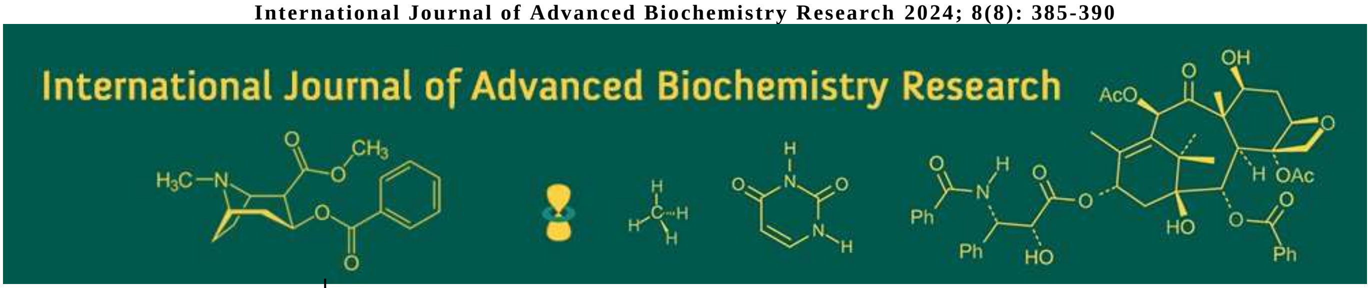

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Assessment of surface water availability in Arjuna river basin using ArcSWAT

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Abstract

The present investigation was to study water availability in Arjuna River basin of Ratnagiri District of the Maharashtra state utilizing the ArcSWAT model, an advanced tool for hydrological simulation. The study encompasses the collection and analysis of extensive historical meteorological and hydrological data, aiming to understand the dynamics of surface water availability across different seasons and from 1996-2016 with the model undergoing rigorous calibration and validation processes to ensure accuracy. Employing the ArcSWAT model for hydrological simulation, the research aims to understand the intricate dynamics of water availability and its distribution across the basin, essential for strategic planning and sustainable management. The entire basin was divided into 8 subbasins, each further subdivided into 294 hydrological resource units (HRU) based on land use, land cover and topography. ArcSWAT underwent calibration and validation, including a 3-year model warm-up period. Output data covered a span of 21 years from 1996 to 2016. Calibration occurred from 1996 to 2003, followed by validation from 2007 to 2012. The ArcSWAT model demonstrated statistically promising results in hydrological simulations, with R^2 values of 0.78 for calibration and 0.67 for validation, indicating satisfactory performance in replicating monthly runoff values. NSE values of 0.75 for calibration and 0.65 for validation, as well as RMSE values of 0.50 for calibration and 0.60 for validation, further confirmed the model's effectiveness.

Keywords: ArcSWAT, water availability, hydrological components

Introduction

The two most crucial natural resources for crop production worldwide are land and water. Throughout their life cycle, plants require water to survive continually, while soil supplies the necessary nutrients and physical support. These resources are crucial for economies that depend on agriculture. India being an agrarian economy, where 54.6 per cent of the population directly depends on agriculture, is highly vulnerable to the impacts on water and land resources (Mehla *et al*., 2023) [7]. Serious effects on agriculture and related industries are caused by temperature change, variations in precipitation and the increased frequency of extreme events they bring about, land degradation, and rising sea levels. As temperatures rise, variations in rainfall are making water resources in western India's semi-arid regions more vulnerable (Fang *et al*., 2019) [2]. Severe droughts are caused by an increase in dry spell events and abrupt monsoon changes (Ma *et al*., 2019) [6]. High temperature and seasonal water scarcity have detrimental effects on agriculture's output and, eventually, the nation's food security. The region's vulnerability and land resource availability are the primary determinants of the agriculture field's sustainability (Fitton *et al*., 2019) [3]. Because of the growing population, pressure on land resources is expanding quite quickly Area under agriculture in many parts of the country is reducing day by day due to stiff competition of different stake holders (Pandey and Ranganathan, 2018) [9]. For appropriate and prudent planning and management of water and land resources to maximize economic returns per unit area, more precise knowledge on their availability and implications is needed. Conventional techniques for evaluating these natural resources are incredibly labor-intensive, time-consuming, and expensive. Now a day's geographical information system is one of the recent proven technologies for site specific assessment and planning of water and land resources. Numerous hydrological models are combined with this technology to simulate and evaluate the land and water resources in the study area.

Numerous hydrological models, including MODFLOW, HEC-HMS, HEC-GEOHMS, HEC-WMS, HEC-RAS, WEAP, AGNPS, HYDRUS, HATWAB, and SWAT, are available and can be used with a GIS interface. Among these are Texas A&M University, the USDA's Agricultural Research Service, and the GIS interface For basin-scale studies, the SWAT model is more dependable and useful (Gassman *et al*., 2014) [4]. With appropriate calibration and validation, this tool is widely used for a variety of tasks including crop planning, water budgeting, water quality analysis, water and land resource evaluation, and many more (Aloui *et al*., 2023) [1].

Study Area

The Arjuna River rises in the Sahyadri hills, near to Barki village in the Shahuwadi tehsil of Kolhapur District, at a height of 1000 meters above mean surface level. It is a tributary of the Kodawali River, which finally empties into the Arabian Sea after flowing westward. The confluence of the Arjuna river with the Kodawali river occurs at Rajapur in the Ratnagiri district of the Konkan region. The Arjuna River basin spans from latitude 16° 76' N to 16° 66' N and longitude 73° 83' E to 73° 84' E.

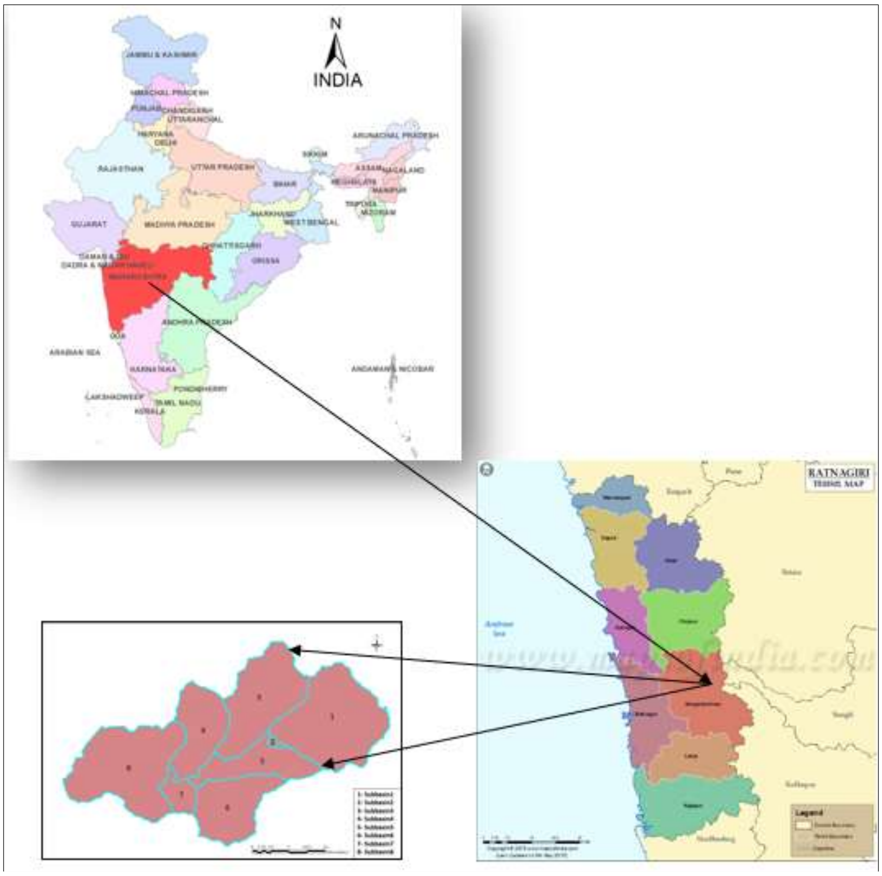

Fig 1: Location map of study area

Methodology

The ArcSWAT model was used in the current study to analyze water availability of the Arjuna River basin. Compatible raster/vector datasets (such as shape files and feature data) and database files in SWAT's standard formats are required for the database creation of the SWAT model. In order to assess the hydrological processes, the SWAT model needs four different types of datasets: soil, topographical, hydro-meteorological, and land use/land cover (LULC). In the present study data were procured from various sources.

Data Collection and model setup

The ArcSWAT model workflow comprises two major steps: ArcSWAT input data and ArcSWAT operation. A detailed workflow is illustrated in Figure 2.

ArcSWAT input data Land use/ Land cover (LULC) data

The land use and land cover data (2012) for the Arjuna River Basin were obtained from the Regional Remote Sensing Service Centre, Nagpur, Maharashtra. The map was projected to WGS1984 UTM Zone 43N using raster projection in ArcMap 10.3 before being imported into ArcSWAT. The LULC map of Arjuna River basin is shown in Figure-3.

Soil data: The soil data for the Arjuna River basin was obtained in the shapefile format at a scale of 1:50,000 from the Regional Remote Sensing Service Centre (RRSSC), Nagpur, Maharashtra. Subsequently, the soil map underwent projection to WGS1984 UTM Zone 43N using raster projection in ArcMap 10.3 before being imported into the ArcSWAT model. Additional hydrological attributes, such as porosity and saturated hydraulic capacity, were computed using the SPAW model. Layer-wise soil data for each soil type was then integrated into the ArcSWAT user soil databases. The Soil map of Arjuna River basin is shown in Figure-4.

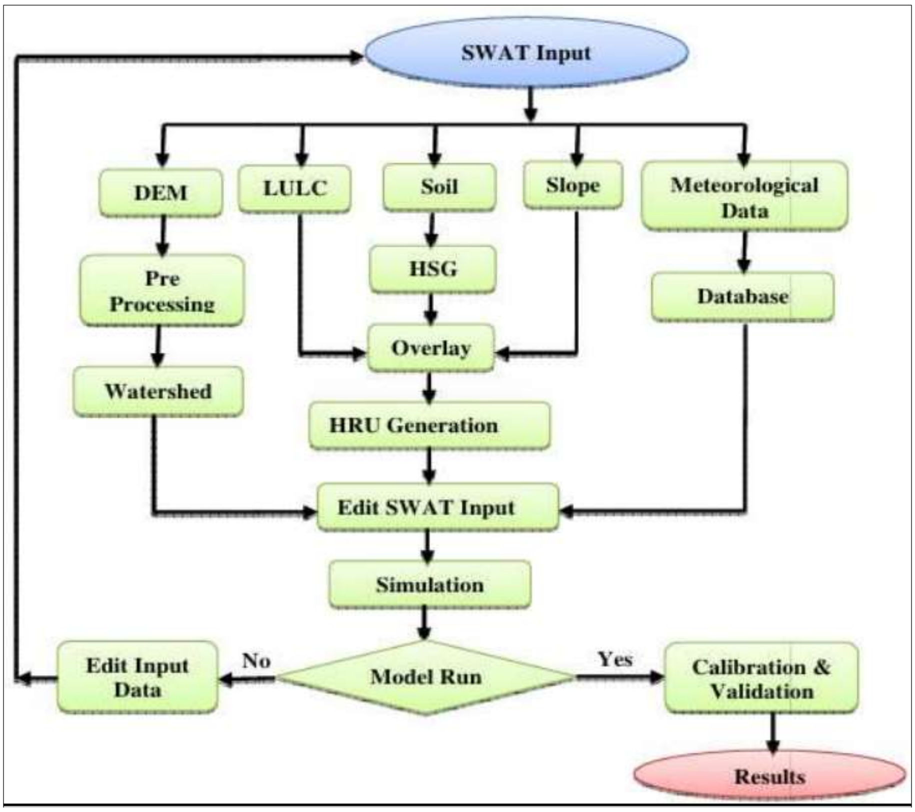

Fig 2: Flow chart of SWAT operations

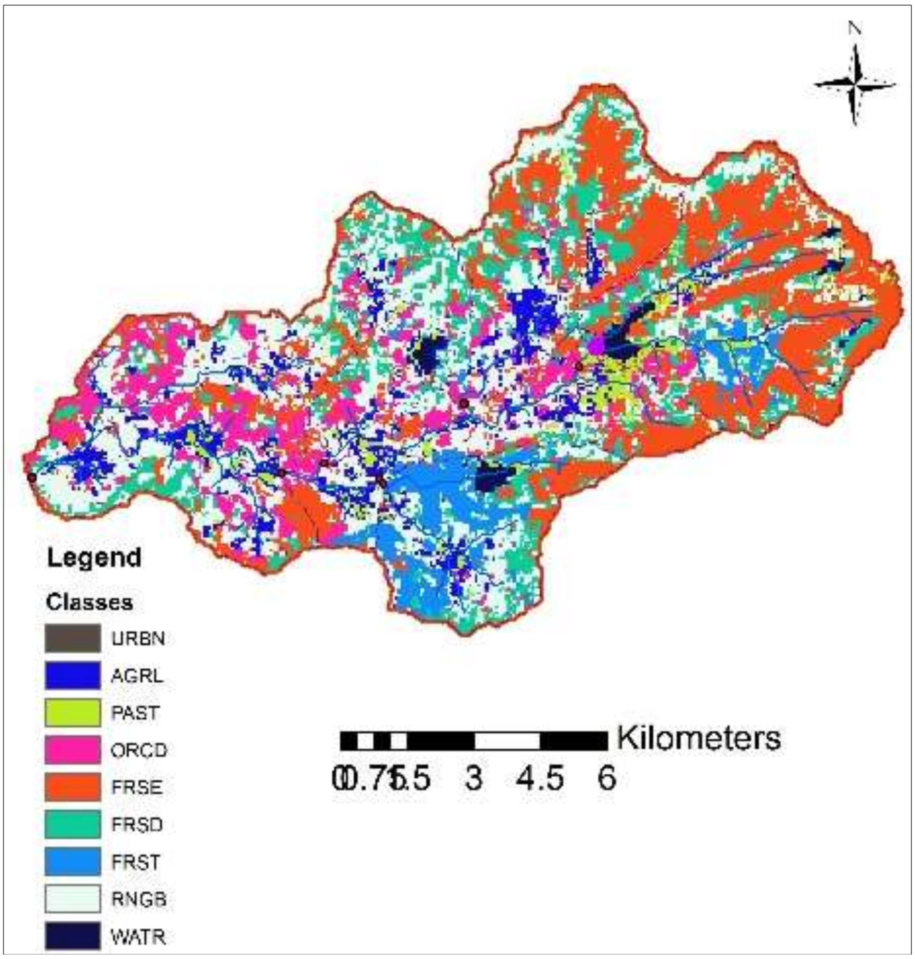

Fig 3: Land use/Land cover map of Arjuna River basin

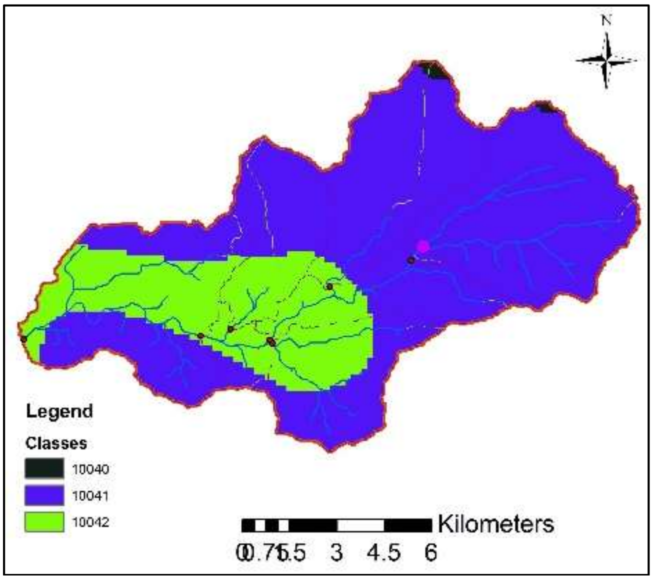

Fig 4: Soil map of Arjuna River basin

Meteorological data

For this study, a 31-year daily meteorological dataset (1985 to 2016) such as rainfall (mm), maximum and minimum temperature (^{0}C), maximum and minimum relative humidity (%), sunshine duration (hrs) and wind speed (km/hr) was obtained from the Karak station (Latitude: 16° 43' 7" N, Longitude: 73° 46' 13" E) within the Arjuna River basin. This data, sourced from the Water Resources Department, Hydrology Project, Nasik, Government of Maharashtra. In this study, 21 years meteorological data was used i.e from 1996 to 2016 for input of ArcSWAT model.

Water balance in basin

In this study, the ArcSWAT was utilized to simulate and analyze various components of the water balance within the Arjuna River basin. These components include evapotranspiration, surface runoff, baseflow and total precipitation. Each element plays a crucial role in understanding the hydrological dynamics and water availability in the area. Below is a detailed explanation of each component.

Total precipitation

The total precipitation is the sum of all forms of precipitation (Rain, snow, sleet, etc.) that fall over a specified period. It serves as the primary input in the water balance equation and is critical for initiating the hydrological processes within the watershed. In the Arjuna River basin, precipitation predominantly occurs as rainfall, a characteristic feature of the region's climate.

Surface runoff

ArcSWAT calculates surface runoff using the Soil Conservation Service (SCS) Curve Number method, which takes into account land use, soil type, and antecedent moisture conditions.

Evapotranspiration (ET)

ArcSWAT estimates ET using several methods, including the Penman-Monteith equation, which considers factors like temperature, solar radiation, wind speed, and relative humidity.

Baseflow

ArcSWAT simulates baseflow using a recession constant that models the rate at which groundwater contributes to river flow, based on the physical properties of the watershed. Baseflow is a crucial component for the continuous support of aquatic ecosystems and for providing a stable water supply.

Integration of components into water balance

ArcSWAT calculates the water balance by using equation 1 as follows, (Neitsh *et al*., 2009) [8].

$$SW_t = SW_0 + \sum(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad (1)$$

Where,

SW_t is the final soil water content, mm
SW_0 is the initial soil water content, mm
R_{day} is the precipitation, mm
Q_{surf} is the surface runoff, mm
E_a is the evapotranspiration, mm
W_{seep} is the water entering the vadose zone, mm
Q_{gw} is the return flow or baseflow, mm

At the HRU level, which is the smallest spatial unit in SWAT, the water balance equation includes additional components, such as groundwater flow from upland HRUs and lateral flow contributions (Terskii *et al*., 2019) [10].

Results and Discussion

Assessment of surface water availability in Arjuna River basin

The ArcSWAT model was calibrated, validated and subsequently applied to the Arjuna River basin to evaluate surface and groundwater availability along with their seasonal variations. Prior to its application in the basin, the hydrologic model underwent calibration and validation processes. Adjustments to simulated stream flow observations were made to fine-tune the model output and improve the model efficiency. The analysis obtained after running the SWAT model was river flow availability of the Arjuna River basin.

Subbasin-wise monthly river flow availability of Arjuna River basin

The analysis of subbasin wise monthly mean of river flow in the Arjuna River basin, as presented in Table 1, reveals notable variations throughout the year.

Particularly, heightened river flow is evident during the rainy months of June, July, August and September, predominantly driven by rainfall. The heavy monsoon accumulated in the form of the river flow in Arjuna River basin. Similar observed were reported by the Mohapatra and Mohanty, 2005 [11] in Odisha due to the intense rainfall and the rainfall is particularly intense in July and August and is often associated with low pressure systems developing over the Bay of Bengal, leading to increased river flow. Khalid *et al*., 2018 [5] in upper Indus basin found high river flow due to intense and abnormal rainfall patterns in the Upper Indus Basin region, particularly during the months of July, August and September.

Table 1: Subbasin-wise monthly river flow (Cumec) availability of Arjuna River basin

Month	Sub-basin1	Sub-basin2	Sub-basin3	Sub-basin4	Sub-basin5	Sub-basin6	Sub-basin7	Sub-basin8
January	0.20	0.00	0.11	0.08	0.18	0.10	0.39	0.57
February	0.07	0.00	0.04	0.02	0.05	0.03	0.10	0.14
March	0.06	0.00	0.04	0.02	0.05	0.02	0.10	0.13
April	0.05	0.00	0.04	0.02	0.05	0.02	0.09	0.12
May	0.22	0.00	0.18	0.11	0.28	0.11	0.52	0.73
June	6.75	13.02	5.21	3.32	21.03	3.57	28.81	35.60
July	12.95	38.72	9.75	6.27	53.76	6.87	68.63	81.64
August	9.59	27.90	7.15	4.60	38.93	5.06	49.87	59.43
September	5.49	14.01	4.03	2.57	20.21	2.85	26.36	31.72
October	2.84	5.61	2.02	1.29	8.71	1.46	11.83	14.55
November	1.12	0.38	0.73	0.48	1.51	0.59	2.73	3.80
December	0.57	0.06	0.36	0.24	0.61	0.30	1.23	1.76

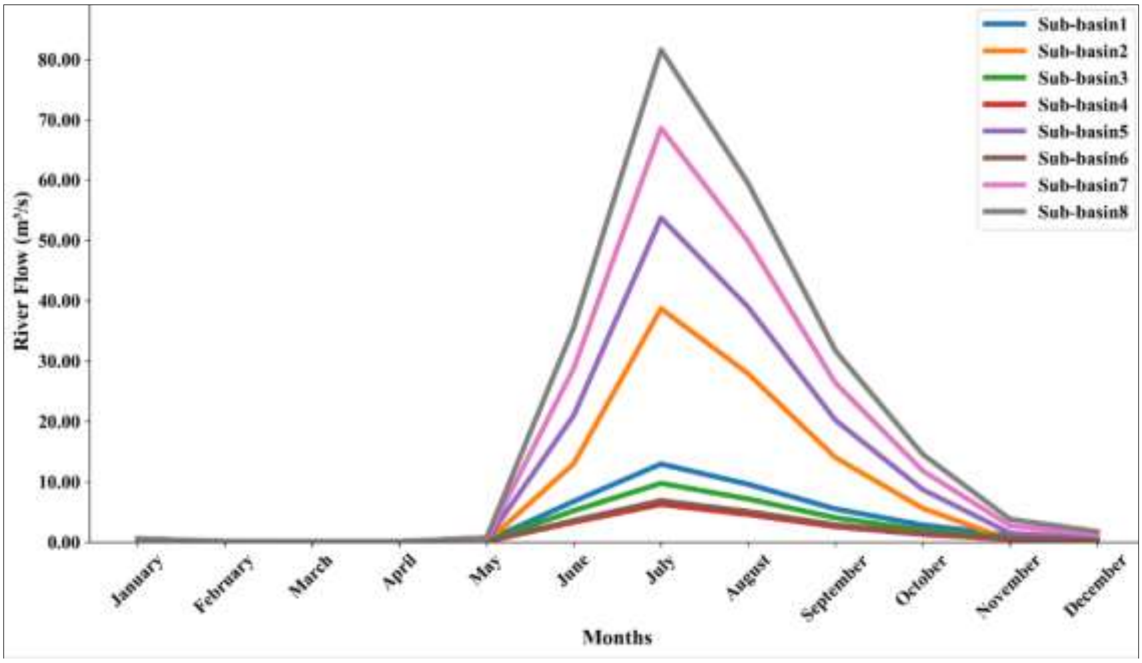

Fig 5: Monthly river flow in subbasins of Arjuna River basin

From Fig 5, it becomes apparent that July consistently witnesses the highest river flow across all subbasins within the Arjuna River basin because of the high rainfall received during this month. Notably, Subbasin1, situated in the upper reaches of the basin and contributing runoff to the Arjuna Dam, demonstrates substantial river flow during these peak months. Conversely, Subbasin2, representing the outlet of the Arjuna Dam, indicates minimal river flow as it primarily stores runoff from the upstream watershed. The minimal flow at Subbasin2 (Arjuna Dam outlet) in peak months reinforces the importance of the dam in capturing the intense but short-lived monsoon runoff. Analyzing its storage capacity relative to basin-wide demands could reveal potential for additional reservoirs to enhance water security.

Furthermore, an observable trend emerges wherein river flow increases along the trunk order stream from Subbasin1 to Subbasin8, correlating with the expanding contributing area towards the outlet point of Subbasin8. However, Subbasins 3, 4 and 6 exhibit comparatively lower river flow compared to their upstream counterparts along the mainstream. Throughout the analysis period, river flow generally peaks during June and July, gradually tapering off thereafter until April. Notably, river flow during January to May and December remains consistently below 1 cubic meter per second across most basins, indicating minimal groundwater contribution to the overall river flow during these months. This underscores the significant influence of rainfall on river flow dynamics within the Arjuna River basin. The SWAT model results illuminate the monsoon-driven hydrological regime of the Arjuna River basin. Peak flows occur in July across all subbasins, highlighting the region's dependence on monsoon rains for water resources. Management interventions, such as optimizing reservoir storage and exploring the potential for additional reservoirs, will be crucial for capturing these seasonal flows to ensure water security throughout the year. Differences in flow patterns between subbasins on the main flow line warrant further investigation into land use and localized water usage to inform water use optimization.

The ArcSWAT model demonstrated statistically promising results in hydrological simulations, with R^2 values of 0.78 for calibration and 0.67 for validation, indicating satisfactory performance in replicating monthly runoff values. NSE values of 0.75 for calibration and 0.65 for validation, as well as RMSE values of 0.50 for calibration and 0.60 for validation, further confirmed the model's effectiveness.

Conclusions

In small, medium, and large watersheds, the SWAT model have capability to simulate surface runoff. Throughout eight subbasins and 294 Hydrologic Response Units, the ArcSWAT model successfully evaluated the water and land resources in the Arjuna River Basin, highlighting important hydrological patterns. The basin features highly undulating terrain with steep slopes throughout its area. River flow dynamics, with increases from June to July and decreases till April, highlight the challenges in managing water resources in a seasonally fluctuating environment. River flow during January to May and December in almost all basins is less than 1 cubic meter per second, indicating minimal groundwater contribution.

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