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Application of Arc-SWAT Model for Water Budgeting and Water Resource Planning at the Yeralwadi Catchment of Khatav, India

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ABSTRACT

Every facet of life, including human habitation, economic development, food security, etc., depends on water as a valuable resource. Due to the burgeoning population and rapid urbanization, water availability needs to be simulated and measured using hydrologic models and trustworthy data. To fulfill this aim, the SWAT model was processed in this work. The SWAT model was formulated to estimate the hydrological parameters of Yeralwadi using meteorological data from IMD (India Meteorological Department) for the period 1995-2020. The observed discharge data was collected from the HDUG Nasik group and used in the calibration and validation of the Model. The SWAT model was corrected & validated through the SUFI-II algorithm in SWAT-CUP to get a better result. The model's sensitivity is checked by using statistical parameters like Nash-Sutcliffe Efficiency (NSE) and a coefficient of determination (R^2). NSE values were 0.72 and 0.80 in calibration and validation, and R^2 were 0.80 & 0.76 in calibration and validation, respectively, indicating the acceptance of the model. Results show that 40.6% of the total yearly precipitation was lost by evapotranspiration. The estimated total discharge from the Yeralwadi catchment was 55.6%, out of which 41.2% was surface runoff and 14.4% was baseflow. The other 17.8% was made up of percolation into confined and unconfined aquifers, which served as soil and groundwater storages. The surface runoff is influenced by Curve number (CnII), SOL_AWC, ESCO, and base flow was influenced by ALPHA-BF and GW_REVAP. This study will be useful to water managers and researchers to develop sustainable water resource management and to alleviate the water scarcity issues in the study basin.

INTRODUCTION

Water is not a luxurious thing but is necessary for all living beings. It plays a very important role in the survival of all living beings. Moreover, relatively substantial amounts of water are necessary for both to function properly; hence, it is more important to study the water requirement (Singh 2014). Water availability has an impact on domestic and international relations, economic success, quantity of food supply, relocation of people, and habitats for humans and other animals. The connection between issues concerning water availability & supply for groundwater-dependent irrigation systems has lately come up in various discussions (Dovie & Kasei 2018). Water resources are under a lot of pressure due to rapid economic development, burgeoning population (Samimi et al. 2020), as well as global climate change (Ross 2018), particularly in arid, semiarid, and water-scarce regions (Prabhanjan et al. 2015). The regional and season-wise water distribution across the basins is influenced by factors like land use, prevailing cropping patterns, locations of water applicants, and water usage timing (Du et al. 2022). There is limited availability of water resources in many arid region and semi-arid regions, which influences the potential demand for it.

It is a need of the 21st century to estimate and understand the water metrics and how to manage it sustainably. Most water resource projects are influenced due to climate change (Dovie & Kasei 2018). Therefore, throughout the globe, researchers are working on water budgeting by quantifying the water by taking into account different water users like domestic, industrial, agricultural, and public use (Ridoutt et al. 2009, Vairavamoorthy et al. 2008). Use of hydrologic models like ArcSWAT (Sabale et al. 2023, Sabale & Jose 2021, 2022, 2023), MODFLOW (Abdalla 2009, Baalousha 2016), MIKE (Kaleris & Langousis 2017) and HEC-RAS with accurate data sets proves very efficient in hydrological modeling. These GIS-based Agro-hydrological models required the following data as inputs: meteorological data, socio-economic data, Infrastructure and technological data, and agricultural information to quantify the availability of water in the study basin.

The cropping pattern and water usage at one sector affect the water consumption and outputs from another sector, e.g., the water discharge downstream of the river is decreased by irrigation along river basins. Although the water resources are overwhelmed due to climate change and over-demand from different water users, such minute approaches will aid in the sustainable development of water resources. The heuristic rainfall-runoff models are formulated by (Oki et al. 2001) to better understand and simulate the changes in water use caused by anthropogenic activities. Through numerical simulations and testing of different management scenarios, the computing power of those models allows users to better understand and estimate the attributes of water resources (Ninija Merina et al. 2019). Users can evaluate the hydrological relationships in river basins using these numerical models, which combine several empirical equations and fundamentals of science (Neitsch et al. 2002, 2005).

The most precise and practically applicable way to predict water availability and its distribution in the study basin under various demand and operating scenarios is to use hydrologic models. SWAT model, which is an agro-hydrological, process-based, and semi-distributed model, is used to represent both runoff generation processes and their influence on the hydrology of the study area. Authors have tried these models to correlate water use and water availability to ascertain the long-term effect of an environmental change on the hydrologic response of the basin (Liu et al. 2013, Neitsch et al. 2002, Saraf & Regulwar 2018).

This study aims to predict the volume of water available in the Yeralwadi catchment using the SWAT hydrological model. The meteorological data to process the SWAT model was taken from the India Meteorological Department (IMD). Also, the available observed hydro-meteorological data from the HDUG group was used to correct and validate the SWAT model. The outcomes of this work will provide information to researchers, decision-makers, and water policymakers about the water resources in the Yeralwadi catchment, as well as to adapt the best practices (BMPs) for boosting sustainable agricultural output and ensuring food security.

MATERIALS AND METHODS

Materials Used

The present work is devoted to ascertaining the application of the ArcSWAT model for the estimation of water availability at the Yeralwadi basin of Khatav taluka of Maharashtra in India. The selected study area is almost dry and semi-arid, as declared by CGWB, with issues like water scarcity, secondary soil salinization, and waterlogging in a few places. By processing the SWAT, authors are interested in estimating the water available, and according to that, irrigation scheduling and best management practices for the acceleration of sustainable development of water resources are suggested.

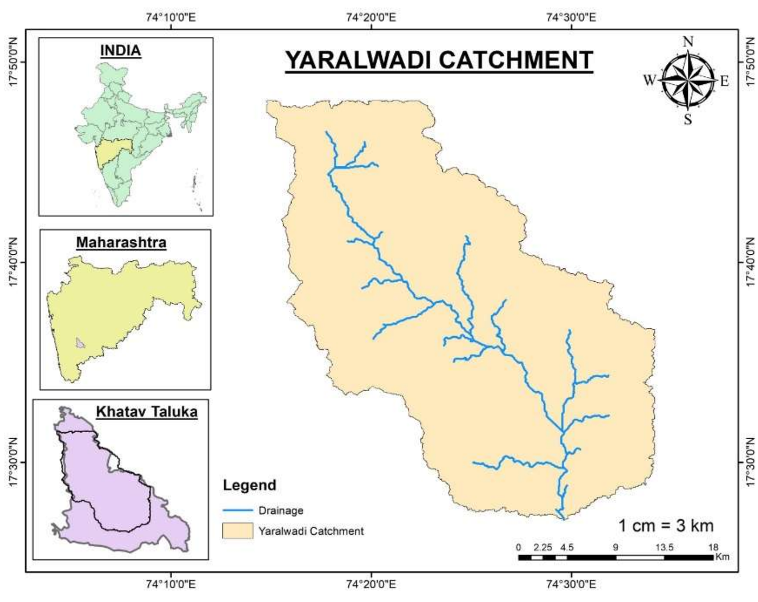

Fig. 1: Index map of the study area.

Study Area

Fig. 1 shows an index map of the study area, i.e., Yeralwadi catchment, which is located in Khatav taluka (17.5279° N, 74.4893° E) of Satara district in the state of Maharashtra. Khatav taluka is a semi-arid region and measures geographically 1358 sq. km. In the present work, the SWAT model was processed on a 790 sq. km area. Yerala River is one of the major tributaries of the Krishna River flowing through the study basin. The study area receives an average annual rainfall of 560 mm (CGWB 2017). Moreover, the average temperature ranges from 13°C to 40°C, and the average wind speed observed in the study area is 7 $Km.hr^{-1}$. In general, the topographical distribution of the Yeralwadi catchment is characterized by moderate flatlands with slopes ranging from 0% to 3%, 3% to 15%, and more than 15%, representing 18.22%, 73.73%, and 8%, respectively.

The land use of the study area comprises maximum agricultural use, and most of the land is barren. The prevailing crops observed in the study area are Paddy, Jowar, Soyabin, and Sugarcane. The Ner Dam, Yeralwadi Dam, and Mayani Lake are prominent surface water sources in the study area.

Input Data Formulation

Digital elevation model (DEM): To process SWAT, the inputs are provided as meteorological data, digital elevation model (DEM), Soils, and Landuse Land cover details. The meteorological data for the period 2000 to 2020 was taken from IMD and NASA websites. The daily data like rainfall (mm), maximum and minimum temperature (°C), relative humidity (%), wind speed ($Km.hr^{-1}$), and solar radiation were collected for Ambavade (Khatav) station. The Digital Elevation Model (DEM) for the Yeralwadi area was taken from the USGS database with 30 m resolution (Fig. 2). The soil map was prepared by using FAO soils, and Landuse map was processed using the image classification tool in ArcSWAT with the maximum likelihood option. The Landsat-8 images are used for 2018-2019 to process the LULC map.

Land use (LULC) map: This map depicts the physical characteristics and usage of the basin, like forest area, built-up, and barren land. It describes how the area is being used (Fig. 4). In this work, to process the SWAT model, the LULC data for (2018-2020) was downloaded from the earth-explorer website, and the precaution has

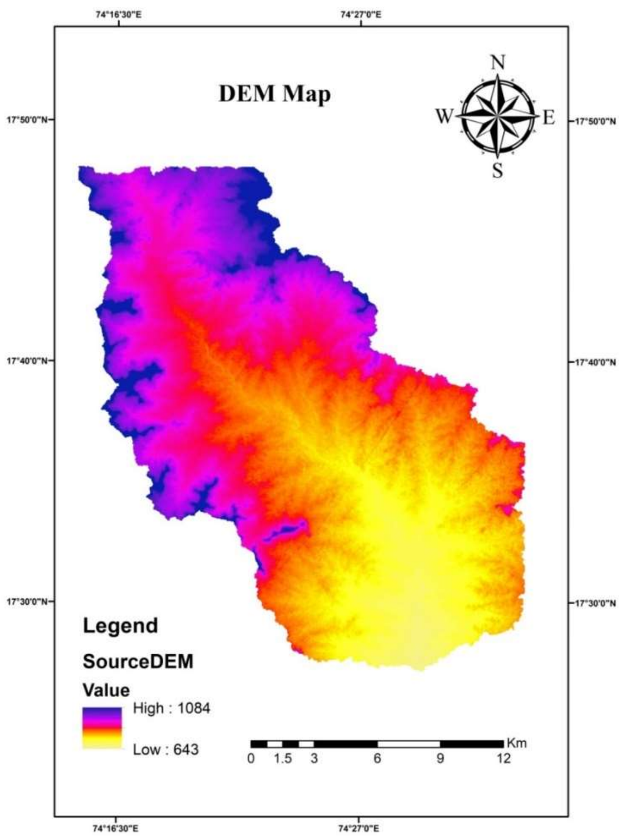

Fig. 2: Digital Elevation Model (DEM).

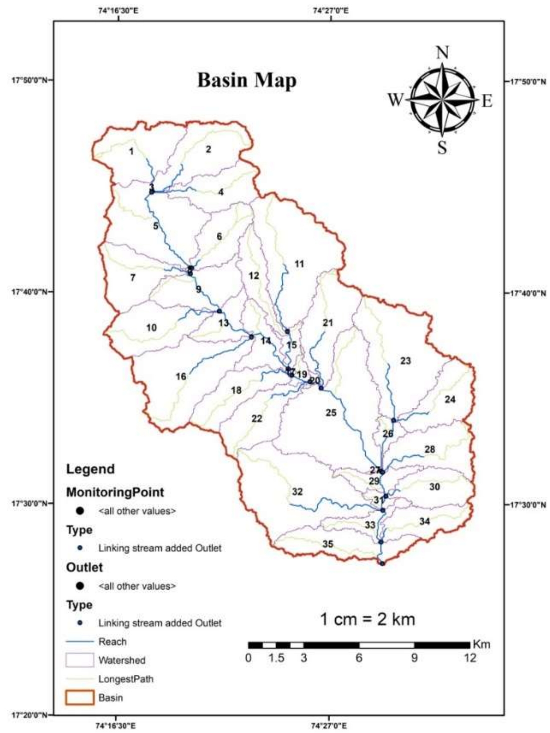

Fig. 3: Basin map.

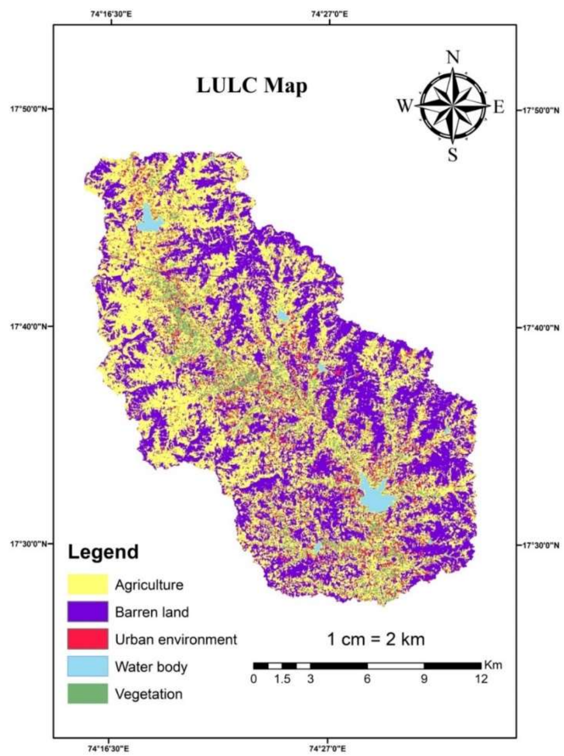

Fig. 4: The LULC map.

Table 1: Land use details of the study area.

LULC Details	Area [ha]	% Watershed Area
Agriculture	37824.67	48.50
Barren Land	30077.14	38.57
Residential low density	4829.70	6.19
Water	961.40	1.23
Forest	4293.72	5.51

been taken that selected data having clouds less than 10%. For the present work, the land use land cover map for the Yeralwadi basin was formulated using image classification in ArcSWAT-2012 and using Landsat-8 imagery. In the present work, the Land is being used as agricultural land 48.50%, Barren land 38.57%, Water bodies 1.23%, dense Forest 5.51%, and Low density residential built area 6.19% (Table 1). From LULC attributes, it is observed that such land use land cover is more vulnerable to soil erosion, and the reservoirs downstream are more susceptible to siltation.

Soils in the study area: Highly accurate soil data are more important to process the SWAT model (Stadnyk & Holmes 2023). The SWAT Model has built information on soils from the world and Indian continents. In the present work, the soil data was taken from the Soil Survey Department of India (NBSSLUP) to a scale of 1:250,000 (Kumar et al. 2015). The soil data was accessible in a detailed format, and that gives the soil texture profile. Then, in the SWAT model, it was digitized for further processing (Dutta & Sen 2018). Fig. 5 depicts the soil types found in the study region. The four types of soil were found in the study area. Table 2 shows the percentages of soil.

Methodology Adopted

In this work, the semi-distributed model SWAT, which the US Agriculture Research Department developed, was used (Arnold et al. 1998, Kim et al. 2008, Neitsch et al. 2002). The SWAT is a GIS-based, semi-distributed, physical model that simulates the rainfall-runoff process and also predicts the hydrological parameters (Eini et al. 2023). The SWAT model is highly efficient, and it is capable of running over a long period. The model uses

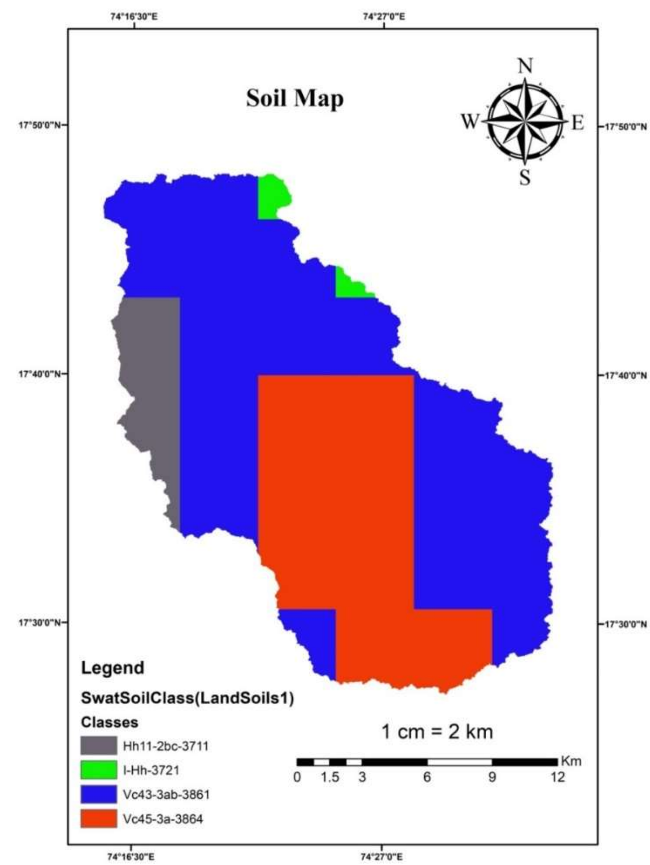

Fig. 5: Soil map.

GIS-based information like digital elevation. Land uses land cover (LULC) of the study area, climate data, and soil data to process and yield simulated results in terms of water available, loss of water, transportation of nutrients and pesticides, etc. The basic principle that governs the SWAT model is as given below (Eq. 1) (Jajarmizadeh et al. 2017),

$$SH_t = S_0 + \sum_{i=1}^{t}(P_{day} - R_{Surf} - Q_{Seep} - E_0 - Q_{gw}) \quad \ldots(1)$$

Where,

SHt = soil humidity (mm), S_0 = soil base humidity (mm), t = Time period (days), P_{day} = Precipitation volume (mm), R_{surf} = surface runoff, E_0 = evapotranspiration (mm), Qseep = seepage of water from the soil into deep layers, Qgw = underground runoff (mm).

SWAT Model

ArcSWAT - 2012 version was used to set up the surface water model (Fig. 6). In the first step, using digital elevations, the whole study area is delineated into the number of sub-basins. The delineation process provides the information as sub-watersheds, main reach, lateral reach, and slope (Fig. 3). The sub-basins are again divided into smaller homogenous units called HRU (Hydrological Response Units) (Santhi et al. 2001). The HRUs are smaller portions having unique slopes, types of soil, and land use patterns. In the present study, after delineation, the catchment is divided into 35 sub-basins (Fig. 3) consisting of 196 HRUs. The four types of soil were found in the catchment, as given in Table 2.

The model's performance statistics were reviewed, and using water balance ratios, the water availability of the catchment was calculated.

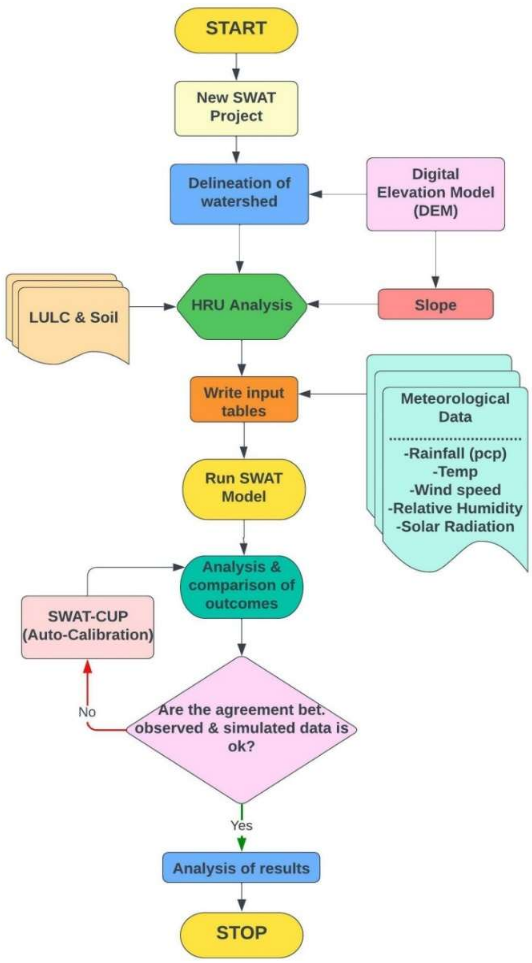

Fig. 6: Flow chart-SWAT Model.

Table 2: Detail of Soils.

Sr. No.	Class of Soil	Name of Soil	% of Soil
1.	Hh11-2bc-3711	Clay_Loam	7.3%
2.	I-Hh-3721	Loam	1.2%
3.	Vc43-3ab-3861	Clay	58.07%
4.	Vc45-3a-3864	Clay	33.30%

Calibration of SWAT

The calibration of the model consists of the systematic approach to adjust the model's parameters until the results show good agreement with observed field data (Zomorodian et al. 2017). Eq. (2) presents the calibration of the SWAT model (Beven 2006) (Fig. 7).

$$q(x,t) = M(\Theta,x,t) + \varepsilon(x,t) \quad \ldots(2)$$

Where,

q(x,t)- Volume of flow at time 't'

M (Θ,x,t)- Volume of flow at different parameters

ε (x,t)- error at a specific time.

Both manual and automatic calibration was carried out, with the parameters adjusted as necessary to fit the data collected (Guzman et al. 2015). The SWAT CUP tool was used for the calibration of the SWAT model with the SUFI-2 algorithm. Multiple iterations were performed to re-adjust the parameters to best match the observed values. The SWAT model was calibrated by using observed stream flow data from the year 2003 to 2012. However, the SWAT model is capable of a two-way calibration-validation and is reliable in modeling watersheds in the tempo-spatial aspect (Grusson et al. 2017, 2018). As a result, the calibration period of 2003–2012 was chosen, and it was contrasted with the same period of river flows. The R^2 value for calibration was observed at 0.80, and NSE was 0.72.

Validation of SWAT

After the calibration process, SWAT model validation involves putting the calibrated model to the test by observed field data (a few set of data that is not utilized in the calibration process) with the model predictions while maintaining the values of all input parameters (Moradi-Jalal et al. 2007). In the present work, to validate the model, the discharge data from the years 2013 to 2016 were used (Fig. 8). The R^2 value obtained during validation is 0.76, and NSE was 0.80.

RESULTS AND DISCUSSION

The following hydrological parameters (Table 3) were assessed to ascertain their sensitivity during the calibration and validation process. After trial and error, it was observed that the CN II, i.e., initial Soil Conservation System Number, SURLAG, and ESCO (The soil evaporation compensation factor) were highly sensitive parameters as their rank is higher. Initially, CN II was given by model was 90, but after the calibration process, CN II was best fitted to 78. The ESCO, EPCO, ALPHA_BF, SLSUBBSN, and groundwater delay time (GW_DELAY) these factors significantly affect the calibration process.

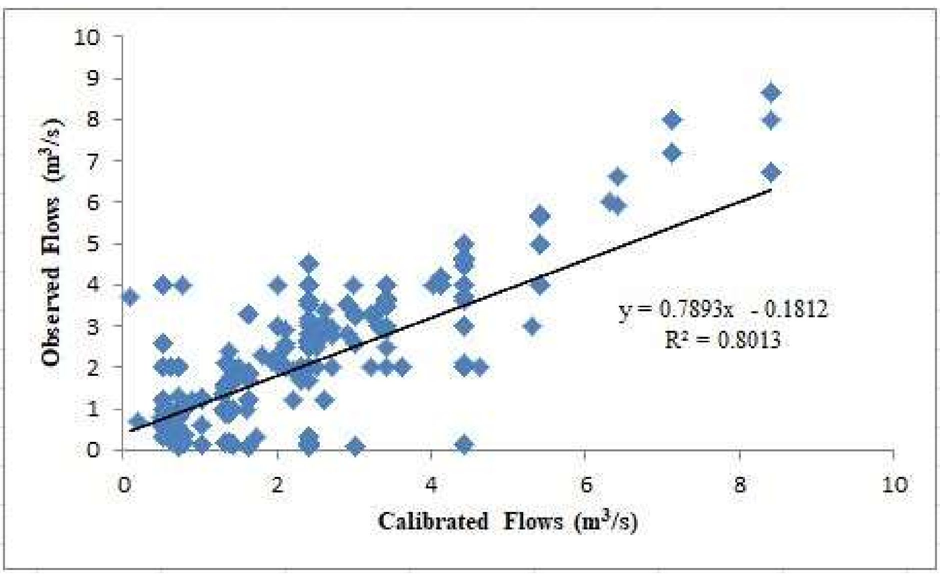

Fig. 7: Calibration of SWAT Model.

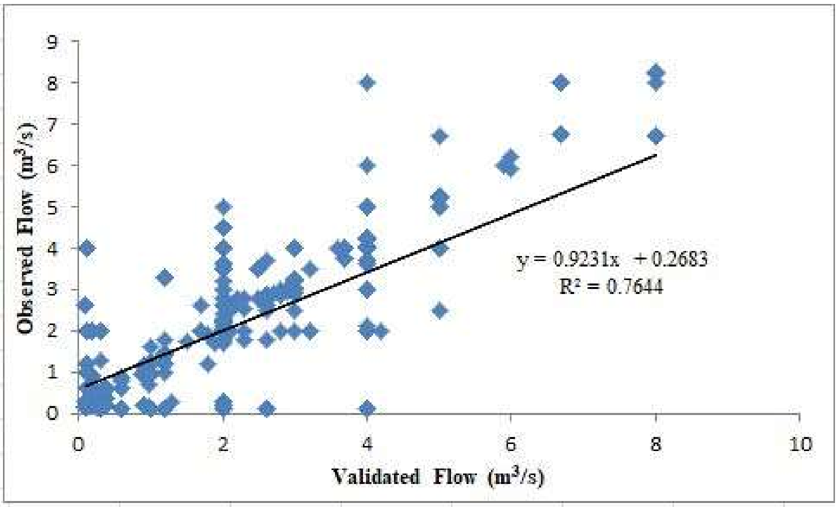

Fig. 8: Validation of SWAT Model.

Hydrology of Study Area

Fig. 10 shows the hydrological presentation of the study area. The average actual evapotranspiration of the study area is 398.4 mm, and precipitation is 978 mm. Table 4 explains the hydrological parameters in the calibration and validation process. The surface runoff from the basin was observed as 403.46 mm. The results show that the total sediment yield from the basin was 64.3 $x10^5$ $ton.ha^{-1}$ for the period of (2010-2020). Moreover, the sub-basins numbers 33, 34 & 35 are more prone to soil erosion & they must be treated for control of soil erosion.

Model Performance

For the present work to carry out calibration and validation, the SWAT-CUP tool with the SUFI II algorithm was used. Statistical parameters like NSE (Nash-Sutcliffe efficiency) and coefficient of determination (R^2) (Eq.4) were used to check the sensitivity of the work. The NSE is a widely used tool to determine the residual variance of hydrological models, and its formula is given by Eq.(3),

$$\text{NSE} = 1 - \left\{ \frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2} \right\} \quad \ldots(3)$$

Table 3: Ranges of parameter and their values used in the sensitivity analysis.

Abbreviations	Details of Parameters	Range	SWAT Values	Final Values
ALPHA_BF.gw	Baseflow factor (days)	0-1	0.045	0.01
CN.mgt	Initial SCS CN II value	35-98	90.97	78
ESCO.hru	Soil evaporation compensation factor	0-1	0.94	0.4
GW_DELAY.gw	Groundwater delay (days)	0-500	41	41
GWQMN.gw	Depth of water in the shallow aquifer	0-5000	1200	1280
REVAPMN.gw	Threshold depth of water in the shallow aquifer for “revap” to occur (mm)	0-1000	740	856
SURLAG.hru	Surface runoff lag time in the HRU (days)	0.05-24	3	0.5

Table 4: Assessment of hydrological parameters.

Parameters	Values in Calibration [mm]	%	Values in Validation [mm]	%	Average	%
Rainfall	978.7	100	992.3	100	985.5	100
Evapotranspiration	398.4	40.7	412.3	41.6	405.35	41.15
Lateral Flow	3.3	0.3	4.1	0.4	3.7	0.35
Surface Runoff	403.46	41.22	421.6	42.48	412.53	41.85
Deep Aquifer recharge	8.66	0.8	6.98	0.7	7.82	0.75
Shallow Aquifer storage	173.14	17.6	159.36	16.1	166.25	16.85
Return Flow	140.72	14.31	124.36	12.5	132.54	13.40

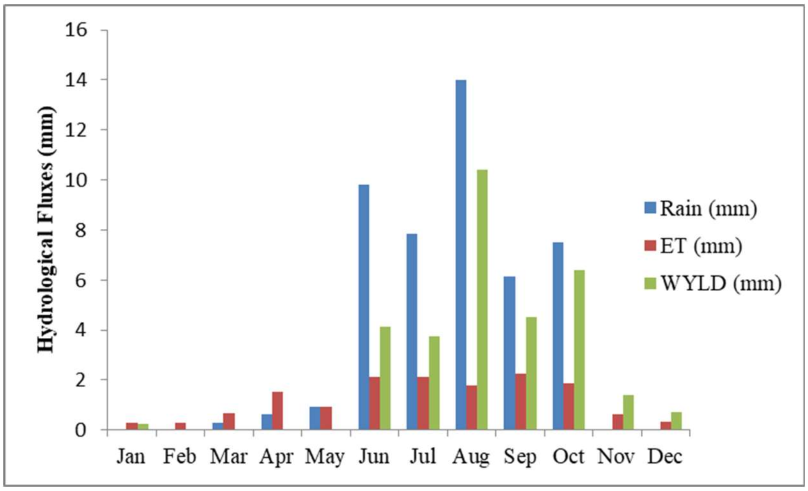

Fig. 9: Water budget.

Where, Y^{obs}= Observed data

Y^{sim} = Simulated data and Y^{mean} = Mean observed data

$$R^2 = \frac{\left[\sum_{i=1}^{n}(Oi-\overline{O})(Pi-\overline{P})\right]}{\sum_{i=1}^{n}\left[(Oi-\overline{O})\sum_{i=1}^{n}(Pi-\overline{P})^2\right]} \quad \ldots(4)$$

Water Budget

In the water budgeting of the study basin (Fig. 9), the SWAT model is calibrated and validated; the outputs of water balance are presented in (Table 5). The findings show that there is no significant variation between the two models.

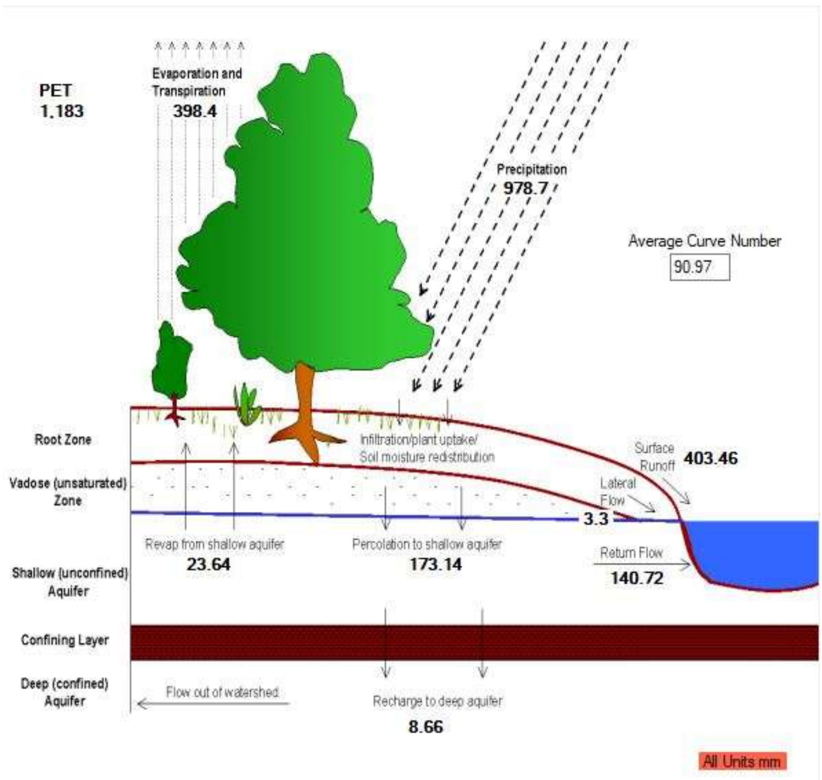

Fig. 10: Hydrology of the study area.

A few previous works (Moriasi et al. 2007) used both calibrated and verified data in their analysis and found that the results were not significantly different. The Yeralwadi area has an annual rainfall of about 978 mm. The major loss of water happens in terms evapotranspiration process and is one of the highly influencing hydrological components that accounts for 400 mm of water, i.e., 40.07% of total rainfall. The previous work (Kaleris & Langousis 2017, Kumar et al. 2015) has estimated the rate of evapotranspiration as the highest component within the catchment responsible for water loss. Moreover, the reasons for this higher loss are prevailing high temperatures, low precipitation, and low relative humidity trends.

Finally, the yearly total discharge was calculated to be 544.18 mm, or 55.6% of the annual precipitation (41.2% from surface runoff and 14.4% from baseflow). Moreover, the estimated percolations of the shallow and deep aquifers were 173.14 mm and 8.66 mm, or 17% and 0.8% of the annual precipitation, respectively. It was observed that despite a decade and separation of time between the calibration (2003-2012) and validation (2013-2016), the outcomes showed that the basin properties had not changed appreciably over more than a decade, as depicted in Fig. 10.

Available Water

The findings indicate that evapotranspiration accounts for around 40.07 % of the catchment's water loss. The remaining percentage is divided between the percolation tank and outflow (surface runoff, lateral flow, and return flow). By comparing the discharge metrics (Table 5), the surface runoff from the basin is greater than 40%. Moreover, the maximum rainfall was observed in July & August, which yields a high volume of runoff as maximum soil gets saturated, as shown in the hydrograph (Fig. 9), which aids the flood situation in the study basin. This scenario shows that there is a higher possibility that basin water users rely on surface runoff by storing excess water at the time of high flood season and utilizing it in the water deficit period.

The amount of water that percolates into the soil depends on its water-bearing capacity. It is crucial for calculating the amount of soil water that may be used to replenish aquifers. Around 173.14 mm means 17.69% of total rainfall volume is going to infiltrate shallow aquifers, and about 1% is added to deep aquifers. The shallow aquifer recharge is divided into 14.3% water loss as return flow that feeds the basin outlet. So, it is observed that the water table is at a low level, which holds a sufficient volume of water that can be utilized for irrigation. This scenario is validated by taking wells in shallow aquifers.

Table 5: Performance indicators used.

Statistical Parameters	During Calibration	During Validation
Coefficient of Determination (R^2)	0.80	0.76
Nash-Sutcliffe Efficiency (NSE)	0.72	0.80

Monthly average values for a few hydrologic components were calculated and are shown in Fig. 7. The rate of evapotranspiration progressively rises as seasons get wetter. During the dry season, it falls gradually. It also showed that the Yeralwadi catchment has a high water yield.

CONCLUSIONS

In current research work, the SWAT model was processed to estimate the surface water available in the Yeralwadi basin. The simulation work shows good statistical values for the Nash-Sutcliffe Efficiency (NSE > 0.8) and correlation coefficients R^2 (0.80) (Table 5). The model's performance was satisfactory (Table 6). The findings significantly increased our understanding of the water availability in the watershed, especially the surface runoff and the percolation tank. The shallow aquifer (depth up to 80 Feet) contains more water, which may be acquired for use with less input cost during the dry season. The findings also demonstrated the possibility for surface runoff that made up the majority of the total flow to be captured in well-designed water harvesting structures such as dams and ponds that may be used for irrigation and a variety of other uses during the dry seasons. Also, the SWAT model is able to estimate the sediment load transported from the basin, so vulnerable basins for soil erosion are also identified by SWAT.

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Table 6: Values/range of statistical parameters. (Moriasi et al. 2007, Nash & Sutcliffe 1970).

Performance ratings	NSE	R^2	Percentage bias [%]	
			Sediment	Flow
Very good	0.75-1	0.75 -1.00	< ± 15	< ± 10
Good	0.65-0.75	0.65-0.75	± 15 to ± 30	± 10 to ± 15
Satisfactory	0.50-0.65	0.50-0.65	± 30 to ± 55	± 15 to ± 25
Unsatisfactory	< 0.50	< 0.50	> ± 55	> ± 25

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