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Application of SWAT Model for Water Resources Management and Planning in the Lower Vellar Sub-Basin, Cuddalore District, Tamil Nadu, India

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Abstract

Geospatial techniques, including Geographic information systems (GIS) and remote perception, are used to analyze the spatial distribution of rainfall and its relationship with topographic and climatic factors. This research aims to identify and prioritize potential sites for artificial recharge structures using a multidisciplinary methodology that integrates morphometric analysis, rainfall pattern analysis, water quality evaluation, hydrological modeling via SWAT and spatial multi-criteria decision-making through the Analytical Hierarchy Process (AHP). SWAT modeling allowed the simulation of surface runoff, evapotranspiration, water yield and percolation, based on 24 delineated mini-watersheds. Surface runoff averaged 235–248 mm annually, while percolation ranged between 127–149 mm, suggesting a moderate recharge capacity. The outcomes are expected to contribute to long-term aquifer sustainability, enhance water security and improve agricultural productivity in vulnerable watersheds like the Lower Vellar Sub-watershed.

Keywords: SWAT, Lower Vellar Watershed, Solar Radiation, Humidity, Wind Speed.

1. Introduction

The Soil and Water Assessment Tool (SWAT) is a robust, physically-based, semi-distributed hydrological model that simulates basin-scale water balance dynamics, developed by the United States Department of Agriculture (USDA) Agricultural Research Service (Karki *et al*., 2020; Wang *et al*., 2019; Sehgal *et al*., 2018) [1, 5]. SWAT is expressly designed to simulate overland flow, subsurface flow, sediment transport, and nutrient flux across heterogeneous landscape topologies, rendering it a crucial tool for analyzing water resource dynamics, land use impacts, and ecohydrological management. The model assimilates diverse spatial and temporal datasets, including digital terrain models, pedological characteristics, land cover patterns, meteorological data, and topographic information, to simulate hydrological processes at catchment and sub-catchment scales. In groundwater utilization research, SWAT provides detailed insights into aquifer replenishment kinetics by modeling hydrological flux through different soil layers, estimating subsurface water discharge to fluvial systems and predicting potential subterranean water prospect areas. Researchers and water resource managers utilize SWAT to assess catchment hydrological processes, evaluate terrain stewardship strategies, predict hydrological output, analyze diffuse pollution sources and develop effective hydro-resource governance methodologies across various meteorological and geotectonic settings.

A catchment is a spatially and temporally dynamic geo-ecological entity whose attributes and functionality vary across different spatial and temporal scales. Considering the intricacy of ecohydrological and biogeophysical processes within a catchment, hydrological cycle models are vital instruments for analyzing these processes. These models are paramount for comprehending catchment-scale hydrological dynamics, formulating sustainable land and water stewardship strategies, and evaluating the long-term consequences and advantages associated with diverse land-cover practices (Spruill *et al*., 2000) [6]. Overland flow, which stems from precipitation, embodies the integrated hydrological response of a catchment's terrestrial surface. Predicting surface flow in unmonitored catchments remains a significant hurdle and accomplishment in hydrological evaluation. Precise modeling of overland flow processes is crucial not only for quantifying aquifer recharge potential but also for demarcating zones of hydrological vulnerability. Surface runoff, consequently, constitutes a fundamental input for any catchment hydrological modeling endeavor. With this comprehension, the current investigation utilizes the QGIS-integrated SWAT (Soil and Water Assessment Tool) model to simulate and estimate overland flow in the study region, aiming to improve hydrological characterization and facilitate informed resource governance. SWAT is a conceptual, continuous catchment

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simulation model that functions on a daily temporal scale for long-term prognostications.

It was developed in the early 1990s by integrating the Hydrological Simulation Model for Rural Watersheds (HSMRW) and Hydrological Routing to Outlet Systems (HROS) by the United States Department of Agriculture - Agricultural Research Service (USDA-ARS), Grassland, Soil and Water Research Laboratory, Texas. It has undergone comprehensive assessments and expansions of its capabilities since its inception (Arnold *et al*., 1998; Neitsch *et al*., 2002; Neitsch *et al*., 2005) [3, 4]. It permits a watershed to be segmented into numerous grid cells or hydrological units and can model for centennial or longer timescales

2. Material and Methods

2.1. Swat Model

The Soil and Water Assessment Tool (SWAT) is a process-oriented, semi-distributed hydrologic simulation model devised by the USDA Agricultural Research Service to simulate the impacts of land utilization patterns, pedological characteristics, topographical features, meteorological conditions, and agronomic practices on hydrological regime and water quality parameters in large, complex watersheds. Designed to operate over long periods with daily time increments, SWAT facilitates detailed analysis of water cycle components, including overland flow, evapotranspirative losses, infiltration rates, percolation processes, and subsurface flow regimes. By incorporating Spatial Information Systems (SIS), SWAT permits the geospatial characterization of catchment attributes, making it particularly suitable for evaluating watershed management scenarios, including aquifer conservation, across diverse land cover configurations and climatic regimes.

i). QSWAT Setup: QSWAT 1.9 serves as a QGIS-integrated interface for the SWAT model, facilitating spatially distributed hydrological modeling within an intuitive environment. By seamlessly integrating with QGIS, QSWAT 1.9 enables streamlined preprocessing and configuration of crucial input datasets, including digital elevation models (DEM), land use/land cover (LULC) classifications, soil data, and daily climate records (refer to Figure 1). The software's modular, step-by-step approach allows users to effortlessly conduct watershed delineation, sub-basin segmentation, and Hydrologic Response Unit (HRU) demarcation. This iteration boasts advanced functionalities and improved robustness, rendering it particularly adept at simulating intricate hydrological phenomena and evaluating the consequences of various land and water management practices. In the present study, QSWAT 1.9 was utilized to model surface-groundwater interactions and formulate efficacious groundwater conservation strategies for the Lower Vellar Watershed.

ii). DEM Configuration: The Digital Elevation Model (DEM) serves as the basis for watershed demarcation and hydrological routing in the QSWAT 1.9 configuration. This investigation utilized the Shuttle Radar Topography Mission (SRTM) DEM, characterized by a 30-meter spatial resolution, to precisely depict the topography of the Lower Vellar Watershed. The DEM underwent processing within QGIS to rectify depressions and eliminate topographic anomalies, thereby ensuring unobstructed flow trajectories. Subsequently, it was employed to delineate the watershed boundary, extract the drainage network, further subdivide the watershed into sub-basins, and generate a slope map (Refer to Figure 2).

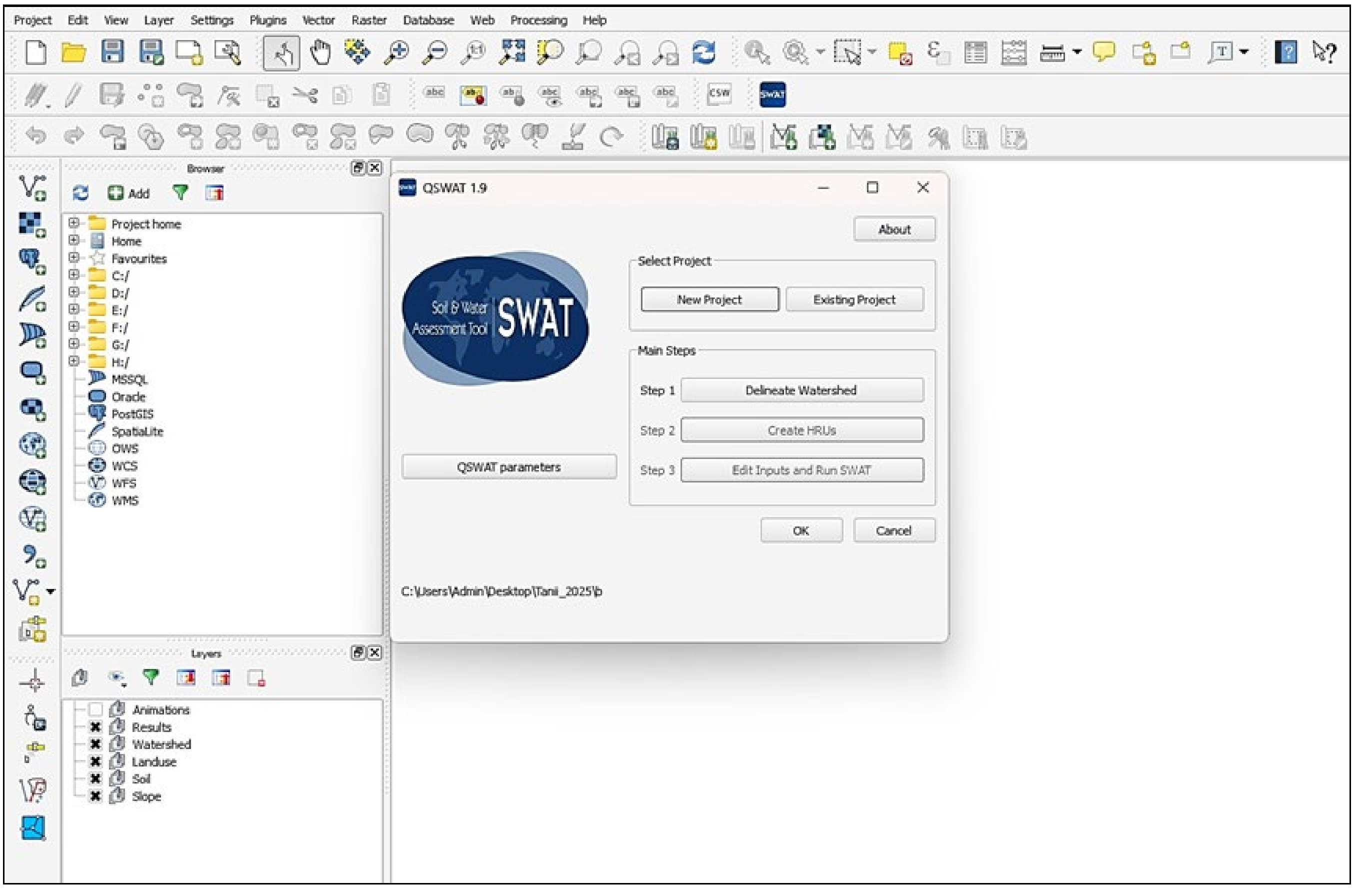

Fig 1: New project setup in QSWAT 1.9

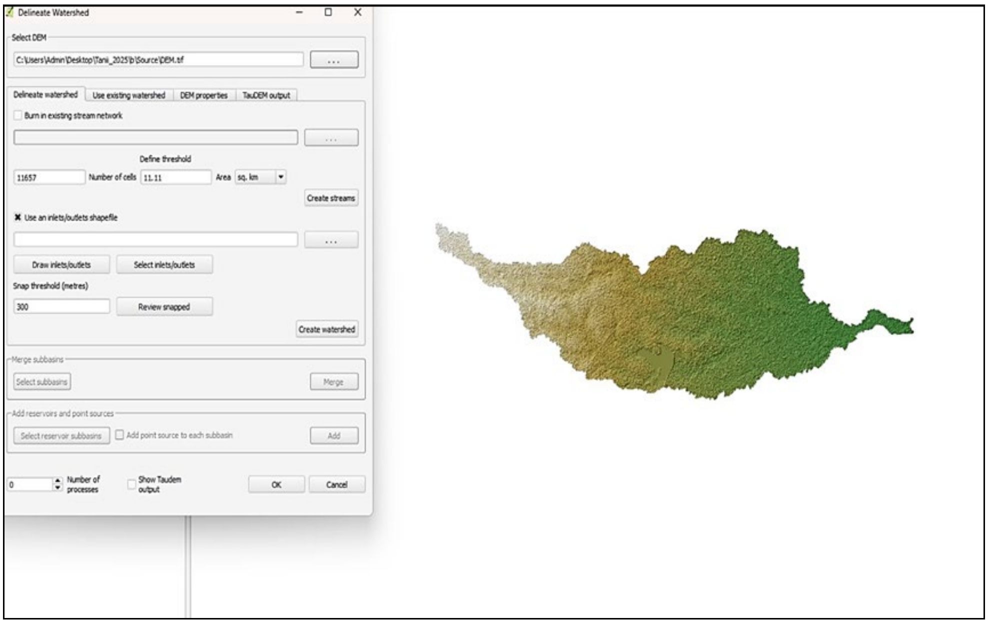

Fig 2: Importing digital elevation model (DEM)

iii). Stream Network Extraction

The derivation of the stream network from the Digital Elevation Model (DEM) delineates the flow pathways and hydrological connectivity within the terrain. The DEM was processed using QSWAT 1.9 to extract the stream network for the Lower Yellar Watershed. The procedure commences with the creation of a Flow Direction raster, which indicates the direction of water flow from each cell to its adjacent cells. This is computed by analyzing the steepest slope from each cell to one of its eight neighboring cells, taking into account the topographic variations between them. Upon establishing the flow direction, the Flow Accumulation raster is generated by aggregating the number of upstream cells that contribute to the flow in each grid cell. The accumulation value facilitates the identification of areas prone to forming stream channels by detecting regions of concentrated water flow. A predefined threshold is applied to the flow accumulation raster to delineate the stream network, which identifies cells where the accumulated flow exceeds a specific value, indicating stream or river channels. Following stream extraction, the Stream Link raster is generated, which assigns unique identifiers to each stream segment within the network.

iv). Delineation of mini-watersheds

The demarcation of micro-watersheds enables the hydrological flux simulation across more manageable units within the watershed. The discharge points serve as the foundation for dividing the entire watershed into smaller sub-basins (Refer Figure 3). Each sub-basin is assigned a unique identifier, ensuring accurate tracking of runoff, infiltration, and groundwater recharge processes at a finer scale. QSWAT's automated watershed demarcation module refines the boundaries of these sub-basins, ensuring they align with natural topographic features, such as ridgelines and stream networks (Refer Figure 4). By delineating the watershed into sub-basins, QSWAT enhances the precision of hydrological modeling by capturing local variations in water circulation, runoff, and recharge. The discharge points provide crucial locations for model calibration and validation, where observed flow data can be compared to model outputs, improving the reliability and predictive capacity of the simulation for groundwater conservation and water management strategies in the Lower Vellar watershed.

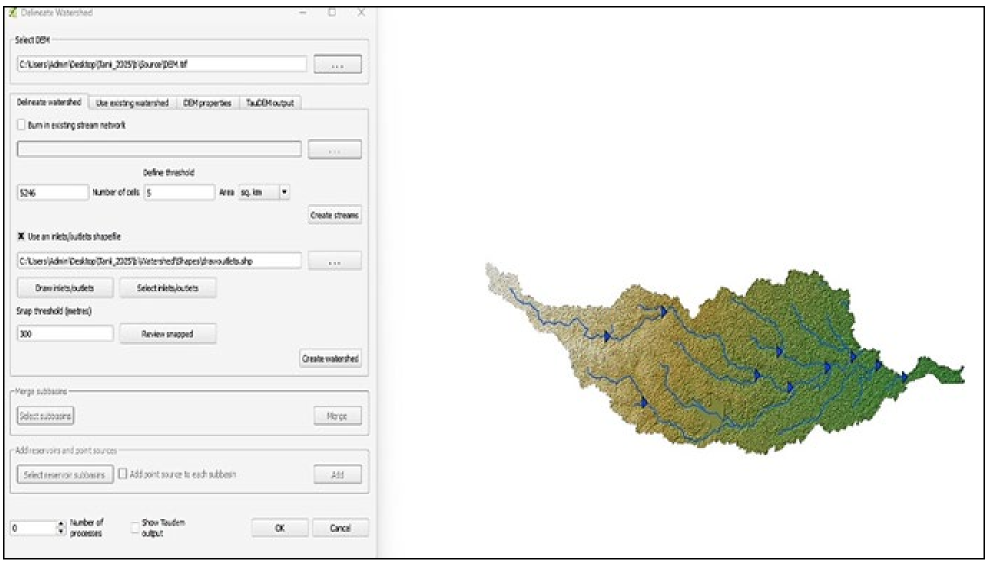

Fig 3: Assigning stream Outlets

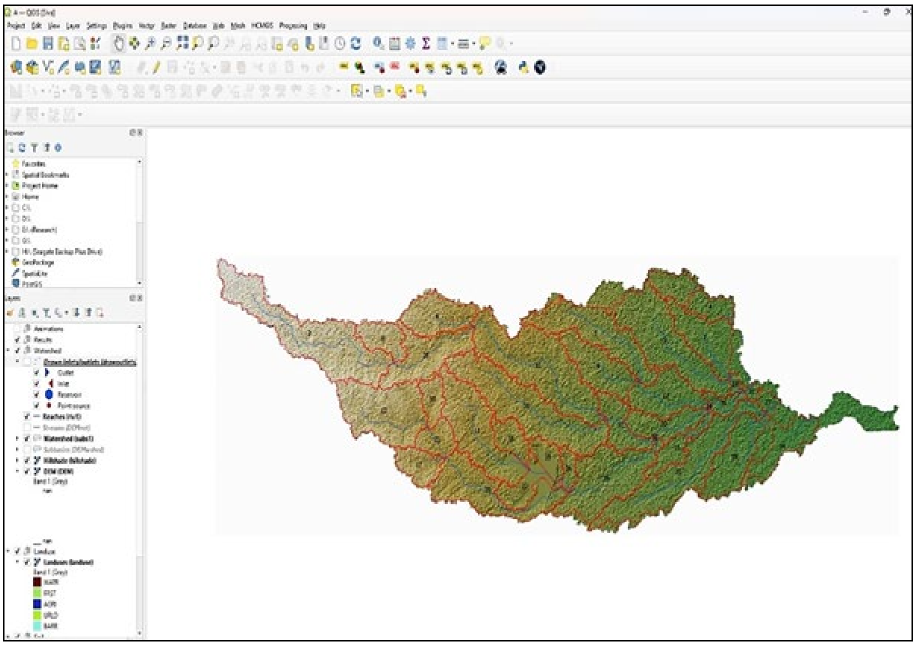

Fig 4: Delineating sub watersheds

v). Hydrologic Response Units

The SWAT model facilitates the delineation of Hydrologic Response Units (HRUs) to encapsulate the spatial variability of the watershed with respect to land use/land cover (LULC), soil type, and slope (Refer to Figure 5). The HRU delineation was accomplished utilizing the QSWAT interface within QGIS, wherein input datasets, including a Digital Elevation Model (DEM), a classified land use map, and a soil map, were seamlessly integrated. The land use and soil datasets underwent reclassification to align with SWAT-compatible codes via lookup tables, while slope classes were derived from the DEM and subsequently categorized into predefined intervals, thereby representing a range of terrains from flat to steep.

vi). SWAT Run

Subsequent to the demarcation of Hydrologic Response Units (HRUs), the SWAT model was executed to replicate the hydrological dynamics of the watershed under specified physiographic and climatic regimes. Prior to simulation, essential meteorological parameters, including daily precipitation, maximum and minimum temperatures, solar irradiance, relative humidity, and wind velocity, were procured from credible sources such as proximate meteorological stations or national datasets (Refer to Figure 6). These data were pre-processed and formatted into CSV files to serve as input for the weather generator module ("wgn" user) of the SWAT model. Each weather station CSV file comprised specific columns representing requisite statistical attributes for the generator, including station identifier, latitude, longitude, elevation, mean monthly precipitation, standard deviation of precipitation, skewness coefficient of precipitation, average number of wet days per month, mean daily maximum and minimum temperature, standard deviations of temperature, mean solar irradiance, relative humidity, and wind velocity. These files were subsequently imported into the SWAT weather generator database, which is stored in Microsoft Access format (*.mdb), utilizing the SWAT interface tools. Upon importation, the weather generator computed synthetic daily weather time series based on monthly statistics, thereby ensuring continuity in climatic input where observed data were incomplete or unavailable. These generated weather datasets were then linked to respective sub-basins in the model and utilized to drive hydrological simulations across all HRUs.

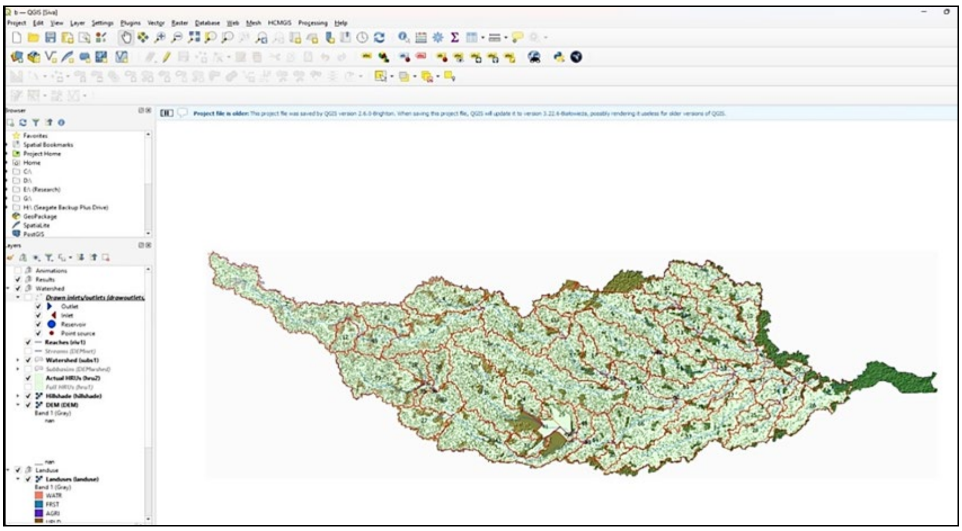

Fig 5: Hydrologic Response Units

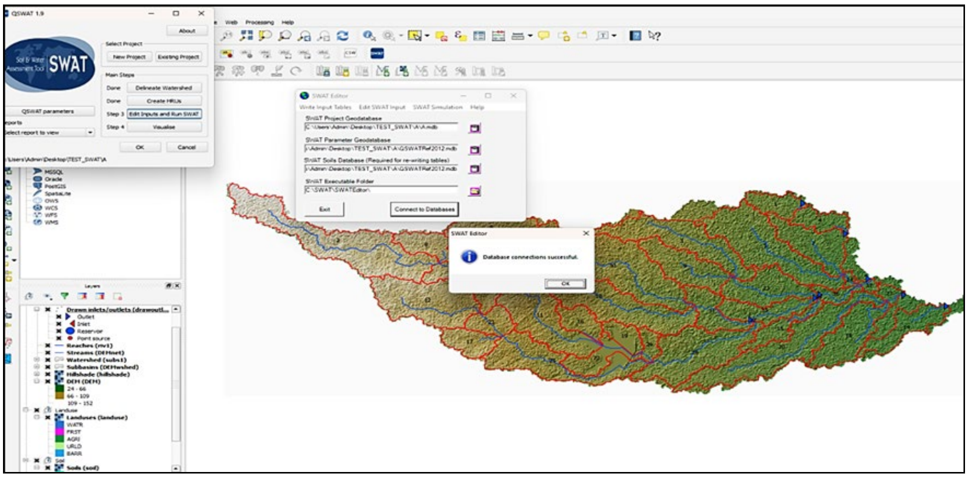

Fig 6: Connecting database to SWAT project

vii). Calibration and Validation

Upon successful deployment of the SWAT model, the SWAT-CUP (SWAT Calibration and Uncertainty Procedures) tool was utilized to perform a sensitivity analysis, calibration, and validation of the simulated hydrological outcomes against observed streamflow data. The SUFI-2 (Sequential Uncertainty Fitting, version 2) algorithm, integrated within SWAT-CUP, was selected owing to its efficacy in handling parameter uncertainty and its ability to achieve rapid convergence with a minimal number of iterations. Streamflow data, recorded daily or monthly at the watershed outlet, were aggregated, rigorously quality-assessed, and formatted in accordance with SWAT-CUP specifications (Figure 7).

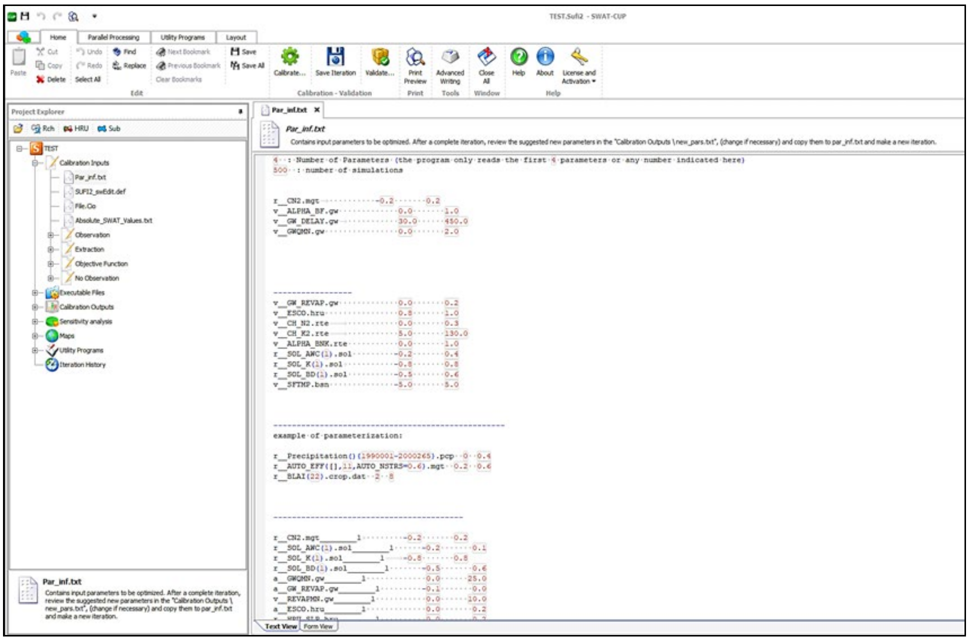

Fig 7: Calibration parameters in SWAT-CUP

3. Result and Discussion

3.1. QSWAT Model Setup

The SWAT model can simulate long-term outputs to assess the impacts of land use strategies (Arnold and Allen, 1999). The hydrological processes simulated by the SWAT model include precipitation, infiltration, surface runoff, evapotranspiration, lateral flow, and percolation. This study utilized QSWAT version 1.4 on the QGIS (version 2.6.1) platform, requiring inputs such as Digital Elevation Model (DEM), land use, soil type, slope, and daily meteorological data.

i). Digital Elevation Model (DEM)

The Digital Elevation Model (DEM) constitutes a critical component in SWAT model development, delineating the watershed's topographical characteristics and influencing hydrological processes, including flow direction, accumulation, and watershed delineation. In this investigation, 1-arc-second (30m × 30m) SRTM data were employed to represent the surface topography. The Shuttle Radar Topography Mission (SRTM), undertaken collaboratively by NASA and the National Geospatial-Intelligence Agency (NGA) in 2000, furnishes globally consistent elevation data that are essential for hydrological modeling. All geospatial inputs for the SWAT model must be in a projected coordinate system to ensure spatial accuracy. Consequently, the Universal Transverse Mercator (UTM) Zone 44N projection, which preserves conformity and facilitates precise area and distance calculations, was applied to all spatial datasets utilizing the warp transformation tool in QGIS. DEM preprocessing involved identifying and filling sinks using QGIS raster processing tools to ensure unobstructed surface flow paths. To augment visualization and interpret terrain morphology, a shaded relief layer was generated, providing a three-dimensional perspective of the Lower Vellar Sub-watershed (Figure 8). The hypsometric profile of the Lower Vellar Sub-watershed spans from 24 to 152 meters. The western region, particularly around Pillanthurai, exhibits the highest elevations (109-152 m), whereas the eastern part, near Karumangudi, is located at the lowest elevation range (24-66 m), with moderate terrain situated between 66 and 109 meters.

ii). Slope

Slope denotes the rate of elevation change over horizontal distances and serves as a crucial topographic attribute for delineating landforms such as plains, uplands, and escarpments. The slope is derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data (Figure 9). It substantially influences surface runoff, infiltration capacity, erosion propensity, and land use appropriateness. In the Lower Vellar Sub-watershed, slope gradients were computed from the processed DEM and classified into three categories based on percentage ranges: 0–5%, 5–10%, and >10%. Most of the study area falls within the gentle to moderate slope category, whereas the westernmost part exhibits a relatively steep slope.

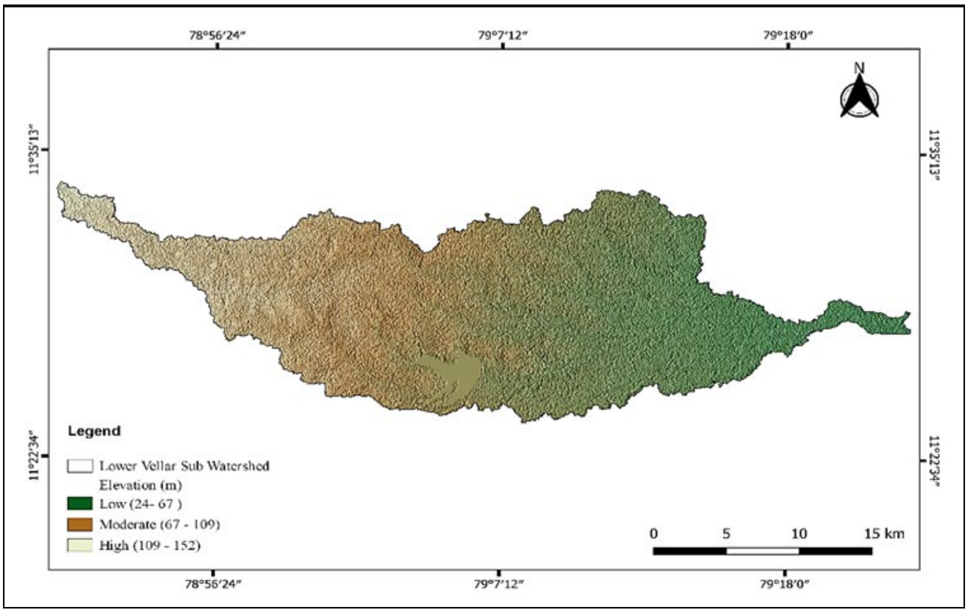

Fig 8: SRTM DEM map of the Lower Vellar Subwatershed

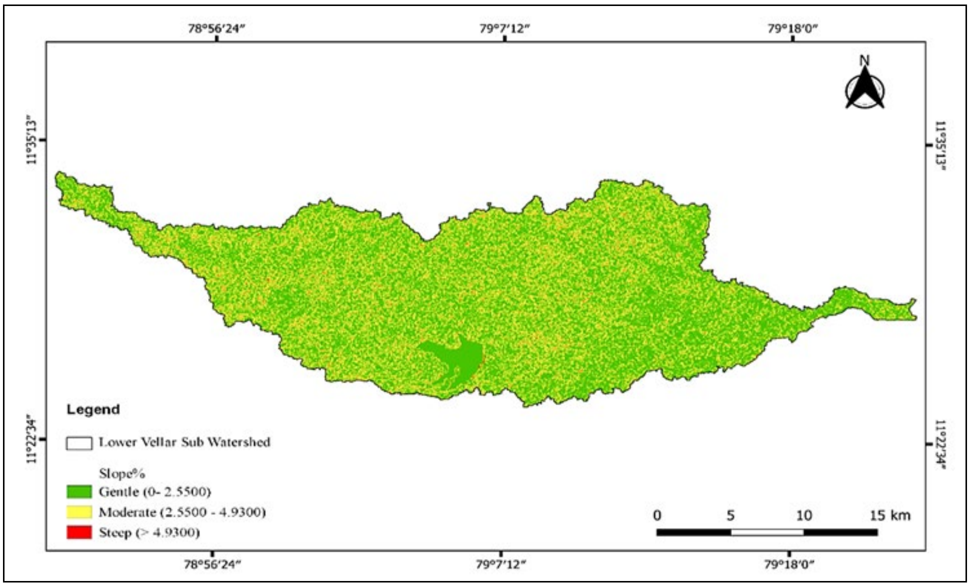

Fig 9: Slope map of the Lower Vellar Subwatershed

iii). Land use and Land Cover

The Land Use Land Cover (LULC) map plays a pivotal role in hydrological modeling, as it significantly influences runoff and water yield. Therefore, it is crucial to perform a comprehensive mapping and analysis of LULC in the study area (Figure 10). A Sentinel L2A satellite image with a spatial resolution of 10 meters was pre-processed and employed for supervised image classification. The satellite data were categorized into five distinct classes: Urban (Built-up), Agricultural land (AGRI), Forest cover (FRST), Barren land (BARR), and Water bodies (WATR). To facilitate the integration of the land use map with the QSWAT database (Table 1), a land use lookup table was created using the SWAT code. The study area is predominantly composed of Agricultural land (411.90 square kilometers), followed by Urban areas (29.27 square kilometers), Barren land (11.4

square kilometers), Water bodies (10.96 square kilometers), and Forest cover (8.14 square kilometers) (Figure 11).

Table 1: Lookup table for Land use land cover

LANDUSE_ID	SWAT_CODE
1	WATR
2	URLD
3	FRST
4	BARR
5	AGRl

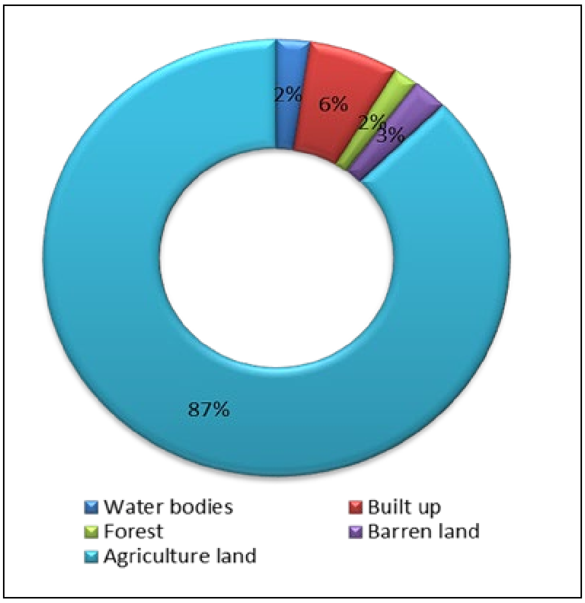

Fig 10: Land use area (%) in study area

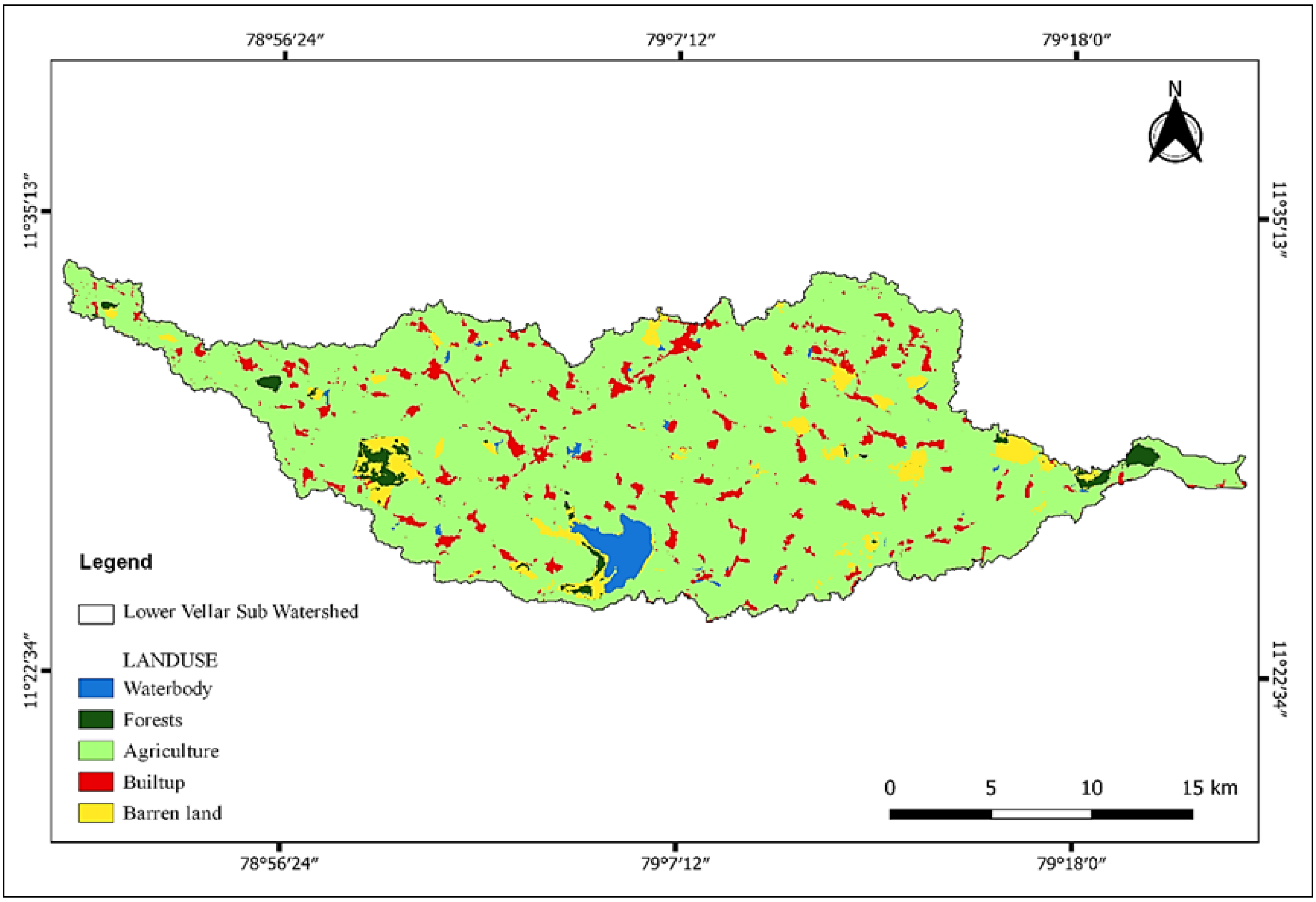

Fig 11: Land use Land cover map of the Lower Vellar Subwatershed

iv). Hydrological Soil Map

The soil data is obtained from the Food and Agriculture Organization (FAO). This dataset is crucial for delineating Hydrological Response Units. Analogous to Digital Elevation Models (DEMs), the soil data substantially influences streamflow modeling. The study area is characterized by a predominance of clayey loam and clay soils. The soil data was integrated into the database via the Soil Lookup Table (Table 2). Clayey loam dominates the majority of the sub-basin, whereas clay is confined to a smaller area in the eastern sector. Clay loam and clay soils exhibit distinct differences in their physical properties, which directly impact surface runoff and groundwater recharge.

Clay loam is comprised of a balanced mixture of sand, silt, and clay, typically containing less than 40% clay content. This composition yields a moderately fine texture with enhanced structural integrity and higher permeability relative to pure clay (Figure 12). Consequently, clay loam displays moderate infiltration rates, resulting in moderate runoff and a relatively higher potential for groundwater recharge. In contrast, clay soils possess a significantly higher clay content, leading to an extremely fine texture, a dense structure, and very low permeability.

Table 2: Soil look-up Table

SOIL_ID	SNAM	SOIL_TYPE
1	Lc75-2b-3781	Clayey loam
2	Vp20-3a-3866	Clay

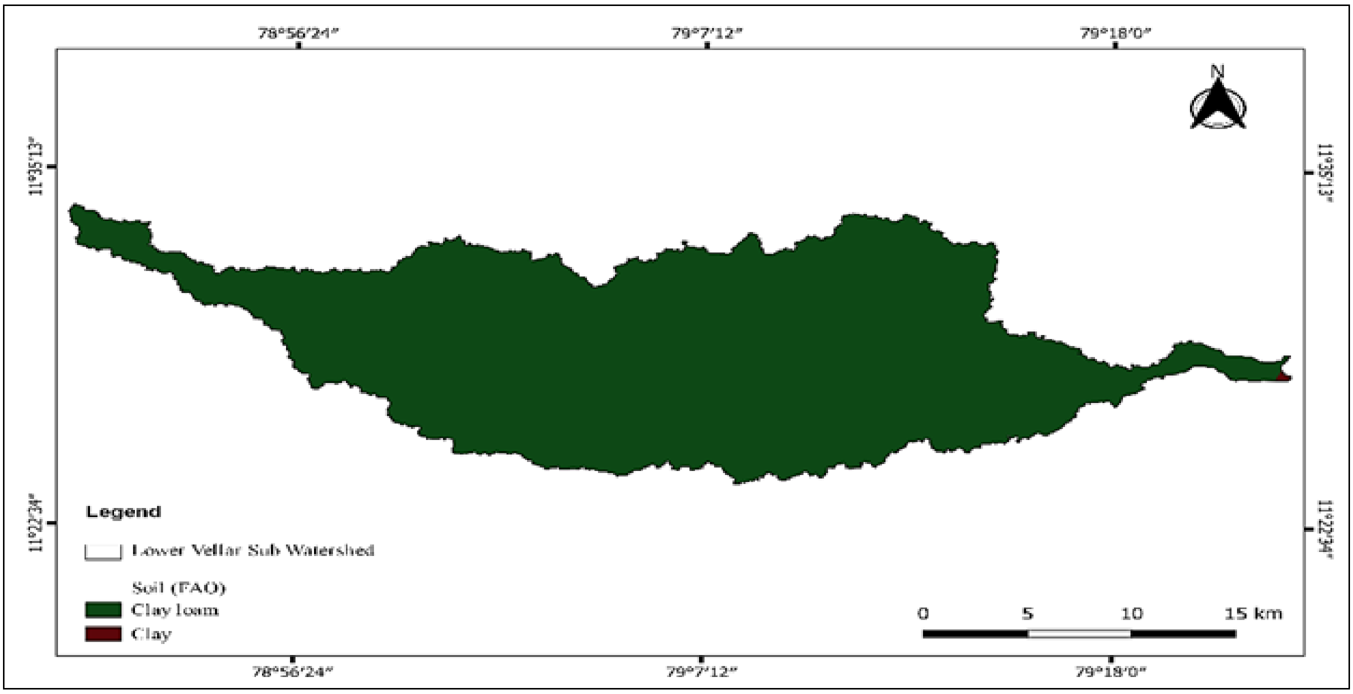

Fig 12: FAO soil map of the Lower Vellar Subwatershed

3.2. Preparation of Weather Database

The SWAT model necessitates extensive daily meteorological data to operate effectively. The requisite daily meteorological parameters encompass ambient temperature (°C), precipitation (mm), wind velocity (m/s), solar irradiance (MJ/m²), and relative humidity (%). In this investigation, meteorological data were compiled over a span of 21 years (2001-2021). With respect to the spatial domain, meteorological data from three weather monitoring stations—Lakkur, Thittakudi, and Veppur—were utilized to construct the meteorological database (WGEN_user) (Figure 13). Table 3 furnishes detailed information regarding the Station ID, Station Name, Geographical Coordinates, and Elevation.

Table 3: Co-ordinates and elevation of the weather stations

Station Code	Station Name	Latitude	Longitude	Elevation (m)
1	Thittakudi	11° 24′ 27″ N	79° 7′ 2″ E	94
2	Lakkur	11° 28′ 29.86″ N	79° 0′ 19.48″ E	120
3	Veppur	11° 31′ 55.56″ N	79° 7′ 21.14″ E	96

i). Precipitation (Pcp)

Prior to configuring the model, it is crucial to compute the statistical parameters pertinent to precipitation. The WGEN_user file serves as a comprehensive weather generator parameter database utilized within the SWAT framework, encapsulating monthly meteorological statistics for various weather stations. The specifics of the diverse meteorological parameters calculated are delineated in Table 4. The model simulates precipitation employing either a Markov chain model with skewed distribution or a Markov chain model with an exponential distribution (Williams, 1995).

Table 4: Weather parameters and its description

S. No.	Parameter Name	Parameter Specifics
1	TMPMX	Average Monthly Maximum Temperature
2	TMPMN	Average Monthly Minimum Temperature
3	TMPSTDMX	Monthly Temperature Standard Deviation
4	PCP_MM	Average monthly precipitation [mm]
5	PCPSTD	Standard deviation
6	PCPSKW	Skew coefficient
7	PR_W1	Probability of a wet day following a dry day
8	PR_W2	Probability of a wet day following a wet day
9	PCPD	Average number of days of precipitation in month
10	RAINHHMX	Maximum 0.5-hour rainfall in entire period of record for month
11	SOLARAV	Average daily solar radiation for month
12	DEWPT	Average daily dew point temperature for each month (or relative humidity can be used as an input)
13	WNDAV	Average daily wind speed in month (m/s)

Precipitation statistics are a crucial element of the WGEN_user dataset, furnishing a comprehensive overview of monthly pluvial patterns. Each station encompasses values for the mean monthly precipitation (PCPMM1 to PCPMM12), representing the long-term average pluviometric readings in millimeters. To capture the variability of rainfall, the standard deviation (PCPSTD) of daily precipitation is incorporated, providing insight into the fluctuations in rainfall amounts from day to day each month. The skewness coefficient (PCPSKW) is another significant parameter reflecting the asymmetry in the rainfall distribution, essential for modeling extreme pluvial events. Additionally, the dataset includes the number of rainy days per month (PCPD) and the maximum recorded 30-minute rainfall for each month (RAINHHMX), both critical for modeling surface runoff, peak discharge, and soil erosion potential. The average monthly precipitation is approximately 89.6 mm, indicating a moderately humid climate overall. The standard deviation of daily rainfall is around 6.14 mm, suggesting that rainfall events tend to vary but are not excessively capricious. Notably, the skew coefficient is 4.85, which is quite high: this indicates that while most days may experience light or no precipitation, there are occasional intense storm events that significantly impact totals. On average, there are about 25.5 rainy days per month, indicating frequent precipitation, possibly with daily or near-daily showers. The maximum 30-minute rainfall observed averages 6.45 mm, which is useful in erosion modeling, particularly in regions with exposed soils or steep topography.

ii). Temperature Data (Tmp)

For each station, the dataset encompasses twelve monthly values for the mean diurnal maximum temperature (TMPMX1 to TMPMX12) and mean diurnal minimum temperature (TMPMN1 to TMPMN12), both quantified in degrees Celsius. These values signify the long-term monthly averages derived from historical observations. In addition, the datas*et al*so includes the standard deviation for both maximum (TMPSTDMX) and minimum (TMPSTDMN) temperatures, which indicates the temperature variability within each month. The average maximum temperature across all months and stations is approximately 33.3°C, while the average minimum temperature is around 23.2°C. These values reflect the climatic conditions of a generally warm to hot region, suggesting a significant diurnal temperature range. The SWAT model utilizes this temperature data to drive critical components such as evapotranspiration and phenological cycles.

iii). Humidity (Hmd)

Atmospheric moisture in the WGEN_user dataset is quantified using monthly dew point temperatures (DEWPT1 to DEWPT12), serving as a surrogate for ambient moisture levels. The dew point temperature, measured in degrees Celsius, represents the temperature at which the air becomes saturated with water vapor, thereby closely correlating with relative humidity. Elevated dew point values signify more humid conditions. In hydrological and agricultural modeling, dew point data is utilized to estimate relative humidity, a crucial parameter for calculating potential evapotranspiration (PET), evaluating plant water stress, and understanding evaporative demand. In arid climates or during growing seasons, the dew point can substantially influence plant health and soil moisture equilibrium. The database represents humidity using dew point temperature, with an average value of approximately 70.8°C. The elevated dew point temperature corresponds to reduced evaporative demand and a humid environment, potentially impacting soil moisture retention, plant water utilization, and evapotranspiration calculations. In the SWAT model, dew point temperature is frequently employed to estimate relative humidity, thereby refining the energy balance and water flux simulations.

iv). Solar Radiation (Slr)

The dataset furnishes monthly mean solar radiation values (SOLARAV1 to SOLARAV12), quantified in megajoules per square meter per diem (MJ/m²/day). Solar irradiance is a pivotal driver of the hydrological cycle and vegetation growth in SWAT. It modulates the rate of evapotranspiration, influences photosynthetic processes, and plays a crucial role in governing the dynamics of soil and water temperatures. These values are utilized in conjunction with temperature and humidity data to simulate energy balance components within the watershed. In the study area, the average solar irradiance is approximately 20.4 MJ/m²/day, signifying a high solar energy environment characteristic of tropical or subtropical regions. This level of irradiance provides a potent energy driver for evapotranspiration and photosynthesis, thereby influencing plant productivity and the hydrological cycle.

v). Wind velocities (Wnd)

The WGEN_user file incorporates monthly mean wind velocities (WNDAV1 to WNDAV12), quantified in meters per second. Aerodynamic forcing plays a crucial role in modulating surface energy fluxes by augmenting the rate of evapotranspiration and plant water loss. In the SWAT model, wind velocity is utilized to calibrate the estimation of potential evapotranspiration, particularly in arid and semi-arid regions where wind can substantially exacerbate water loss from soils and vegetation. In the study domain, the average wind velocity is 3.84 m/s, a moderate magnitude that is vital for enhancing evaporative fluxes. This wind velocity can amplify soil and canopy evaporation and may also impact crop transpiration rates.

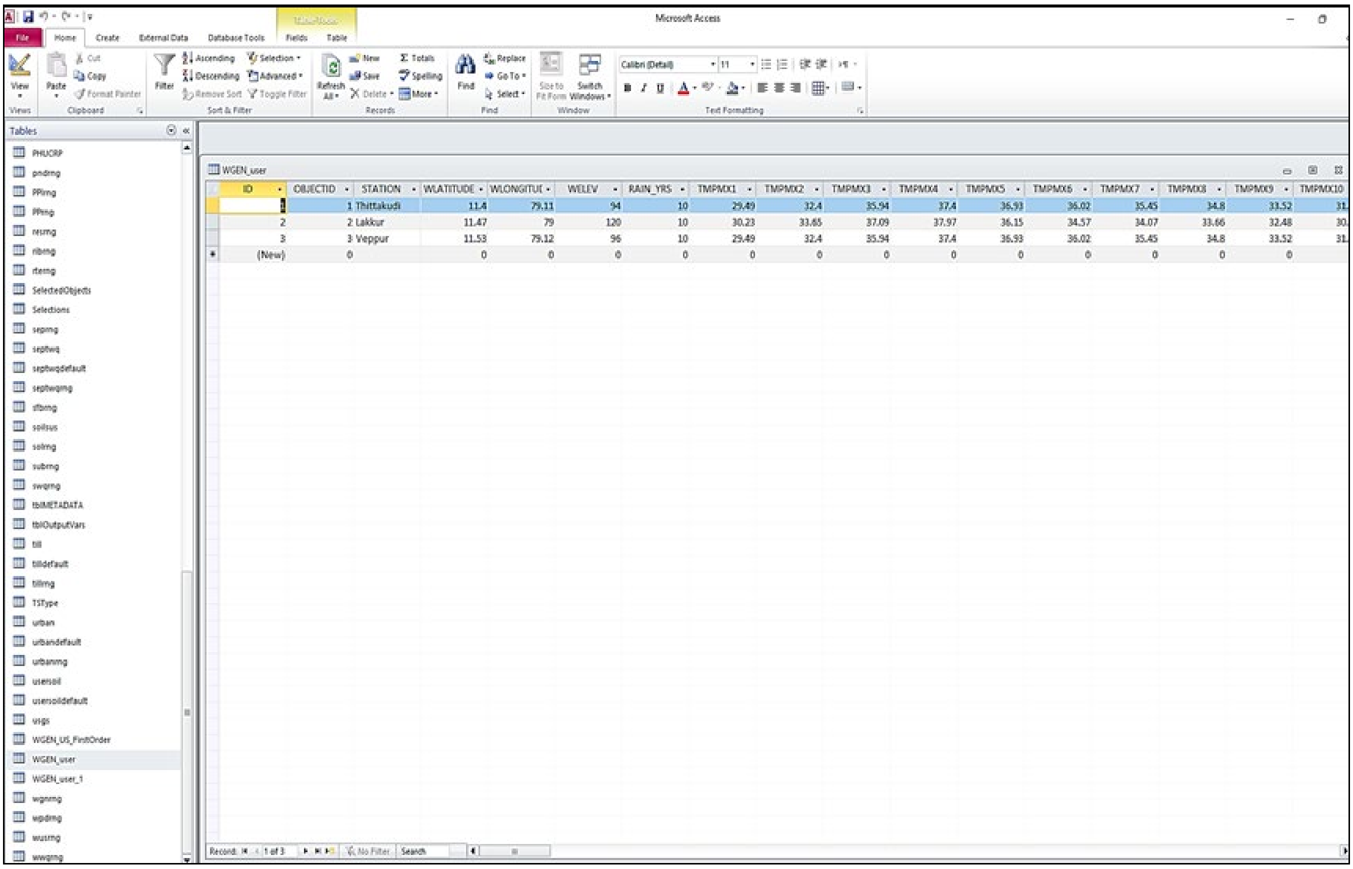

Fig 13: WGEN_user database contains weather parameters

3.3. Watershed Delineation

A watershed is a hydrologically defined geographic area of land where all precipitation and surface runoff converge to a common outlet, such as a river, lake, or ocean. It functions as a natural hydrologic entity, capturing rainfall and channeling water through a network of streams and rivers. Watershed delineation is the process of demarcating and mapping the boundary of this land area based on topomorphological and hydrological features, typically utilizing digital elevation models (DEMs) and GIS tools. This process defines the spatial extent of the watershed and its drainage patterns. Within a sub-watershed, there are often sub-catchments, which are smaller drainage areas that contribute to tributaries or segments of the main watercourse. Sub-catchments facilitate detailed hydrological analysis and are crucial for localized water resource management, land-use planning, and environmental conservation. Initially, the DEM is pre-processed to fill depressions and establish flow direction and accumulation. A user-defined threshold area is then applied to determine the stream network and identify outlet points where streams are assumed to converge. Based on this hydrological data, the subwatershed boundary is generated automatically, and it is further subdivided into sub-catchments according to topographic and hydrographic characteristics. In the present investigation, 24 sub-watersheds were demarcated (Figure 14). The delineated sub-watersheds were morphometrically analyzed based on their areal extent, percentage of total catchment coverage, and boundary perimeter (Table 5). A total of 24 sub-watersheds were identified, encompassing a cumulative area of 513.38 km². The largest sub-watershed, SW8, was delineated with an areal extent of 68.51 km², accounting for 13.35% of the total catchment area and exhibiting the maximum perimeter of 90.20 km. Conversely, SW14 was identified as the smallest, with an areal extent of merely 0.25 km², contributing a mere 0.05% to the catchment and possessing the shortest perimeter at 3.64 km. The mean areal extent and perimeter of the sub-watersheds were computed to be 21.39 km² and 38.29 km, respectively. Sub-watersheds such as SW1, SW8, and SW20 were delineated as the predominant contributors in terms of spatial extent, collectively covering over 33% of the total catchment area, indicating their potential impact on overall hydrological regimes. Smaller sub-watersheds, such as SW14, SW15, and SW24, were found to have limited spatial influence, which may suggest localized drainage patterns or upland topographic features. A wide range of perimeters indicates significant variability in morphological complexity, with some sub-watersheds, such as SW11 and SW3, exhibiting relatively high perimeter-to-area ratios, which may reflect irregular topographic configurations or elongated catchment shapes.

Table 5: Morphometry of delineated mini-watersheds

Mini-watersheds	Area (Sq. km)	Area (%)	Perimeter (Km)
SW1	63.73	12.41	89.71
SW2	13.04	2.54	27.23
SW3	24.10	4.69	51.09
SW4	29.63	5.77	52.54
SW5	14.85	2.89	32.66
SW6	15.24	2.97	30.62
SW7	35.11	6.84	60.20
SW8	68.51	13.35	90.20
SW9	48.83	9.51	63.84
SW10	5.23	1.02	15.96
SW11	30.62	5.97	69.09
SW12	16.75	3.26	28.14
SW13	14.78	2.88	31.74
SW14	0.25	0.05	3.64
SW15	0.88	0.17	6.67
SW16	4.61	0.90	11.86
SW17	18.07	3.52	30.25
SW18	13.74	2.68	31.32
SW19	25.64	4.99	44.52
SW20	38.30	7.46	54.02
SW21	9.53	1.86	26.67
SW22	17.04	3.32	42.97
SW23	3.61	0.70	15.00
SW24	1.31	0.25	9.14
Sum	513.38	100.00	919.07
Min	0.25	0.05	3.64
Max	68.51	13.35	90.20
Mean	21.39	4.17	38.29

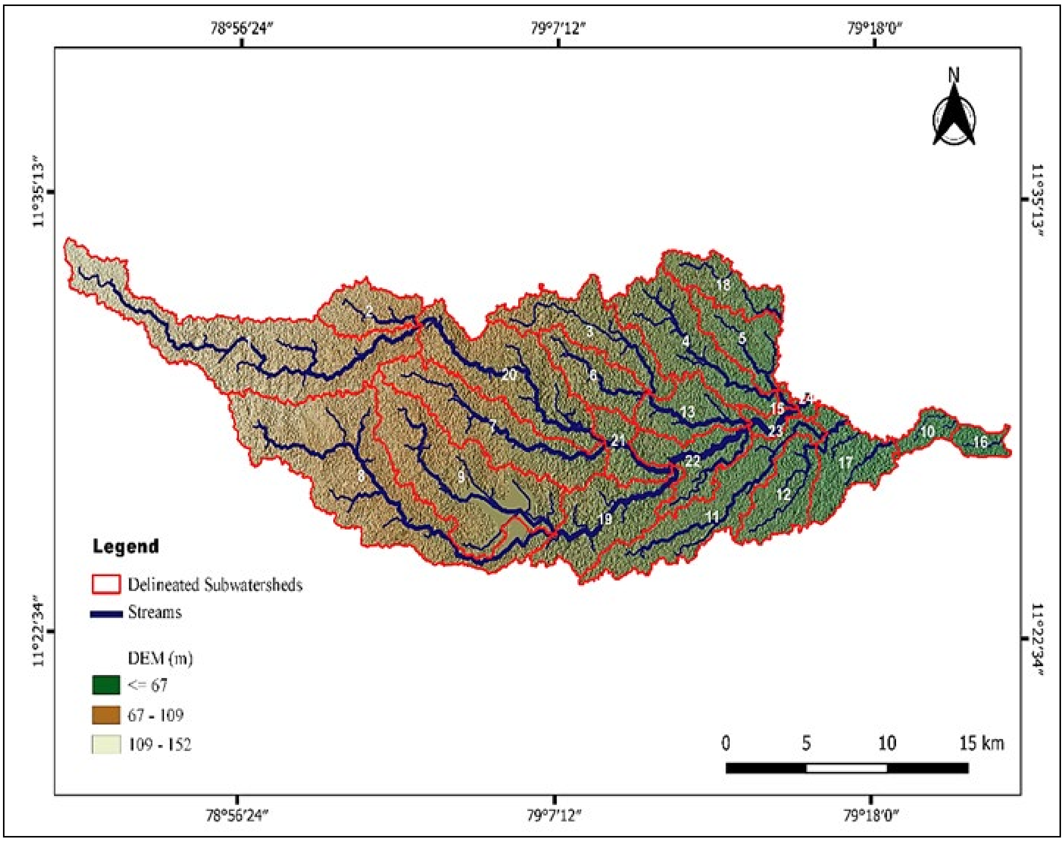

Fig 14: Delineation of sub watersheds in the study area

3.4. Hydrological Response Units

Hydrological Response Units (HRUs) are spatially delineated zones within a watershed, distinguished by distinct combinations of land cover, soil classification, and topographic slope, which impact hydrological processes including runoff, infiltration, and evapotranspiration. In hydrological modeling, particularly within the SWAT framework, HRUs are employed to represent regions with analogous hydrological responses, facilitating the simplification of intricate watershed systems. The demarcation of HRUs is based on threshold criteria for land cover, soil type, and slope, with each HRU assumed to exhibit homogeneous hydrological behavior. This discretization enables the efficient simulation of hydrological dynamics over extensive areas while accounting for spatial heterogeneity in watershed characteristics. In this SWAT model, 1779 HRUs were delineated (Figure 15).

3.5. Execution of SWAT

The SWAT model was executed successfully, generating a wide range of simulated outputs that can be analyzed at daily, monthly, and annual timescales. Crucial hydrological processes, including actual evapotranspiration, potential evapotranspiration, groundwater recharge, subsurface flow, surface runoff, and water yield, were simulated over the period from 2003 to 2021, incorporating a two-year spin-up period to ensure model stability. Throughout the simulation, the watershed was discretized into 24 sub-watersheds and further subdivided into 1,779 Hydrological Response Units (HRUs), facilitating a spatially explicit representation of land cover, soil type, and topographic characteristics. Following the completion of the setup, the SWAT model simulation was initiated, displaying a confirmation message "SWAT run successful" (Figure 16). The QSWAT interface facilitates both numerical and spatial visualization of model outputs, providing a holistic understanding of watershed dynamics. As the primary objective of this study is to accurately forecast water yield, surface runoff, and lateral flow, the pertinent output files output.rch (reach files), output.hru (HRU files), and output.sub (sub-basin files) were deliberately selected. These outputs were subsequently reloaded and systematically archived in the project database for further examination.

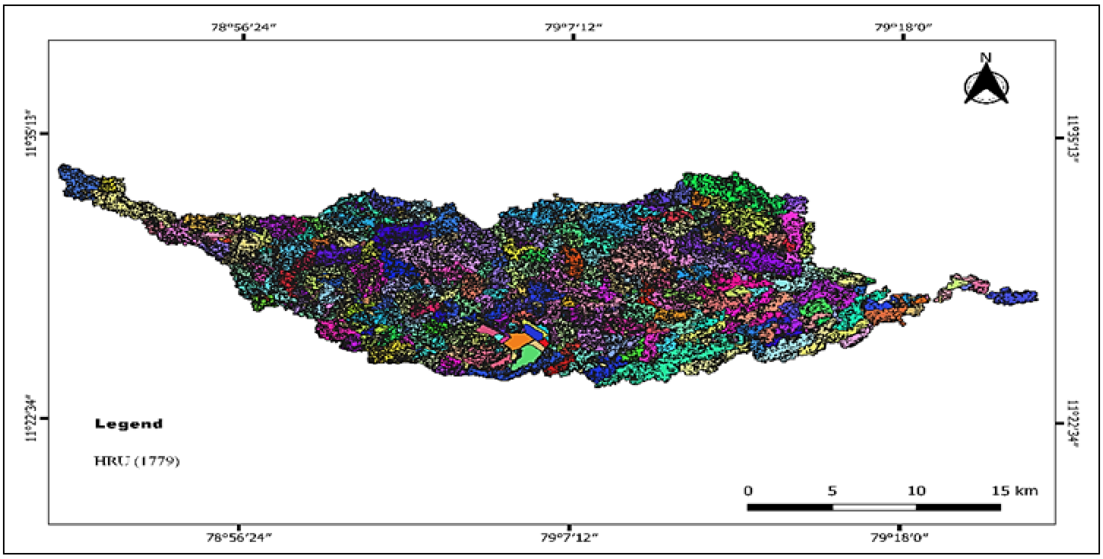

Fig 15: Hydrological Response Units (HRU) in the study area

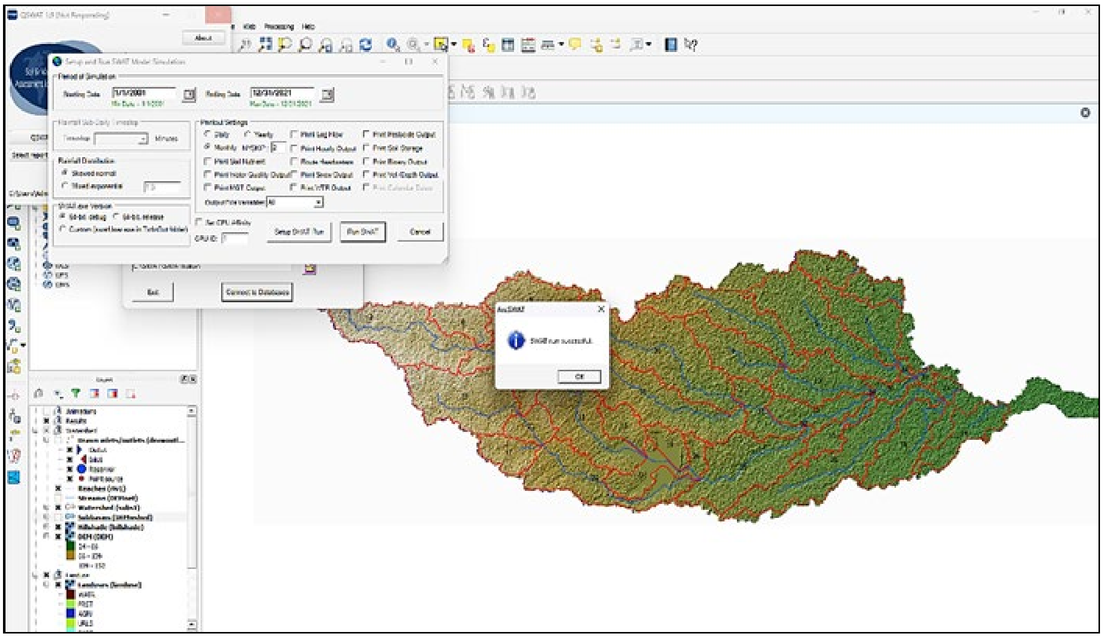

Fig 16: Successful execution of QSWAT

4. Conclusion

The SWAT model was used to simulate key hydrological processes, including surface runoff, lateral flow, water yield and groundwater contribution. The watershed was divided into 24 sub-watersheds and 1,779 Hydrological Response Units (HRUs). The model inputs were derived from high-resolution digital elevation models (DEM), FAO soil data and Sentinel-2 L2A-based land use classifications. The dominant land cover was agricultural land (411.9 km^2), followed by built-up areas, barren land, water bodies and forest. Soils were mainly clay loam, with minor clay deposits in the eastern regions, affecting infiltration rates and water retention capacity. Weather inputs were gathered from three meteorological stations and statistical parameters of precipitation and temperature were utilized to generate realistic long-term simulations through the SWAT weather generator.

Abbreviations List

SWAT: Soil and Water Assessment Tool
GIS: Geographic Information System
DEM: Digital elevation models
LULC: Land use/land cover
HRU: Hydrologic Response Unit
SRTM: Shuttle Radar Topography Mission
NGA: National Geospatial-Intelligence Agency
FAO: Food and Agriculture Organization

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