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SWAT HYDROLOGICAL MODEL OF ZAMFARA WATERSHED OF SOKOTO-RIMA RIVER CATCHMENT, NORTH WEST NIGERIA

AUTHORS:
A. M. Shuaibu[1,*], and K. A. Murana[2]

AFFILIATIONS:
[1]Department of Geology, Faculty of Science, Federal University Lokoja, Kogi State.
[2]Department Geological Sciences, Faculty of Science, Federal University Gusau, Zamfara State.

***CORRESPONDING AUTHOR:**
Email: mahalkufr@gmail.com

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Abstract

This study employs the Soil and Water Assessment Tool (SWAT) hydrological model to comprehensively analyze the water dynamics within the Zamfara watershed. The model's efficacy in assessing diverse hydrological processes is established through meticulous calibration and validation processes. A sensitivity analysis scrutinizes the model's responsiveness to various thresholds in sub-basin delineation and the definition of Hydrologic Response Units (HRUs). The study's outcomes reveal discernible patterns in annual precipitation, groundwater recharge, and evapotranspiration within the basin. These findings shed light on crucial factors that influence the basin's water balance. They underscore the vital necessity of a thorough hydrological understanding to effectively manage water resources in the Zamfara watershed. The assessment of the catchment's hydrology indicates an average annual precipitation of 876.61 mm. Groundwater recharge accounts for 25.07% of the total groundwater system input, averaging 219.77 mm annually. Notably, only 5% of the overall groundwater recharge contributes to replenishing deep groundwater recharge storage, while the remaining portion refills the shallow aquifer. Consequently, evapotranspiration emerges as the most substantial constituent of the water balance, representing 57% with an average of 500.79 mm per year. Runoff constitutes a mere 12.44% of the total basin output, while the remaining components of precipitation are lost. It is essential to highlight that evapotranspiration serves as the primary mechanism for water loss from the catchment. The calibration and validation phase exhibited by the SWAT model within the confines of the study area showcased exceptional efficacy, achieving notably high R-squared (R^2) values surpassing the threshold of 0.80 for the designated gauging sites. This remarkable achievement underscores the SWAT model's commendable aptitude and reliability in conducting precise hydrological assessments within the intricate dynamics of the Zamfara watershed. The total groundwater reserve of the watershed catchment area is estimated at 24,767,082 m^3. This suggests high amount of groundwater reserve within the study area for both agricultural and domestic usage.

1.0 INTRODUCTION

Water stands as an indispensable element crucial for the sustenance of all life forms, playing a pivotal role in the physiological functions of both animals and plants [1]. Its accessibility profoundly impacts a wide spectrum of factors, ranging from habitat preservation, economic considerations, and ensuring food supply to influencing migration patterns and even international diplomatic relations [2 – 4]. The interconnection between water-induced stress and irrigation, particularly reliant on groundwater, has

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ignited recent discussions [5 - 9]. These conversations have gained significant traction, especially in light of the challenges posed by rapid population growth and economic development [10]; particularly in regions grappling with water scarcity.

The geographic location and timing of water utilization play a pivotal role in determining water allocation across basins [11]. This becomes especially critical in arid and semi-arid areas where water resources are scarce [12 – 15]. The intricate balance of when and where water is used significantly affects how it's distributed and managed across these regions [16]. Given the formidable challenges that have arisen due to the ever-pressing issue of climate change, obtaining a comprehensive understanding of water resource dynamics has become imperative for ensuring sustainability [17 - 19]. Employing robust datasets that encompass hydro-meteorological, socio-economic, technological, and agricultural information, hydrologic models serve as invaluable tools in precisely quantifying water availability [20 – 21]. These models enable the anticipation and projection of water distribution under diverse demand loads and varying operational circumstances [22]. Through the utilization of process-based models, detailed analyses of water availability and consumption dynamics can be conducted, particularly concerning their responses to environmental shifts and alterations [23 – 24].

The application of the Soil and Water Assessment Tool (SWAT) model within the context of sub-Saharan Africa has been instrumental in addressing a multitude of water-related challenges [25]. Notably, previous studies leveraging the SWAT model have successfully evaluated the impact of land cover changes and climate variations on the water balance components of the White Volta [26]. Furthermore, in Ghana, the SWAT model has been effectively employed to accurately estimate surface and groundwater recharge, alongside assessing the influence of climate change on various hydrological processes [7; 27 – 28].
The primary objective of this study is to harness the capabilities of the SWAT hydrological model by integrating observed hydro-meteorological data. Through this integration, the study aims to precisely estimate water availability within the Sokoto-Rima hydrological basin. The anticipated outcomes hold significant promise in furnishing invaluable insights for farmers and decision-makers operating within the Zamfara river catchment. These insights will offer a comprehensive understanding of the current water availability scenario, enabling informed decisions regarding water resource management strategies in the region.

By employing the SWAT hydrological model in conjunction with meticulous analysis of observed hydrometeorological data, this study endeavors to offer a robust and accurate estimation of water availability. The acquired results are poised to serve as a fundamental resource for stakeholders, empowering them with critical information to optimize agricultural practices and make well-informed decisions pertaining to water usage and allocation within the Zamfara river catchment area.

2.0 STUDY AREA

The study area constitutes an integral part of the Sokoto-Rima Hydrogeological Province located in the northwest region of Nigeria, spanning longitudinally from 4^{o} 56' 0"E to 6^{o} 48' 0"E, and latitudinally from 10^{o} 40' 0" N to 12^{o} 30' 0" N (Figure 1). The precipitation in the river catchment averages around 876 mm per year, with an evapotranspiration rate measured at 500 mm per year.

The river originates from the southern region of Zamfara state, meandering through the central area before traversing towards the western part, where it ultimately converges with the river Rima at Raba in Sokoto State. Primarily coursing through the basement complex rock formations, the river's path predominantly encounters Schist, Pan-African granitoids, and pegmatite dykes. However, as it progresses towards the western extent of the study area, it encounters the Gundumi formation, marking a geological transition in its trajectory.

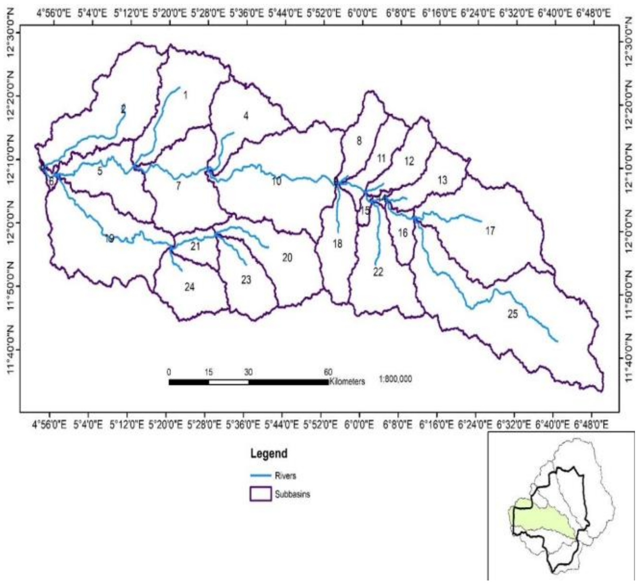

Figure 1: Zamafara river watershed/subbasins of the study area

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3.0 MATERIALS AND METHODS

3.1 SWAT Hydrological Model for Assessing Watersheds of the Study Area

The SWAT hydrological model has gained commendation owing to its robust process-based methodology, computational efficiency, and its capability to conduct continuous simulations over extended temporal spans [29]. Employing spatially distributed inputs such as topographic data, land-use classifications, soil properties, and meteorological information, this model adeptly reproduces outputs related to water flow, sediment movement, and groundwater recharge dynamics [30 - 33].

The intricate hydrological processes encapsulated within the SWAT model, represented graphically in Figure 2, adhere to a meticulously balanced equation identified as Equation (1). This equation encapsulates a comprehensive representation of the various interdependent factors influencing water movement, offering a systematic and methodical depiction of the hydrological phenomena under consideration.

$$SW(t) = S_{w0} + \sum_{i=1}(R_{annual} - Q_{surface} - S_{eepage} - E_a - Q_{gw}) \quad (1)$$

In the provided context, $SW(t)$: This variable represents the soil moisture content at a specific time 't' (measured in millimeters - mm). S_{w0}: 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. This 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).

These variables collectively contribute to the overall water balance and hydrological processes within a given area or system, reflecting the interactions between precipitation, runoff, evapotranspiration, soil moisture changes, and groundwater recharge.

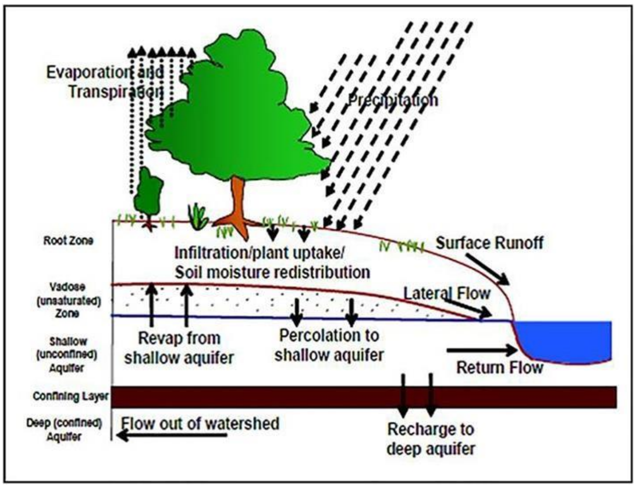

Figure 2: The Hydrological process of the SWAT model [16]

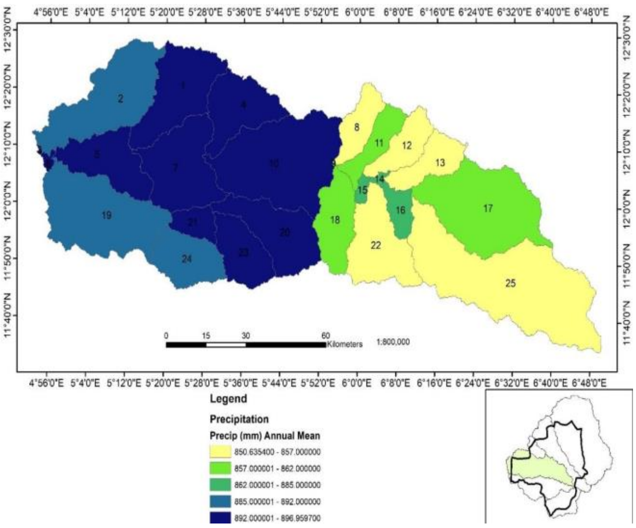

Figure 3: Precipitation distribution within river Zamfara watershed

3.2 Input Data

Extensive datasets covering precipitation, maximum and minimum daily air temperatures, relative humidity, wind speed, and solar radiation, spanning the period of twenty-eight years (28 years) which range between 1993 to 2021, were meticulously compiled from Nigeria Meteorological Agency (NiMet). Concurrently, runoff data, crucial for comprehensive hydrological assessments, was acquired from the Bakolori dam management and the

Nigeria Hydrological Service Agency. These datasets, ranging from 1993 to 2021, which is for the period of twenty-eight years were meticulously gathered through continuous measurements utilizing river water gauges.

Figures 3, 4, and 5 showcase a selection of the input models, each representing a distinctive aspect of the complex interplay between meteorological parameters and hydrological processes. These models serve as pivotal tools, offering insight into the intricate dynamics shaping the hydrological behavior observed within the studied region across the designated time span.

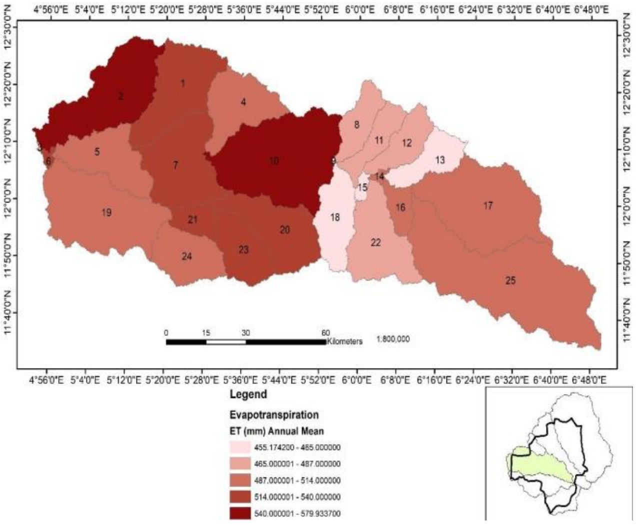

Figure 4: Evapotranspiration distributions within the Zamfara river watershed

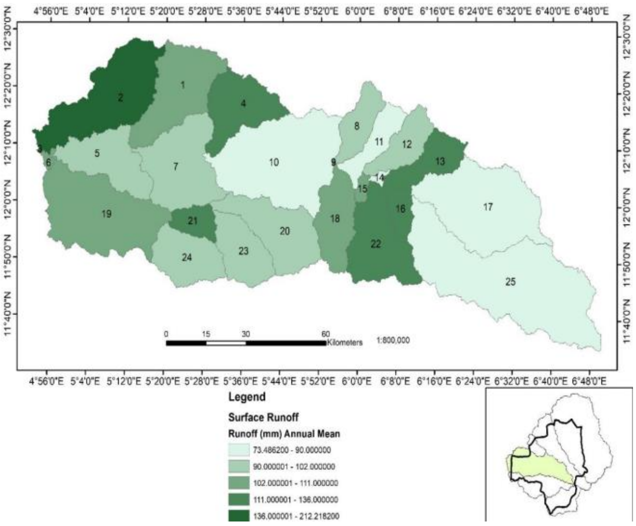

Figure 5: Runoff potential for the Zamfara river watershed

The soil data essential for this study, as delineated in Figure 6, was sourced from the comprehensive repository hosted on the WaterBase website (http://www.waterbase.org/download_data.html).

This invaluable database is meticulously curated by the Food and Agriculture Organization (FAO) of the United Nations, providing a wealth of information pertinent to soil properties and characteristics. The utilization of this meticulously compiled soil dataset, obtained from the esteemed repository maintained by the FAO through the WaterBase platform, forms an integral part of the study's framework. This resource serves as a cornerstone, offering critical insights into the diverse soil parameters and properties essential for conducting a detailed analysis of the hydrological dynamics within the research area.

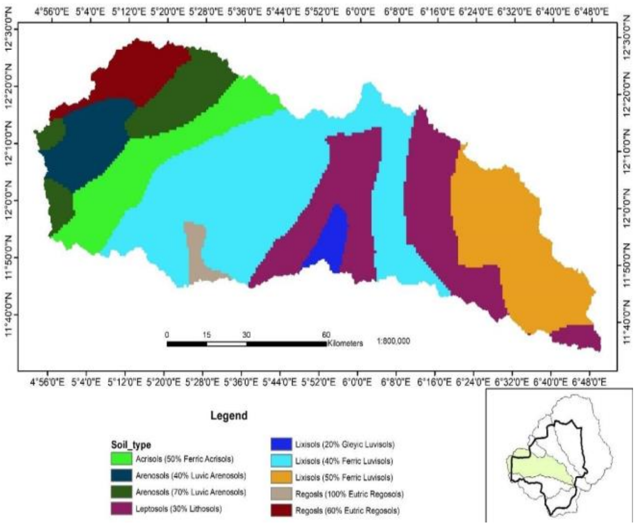

Figure 6: Soil map of the Zamfara river watershed

An intricately detailed Digital Elevation Model (DEM) boasting a resolution of 30 meters by 30 meters was meticulously acquired from the reputable database maintained by the United States Geological Survey (USGS). This highly refined DEM serves as a fundamental geospatial dataset, offering precise representations of the terrain's elevation variations within the study area.

Simultaneously, the Land Use and Land Cover (LULC) map, depicted in Figure 7, was meticulously derived from a composite of Landsat Enhanced Thematic Mapper (ETM) imagery amalgamated on October 25th, 2018. The creation of this comprehensive LULC map involved a sophisticated process employing supervised classification techniques on the false color composite derived from Landsat bands 4, 3, and 2. The integration of these bands was executed within the sophisticated framework of the ArcGIS 10.8.1 software platform, ensuring the precision and accuracy required for delineating distinct land use and cover classes across the study area.

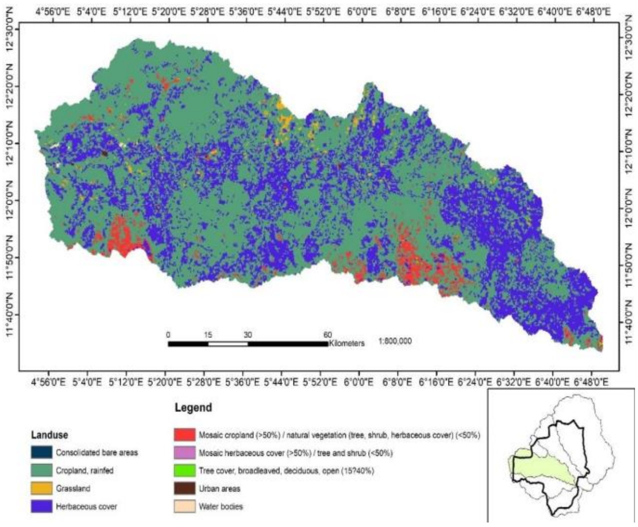

Figure 7: Landuse map of the Zamfara river watershed

3.3 SWAT Setup

The integration of the ArcSWAT extension into the SWATs version (2009) significantly enhanced and streamlined the model configuration process. Leveraging the ArcSWAT watershed delineator, the watershed underwent meticulous segmentation, delineating it into sub-watersheds, slopes, drainage areas, and various other essential units derived from the Digital Elevation Model (DEM). These delineated sub-watersheds were further subdivided into homogeneous units known as hydrologic response units (HRUs), meticulously designed to capture distinct hydrological characteristics within the study area.

For each of these delineated sub-watersheds and HRUs, comprehensive data inputs were carefully categorized, encompassing a spectrum of crucial information such as weather parameters, land cover classifications, soil characteristics, and management practices prevalent within the specific sub-basins. The model employed these intricate inputs to simulate the complex dynamics of runoff and sediment loading, meticulously tracking their movement into the primary channel. It accounted for a myriad of diverse physical processes that significantly influence the hydrological regime within the watershed.

Meteorological data played a pivotal role throughout the calibration and validation phases of the model, rigorously adhering to the procedural guidelines outlined in Figure 8. Leveraging this data, the model generated detailed hydrograph maps, enabling precise estimation of the water balance within the studied catchment.

Furthermore, a thorough analysis of performance metrics was conducted, encompassing an assessment of various factors affecting water availability within the catchment. This assessment was achieved by employing water balance ratios, providing a comprehensive evaluation of the hydrological processes and their implications on water resources within the watershed.

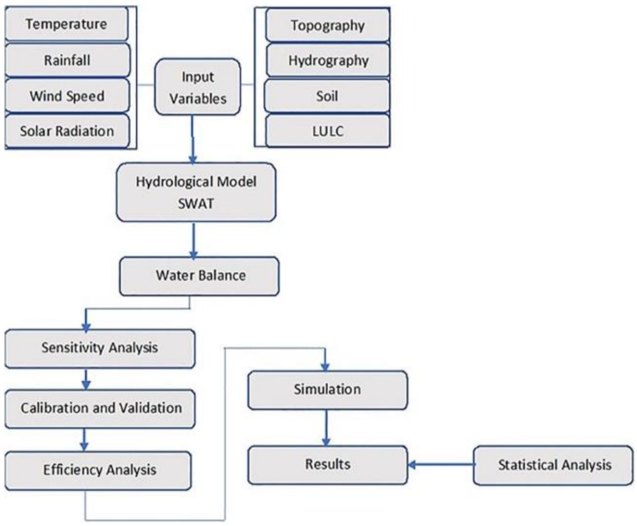

Figure 8: SWAT model flow Structure

4.0 RESULTS AND DISCUSSION

The extensive analysis of the Zamfara watershed revealed its intricate composition, comprising a total of twenty-five (25) distinct subbasins, each contributing uniquely to the overall hydrological dynamics of the region. Within this watershed, a meticulous delineation identified a comprehensive total of 158 hydrological response units (HRUs), as visually depicted in Figure 8. These HRUs, intricately interconnected, encapsulate various hydrological characteristics crucial for a comprehensive understanding of the watershed's complex behavior.

Figures 3, 4, 5, 6, and 7 stand as pivotal representations showcasing a diverse array of input hydrological data meticulously incorporated into the water balance model. These figures encapsulate an extensive range of crucial information, including meteorological parameters, terrain features, land use classifications, soil properties, and additional pertinent data essential for facilitating the comprehensive modeling of the water balance within the Sokoto river watershed. Throughout the duration of this comprehensive study, a meticulous evaluation was conducted on the relative sensitivity values obtained during the paramount parameter estimation phase. A total of thirteen key parameters were meticulously identified as possessing significant sensitivity, each accompanied by its respective relative sensitivity values. These pivotal parameters collectively encompass a wide spectrum of crucial hydrological factors crucial for accurate modeling and simulation within the study area.

The parameters identified encompass various facets of hydrological processes, including the initial Soil conservation Service (SCS) runoff curve number (CN2) for moisture condition II, base flow alpha factor (ALPHA_BF), groundwater delay time (GW_DELAY), threshold depth of water in the shallow aquifer for return flow (GWQMN), groundwater "revap" coefficient (GW_REVAP), soil evaporation compensation factor (ESCO), Manning's "n" value for the main channel (CH_N2), effective hydraulic conductivity in the main channel alluvium (CH_K2), base-flow alpha factor for bank storage (ALPHA_BNK), available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), moist bulk density (SOL_BD), and plants uptake compensation factor (SFTMP) [16].

These identified parameters, recognized for their sensitivity, played a pivotal role in the meticulous calibration process utilizing the sophisticated SWAT-CUP model, as detailed in Table 1. The calibration period for the models spanned from 1993 to 2021, encompassing an extensive timeframe to ensure the accuracy and reliability of the model outcomes. Moreover, the validation phase extended from 2001 to 2021, providing an additional rigorous evaluation period to validate the model's predictive capabilities and robustness against real-world data.

Table 1: General summary of the model parameter

Parameters	Range	SWAT default	Final Value
Initial SCS CN II value	25-76		47.7-75
Baseflow alpha factor (days)	0 -3	0.048	0.03
Groundwater delay (days)	0 - 400	21	21
Threshold depth of water in the shallow aquifer for “revap” to occur (mm)	0-900	680	942
Deep aquifer percolation fraction	0 -1	0.05	0.08
Specific yield of the shallow aquifer (m^3/m^3)	0 -0.4	0.003	0.0036
Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	0 -5000	1000	1178
Surface runoff lag time in the HRU (days)	0.05-24	4	0.5

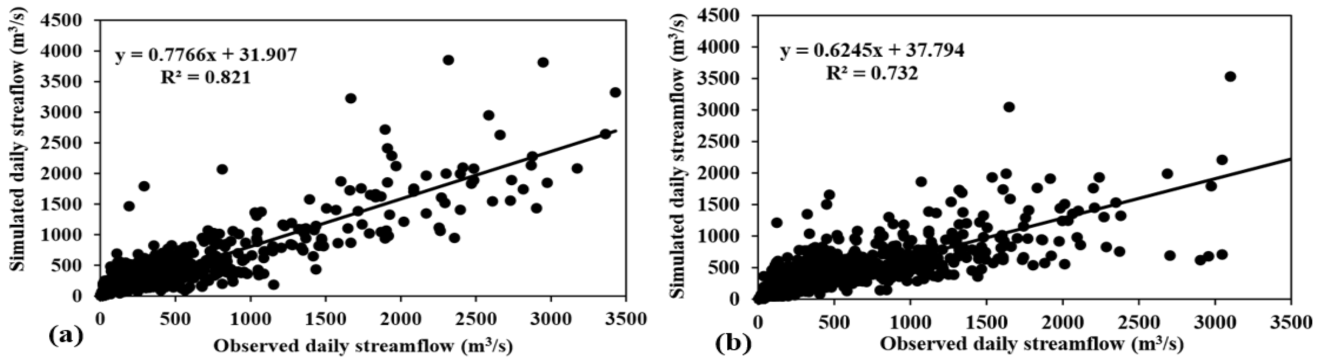

Figure 9: Plot of daily stream flow (river) for **(a)** Calibration period (1993-2021) and **(b)** Validation period (2001-2021)

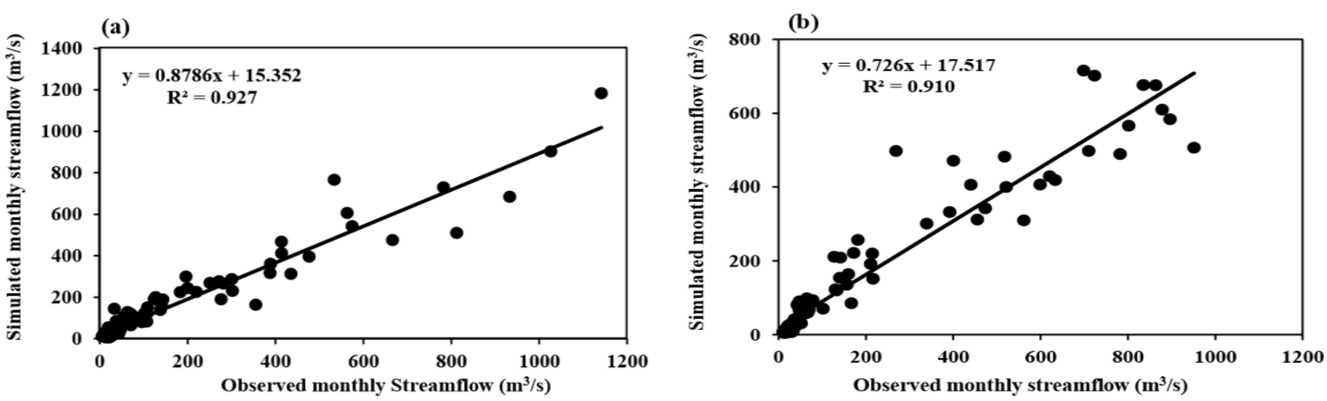

Figure 10: Plot of monthly river stream flow for **(a)** Calibration period (1993-2021) and **(b)** Validation period (2001-2021)

4.1 Water Balance

The comprehensive findings derived from the SWAT model, specifically tailored for the designated study area, are vividly illustrated in Figure 11. Through a meticulous evaluation of the catchment's hydrology, essential insights into the regional water dynamics have been revealed. An in-depth analysis of the hydrological parameters highlights an average annual precipitation of 876.61 millimeters within the study area, significantly influencing the overall water balance and subsequent processes. Particularly noteworthy is the identification that groundwater recharge accounts for a substantial portion, precisely 25.07%, of the total input into the groundwater system, averaging at 219.77 millimeters per annum, as explicitly depicted in Figure 11.

Of significant interest is the revelation that within this recharge volume, only a minimal fraction, merely 5% of the total groundwater recharge (from the overall 25.07%), contributes to the replenishment and storage of the deep groundwater aquifers. The overwhelming majority of this recharge, constituting the remaining percentage, facilitates the replenishment of the shallow aquifer layers, underscoring the intricate dynamics and partitioning of groundwater resources within the catchment [12].

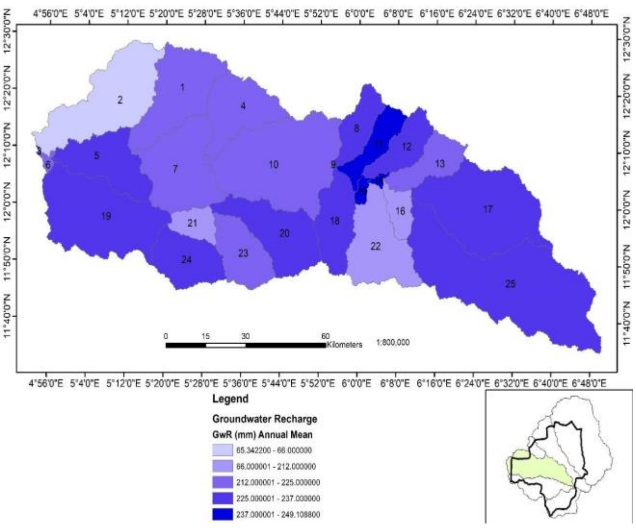

Figure 11: Groundwater recharge distribution for the Zamfara river watershed

Consequently, within the intricate water balance framework of the study area, evapotranspiration emerges as the most substantial component, commanding a notable 57% share, equating to an average of 500.79 millimeters per annum. This significant proportion underscores the critical role played by evapotranspiration in governing the overall water dynamics within the catchment, accentuating its pivotal influence on the regional water budget.

Conversely, the contribution of runoff within this intricate balance remains comparatively modest, representing a mere 12.44% of the total output from the basin. This limited share emphasizes the relatively smaller role played by direct runoff compared to other water balance components. Notably, the remaining components of precipitation are effectively lost within the catchment area, as succinctly highlighted in Table 2. The total groundwater reserve of the watershed catchment area is estimated at 24,767,082 m^3 as the product of the total catchment area of the watershed which is 11,309,170 m^2 and average groundwater recharge which is 2.19 m.

Highlighting the paramount significance, it's crucial to underscore that evapotranspiration serves as the primary mechanism responsible for the loss of water from the catchment. This emphasizes the vital role played by vegetation and soil surfaces in the local hydrological processes, accentuating the significance of evapotranspiration in regulating the overall water balance dynamics within the studied area.

Table 2: Water balance for the Zamfara river watershed

Parameters	Minimum	Maximum	Sum	Mean	Std. Deviation
Groundwater recharge	65.34	249.11	5494.26	219.77	34.29
Precipitation	850.64	896.96	21915.32	876.61	18.92
Evapotranspiration	455.17	579.93	12519.63	500.79	29.03
Runoff	73.49	212.22	2725.49	109.02	27.10

However, at the peak of the rainy season, notably in the months of August and September, the catchment experiences a substantial surge in surface runoff volumes. This surge is predominantly attributable to the saturation of soils, a common occurrence during this period, leading to an increased propensity for localized flooding events. These occurrences underscore the region's vulnerability to inundation and the challenges posed by surplus water during these peak rainfall months.

Remarkably, this surge in runoff volumes during the rainy season presents an intriguing opportunity for harnessing and managing this excess water resource. The potential lies in the capture and storage of this runoff within strategically designed ponds or reservoirs, providing a viable mechanism for efficient water retention and storage. This captured water resource could subsequently be utilized judiciously during the dry season, offering a valuable means of augmenting water supplies during periods of reduced precipitation and heightened water demand. The prospects of such water capture and storage initiatives present a promising avenue for mitigating the challenges posed by seasonal water scarcity. This proactive approach not only addresses the issue of localized flooding but also unlocks the potential for sustainable water resource management by utilizing surplus water resources effectively during periods of scarcity.

In summary, the hydrologic SWAT model analysis emphasizes that a significant portion, over 50%, of the annual precipitation within diverse water catchments is lost through evapotranspiration. This loss underscores the substantial role played by evapotranspiration in the overall water balance within these regions. The residual components encompass discharge, comprising various elements such as surface runoff, lateral flow, and return flow, alongside percolation occurring within distinct zones including the unsaturated zone, shallow unconfined aquifer, and deep aquifer. A detailed analysis of the discharge components, as outlined in Table 1, highlights that surface runoff constitutes more than 16% of the total discharge, showcasing its significance in the overall water dynamics.

Notably, during the peak of the rainy season, specifically in August and September, the region frequently experiences substantial surface runoff volumes due to saturated soils, leading to recurrent flooding incidents across various catchment areas. This scenario emphasizes the potential for capturing and storing such runoff in ponds or reservoirs, presenting a viable solution for managing excess water and mitigating flood-related issues.

Moreover, the stored water from such capture mechanisms could be efficiently utilized during the dry season. This stored water can serve as supplementary irrigation, particularly beneficial for late crops requiring additional water resources as rainfall diminishes, thereby aiding in sustaining agricultural activities even during drier periods. This comprehensive overview highlights both the challenges posed by excessive runoff during specific periods and the potential opportunities for efficient water resource management and agricultural sustainability through proactive capture and utilization of surplus water resources.

The hydrological analysis indicates that an average of 120 millimeters per annum, roughly equivalent to about 19% of the total precipitation, infiltrates into the groundwater reservoirs across the catchment area. This infiltration process encompasses several pathways, including the unsaturated zone, shallow unconfined aquifer, and deep aquifer layers, crucial for the overall groundwater recharge. Throughout this percolation process, approximately 5% of the infiltrated water is lost as return flows, eventually contributing to the outlets within the watershed. Despite this loss, around 3% of the percolated water effectively recharges the deep aquifer, replenishing the deeper groundwater reservoirs within the catchment.

Meanwhile, the majority of the percolated water, constituting the residual portion after accounting for losses and deep aquifer recharge, is stored in the more accessible unsaturated and shallow aquifers. These aquifers, being more readily accessible, play a crucial role in the local groundwater dynamics and contribute significantly to the overall groundwater resources available for utilization within the catchment area. This detailed overview emphasizes the complex dynamics of groundwater infiltration, highlighting the various pathways and mechanisms through which precipitation infiltrates the subsurface and contributes to the replenishment of the groundwater reservoirs within the study area.

5.0 CONCLUSION

This study rigorously employed the SWAT model to calibrate and subsequently validate the hydrological stream model tailored for the Sokoto River basin. The calibration and validation procedures demonstrated the model's robustness and efficacy in replicating the hydrological dynamics within the basin across distinct periods, specifically spanning from 1993 to 2021 for calibration and 2001 to 2021 for validation. These timeframes were substantiated by robust likelihood measures, underscoring the model's ability to reliably represent the observed hydrological behavior within the study area.

During the calibration period, the model exhibited commendable performance metrics for daily simulations, attaining R-squared (R^2) and Nash-Sutcliffe Efficiency (NSE) values of 0.821 and 0.819, respectively. These metrics indicate strong agreement between observed and simulated values. Similarly, during the validation phase, the model demonstrated good performance, albeit slightly reduced, with daily R^2 and NSE values of 0.732 and 0.707, respectively, implying reliable predictive capabilities even during the validation period.

Moreover, when assessing monthly results, the model exhibited even higher levels of agreement. During calibration, the monthly R^2 and NSE values were recorded at 0.927 and 0.925, respectively, showcasing a robust model performance in replicating the monthly hydrological patterns. The validation phase revealed slightly reduced but still commendable monthly R^2 and NSE values of 0.910 and 0.856, respectively. Additionally, through sensitivity analysis, it was identified that the flow dynamics within the basin were notably more sensitive to variations in Hydrologic Response Unit (HRU) definition thresholds compared to the effects stemming from sub-basin delineation. This sensitivity insight provides valuable information regarding the influential factors governing the hydrological behavior within the Sokoto River basin and aids in refining model calibration strategies for enhanced accuracy in future analyses.

The hydrological evaluation conducted on the water catchment reveals an average annual precipitation of 876.61 millimeters. Within this hydrological framework, groundwater recharge constitutes a significant portion, accounting for 25.07% of the overall input into the groundwater system. This recharge volume averages approximately 219.77 millimeters per annum, significantly contributing to the replenishment of groundwater resources within the catchment area. A notable aspect is the partitioning of this groundwater recharge. Only a minimal portion, specifically 5% of the total groundwater recharge, contributes to the storage of deep groundwater recharge, effectively replenishing the deeper aquifer layers within the catchment. In contrast, the remaining majority of this recharge replenishes the more readily accessible shallow aquifer, playing a pivotal role in sustaining local water resources.

Interestingly, within the intricate water balance of the catchment, evapotranspiration emerges as the predominant mechanism responsible for water loss. This process involves the combined loss of water through direct evaporation from surfaces and transpiration from plants. Evapotranspiration represents the highest proportion of water loss from the catchment, underscoring its significant role in regulating the overall water budget within the study area. This comprehensive overview sheds light on the critical components influencing the water balance within the catchment, emphasizing the substantial contribution of groundwater recharge and the substantial impact of evapotranspiration on the catchment's water dynamics.

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