Review Article

A Brief Review on Hydrological Modelling

Abstract:

The interaction between water, climate, soil and land use is primary to the hydrological modelling concept. Hydrological models include spatial and temporal features. Hydrologists utilize hydrologic models as a primary tool for a variety of tasks including managing water resources, managing urban and rural areas, modelling ground water and more.In order to implement hydrologic models with ease, it is necessary to thoroughly comprehend their properties which have been developed and improved through the years. It is difficult to categorize hydrologic models precisely and various hydrologists may use different criteria. The reason is that while numerous models share common traits, the nature of the model is frequently the same. In this paper, the discussion starts with an introduction to ancient hydrology followed by the anthropogenic factors which directly or indirectly affect hydrological flows.Further the paper reviews hydrological modelling and the evolution of hydrologic models. The research aims to demonstrate classification of hydrologic models. The proper application of a model requires an in-depth understanding of it. In this research, eleven watershed hydrologic models were reviewed: ANN model, Unit Hydrograph, SCS-CN model, SVM model, HBV, TOPMODEL, PRMS, MIKESHE, VIC, HEC-HMS, MODFLOW and SWAT. SWAT model, one of the non-point source pollution models, is discussed along with its history and its major input variables. This literature also compiles and discusses applications of the SWAT model. SWAT was found to be promising models for long-term continuous simulations in agricultural watersheds.In agricultural watersheds, SWAT has been found to be the most assuring model for long-term continuous simulations.

1.Introduction

The study of hydrology has a long and illustrious history(Biswa, 1970). Hydrology is the study of movement of water in relation to land, very important to deal with most important resource on Earth. Water is a primary and essential resources for the development of socio-life and the environment. It is a valuable natural resource that is handled by the hydrological cycle, which takes into account its circulation, distribution, chemical, physical characteristics as well as its interactions with other environmental factors at various stages (Ray, 1975).In recent years, the water resources has been a global issue. The water crisis has steadily moved up in global agenda. The increasing population is being the main reason for the decreasing per capita availability of water along with the deterioration in water quality.

In ancient Indian civilization, the necessity to manage water fueled the development of hydrologic science. There has been as existence of hydrological and hydraulic related engineering knowledge in ancient India.The *Rigveda*, one of the oldest religious texts, contains many mentions of the water cycle and associated processes (Sarasvati, 2009).The rivers have been main source of water since the ancient times. Also, one of the most anthropogenically impacted ecosystems in the world are rivers. Everyday water needs were fulfilled with surface water including river water, pond, lake springs, etc. Even while the majority of rivers and lakes were generally clean in the Middle Ages, metropolitan areas were heavily polluted, which frequently resulted in diseases. In several industrialized nations, the need for pollution reduction did not become apparent until the late nineteenth century. Environmental engineers, planners and decision-makers focused on treating traditional pollution sources like sewage and industrial wastes during the most of the 20th century (Novotny, 2002).

By the 1800s, the Industrial Revolution brought hazardous impacts on rivers, including severe modifications from industrial use, water extraction, hydroelectric projects and pollution from a growing population. Water is essential for daily life, but industrialization has severely polluted it by discharging untreated waste into rivers, oceans and lakes. This has harmed natural resources, traditional livelihoods and health, causing diseases like typhoid, dysentery and cholera (Rajput, *et al.*, 2017). By the mid-1850s, water treatment emerged as populations recognized water as a finite resource and the need to combat overpopulation-driven pollution. This led to improved sanitation and healthier living conditions.

Humanity has relied on wells for thousands of years, with some of the oldest found in Germany and Harappan sites like Lothal and Dholavira which are 7000 years old. Open wells, easy to dig with basic tools, were the main water source until borewells emerged in the 1960s and 70s. Farmers switched to groundwater as surface water quality declined and deeper borewells became common due to urbanization, population growth and shrinking land holdings. While borewells, now popular in urban India, provided year-round access to water, they obscured groundwater visibility, leading to over-extraction and depletion. Borewells, drilled as deep as 1800 feet, also increased the risk of chemical contamination, as reported by the CGWB. By 2050, India's population is projected to reach 5000–6000 million, making it a water-stressed country with water availability dropping to 1000 cu.m per person per year. This highlights the urgent need for effective water resource planning and management to ensure sustainability and support economic development.

Several other factors like deforestation, climate changes andlulc changes have been occurred in hydrological cycle (Devia, *et al.*, 2015), which impacts the discharges of many Rivers. Water Resource Management is a need of the country for socio-economic development. All these concerns make the water resource management popular topic among various ecologists, hydrologists, meteorologists and agriculturists. Hydrological modelling is performed for development of a water resource management plan for which, it is necessary to study hydrological cycle thoroughly.

2. Hydrological Modelling

There has been a growth in the technical world, giving large opportunities to the researchers in context of experiments.Advancements in technology have significantly simplified the process of modeling, making research more effective and aiding water resource management. Hydrological modeling is one such invention that has proven instrumental in addressing challenges in water resource management. Sorooshian*et al.* (2008) define a model as a simplified representation of real-world systems. An effective model produces results that closely resemble reality with minimal parameters and reduced complexity. Runoff models use equations to estimate runoff based on parameters describing watershed characteristics, such as soil properties, rainfall data, vegetation, topography, soil moisture content, groundwater and drainage data. Among various hydrological processes, the rainfall-runoff process holds significant importance alongside evaporation, condensation, precipitation and infiltration.

The history of hydrological modeling dates back to the mid-19th century. Thomas James Mulvaney (1850) introduced the first hydrological model, the Rational Method, to compute peak discharge from rainfall (Singh, V. P., 2018). Darcy's law (1856) laid the foundation for quantitative groundwater hydrology, while Fick's law provided the basis for water quality modeling. Dalton's (1802) law of evaporation established a fundamental understanding of evaporation physics. The development of rainfall-runoff modeling began as a solution to engineering challenges like designing urban sewers, drainage systems for land reclamation and reservoir spillways, with a focus on calculating design discharge. By the 1920s, modifications to the Rational Method addressed issues such as non-uniform rainfall distribution and catchment characteristics, leading to the creation of the modified Rational Method, which incorporated concepts like isochrones and travel times(Dooge, 1957, 1973).

Sherman (1932) introduced the unit hydrograph, which used the principle of superposition to convert rainfall into runoff, assuming consistent catchment behavior over time. Challenges like separating runoff from base flow and estimating rainfall required a trial-and-error approach. By the 1950s, system engineering approaches and mathematical methods, such as Fourier transforms and Laplace equations, were employed to analyze hydrological data. Despite the advantages, these methods faced challenges due to the nonlinear behavior of systems and errors in input-output data. Nash (1958, 1960) introduced differential equations to describe reservoir storage behavior and hydrograph shapes, paving the way for conceptual models. Statistical methods like regression and maximum likelihood were used to model unit hydrographs, correlating parameters with catchment features (Prasad, 1967; Spolia and Chander, 1974).

During the 1960s, the development of rainfall-runoff models took a more physical approach. Models were designed to represent individual components of the hydrological cycle, accommodating diverse watershed characteristics such as soil types, vegetation and slopes. The Tank Model (WMO, 1975), Stanford Model IV (Crawford and Linsley, 1966) and models by the U.S. Corps of Engineers (Rocwood and Nelson, 1966) emerged during this period. These models emphasized connected subsystems and continuous records, allowing for application to large watersheds without separating base flow from storm runoff. Physically based models like those by Wooding (1965–1966) and Freeze and Witherspoon (1966–68) focused on replicating rainfall-surface runoff processes using differential equations such as Darcy's law for groundwater flow, Richards' equation for unsaturated zone infiltration and De Saint Venant's equations for overland and channel flow.

The beginning of digital computers in the 1960s overcame computational limitations, enabling the development of computer-based hydrological models. The Hydrological Simulation Program-FORTRAN (HSPF) was the first such model. Beven (2012) identified the Stanford Watershed Model as one of the most successful and widely used models of its time. The 1970s saw increased attention to soil erosion, pollutant spread and land use changes. Real-time forecasting models were developed for flood-prone areas, facilitating reservoir management. Todini (1988) highlighted advancements during this period, including rainfall-runoff models designed for real-time applications.

The 1980s and 1990s marked the development of integrated hydrological models capable of addressing complex water resource management issues. Models like SWAT (Soil and Water Assessment Tool) were designed for large-scale applications, simulating water flow, sediment transport and nutrient cycling. The increasing focus on water quality led to the refinement of models incorporating chemical and biological processes. Singh (1995) introduced a comprehensive classification of hydrological models, further diversifying their application.

Hydrological models have evolved from empirical formulas to sophisticated systems integrating physical, statistical and conceptual approaches. The incorporation of advanced computational techniques has expanded their scope, allowing for real-time data processing and predictive modeling. These developments have significantly enhanced the ability to manage water resources, mitigate flood risks and address environmental challenges. Today, hydrological modeling continues to be a vital tool for scientists and engineers, enabling sustainable management of water resources in the face of growing environmental and societal demands.

3. Classification of hydrological models

The models are developed to simulate several components of hydrological cycles. The variations of results/outputs of each model is the parameter which differentiate one model from other. These differences are due to time and space variations of inputs. First and foremost input for the process of rainfall-runoff modeling is precipitation on which output of model is highly dependent. The majority of hydrologic models offer a feature for calculating how precipitation is distributed throughout these hydrologic cycle parts. The models can be classified into the following groups depending on the method used in these functions to distribute the precipitation (Fig 1).

a. **Event based and continuous models:** These models estimate runoff using single storm event, whereas, continuous models are capable of flow simulation for a longer period of time.

b. **Conceptual and physically based models:**These models interpret runoff using empirical relationships among different hydrological components. Physically based equations are used in models to represent these processes, which are based on our understanding of the physics of the hydrological processes that regulate catchment response.

c. **Lumped and distributed models:** These models consider whole watershed as a single entity for which every parameter is an average value resulting in non-accurate output. Distributed models consider watershed in sub-basins with respective parameters, resulting in more accurate output due to spatial variability of variables.

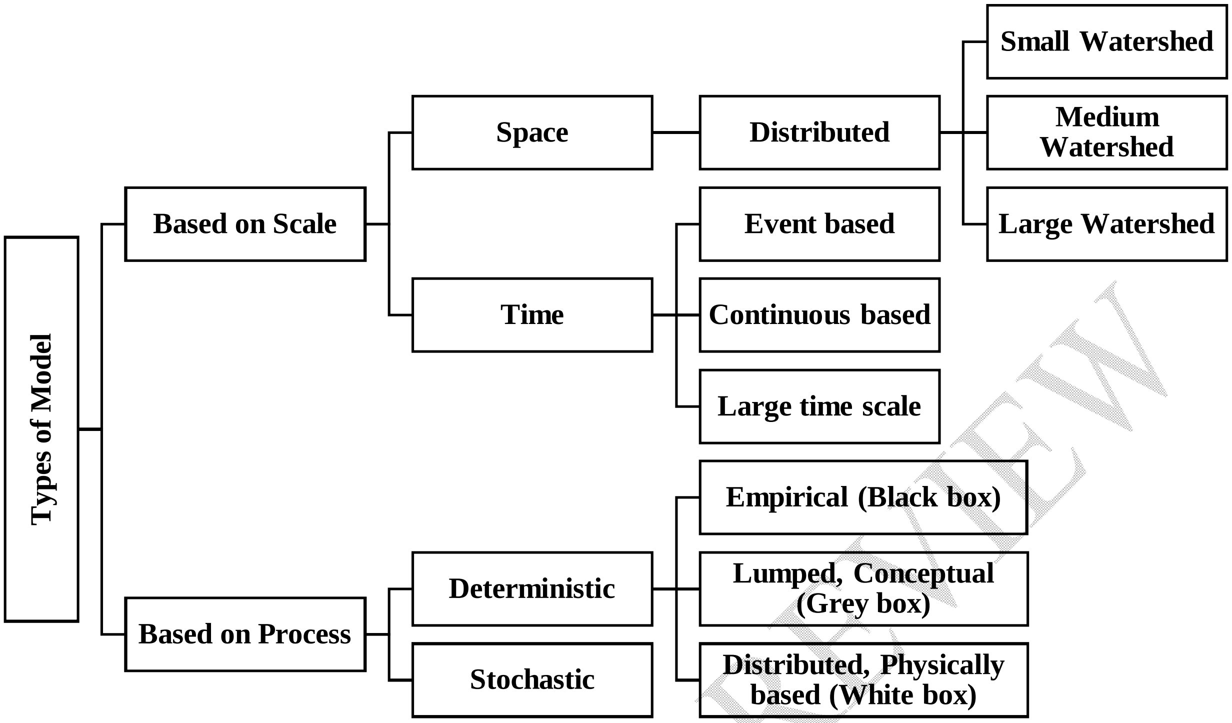

Figure 1. Types of Models

Table 1.Characteristics of models

Empirical model	**Conceptual model**	**Physically based model**
• Uses data and known as black box model • Includes mathematical equations , acquire values from available time series • Considers lesser features and system processes • High predictive power, low explanatory depth • Cannot be produced to be applied in other catchments • Reliable within the limits of the specified area • ANN model, unit hydrograph	• Uses semi-empirical equations to model reservoirs, known as grey box model • Acquire parameters from field data and calibration, easier implementation in computer code. • Multiple hydrological and meteorological data required • Curve fitting and calibration make physical interpretation challenging. • TOPMODEL, HBV model	• Known as white box model • Subjected to spatial distribution, parameters evaluated to describe physical characteristics • Require data about initial state of model and morphology of catchment • Complex model demanding computation skills • Valid for variety of circumstances • Encounter scale-related issues • SWAT model, MIKESHE model

Distributed and semi-distributed hydrologic models are two approaches used in hydrology to simulate the behavior of water in a catchment or watershed.Table 2 describes the comparison of these models.

Table 2. Comparison of Distributed and Semi-distributed hydrologic models

Parameter	Distributed models	Semi-distributed models
Spatial Resolution	Watershed is divided into various sub-basins or grid cells of smaller areas	Watershed is divided into fewer, relatively large sub-basins
Input data	Large amount of spatially distributed data (topography, landuse land cover, soil properties, meteorological data)	Spatially aggregated input data (avg land cover,soil property, meteorological variable for each sub-basin)
Process representation	Considers spatial variations of watershed	Do not capture spatial heterogeneity of watershed
Computational complexity	More intensive, requires powerful resources and longer time for simulation	Less intensive, requires less computational resource and provide faster simulation

4. Description of few models

4.1. EMPIRICAL MODELS

ANN technique

Artificial intelligence (AI) models, particularly artificial neural networks (ANNs), have been widely used in water engineering since the mid-20th century, especially for modeling and predicting water resource variability. McCulloch and Pitts (1943) introduced artificial neurons and since then, ANNs have become a key tool in hydrological forecasting. Maier and Dandy (2000) reviewed neural networks for water resource modeling and by 2010, Maier *et al.* (2010)used them to simulate river systems. Hybrid models combining classic time series methods with ANN have improved forecasting accuracy (Jain and Kumar, 2007). ANN techniques have been used to estimate rainfall, runoff (Meher, 2014) and other hydrological variables, with hybrid models showing better results (Fahimi*et al*., 2017). Kumar *et al*. (2016) demonstrated the effectiveness of ANN in simulating daily runoff in semi-arid catchments, showing significant improvements in hydrological simulations.

Unit hydrograph

Sherman, (1932) developed the unit hydrograph using the superposition technique. It is one of the earliest methods hydrologists have for predicting complete dischargesrather than computing only peak discharges for hydrographs (Todini, 1988). Sherman's unit hydrograph is only appropriate for gauged basins because it is built on the variable observed rainfall and runoff data. Synthetic unit hydrographs are an effort to expand the applicability of unit hydrograph concept to ungauged catchments. They are mostly made out of empirical equations. Synthetic unit hydrographs try to connect watershed features like basin length and size to the structure of the unit hydrograph (Yen and Lee, 1997).Synthetic approaches can be used in ungauged watersheds since they are independent ofobserved runoffdata. Snyder (1938) developed the unit hydrograph method that could be used in ungauged watersheds based on a research on watersheds in the Appalachian Mountains.To simulate unit hydrograph, geomorphologic parameters are used, which are further used create unit hydrographs for ungauged watersheds with comparable hydrological conditions (Jena & Tiwari, 2006).

SCS-CN

The Soil Conservation Service (SCS), founded in 1933 by the NRCS, aimed to implement soil conservation methods and demonstration projects (Williams *et al.*, 2012). The SCS-CN technique, developed in 1954, was documented in the National Engineering Handbook (NEH-4) by the U.S. Department of Agriculture's Soil Conservation Service in 1956 and updated in subsequent years (Mishra, 2003). In the 1930s-40s, SCS installed infiltrometers to measure runoff and define watershed characteristics (Woodward *et al.*, 2002). Sherman (1949) and Mockus (1969) suggested methods to approximate surface runoff using variables like soil type and storm data. Musgrave (1955) classified soils into four categories based on infiltration rates. The SCS developed a uniform runoff calculation method, with the generalized SCS runoff equation based on Andrews and Mockus’s work for watersheds without gauges.

Support Vector Machines (SVM)

Support vector machines (SVMs), developed by Vladimir Vapnik and colleagues at AT&T Bell Laboratories (Deka, 2014), are supervised learning models used for regression and classification. SVMs have been applied to predict groundwater levels (Jin*et al.*, 2009; Mohsen *et al.*, 2010), estimate soil moisture (Gill *et al.*, 2006; Wei *et al.*, 2007; Ahmad *et al.*, 2010) and evaluate groundwater quality (Seyyed*et al.*, 2010). Hybrid SVM models have been developed for better parameterization and efficiency. Sivapragasam*et al.* (2001) used SVM to forecast rainfall and runoff, while Remesan*et al.* (2009) combined SVM with wavelets for real-time flood forecasting. Ozgur and Mesut (2012) explored wavelet and support vector regression models for streamflow estimation andWei and Chih-Chiang (2012) developed SVM models for forecasting precipitation during tropical cyclones. Sudheer *et al.* (2013) proposed the SVMQPSO model for accurate streamflow estimation.

4.2. CONCEPTUAL MODELS

HBV(HydrologiskaByrnsVattenbalansavdelning) model

A rainfall-runoff model called the HBV was used successfully for the first time in 1972 (Bui, M. T.*et al.*, 2020, Bergstrom, S. 1976,1990).HBV model is an illustration of a semi-distributed conceptual model (Bergstrom, 1976). It has three primary parts: subroutines for snowfall and melting, soil moisture accounting and river routing. PULSE is a model that updates the HBV model and is used for simulations and research of water quality in ungauged basins (Bergstrom, 1995).Since the HBV model was created, it is now regarded as a standard tool for a growing number of applications, including the simulation of hazards when designing high hydropower dams, flood forecasting, inflow forecasts to reservoirs of hydroelectric power dams, assessing the effects of climate changes on water resources, etc (Bergstrom, 2006, Osuch, *et al.*,2019). HBV-light, a recent version of the HBV model, employs a warm-up period for which the state variables are given their proper values in accordance with meteorological information and parameter values(Devia, *et al.*,2015).

TOPMODEL

TOPMODEL, developed by Beven and Mike Kirkby, is a physically-based, semi-distributed rainfall-runoff model that predicts the changing patterns of the saturated zone using topographic slope and hydraulic gradient. It represents the storage deficit or depth to the water table through exponential variations in downslope transmissivity. Beven*et al.* (1984) recommended its use for small basins. Purandara (2009) applied it to the Kali river catchment with satisfactory results andVenkatesh & Jain (1997) used it to simulate daily flows in the Malaprabha catchment. Xu*et al.* (2018) utilized the GLUE approach to analyze uncertainty parameters for TOPMODEL, showing that the topographic index is concentrated in high mountains and that including radiation improves runoff simulation accuracy.

4.3. PHYSICAL MODELS

PRMS

The Precipitation-Runoff Modelling System (PRMS), developed by USGS, is a physically-based, distributed parameter watershed model designed to assess the impacts of climate, land use and precipitation on watershed responses (Leavesley*et al.*, 1983; Markstrom*et al.*, 2008). It simulates water-balance variations, flow conditions, peak flood flows, sediment yields, soil-water relationships and groundwater recharge (Borah &Bera, 2003). Integrated with the ANNIE data management program (Lumb*et al.*, 1990) and the U.S. Weather Service's ESP program (Day, 1985), PRMS operates in both long-term and single-storm modes. It can simulate daily and storm flow hydrographs as a lumped or distributed model (Dhami& Pandey, 2013). Islam *et al.* (2012) applied PRMS to simulate daily and monthly streamflow hydrographs, evaluating climatic impacts on streamflows.

MIKE-SHE

MIKE SHE is a physically-based, deterministic, distributed model developed to simulate groundwater and surface water interactions with soil sediments, nutrients and pesticides to address water quality issues in large watersheds. Created by the Danish Hydraulic Institute, SOGREAH and the British Institute of Hydrology in 1977 (Abbott *et al.*, 1986a, 1986b), it works at a continuous time scale. MIKE 11, a one-dimensional model (Havno*et al.*, 1995), is integrated with MIKE SHE and models river and channel flows. Its components include interception and evaporation (Kristensen & Jensen, 1975; Yan & Smith, 1994), unsaturated zone flow (Al-Khudhairy*et al.*, 1999), overland flow (Crawford &Linsley, 1966; Donigian*et al.*, 1995) and water quality (Leonard, 1979). Jaber & Shukla (2012) used MIKE SHE to assess farm reservoir hydrology in the Caloosahatchee watershed.

VIC

The Variable Infiltration Capacity (VIC) model, created by Nijssen*et al.* (2001a), incorporates two soil layers, sub-grid variability in vegetative cover, soil moisture holding capacity and rainfall. It functions as both a water model and a water-energy balance model, addressing surface and groundwater movements and calculating the groundwater table. The VIC model is applicable in cold climates (Gao, 2010) and considers various land covers, including bare soil and upper vegetation cover. The second layer is modeled as non-linear storage and the energy and mass balance simulates snow. The model was improved with the Land Dynamics (LaD) model, adding sensible heat storage, stomata resistance and groundwater storage (Milly &Shmakin, 2002). The PCR-GLOBWB model (vanBeek&Bierkens, 2008) divides soil into three storage buckets, contributing to streamflow as surface runoff, interflow and baseflow.

HEC-HMS

The US Army Force of Engineers Hydrologic Engineering Centre developed the Hydrologic Modelling System (Hec-HMS), which may be used for continuous as well as event-based hydrologic modelling. It offers users a variety of choices for modelling various hydrologic cycle components. For the purpose of modelling dendritic watershed systems, this was developed (USACE, 2010). TheHec-HMS model is a public domain software tool consist of four components namely Basin model, Meteorological model, Input data and Control specification. TheDeficit and constant (D.C.)loss strategy of the HEC-HMS is not used very often as compared to other models SCS-CN, SMA, Green and Ampt, it has been found to be simple and yield reliable results (Sahu, *et al.*,2023).

MODFLOW

MODFLOW is a hydrologic model developed by USGS, having six major releases: MODFLOW-84, MODFLOW-88, MODFLOW-96, MODFLOW-2000, MODFLOW-2005 and MODFLOW 6. Initially, the model focused on groundwater flow, forming the basis for the first three versions. To simulate the behavior of the Loor-Andimeshk plain, the USGS developed the three-dimensional finite-difference MODFLOW model. The model uses the 3-D finite-difference groundwater constant-density flow equation for porous media (McDonald and Harbaugh, 1988).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

Where $K_{xx}K_{yy}$ andK_{zz} are hydraulic conductivities along the Cartesian coordinate axes x, y, z respectively (LT^{-1}).

h -Potentiometric/ piezometric (L) head

W - Volume of volumetric flux (T^{-1})

S_s - Specific storage (LT^{-1})

t - Time (T)

In order to model the groundwater depth of the Indo-Gangetic Alluvial Plains in the Indian state, Uttar Pradesh, during a period of nine years (2005–2013)Shukla and Singh (2018) used Visual MODFLOW. Fuzzy sensitivity analysis was used to explore the source of unreliability due to hydraulic conductivity, porosity andto explain the uncertainty in the anticipated hydrograph value.

5. SWAT Model

Soil and Water Assessment Tool (SWAT) is a continuous, physically based, distributed parameter model developed by U.S. Department of Agriculture (USDA), Agricultural Research Service (ARS) Grassland, Soil and Water Research Laboratory (Neitsch*et al.*, 2002; Arnold *et al.*, 1998). In addition to CREAMS (Knisel, 1980), GLEAMS (Leonard *et al.*, 1987), EPIC (Williams *et al.*, 1984) and ROTO (Arnold *et al.*, 1995), it also incorporates elements of SWRRB (Arnold *et al.*, 1990), which is where it primarily emerged. It was developed to estimate erosion, surface runoff, sediment and nutrient transport from agricultural watersheds for different management practices. The model works in combination with ArcGIS along with ArcSWAT extension which is a graphical user interface designed for SWAT tool (Kangsabanik, S., &Murmu, S., 2017). This model uses wide range of input parameters varying in space and time to transform them into output. The model is widely used in simulating the plant growth, agricultural management, nutrient, pesticides, stream routing, forest growth, land use land cover changes, rainfall and runoff, etc [Arnold and Fohrer2005]. SWAT model is useful in hydrological assessments studies for predicting the water quality effected by land management practices as well as simulating abundant and complex watersheds for long time period of 150-300 years (Kurbah& Jain, 2017). SWAT offers water balance accounting for sub-basin individually (Dessu&Melesse, 2012). Major model components consist of weather, hydrology, soil temperature, soil charcteristics, sedimentation, crop growth, nutrients, pesticides, bacteria and pathogens and land management (Gassman, 2007). The model is unable to route a detailed single-event flood. Fig 2showa the working of SWAT model.

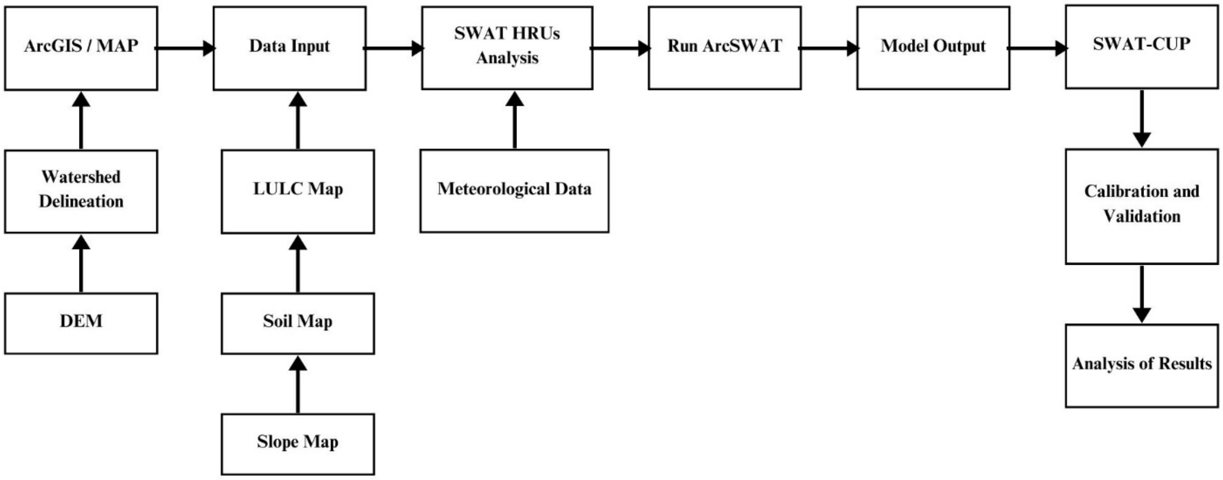

Figure 2. Working of SWAT Model

5.1. Sources and background of SWAT Model

In the early 1980s, the USDA developed the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model to address agricultural non-point source pollution (Knisel, *et al*., 2012). It was later modified into the Simulator for Water Resources in Rural Basin (SWRRB) model for rural basins (Arnold and Williams, 1987). The SWRRB model evolved into Erosion Productivity Impact Calculator (EPIC), a cropping system model and further improved by the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model for better water quality management (Leonard *et al*., 1987). In the 1990s, the SWAT model was developed from these earlier models and has since undergone numerous updates, including incorporating in-stream kinetic practices from the QUAL2E model (Brown and Barnwell, 1987). The SWAT model was further improved into SWAT-G and SWAT/GRASS, with versions such as SWAT2005 adding climatic change simulation features (Griensven and Meixner, 2006). The Extended SWAT (ESWAT) model was also developed for better simulation of sub-hourly precipitation and water quality (van Griensven and Bauwens, 2003).A few of the significant upgrades to SWAT2000 include the addition of bacteria transport routines, infiltration equation by the Green and Ampt , urban routines, better weather generator, a capability to read relative humidity, wind speed, solar radiation, evapotranspiration. Model also includes Muskingum channel routing technique and modified dormancy estimation for tropical areas (Arnold, J.G. and Fohrer, N. 2005). The development of SWAT model is shown in Fig 3.

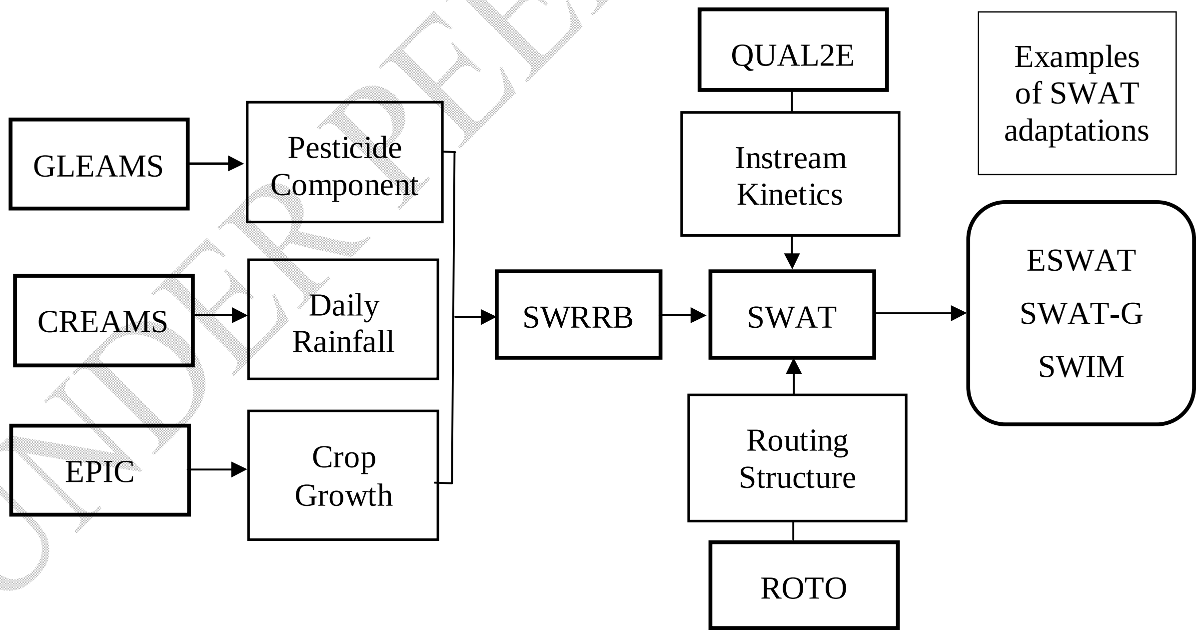

Figure 3. SWAT development history including SWAT adaptations

5.2. Input variables of SWAT Model

The input variables for SWAT modelling depends on the type of analysis to be done on the watershed. The variables associated with the simulation include: (i) quality and quantity of groundwater, (ii) prevention of soil erosion and control, (iii) non-point source pollution control, (iv) rainfall and runoff, (v) sediment yield, (vi) soil moisture, have been derived for past few decades for studying and estimating watershed management practices for soil and water conservation.River discharge data, meteorological and physical data are main inputs of SWAT model. The following input variables to do climatic and hydrological analysis, erosion prediction, plant nutrient analysis and management plans are shown in Fig 4.

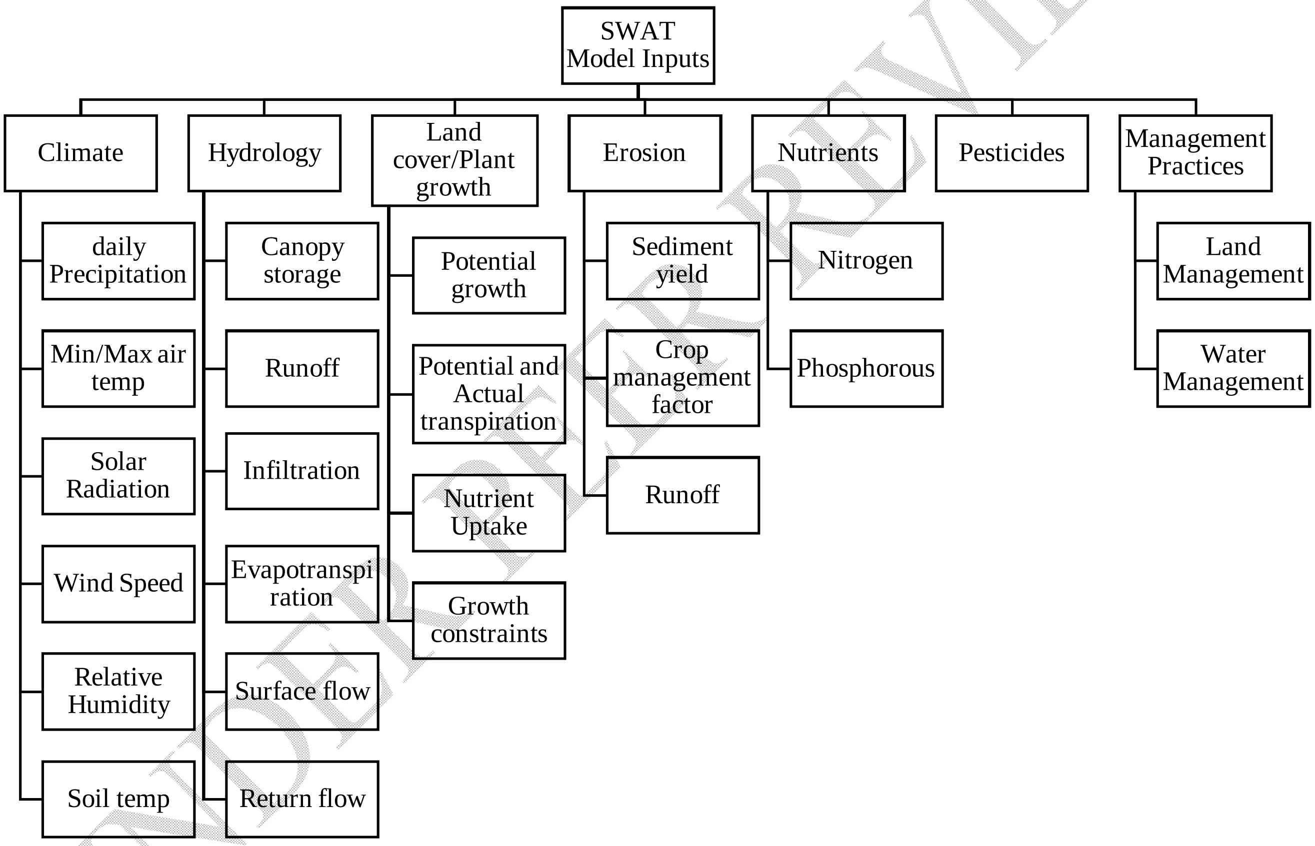

Figure 4. Inputs of SWAT Model

5.3. SWAT Applications

The SWAT model is applied in various management practices including drought management, rainfall-runoff management, soil erosion/ sediment yield estimation, crop management, flood management, extreme flow condition simulations and water balance studies.

Table 3. Various management practices simulated by SWAT model

SWAT model simulates		
Sub-basin components	Reservoir components	Channel components
o Evapotranspiration o Erosion o Soil and water movement o Surface runoff o Carbon cycling and soil nutrient o Crop growth yield o Bacteria degradation	o Water o Sedimentation and pollutants o Degradation of nutrient, pesticides and bacteria	o Routing of flow o Settles and incorporates sedimentation o Degradation of nutrient, pesticides and bacteria

The application of SWAT model in a watershed is simulation of the hydrologic cycle to achieve a water balance for sustainable development. SWAT model is applied to simulate the influences of land and water management practices in a wide range over a long period of time. Arnold, *et al.*, 1998, King *et al.*, 1999, Spruill *et al.*, 2000, Shirmohammadi*et al.*,2001, Van Liew and Garbrecht 2001, Douglas-Mankin, K. R.,2010 ,Qiu and Prato 2001, Benaman*et al.*, 2001, Rosenthal and Hoffman 1999, Rosenthal *et al.*, 1995, Peterson, J.R. and J.M. Hamlett. 1998, Vache*et al.*, 2002, Bingner 1996, Stonefelt*et al.*, 2000, Stone *et al.*,2001, Santhi*et al.*,2001, Varanou*et al.*, 2002, Gassman, P.W. *et al.*, 2007,Chandniha, S.K. *et al.*, (2022),Kelkar *et al.*, (2008), Tripathi, *et al.*,(2002), have described the applications of SWAT model.

The SWAT model has been widely applied in various hydrological and environmental studies. It has been used to predict streamflow and water balance in river basins, assess crop water productivity and identify water-stressed watersheds. The model has also been employed to evaluate the impacts of climate and land use changes on water resources and to simulate rainfall-runoff processes in different river basins. Additionally, SWAT has been utilized for nonpoint source pollution control, sediment and nutrient loss management and channel erosion prediction. Calibration and validation of the model using field-scale data have been performed to improve its accuracy and effectiveness in these applications.

6. SWAT Model Performance

Studies show the model can be calibrated and validated on daily, monthly and yearly scales, using graphical and statistical measures such as R², RMSE, NSE, PBIAS, KGE, t-test and nonparametric tests (Moriasi*et al.*, 2007). Srinivasan *et al.* (1998) calibrated and validated sediment yield forecasts for a Texas watershed, while Benaman*et al.* (2001) noted that the model underestimated sediment yields during high streamflow months in the Cannonsville Reservoir watershed in New York. Baffaut and Sadeghi (2010) reviewed fecal bacteria modeling with SWAT, concluding that calibration and validation processes produce optimal results, but improvements are needed for more accurate future comparisons.

7. Summary and Conclusion

In conclusion, the review of the hydrologic model has provided valuable insights into its performance, strengths and limitations. The hydrologic models have been recognized as a useful tool for simulating and predicting hydrologic processes, aiding in the understanding of water availability, runoff patterns and the overall hydrological response of a given system.

One of the major strengths of the model is its potential to incorporate various input parameters, such as precipitation, land cover, soil properties and topography, to simulate the complex interactions within a watershed. By accurately representing these components, hydrologic models can serve as a valuable decision support tool to provide reliable predictions of streamflow, groundwater levels and other hydrological variables, which are essential for effective water resources management, flood forecasting and environmental impact assessments.The hydrologic model reviewed in this study has demonstrated its potential as a valuable tool for understanding and predicting hydrological processes. Its ability to simulate complex interactions within a watershed and provide insights into water availability and runoff patterns is commendable. However, it is crucial to acknowledge its limitations and uncertainties and exercise caution in interpreting its results. Continued research, data collection and model refinement are necessary to further improve the accuracy and applicability of hydrologic models in addressing real-world water resource challenges.

SWAT model has been used to conduct several long-term and continuous flow simulations, transport of sediment and nutrients and soil erosion in watersheds with various sizes, hydrologic, geologic as well as climatic variables. The model has proven to be useful in exploring influences of climatic changes on water yields for a long time period and the impacts of different management practices on long-term sediment and nutrient loads.In conclusion, the SWAT (Soil and Water Assessment Tool) model has proven to be a valuable tool in the field of hydrological research. Through its ability to simulate complex processes related to water quality and quantity, the SWAT model has enabled researchers to gain a deeper understanding of watershed behavior and the impacts of various land management practices.

The research conducted on the SWAT model has showcased its versatility and applicability in a wide range of environmental and agricultural studies. It has been successfully employed in assessing the impacts of land use changes, such as urbanization and agricultural practices, on water resources. Additionally, it has been instrumental in evaluating the effectiveness of best management practices (BMPs) for mitigating water pollution and improving watershed management strategies.The model's ability to integrate different data sources, including climate data, land use data, soil properties and hydrological characteristics, allows for comprehensive analyses and more accurate predictions. Furthermore, its user-friendly interface and flexibility make it accessible to a wide range of researchers and decision-makers.

However, it is important to acknowledge the limitations of the SWAT model. The accuracy of its predictions relies heavily on the availability and quality of input data, which can be a challenge in certain regions or for specific parameters. Furthermore, the model's complexity may require advanced technical skills and computational resources, posing barriers for some users.Despite these limitations, the SWAT model remains a powerful tool for understanding and managing watershed systems. Future research and development efforts should focus on improving the model's performance, enhancing data availability and refining its calibration and validation processes.

In summary, the SWAT model has proven to be an invaluable asset for studying hydrological processes, water quality management and land use planning. Its ability to simulate and analyze complex watershed systems has contributed significantly to our understanding related to water resources and their response to various land management practices. By leveraging its strengths and addressing its limitations, the SWAT model will continue to play a crucial role in guiding sustainable water resource management in the future.

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