, 2007, pp. 885–900. https://doi.org/10.13031/2013.23153.

[26] T. Jafari, A. S. Kiem, S. Javadi, T. Nakamura & K. Nishida, "Fully integrated numerical simulation of surface water-groundwater interactions using SWAT-MODFLOW with an improved calibration tool", J. Hydrol. Reg. Stud. **35** (2021) 100822. https://doi.org/10.1016/j.ejrh.2021.100822.

[27] S. Park, *Enhancement of coupled surface/subsurface flow models in watersheds: analysis, model development, optimization, and user accessibility by using SWAT-MODFLOW simulation*, Ph.D. dissertation, Colorado State University, Colorado, USA, 2018. https://mountainscholar.org/bitstream/handle/10217/193164/Park_colostate_0053A_15199.pdf?sequence=1.

[28] K. C. Abbaspour, E. Rouholahnejad, S. Vaghefi, R. Srinivasan, H. Yang & B. A. Klove, "A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model", J. Hydrol. **524** (2015) 733. https://doi.org/10.1016/j.jhydrol.2015.03.027.

[29] C. H. Lee, H. F. Yeh & J. F. Chen, "Estimation of groundwater recharge using the soil moisture budget method and the base-flow model", Environ. Geol. **54** (2008) 1787. https://doi.org/10.1007/s00254-007-0956-7.

[30] B. A. Yifru, I. M. Chung, M. G. Kim & S. W. Chang, "Assessment of groundwater recharge in agro-urban watersheds using integrated SWAT-MODFLOW model", Sustainability **12** (2020) 6593. https://doi.org/10.3390/su12166593.

[31] B. R. Scanlon, R. W. Healy & P. G. Cook, "Choosing appropriate techniques for quantifying groundwater recharge", Hydrogeol. J. **10** (2002) 18. https://doi.org/10.1007/s10040-001-0176-2.

[32] R. Rangarajan, D. Muralidharan, S. D. Deshmukh, G. K. Hodlur & T. Gangadhara Rao, "Re-demarcation of recharge area of stressed confined aquifers of Neyveli groundwater basin, India, through tritium tracer studies", Environ. Geol. **48** (2005) 37. https://doi.org/10.1007/s00254-005-1254-x.

[33] R. Chand, S. Chandra, V. A. Rao, V. S. Singh & S. C. Jain, "Estimation of natural recharge and its dependency on sub-surface geoelectric parameters", J. Hydrol. **299** (2004) 67. https://doi.org/10.1016/j.jhydrol.2004.04.001.

[34] A. Shahul Hameed, T. R. Resmi, S. Suraj, C. U. Warrier, M. Sudheesh & R. D. Deshpande, "Isotopic characterization and mass balance reveals groundwater recharge pattern in Chaliyar river basin, Kerala, India", J. Hydrol. Reg. Stud. **4** (2015) 48. https://doi.org/10.1016/j.ejrh.2015.01.003.

[35] P. W. Gassman, A. M. Sadeghi & R. Srinivasan, "Applications of the SWAT model special section: overview and insights", J. Environ. Qual. **43** (2014) 1. https://doi.org/10.2134/jeq2013.11.0466.

[36] E. S. Okonofua, C. N. Emeribe, E. T. Ogbomida, D. C. Leke & F. O. Ajibade, "Precipitation concentration impact on flood frequency, periodicities and return periods in Kaduna River", NIPES - Journal of Science and Technology Research **7** (2025) 266. https://doi.org/10.37933/nipes/7.3.2025.1464.

[37] H. H. Ware, T. D. Mengistu, B. A. Yifru, S. W. Chang & I. M. Chung, "Assessment of spatiotemporal groundwater recharge distribution using Swat-Modflow model and transient water table fluctuation method", Water **15** (2023) 2112. https://doi.org/10.3390/w15112112.

[38] C. Simsek, A. C. Demirkesen, A. Baba, A. Kumanlıoglu, S. Durukan, N. Aksoy, Z. Demirkıran, A. Has¨ozbek, A. Murathan & G. Tayfur, "Estimation groundwa ter total recharge and discharge using GIS-Integrated water level fluctuation method: a case study from the Al azsehir alluvial aquifer Western Anatolia, Turkey", Arab J. Geosci. **13** (2020) 143. https://doi.org/10.1007/s12517-020-5062-0.

[39] H. Delottier, A. Pryet, J. M. Lemieux & A. Dupuy, "Estimating groundwater recharge uncertainty from joint application of an aquifer test and the water-table fluctuation method", Hydrogeol. J. **26** (2018) 2495. https://doi.org/10.1007/s10040-018-1790-6.

[40] A. Gumuła-Kawecka, B. Jaworska-Szulc, A. Szymkiewicz, W. Gorczewska-Langner, M. Pruszkowska-Caceres, R. AnguloJaramillo & J. Simunek, "Estimation of groundwater recharge in a shallow sandy aquifer using unsaturated zone modeling and water table fluctuation method", J. Hydrol. **605** (2022) 127283. https://doi.org/10.1016/j.jhydrol.2021.127283.

[41] E. Park, "Delineation of recharge rate from a hybrid water table fluctuation method", Water Resource **48** (2012) 109. https://doi.org/10.1029/2011WR011696.

[42] A. M. Shuaibu & K. A. Murana, "Groundwater flow model part of Sokoto-Rima hydrological basin, Northwestern Nigeria", Global Journal of Geological Sciences **21** (2023) 251. https://dx.doi.org/10.4314/gjgs.v21i2.8.

[43] A. M. Shuaibu, "Structural analysis, petrographic study and geochemical assessment of Pan-African granitoid, Gusau sheet 54SE Northwest Nigeria", Malaysian Journal of Geosciences **7** (2023) 50. http://doi.org/10.26480/mjg.01.2023.50.63.

[44] C. H. Lee, H. F. Yeh & J. F. Chen, "Estimation of groundwater recharge using the soil moisture budget method and the base-flow model", Environ. Geol. **54** (2008) 1787. https://doi.org/10.1007/s00254-007-0956-7.

[45] B. R. Scanlon, R. W. Healy & P. G Cook, "Choosing appropriate techniques for quantifying groundwater recharge", Hydrogeol. J. **10** (2002) 18. https://doi.org/10.1007/s10040-001-0176-2.

[46] R. Chand, S. Chandra, V. A. Rao, V. S. Singh & S. C. Jain, "Estimation of natural recharge and its dependency on sub-surface geoelectric parameters", J. Hydrol. **299** (2004) 67. https://doi.org/10.1016/j.jhydrol.2004.04.001.

[47] R. W. Healy & P. G. Cook, "Using groundwater levels to estimate recharge", Hydrogeology Journal **10** (2002) 91. https://doi.org/10.1007/s10040-001-0178-0.

[48] M. J. M. Cheema, W. W. Immerzeel & W. G. M. Bastiaanssen, "Spatial quantification of groundwater abstraction in the irrigated Indus Basin",

Groundwater **52** (2014) 25. https://doi.org/10.1111/gwat.12027.

[49] M. Taie Semiromi & M. Koch, "Analysis of spatio-temporal variability of surface–groundwater interactions in the Gharehsoo River Basin, Iran, using a coupled SWAT-MODFLOWModel", Environ. Earth Sci. **78** (2019) 201. https://doi.org/10.1007/s12665-019-8206-3.

[50] S. Dowlatabadi & S. M. Ali Zomorodian, "Conjunctive simulation of surface water and groundwater using SWAT and MODFLOW in Firoozabad Watershed", KSCEJ. Civ. Eng. **20** (2015) 485. https://doi.org/10.1007/s12205-015-0354-8.

[51] B. Bhatta, S. Shrestha, P. Shrestha & R. Talchabhadel, "Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the Himalayan River Basin", Catena **181** (2019) 104082. https://doi.org/10.1016/j.catena.2019.104082.

[52] K. Bieger, G. Hormann & N. Fohrer, "Detailed spatial analysis of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China", Hydrolog. Sci. J. **60** (2015) 784. https://doi.org/10.1080/02626667.2014.965172.

[53] K. Bieger, J. G. Arnold, H. Rathjens, M. J. White, D. D. Bosch, P. M. Allen, M. Volk & R. Srinivasan, "Introduction to SWAT+, a completely restructured version of the soil and water assessment tool", J. Am. Water Resource Assoc. **53** (2017) 115. https://doi.org/10.1111/1752-1688.12482.

[54] E. O. Akudo, B. C. E. Egboka, E. Aniwetalu, H. O. Nwankwoala, E. Odumoso & S. N. Chibuzor, "Soil and water assessment tool (SWAT Model) for estimating groundwater recharge in Sokoto-Rima River Basin, Northwestern Nigeria", Journal of Mining and Geology **58** (2022) 237. https://www.researchgate.net/publication/360345497.