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Surface water assessment methods and tools for water resource management

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Abstract
Assessing surface water availability is important for resources planning and management. Surface water resources are vital for sustainable water management amid growing global water demand driven by population growth, urbanization, and agricultural and industrial expansion. Various methods are used to measure and analyse surface water availability, each with specific strengths and limitations. Direct measurement methods, such as timed-volume and dilution gauging, are accurate for small streams but limited in scale. Velocity-area techniques, including float and current meter methods, provide reliable stream flow estimates but require specialized equipment. Formed constriction methods, such as weirs and flumes, are effective but environmentally disruptive. Rainfall-runoff models like Cook's Method, the Rational Method, and the Curve Number (CN) Method are widely used, though their accuracy varies based on watershed size and characteristics. Hydrological models, including SWAT, HEC-HMS, and MIKE SHE, simulate water movement across watersheds, with SWAT being particularly effective for long-term assessment of both surface and groundwater dynamics, especially in agricultural regions.

Keywords: Assessment methods, surface water, hydrological model

1. Introduction

Water is at the core of sustainable development and is critical for socioeconomic development and the necessity for life, agriculture, healthy ecosystems, and human survival. Water is one of the important natural resources essential for every civilization's survival and livelihood, including food production, access to clean drinking water, sanitation, and hygiene. Adequate water in both quantity and quality underpins health and basic quality of life. It influences the course of a wide variety of ecosystem services. Water availability is the critical link for major development challenges including food security, rapid urbanization, sustainable rural development, disaster risk management, and adaptation to climate change. The planning, development, operation, and maintenance of all the water resources for the security of the population, in response to the growing need for drinking water, industrial production, agricultural products, and electricity, a general improvement of living conditions is of utmost importance. Global water demand has surged by 600% in the last century, currently increasing at the rate of about 1% annually. By 2050, demand is projected to rise by 20-30%, reaching 5,500-6,000 km³ per year. Population growth, especially in Africa and Asia, and urbanization drive this trend. Agricultural water use, presently 70% of the total available water, expected to increase by 60% by 2025 due to increasing food demand. With manufacturing demand quadrupling, industrial water use, now 20% of the total, will significantly increase, especially in Asia. Energy sector water use will rise by 85% by 2050. Domestic water use, currently 10% of total demand, will grow notably, particularly in Asia [1].

In India, approximately 60-70% of the total irrigation water demand is met by groundwater, making it the largest consumer of this resource in the world [2]. As per the latest assessment (2022), the Annual Extractable Ground Water Resource is 398 BCM. The Annual Ground Water Extraction for all uses is 239.16 BCM, out which 208.49 BCM (87%) has been utilized for agriculture activities. However, the over-reliance on groundwater for irrigation has led to a rapid depletion of aquifers. Studies indicate that groundwater levels in major agricultural regions have been declining at an alarming rate of 0.2 to 1 meter per year, with regions like Punjab and Haryana experiencing even higher rates of depletion.

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Study conducted in Konkan region shows that region is already facing moderate to poor groundwater potential in nearly 71% of its area. If unregulated extraction continues, aquifers may collapse or become irreversibly depleted, leading to long-term water scarcity [3, 4].

The consequence is a vicious cycle: as groundwater levels drop, farmers are compelled to drill deeper wells, leading to higher energy consumption and increased production costs. Moreover, excessive withdrawal disrupts the natural hydrological balance, leading to land subsidence, reduction in streamflow, and loss of wetlands, which in turn affects biodiversity and ecosystem services [5]. The quality of groundwater is also deteriorating due to contamination from agrochemicals, such as fertilizers and pesticides, which leach into aquifers. High levels of nitrates, heavy metals, and salinity have been reported in many regions, rendering the water unfit for drinking and even irrigation purposes in some cases [6, 62]. Additionally, industrial and domestic effluents further compound the pollution problem, particularly in peri-urban areas where wastewater management is inadequate. Given the critical importance of groundwater, its sustainable management is essential. Restricting groundwater withdrawal is necessary to prevent irreversible damage to aquifers and to ensure long-term water security. Effective policies such as regulated extraction, improved irrigation efficiency through drip and sprinkler systems, and conjunctive use of surface and groundwater can help mitigate the over-extraction issue. Supply-side measures encompass the construction of groundwater recharge structures and improved accessibility to surface irrigation [7]. Ultimately, balancing groundwater withdrawal with natural recharge rates and addressing pollution challenges is crucial for achieving sustainable agricultural productivity and safeguarding water resources for future generations.

Assessing surface water availability is important for resources planning and management. This also can be used to study climate change impact, natural hazards trends as well as different land use and land cover water retention capacity. It also provides information about status and trend in water quality. This also can be used as a tool to understand the contribution of water to economic development and human well-being. Advances in scientific knowledge, along with improvements in measurement and modelling techniques, have emphasized the importance of investigating effective conservation and management strategies for these critical resources [8]. Main objective of this paper is to study various methods used for assessing surface water resource availability and their suitability across different agroecological regions.

2. Different methods of surface water assessment

Streamflow monitoring methods are tailored to different stream types. Stream channels can be classified based on eight major variables width, depth, velocity, discharge, slope, roughness of bed and bank materials, sediment load and sediment size. Various methods exist for quantifying and monitoring surface water flow, categorized as follows [9-11]: (a) direct measurement methods, (b) velocity-area methods, (c) formed constriction or constricted flow methods, (d) Rainfall-Runoff method, and (e) non-contact measurement methods. These methods can be further classed as shown in Table 1.

Table 1: Different methods of surface water assessment

A) Direct measurement methods	B) Velocity-area methods	C) Formed Construction or constricted flow method	D) Rainfall-Runoff method	E) Non-contact measurement method
Timed volume method	Float Method	Weir Method	Rational Method	Particle image velocimetry method
	Dilution Gauging method	Flume Method	Cooks Method	Hydrological Modelling
	Current meter method		Curve Number method	
	Trajectory method		Unit Hydrograph Method	
	Electromagnetic Method		Infiltration Method	
	Acoustic Doppler current profiler method (ADCP)		Empirical Formulae	
	Salt-Velocity Method			

Based on Volume of water to be measured, the degree of accuracy desired, type of installation i.e. permanent or temporary, financial investment required, and availability of data method can be selected for further study.

2.1 Direct measurement method

In this method, known as time-volume method, the flow rate is determined by measuring the time it takes to fill a container of known volume. This technique is particularly useful for streams where the entire flow converges into a single descent. To ensure accuracy and reliability, a large container should be used, and the flow rate should be measured at least five times, with more than three replications across different stream width and depth [12, 13]. The flow rate is then calculated as the ratio of the average stream cross-sectional area to the average time taken to fill the container.

It operates on the time-volume principle and known for being accurate, cost and time-efficient, and environmentally friendly. Additionally, it requires minimal resources and technical expertise [14, 15]. However, this method is best suited for small, narrow streams with uniform cross-sectional area [16, 17].

2.2 Velocity-Area method

Velocity-area methods are based on the principle of fluid flow continuity and are used for instantaneous streamflow measurements and establishing the stage-discharge relationship [18] Discharge and stage measurements are crucial in areas where water management is a priority. This method involves determining the cross-sectional area of the stream flow and the mean velocity, multiplying these values to calculate the stream flow.

The float method is simple, non-polluting, and requires minimal resources, but it is often inaccurate due to vertical turbulence causing differences in surface velocities of flow. It works best in small, straight streams with uniform flow but is unreliable for larger water bodies [19, 20]. The dilution gauging method is effective in turbulent conditions where conventional methods struggle. However, errors may arise due to incomplete mixing or tracer loss, and obtaining permission for tracer use can be challenging due to pollution concerns [21, 22].

The current meter method offers accuracy and efficiency, especially in hilly terrains, but its high cost limits its use to short-term applications [23]. The trajectory method is useful for discharge measurements in diverted flows or small open channels but requires trained personnel and complex calculations [24]. Electromagnetic methods work well in streams up to 70 m wide, though they require specialized training [25]. The ADCP method is fast and accurate for large streams, though expensive and requiring skilled operators. It can be adapted for smaller rivers using tethered boats or catamarans [26, 27].

2.3 Formed construction or constricted flow method

The weir method involves constructing a physical barrier or check-dam in a stream's cross-section to measure discharge. A weir can be made from materials like plywood, wooden boards, or reinforced concrete, and can be either permanent or portable. The water flows over the weir's notch, which may be rectangular, trapezoidal, or triangular. Rectangular and 90° V-notch weirs are most used.

Discharge through the weir is estimated using predefined tables [28] or a weir equation that accounts for flow rate, water head height, and crest width [29, 30]. The weir method is accurate but requires careful installation, skilled operation, and specific conditions, such as a significant water surface drop between the upstream and downstream sides. This method also necessitates the construction of a pool or stilling basin upstream of the weir to slow down water velocity, which can be time-consuming and disruptive to local habitats [31]. The major limitations of the weir method include siltation, which can affect accuracy, and its inability to handle wide flow ranges without using compound weirs. Moreover, it may not easily integrate with other water infrastructure, and a pre-measured flow rate is required before installation [32].

Flumes are artificial open-channel structures that narrow the stream cross-section and alter its slope, increasing the water velocity to calculate discharge. Unlike weirs, flumes do not cause water impoundment, which can reduce flow disruption. Discharge is determined by measuring water height using a stilling well [33], and flow is calculated using standardized tables [34, 35]. There are different types of flumes, each designed for specific uses. For example, HL, H, and HS flumes are used for intermittent runoff, while venturi flumes measure irrigation water, and San Dimas flumes are suited for debris-laden streams [36]. Flumes, when manufactured and installed correctly, offer accurate flow measurements without requiring calibration, but their accuracy can be influenced by water approach velocity and siltation [35]. Flumes are more limited than weirs in terms of the flow range they can measure and are generally suitable for smaller streams. Additionally, the construction and installation of flumes are more challenging compared to weirs, especially in areas with debris or high sediment loads.

Ultrasonic gauging measures water velocity by transmitting sound waves across the stream and recording the time differences between sound pulses. This method is particularly useful in rivers up to 300 meters wide, where constructing a physical structure would be impractical or too costly. It is ideal in conditions where backwater effects, such as tides or dams, influence water flow. However, the ultrasonic method can be affected by factors like an unstable cross-section, fluctuating weed growth, suspended solids, and changes in water temperature or salinity, all of which can alter signal velocity and flow measurements. Calibration is often performed using the current-meter method. The choice of flow measurement method depends on stream characteristics and operational requirements. While weirs and flumes offer precise flow measurement for smaller streams, they require careful installation and can be limited by site conditions. The ultrasonic method, though less intrusive, may face accuracy challenges in certain environments.

2.4 Rainfall-Runoff method

This category includes methods such as Rational Method, Cook's Method, Curve Number Method, Unit Hydrograph, and various empirical formulae, including Runoff Coefficient Method, Inglis Method, Khosla's method. Rational method is suitable for small watershed area, where it is easier to account for variations in hydrological responses. This method is usually used to calculate peak runoff rate from small watershed. It involves formula for computing design runoff

$$Q_{Peak} = 1/360\times(CIA)$$

Where, Q_{Peak} is peak runoff rate, m^3/s; C = runoff coefficient; I is rainfall intensity, mm/h, for duration equal to time of concentration and given recurrence interval; and A is watershed area, ha However, it has limitations, as it assumes constant rainfall intensity over the entire watershed during the storm, which is not common. It also neglects losses due to declining storage and infiltration. Additionally, the runoff coefficient used in this method does not account for seasonal variations or changes in rainfall characteristics. One of the primary drawbacks of the Rational Method is that it typically provides only a single point on the runoff hydrograph.

Cook's Method is an empirical approach to estimating peak runoff rates based on the characteristics of a watershed. The method evaluates four key factors: relief, infiltration rate, vegetation cover, and surface storage, assigning numerical values to each characteristic based on their similarity to other watersheds with known conditions. The sum of these values (∑W) is used to calculate an initial, uncorrelated runoff value from a runoff curve. This method is relatively simple and accessible to practitioners with limited hydrological expertise. It relies on numerical values derived from watersheds with similar conditions. As an empirical method, it is based on observations rather than theoretical principles, which can limit its accuracy if local conditions differ significantly from those used to develop the method.

The Curve Number method computes the direct runoff or excess, Strom wise. This method is based on potential retention capacity of watershed, which is determined based on antecedent moisture condition and physical characteristics of watershed. This method assumes that the ratio of direct runoff to rainfall depth minus initial losses (interception, infiltration, depression storage etc) is equal to ratio of actual retention of rainfall to retention capacity. It is widely accepted due to its simplicity and minimal input requirements. It has been successfully applied in various hydrological studies and engineering projects. Based on extensive empirical data and field observations, this method is reliable for a range of agricultural conditions, soil types, land uses and moisture levels. It also integrates with Geographic Information System (GIS) for spatial analysis and large-scale hydrological modelling however, the method is sensitive to the choice of curve number, leading to potential variability in runoff estimates. Additionally, it assumes uniform rainfall distribution across the catchment, which is often unrealistic. The method may not be suitable for large or highly urbanized watersheds where hydrological processes are more complex.

The Unit Hydrograph (UH) is a fundamental concept in hydrology used to describe the temporal distribution of runoff generated by a unit volume of effective rainfall (typically 1 cm) distributed uniformly over a watershed area. It helps in predicting the runoff hydrograph resulting from any given rainfall event. In this method portion of the total rainfall that contributes to runoff after accounting for losses like infiltration and evaporation is calculated. Then a hydrograph that represents runoff from a unit depth of effective rainfall distributed evenly over the watershed for a specific duration is created. Runoff hydrograph is derived from applying unit hydrograph to the actual effective rainfall using convolution [47]. This method is suitable for small to medium-sized watersheds (more than 25 km^2) and assumes uniform rainfall distribution and homogenous watershed characteristics. It is particularly useful in areas where rapid runoff response is important for flood forecasting and management. However, the assumption of uniform distribution makes it less applicable for large or heterogenous watersheds. This method is not recommended for large, urbanized watersheds with significant spatial variability in rainfall and land use, or where detailed physical modelling is required.

2.5 Non-contact measurement methods

These methods are based on the principle of radar system and may be used to make continuous, near-real-time flow measurements during high and medium flows.

Particle Image Velocimetry (PIV) is a widely used non-contact technique for measuring fluid flow velocity by tracking the movement of small tracer particles within the fluid. These particles, typically light and small enough to accurately follow the local fluid velocity, are illuminated by a laser light sheet, which scatters light that is captured by a high-resolution CCD camera [37, 38]. In most applications, tracer particles are added to the fluid to ensure that they closely follow the flow dynamics [39]. The fluid is illuminated twice, with a short time interval between two superimposed laser pulses. This creates two consecutive exposures of the fluid flow, captured by the CCD sensor [40]. The time interval between the laser pulses, combined with the camera calibration data (including image magnification and projection of the local velocity vector), defines small interrogation areas within the recorded images. For each interrogation area, the particle displacement is computed as the distance between the particle positions in the two consecutive images. The velocity of the fluid is then calculated by dividing the particle displacement by the time interval between the laser pulses [41]. PIV provides detailed, high-resolution flow velocity data over a two-dimensional plane at a specific moment in time, making it a valuable tool for flow analysis [42]. However, the method requires specialized equipment and training and is generally best suited for flat terrains [44]. Despite its precision, PIV does not involve direct measurement, necessitating result validation through other methods [45].

Traditional method for assessing natural resources is often cumbersome, time-consuming and not cost-effective. Geographic Information System have emerged as a proven technology for site-specific assessment and planning of water and land resources. GIS is now integrated with various hydrological models to assess and simulate land and water resources in areas of interest.

Hydrological modelling is a vital tool in hydrology used to estimate the movement, distribution, and quality of water within a watershed. By applying mathematical models and incorporating remote sensing data, hydrologists can replicate the hydrological cycle and predict water flow and storage across various environmental components. A model is simplified representation of real-world system, and the best model is one that closely approximates reality while minimizing the number of parameters and complexity. Models are primarily used for predicting system behaviour and gaining insights into different hydrological processes. The selection of a hydrological model depends on the purpose of study, data availability and the model's capability and suitability for both small and larger catchment hydrologic applications. Hydrological models vary in terms of input parameters and the extent of physical principles they incorporate. Models can be classified based on model input, parameters and the degree to which they incorporate physical principles. They can be classified as lumped and distributed models based on the whether parameters are a function of space and time, and into deterministic and stochastic models depending on how uncertainty is handled with specific details provided in Table 2.

Table 2: Distinguishing characteristics of different models [46]

Parameters	Empirical Model	Conceptual Model	Physically based model
Type	Data based or black box model	Parametric or grey box model	Mechanistic or white box model
Based On	Mathematical equations, derived values from available time series	Model of reservoirs and on physical basis include semi-empirical equations	Spatial distribution based, evaluation of parameters describing physical characteristics
Consideration	Little consideration of features and process system	Parameter derived from field data and calibration	Require data about initial state of model and morphology of catchment
Features	High predictive power, low explanatory depth	Simple and can be easily implemented in computer code	Complex model, requires human expertise and computation capability
Limitations	Cannot be generated to other catchments	Require large hydrological and meteorological data	Suffer from scale related problems
Examples	ANN, Unit hydrograph	TOPMODEL, HBV model	SHE or MIKE SHE models, SWAT
Other	Valid within the boundary of given domain	Calibration is involved, curve fitting makes difficult physical interpretation	Valid for wide range of situations

2.5.1 Variable Infiltration Capacity Model (VIC Model)

VIC Model is a semi distributed, macro-scale, grid-based hydrology model that incorporates both energy and water balance equations. The primary inputs for the model include precipitation, daily minimum and maximum temperatures, and wind speed. The model allows for multiple land cover types within each model grid cell. Key hydrological processes such as infiltration, runoff, and base flow are modelled using various empirical relationships. Surface runoff is generated through two mechanisms: infiltration-excess runoff (Hortonian flow) and saturation excess runoff (Dunne flow). The VIC model simulates saturation-excess runoff by accounting for soil heterogeneity and precipitation patterns [48]. It incorporates the representation of sub-grid variability of precipitation with representation of spatial variability of infiltration to simulate energy and water budget.

VIC model is coupled with simple grid-based network which shows it perform well in moist area [49]. VIC model represents sub-grid variability in soil moisture storage capacity as a spatial

probability distribution which is related to surface runoff [50]. VIC Model applied this model for irrigation planning in small watershed and found that it can be efficiently used for management of water for agricultural purposes [51]. VIC model applied on Ashti catchment to assesses the impact of LULC change and rainfall trend on hydrological model [52].
Various hydrological models are available that integrate GIS interface, including HEC-HMS, VIC, MIKE SHE, WEAP and SWAT. Specifications of these models are given in Table 3.

Table 3: Hydrologic models with their specifications [46]

Model	HEC-HMS	Swat	Mike	Vic
Advantage	Focus on runoff, channel routing and water control structures	Focus on water quantity, quality and representation of groundwater	Simulates complete land phase of hydrologic cycle	Sub grid variability, Macroscale model, large scale effect
Limitations	Suitable only for events and not for long-term hydrological simulations	Snow process representation requires improvement	Simplified representation of forest cover	Large grid size, does not consider urban class in LULC
Runoff	Empirical	Empirical	Physical	Physical
Baseflow/ Groundwater	Empirical	Empirical	Physical	Physical
Watershed Scale	Small to Large	Small to Large	Small to Large	Medium to Large
Climate Regime	Rain or snow	Rain or snow	Rain or snow	Rain or snow/Mixed
Output	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO, SE, NF, WQ	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO, WQ	FH, AY, PF, LF, SW, ET, WB, SM, IF, OF, SF, GF, RO

FH = Full hydrograph, AY = Annual Yield, PF = Peak Flow, LF = Low flow, SW = Snow water equivalent, ET = Evapotranspiration, WB = Water balance, SM = Soil moisture, IF = Infiltration, WT = Water Table, OF = Overland flow, SF= Shallow subsurface flow, GF = Groundwater flow, RO = Basin total runoff, SE = Sediment soil erosion, NF = Nutrient Fluxes, WQ = Water quality

2.5.2 MIKE SHE model (System Hydrologique European)
The model developed in 1990, is physically based and thus requires extensive physical parameters. It simulates various processes of the hydrological cycle, including precipitation, evapotranspiration, interception, river flow, saturated ground water flow, unsaturated ground water flow. The model is capable of simulating surface and groundwater movement, their interactions, and transport of sediment, nutrient and pesticides within the model area. It is also useful for addressing various water quality issues and can be applied to large watersheds. The model includes pre-processing and post-processing modules and offers various options for displaying results.
Yang *et al* (2000) compared three models and suggested that MIKE SHE model can be used in smaller catchments [53]. MIKE SHE requires extensive model data and physical parameter which may not be available all the time and make it difficult to set up model. It has extensive graphical capabilities for pre and post processing.

2.5.3 HEC-HMS (HEC-Hydrological Modelling System)
The HEC Hydrological Modelling System (HMS) is a conceptually lumped and straightforward model that requires a few parameters, most of which can be derived from land cover data. It is sensitive to land cover changes and provides a convenient platform for simulating rainfall-runoff processes, as well as impacts assessing the impacts of land use and land cover changes. The model mainly focusses on runoff, channel routing and water control structures. HEC-HMS consists of three components: the basin model, the meteorological model and control specifications. These components offer various options for simulating different hydrological processes at lumped scales.

2.5.4 Water Evaluation and Planning (WEAP)
The Water Evaluation and Planning (WEAP) system, along with integrated hydrology models, has a long history of development and application in the water planning, effectively addressing the complex dynamics of water system. WEAP can be applied at local scales as well as in more complex river basin systems. It operates on the fundamental principle of water balance accounting. The model's hydrologic processes can be utilized as both forecasting tool and a policy analysis tool.

2.5.5 Soil and Water Assessment Tool (SWAT)
SWAT is complex physically is a complex, physically based model designed to simulate and forecast water and sediment circulation, as well as agricultural production and chemical transport in ungauged basins. It is highly efficient for performing long-term simulations. The model divides the entire catchment into sub-catchments, which are further broken down into Hydrologic Response Units (HRUs) based on land use, vegetation and soil characteristics. The model utilizes daily inputs of rainfall, maximum and minimum air temperatures, solar radiation, relative humidity and wind speed to describe water and sediment circulation, vegetation growth and nutrients dynamics. Snowfall rates can be determined based on precipitation levels and mean daily air temperatures. For estimating evapotranspiration, SWAT employs methods such as Penman Monteith, Priestly-Taylor and Hargreaves. Accurate forecasting of water, nutrient and sediment circulation requires simulating the hydrologic cycle, which integrates overall water circulation in the catchment area, and SWAT uses the following water balance equation for this purpose.

$$SW_t = SW_0 + \sum_{i=0}^{t}(R_v - Q_s - W_{seepage} - ET - Q_{gw})$$

Where, SW_t is humidity of soil; SW_0 is base humidity; R_v is rainfall volume in mm water; Qs is surface runoff; $W_{seepage}$ is seepage of water from soil to underlying layers; ET is evapotranspiration; Q_w is groundwater runoff and t is time in days.
Soil Water Assessment Tool (SWAT) model, developed by the USDA Agricultural Research Service in collaboration with Texas Agricultural University, is widely regarded as a reliable tool for basin-scale studies [55]. This GIS-based interface is universally adopted for various works such as water and land resource planning, water quality analysis, crop planning, and water budgeting, provided proper calibration and validation are conducted [57]. The Arc SWAT model has been applied across diverse regions, watershed scales, climatic zones, environmental conditions and management systems globally, showcasing its capacity for quantitative evaluating hydrological regimes and water resources [56].

SWAT offers comprehensive capabilities for assessing and modelling surface water, groundwater dynamics, soil water, snow processes, irrigation systems, impoundment and water management strategies. It also evaluates water quality by analysing nonpoint-source pollution, sediment transport and losses. Furthermore, SWAT is effective in assessing the impact of best management practices (BMPs) in agriculture, urban settings and land use changes. It can evaluate the effects of global and regional climate change and human activities such as land-use expansion, deforestation, and unsustainable water use on hydrological balance components.

The model estimates daily overland flow for each Hydrologic Response Unit (HRU) by resolving water budget components, including precipitation, runoff, evapotranspiration, percolation, and groundwater flow. SWAT conceptualizes landscapes as large fields (HRUs) with uniform soil and vegetation sloping towards streams, though real-world flow paths are often more complex. HRUs, which represent unique combination of land use, soil type and slope, dictate hydrologic responses. SWAT partitions daily rainfall into infiltration and runoff using a modified curve-number method and calculates evapotranspiration based on soil moisture and climate. It also accounts for runoff interception by ponds and wetlands within subbasins.

Compared to other land surface models, the following are the distinguishing hydrologic features of SWAT model:

- SWAT divides watersheds into sub-basins, which are further subdivided into hydrologic response units (HRUs) based on land use, soil type, and slope. This approach allows for a detailed spatial representation of the watershed characteristics [57].
- SWAT can integrate various climate change scenarios and LULC changes to evaluate their impacts on hydrology and water resources, making it a valuable tool for assessing the effect of both climate change and LULC changes in related studies [58].
- SWAT integrates surface water and groundwater interactions, enabling a comprehensive assessment of water movement, storage and dynamics within the watershed. This can be used for gauged as well as ungauged river basin.
- SWAT has capability to model urban hydrology, accounting for the effects of impervious surfaces, stormwater runoff, and the implementation of urban best management practices [59].
- It provides a user-friendly interface and extensive documentation, making it accessible to a broad range of users, including researchers to practitioners [60].

3. Conclusion

Effective assessment of surface water resources is critical for sustainable water management, particularly considering increasing global water demand due to population growth, urbanization, and agricultural and industrial expansion. Various methodologies are employed to measure and analyse surface water availability, each with specific applications, advantages, and limitations. Direct measurement methods, such as the timed-volume and dilution gauging techniques, offer accurate, cost-effective solutions for small streams but are limited in scale and duration. Velocity-area methods, including float and current meter techniques, are widely used for streamflow estimation and provide reliable results in turbulent conditions, though they require specialized equipment. Formed constriction methods, such as weirs and flumes, accurately measure discharge in small to medium-sized streams but can disrupt ecosystems and are sensitive to site-specific factors.

Rainfall-runoff models, including Cook’s Method, the Rational Method, and the Curve Number (CN) Method, are essential for runoff estimation in watersheds. Cook’s Method is a simple empirical approach, though it lacks accuracy when applied outside its region of origin. The Rational Method, suitable for small watersheds, is limited by its assumption of constant rainfall intensity. The CN Method is widely used due to its simplicity and integration with Geographic Information Systems (GIS), though its performance declines in larger watersheds. The Unit Hydrograph (UH) method effectively predicts runoff hydrographs for rainfall events, making it valuable for flood forecasting in small to medium-sized watersheds. Hydrological models, such as SWAT, HEC-HMS, and MIKE SHE, simulate water movement and storage across watersheds, integrating GIS data for enhanced analysis. SWAT is particularly effective for long-term simulation of both surface and groundwater dynamics and is widely used to assess watershed responses to land-use and climate changes, especially in agricultural regions.

4. Disclaimer (Artificial Intelligence)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology.

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