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Review Article

Review and Comparative Study of Hydrological Models for Rainfall-Runoff Modelling

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Abstract

Water is considered as an important resource for human existence on the earth. In order to simulate or optimized hydrological data for various water resources management, several hydrological models are very useful to attain this aim for water resources management and as a decision support tools. A rainfall-runoff model is a quantitative prototype explaining the rainfall-runoff interactions at basin scale. The hydrological models have peculiarities in terms of capabilities for various water resources management. This paper reviews over fifty (50) papers that are peculiar to hydrological models as applicable to rainfall-runoff modeling. It involved evaluating and comparing different hydrological models used in simulating rainfall process converting into surface runoff for water use efficiency. Several runoff models such as Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS), Soil and Water Assessment Tool (SWAT), Precipitation-Runoff Modeling System (PRMS), Variable Infiltration Capacity model (VIC), LISt-based Erosion Model (LISEM), MIKE Surface Water - Groundwater Hydrology (MIKE SHE) and Runoff Prophet were critically assessed. Rainfall-runoff models are globally utilized for different applications to enhance water use efficiency across different sectors. However, types of hydrological models by examining various hydrological models, model accuracy by evaluating the accuracy and reliability of each model in predicting runoff from rainfall data, scope of applications by determining the adequacy of the models for numerous geographical regions and climatic circumstances, complexity and usability by assessing the complexity of the models, their data requirements, ease of use and computational efficiency, also the models advantages and limitations in capturing the dynamics of the rainfall-runoff process were critically assessed. This was to aid modeling objectives. It was inferred that HEC-HMS is widely applied for modelling precipitation-runoff processes in watersheds of various sizes, aiding in flood forecasting, reservoir operation, and water management for agricultural and urban water use efficiency. SWAT is used for assessing the impact of land management practices (e.g., crop rotation, irrigation, land use changes) on water resources, including runoff generation and water quality, thus optimizing water use efficiency in agriculture. PRMS is applied to model the transport of water via complex hydrological systems, aiding in watershed management and water use efficiency assessments. In conclusion, this comparative review seeks to guide water scientists, the users of hydrological models and hydrological engineers in selecting the most suitable models for their specific modelling needs for sustainable water resources management.

Keywords: Hydrological models, Rainfall-Runoff simulation, Sustainable water resources management, Earth

Introduction

Hydrological modeling is very significantly used in comprehending the robust principles of the hydrological cycle for an efficient water resources management. Rainfall-runoff models are categorized as event or continuous models. Event models specifically calculate the runoff from an individual storm event and evaluate some parts of the hydrologic processes that influence the catchment (Sorooshian *et al.,* 2008). Most event models use a constant time interval, whose value may typically range from minutes to several hours (Vernon *et al.,* 1991). Modelling of hydrological processes requires interdisciplinary approaches. Rainfall runoff models are a tool which contributes to the wider process of making decision on the most suitable strategies for river basin management (Axel, 2004). They are not replacements for direct data sources but they allow most to be made of existing data where such data are scarce (Seethapathi *et al.,*1997). Figure 1 is a streamlined illustration of hydrological cycle and the hydrological cycle has numerous linked parts, with runoff connecting precipitation to bodies of water (Brewster, 2017; ESRI, 2015). Surface runoff is precipitation that does not infiltrate into the soil and runs through the land surface into surface waters such as streams, rivers, lakes or other reservoirs (Perlman, 2016). Surface runoff varies by time and location, with about one-third of the precipitation that falls on land turning into runoff; the other two-thirds is evaporated, transpired, or infiltrated into the soil (Perlman, 2016). Hydrological modeling can be defined as a powerful technique of hydrologic system investigation for both the hydrologists and the practicing water resources engineers involved in the planning and development of integrated approach for water resources management (Schultz, 1993; Seth, 2008). Modeling runoff helps gain a better understanding of hydrologic phenomena and how changes affect the hydrological cycle (Xu, 2002). Hydrological modeling involves the use of mathematical and computational models to simulate the behavior of hydrological systems, such as rainfall-runoff processes, groundwater flow, and water quality dynamics (Beven and Freer, 2018). These models are essential tools for water resources management, flood forecasting, and assessing the impacts of climate change on hydrological systems (Wagener *et al.,* 2010). Rainfall-runoff models are often used as a tool for a wide range of applications such as the modeling of flood events, the monitoring of water levels during different water conditions or the prediction of floods (Tassew *et al.,* 2019). Several research studies have demonstrated that HEC-HMS is highly effective in simulating runoff based on rainfall data with specific catchment (Tassew *et al.,* 2019; Rangari *et al.,* 2018; Chang *et al.,* 2015). Mukherjee, (2016) revealed that urbanization greatly influenced the runoff generation. Hydrological models are classified into empirical models, conceptual models, physical process-based models, and data-driven models (Beven, 2011, Xu, 2002, Anshuka *et al.,* 2019). The physical process based models follow the principles of physical processes in modelling runoff, and these models represent catchment behavior in terms of differential equations in both space and time (Devia *et al.,* 2015). The models can be calibrated with limited meteorological and hydrological datasets. Certain distributed-parameter, lumped-parameter, and semi-distributed models example is HEC-HMS model while the Semi-distributed and process-based model example is SWAT. Distributed-parameter model example is PRMS while Distributed-parameter and physically-based model example is Variable Infiltration Capacity model (VIC) model. The hydrological models vary in complexity and applicability depending on the particular goals and attributes of the case study. They are essential tools for assessing and optimizing water use efficiency across different sectors, including farming, city water systems, water-generated electricity, and biodiversity preservation. The importance of hydrological modeling lies in its ability to provide insights into the behavior of hydrological systems under different conditions, aiding in decision-making processes related to water resources management and environmental protection (Hrachowitz *et al.,* 2013). By simulating the movement of water through the landscape, hydrological models can help identify areas vulnerable to flooding, optimize water allocation for irrigation, and assess the potential impacts of land use changes on water availability (Batie, 2013). Runoff models depict those effects on water systems resulting from alternatives in land cover, flora, and weather phenomena. Devi *et al;* (2015) defines a runoff model as a set of equations that aid in the estimation of the amount of rainfall that turns into runoff as a function of various parameters used to describe the watershed. Lumped conceptual hydrologic models consider three basic processes within a river basin: the loss of water from storage to atmosphere; storage of water in soil, vegetation, aquifer, and in rivers; routing of flow over the surface (Gosain *et al.,* 2009).

Kisi *et al.,* 2013 performed rainfall-runoff process modeling utilizing artificial intelligence methods. The PRMS models are utilized to some precipitation run-off and snowmelt simulation. Numerous parameters are recognized for comprehensive simulation by complex hydrological models (Eckhardt and Arnold, 2001) where, interaction of parameters requires attention by experts. Abbaspour *et al.,* 2007 pinpointed that two important various variables clusters give analogous signals in the measured data in the adjustment process. The SWAT (Soil and Water Assessment Tool) program is a semi-distributed, continuous-time, process-based model (Arnold *et al.*, 1998, 2012). The model operates on a daily time step, and it has been recently updated to sub-daily time step computations (Jeong *et al.*, 2010). In view of the above introduction, the paper stressed on review and focuses on the comparative analysis of several hydrological models for rainfall-runoff modeling and reveals significant variability in model performance and applicability based on spatial and temporal scales, data availability, and specific catchment characteristics coupled with the application of these hydrological models for various development. The review in all also stressed on providing insights into the best practices and guidelines for selecting the right hydrological models for specific rainfall-runoff simulation demand.

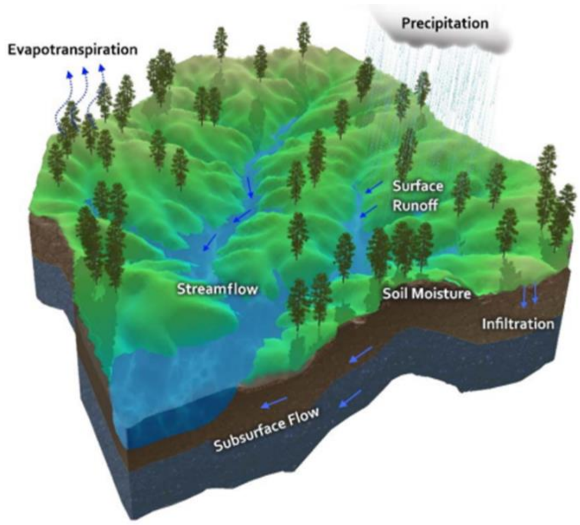

Fig. 1. A streamlined illustration of the hydrological cycle regulated by the water balance equation (Brewster, 2017; ESRI, 2015).

Hydrological Models Categorization

A model constitutes streamlined abstraction of an actual mechanism. The optimal model is the one that yields outputs nearness to exactness while using fewest variables and minimal conditions. Numerous types of hydrological models have been developed aimed at representing the spatial changes of catchment characteristics (Sun *et al.,* 1998). Models can be categorized in reference to the capacity to depict the spatial changes of the basin into lumped, semi-distributed and fully distributed models. Each group of models has its own capabilities and weakness, thus categorizing them to be considered useful for a particular applications to water resources management. Physically based distributed models offer numerous merits in evaluation with traditional lumped. Parameters models in simulating hydrologic response to forest management and global change (Sun *et al;* 1998, 2007). There are several catchment-level hydrologic models. Models selection depends on the intended goals. Hydrological models can typically be categorized into two: the conceptual models and physically-based models.

Conceptual Models

The models simplify hydrological fluxes to better convey the process into several storage components and flow paths. They are typically parameterized using empirical relationships (Chow, 1988). Examples include Tank Model, which represents the watershed as a series of interconnected tanks. Hydrologic Engineering Center-Hydrologic Modelling systems (HEC-HMS) is another example which uses a combination of empirical and semi-distributed approaches (Figure 2). Another example is the Soil Conservation Service Curve Number (SCS-CN) method. Conceptual models balance complexity and simplicity making them widely used in practice. Conceptual models are well known globally in the modeling domain owing to the flexibility in the usage and calibration. With some, there is a likelihood that a previously calibrated model can be used for a different catchment (Vaze, 2012). TOPMODEL (Topography based Hydrological Model), HBV (Hydrologiska Byråns Vattenbalansavdelning), NWSRFS (National Weather Service River Forecast System), and HSPF (Hydrological Simulation Program- Fortran) are other examples of Conceptual models. Table 1 summarized the characteristics of the Model Classifications.

Physically-Based Models

Physically-based models (Figure 2) replicate hydrological fluxes in accordance with the established physical principles. These simulations require detailed data and have a more complex structure. Examples include: Soil and Water Assessment Tool (SWAT) which integrate land surface processes with hydrological cycles. MIKE SHE is another example which involved comprehensive model covering surface water, groundwater and their interactions (Singh, 1995). Physical models, also called process-based or mechanistic models, are based on the understanding of the physics related to the hydrological processes (Vaze, 2012). Physical models integrates spatial and temporal variations within the catchment, closely mirroring real-world systems. They excel when exact data and a deep understanding of hydrological fluxes are available for accurate applications at a scale that's reasonable, despite considerations for computational time. VELMA (Visualizing Ecosystem Land Management Assessments), VIC (Variable Infiltration Capacity Model), PIHM (Penn State Integrated Hydrologic Modeling System), and KINEROS (Kinematic Runoff and Erosion Model) are other examples of a physically based models (Singh, 1995).

Empirical Models

They are also known as black-box models, relying on historical data and statistical relationships to predict hydrological responses. They do not require a deep understanding of the underlying processes but are effective for specific data rich scenarios (Beven, 2012). They are occasionally labeled as data-driven models, employing non-linear statistical correlations between variables and results. They are observation-oriented and depend heavily on input accuracy (Kokkonen *et al.,* 2001). Empirical models can yield accurate simulations in many situations including long time steps and recreating past runoff values (Vaze, 2012; Xu, 2002). Regression equations, and Artificial Intelligence are typical instances of the models that are in this category of models.

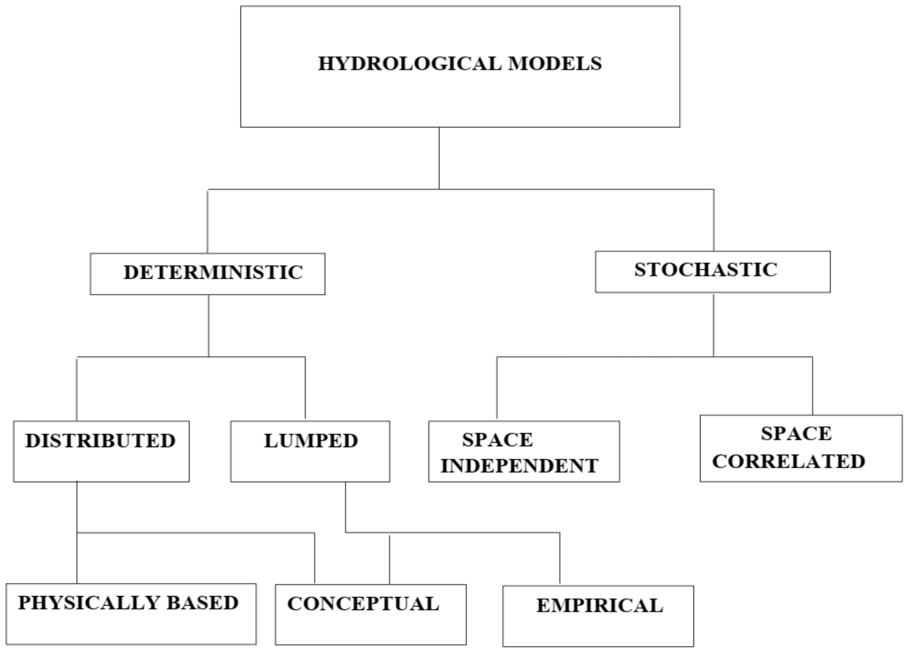

Fig. 2: Types of Models (Singh, 1995).

Table 1: Summary of the Properties of the Model Classifications

Conceptual Models	Physically-Based Models	Empirical Models	Distributed Models	Stochastic Models
Parameterized using empirical relationships	Have a more Complex structure	It is a data driven model	Used for large and heterogeneous watersheds	Used for risk evaluation and long term forecasting
Simulate hydrological process into series of components and flow paths	Simulate hydrological process based on physical laws	A black box model	The simulation model's accuracy enhanced with the precision of the foundational data and parameters provided.	Used randomness and probabilistic approaches for its operation
A grey box model and flexible to use	Required detailed data	Heavy relies on historical data and	The user interface is straight forward and user friendly	The same model input can result in a different model output for the same model setup
Flexible calibrate for simulation from field data and calibration	Possess analogous architecture ,almost the same to the real life system	Incorporate non-linear statistical dependencies to link variables and results	Each components of the model can be computed using separate increment size	Observed value at each time is a random value
Single parameters can often not be measured directly	Strong correlation between model parameters and physical attributes of the catchment	Rely on statistical relationship to predict hydrological responses	only for white box and grey box models, raster and grid based	Uses mathematical model and has the capability to handle uncertainty in the input applied
Examples are Tank Model, HEC-HMS,SCS-CN, TOPMODEL, HBV, NWSRFS	Examples are VELMA, SWAT, SHE, VIC,PIHM,KINEROS,HSPF	Examples are Regression equation, Artificial Intelligence	Examples are MIKE SHE, PRMS, DHSVM TAC^{D}, LARSIM	Examples are Markov-Chain Model, Monte Carlo Model, Regression Model

Distributed Models

These models simulate spatial changes by segmenting the study area within a grid or sub-catchment allowing for detailed representation of land surface characteristics. They are useful for large and heterogeneous watersheds (Maidment,1993). Examples include MIKE SHE and the Distributed Hydrology Soil Vegetation Model (DHSVM). These categories of models are intricate owing to the fact that they describe the spatial diversity in data and criteria and simulate the estimated runoff from individual grid to the closest grid, in accordance with the fundamental laws utilized in evaluating flow trajectory and inherent delays. Distributed models study impacts of basin change on runoff values (Singh, 1995).

Stochastic Models

These incorporate randomness and probabilistic approaches to account for the inherent variability and uncertainty in hydrological processes. They are often used in risk assessment and long term forecasting (Van and Bras, 1990).

Architecture of Hydrological Models

A model's framework depicts the way runoff is estimated and some of the hydrological models can be easily applied with a limited number of parameters whereas others need a multitude of interconnected parameters. The architecture of a model varies from basic to intricate, according to established principles. Physical and conceptual models need thorough understanding of the physics involved in the movement of surface water in the hydrological cycle (Srinivasulu, 2008). Models are deployed based on an established procedures modeling (Figure 3). Many models overlap within this classification of model structure (Pechlivanidis *et al.*, 2011). General structure of a hydrological models is schemed in figure 2 and the modelling flow path way in figure 3. These hybrid models uses the power of more than one model framework, but are predominantly tagged as consisting parts of the framework described in this review. Overall properties of the most of Rainfall runoff models is partitioned of the watershed to various division, primarily vertically organized. Numerous equations are used for simulation to model the fluxes occurring within each of storage units. The General architecture of a hydrological model is shown in figure 2 (Connor, 1976). Manuscript preparation: Please write your text in good
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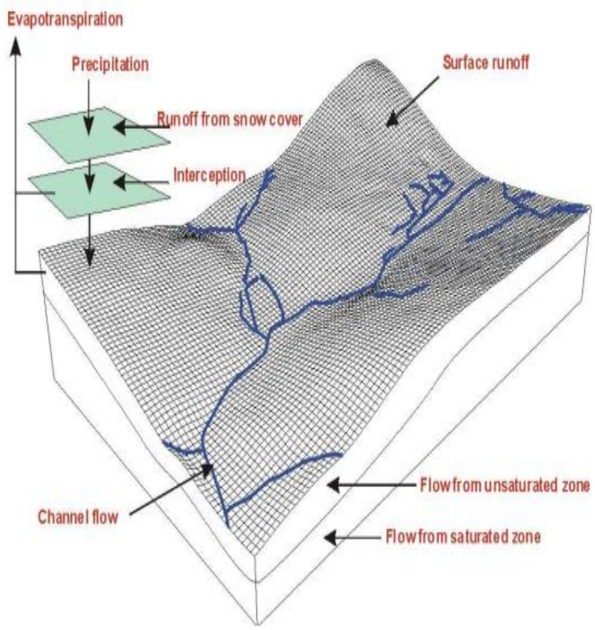

Fig. 2: General Architecture of a hydrological model

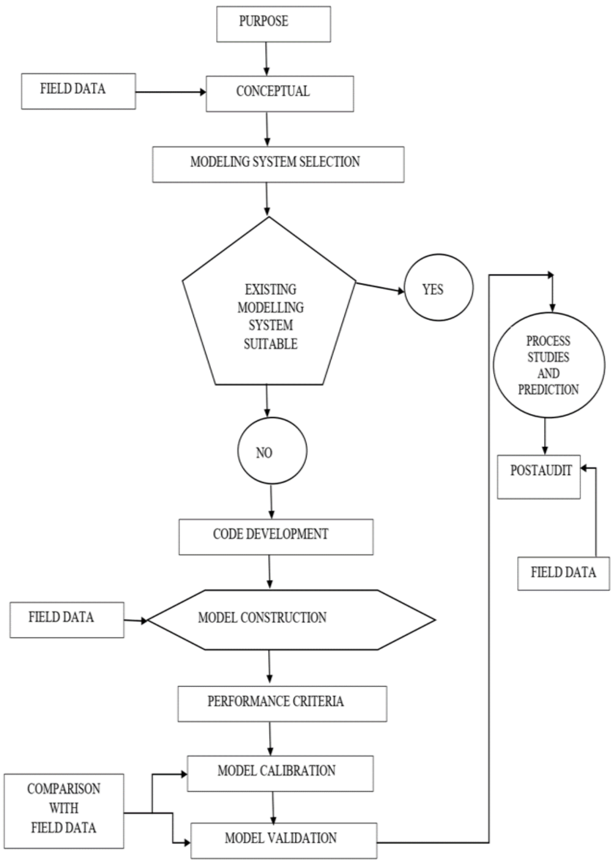

Fig. 3: Flowchart showing Modelling Procedures (Refsgaard, 1996)

Synopsis of Hydrological Models Types

Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS)

HEC-HMS hydrological model is a distributed-parameter, lumped-parameter, and semi-distributed models. It is widely used for simulating precipitation-runoff processes in watersheds of various sizes, aiding in flood forecasting, reservoir operation, and water management for agricultural and urban water use efficiency. It consists of the following components which are Runoff-volume models, Base flow models, direct-runoff models and, a unit Hydrograph method.

Soil and Water Assessment Tool (SWAT)

SWAT is a Semi-distributed, process-based model utilized for assessing the effect of land use practices e.g., crop rotation, irrigation, land use changes on water resources, including runoff generation and water quality, thus optimizing water use efficiency in agriculture. It operates on the principle of the water balance in reference to four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. The water balance is used in individual hydrological domain and runoff is collated over the basin segment. The cumulative loads are ultimately routed through flows and reservoirs to the catchment outlet. The physical fluxes utilized in SWAT are rainfall, interception, evapotranspiration, surface runoff, infiltration, percolation, and sub-surface runoff.

MIKE SHE (MIKE Surface water-Groundwater Hydrology)

MIKE SHE, Système Hydrologique Européen, is a sub-model under the collection of models within the MIKE framework from the Danish Hydraulic Institute (DHI) and a coupled surface water and groundwater model. (Zhao *et al.,* 2018). The model Integrates surface water and groundwater interactions to simulate hydrological processes, influencing water availability and water use efficiency assessments in river basins and urban water supply systems. It is a greatly distributed, physically-based hydrologic modelling domain to model surface flow as runoff and subsurface flow system. The model encompasses the main fluxes in the water cycle and contains flux prototype for evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flow and their interrelationships. The distributed watershed hydrologic simulation model, MIKE SHE originally derived from the SHE model (Abbott *et al.*, 1986a, b). The model explain hydrological and physical fluxes on the basis of partial differential equations of mass and momentum conservation (Zhao *et al.*,2018).The General MIKE SHE Catchment modeling is shown in Figure 4.

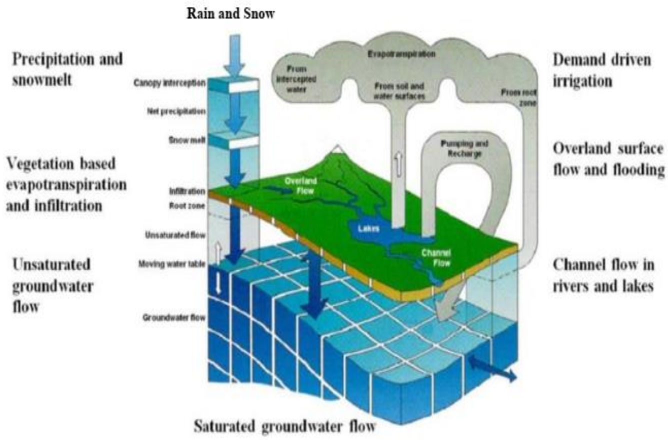

Fig. 4: MIKE SHE Catchment Modelling environment

Precipitation-Runoff Modeling System (PRMS)

The Precipitation-Runoff Modeling System is a deterministic, distributed-parameter, physical process-based modeling system developed by the United States Geological Survey (USGS) to evaluate the response of various combination of climate and land use on streamflow and general watershed hydrology (Markstrom *et al.*, 2015). The model serves to model the flow of water via intricate hydrological systems, aiding in watershed management and water use efficiency assessments (Figure 5). The model interface design gives the users to predominantly join the modules at the interface to have a self-design prototype (Figure 6). At the larger level, the model has been world widely tested and utilized for rainfall runoff modeling in a basin domain. PRMS is a computer models that simulate the hydrologic cycle at a watershed scale facilitate assessment of variability in climate, biota, geology, and human activities on water availability and flow. Figure 5 shows a schematic diagram of a watershed and its climate inputs simulated by the

Precipitation-Runoff Modeling System (Fei *et al.*, 2017) which integrates several input data to simulate hydrologic processes.

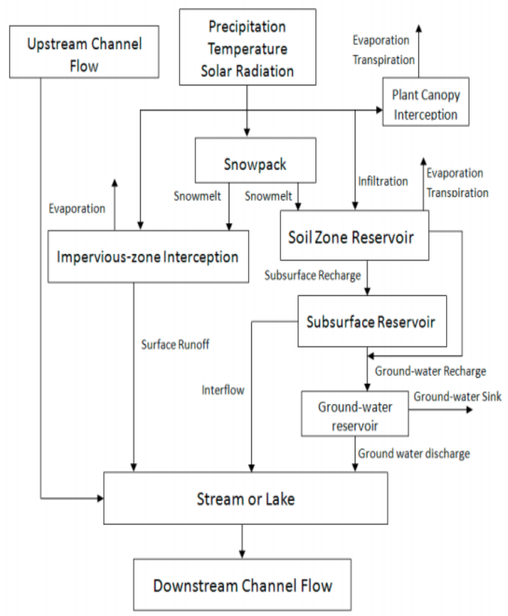

Fig. 5: Schematic diagram of a watershed and its climate inputs simulated by the Precipitation-Runoff Modeling System (Fei *et al.*, 2017).

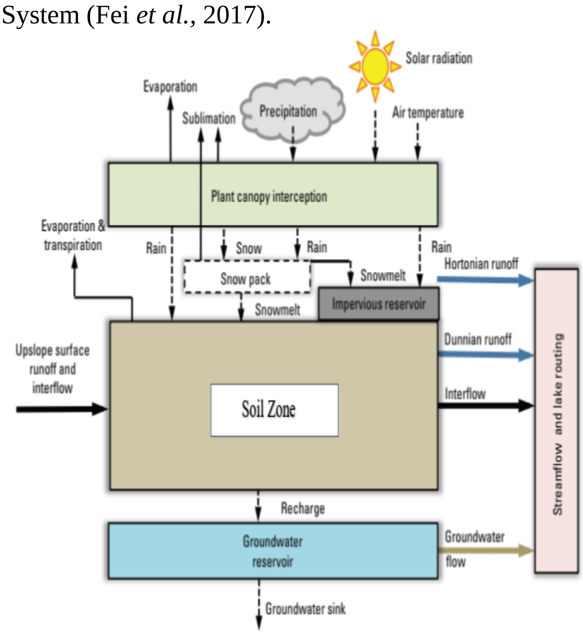

Fig. 6: Hydrological processes simulated by the Precipitation –Runoff Modeling system (Markstrom *et al.*,2008).

Runoff Prophet

Runoff Prophet is a model that simulates river flow in catchment areas. According to Abbot and Refsgaard (1996), it is a simple, predictable model that works on a monthly basis. It only needs the area of the catchment for calculations, without any other geographical details. The model uses water balance equations from Wang *et al.* (2013) and is designed for monthly calculations. It considers two main parts of total discharge: surface flow and groundwater flow, and also accounts for potential evapotranspiration and soil moisture.

Variable Infiltration Capacity model (VIC)

It is a distributed-parameter, physically-based model and it is used for simulating Key elements of the water cycle, encompassing runoff, evapotranspiration, and soil moisture changes across large river basins and regions, supporting water resource management and climate change impact studies. It can he improved VIC model includes Runoff from excess rain, Runoff from saturated soil and impact of soil differences on surface runoff. It can deal with the dynamics of surface and groundwater interactions and calculate ground water table (Gao, 2010) and can be applied in cold climate. The model is now adays used to notable of catchment and enhanced in simulating climate and change in land use within a particular region.

Review of Application of Existing Hydrological Models

Many hydraulic and hydrologic models have been used globally (Neitsch *et al.*, 2005). Most of the researchers applied manual calibration to obtain optimum parameter values (Civita *et al.*, 2009). Few models were calibrated and evaluated by sensitivity and auto calibration procedures.

Muhammad *et al.*, 2019 research on Studying changes in water patterns in Bogura districts, Bangladesh using the MIKE SHE model to predict future groundwater levels and resources. The results show from the simulation that the year 2006 to 2030 in the study area shows water table depletion rates ranging from 0.00 to 2.92 cm/year on average.

In 2021, Mohammed et al, studied how rainfall affects runoff in Kano city's Challawa and Jakara catchment areas. They used Digital Elevation Models (DEMs) and transferred basin models from ArcGIS 10.7 to the Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS). They then developed meteorological models in HEC-HMS, specifying rainfall data and simulation details

Muhammad *et al.* (2022) reviewed advancements in rainfall-runoff modeling for better flood prevention. They discussed the pros and cons of different models for understanding runoff changes and predicting floods. Their study suggested creating hybrid models that blend traditional methods with machine learning to enhance runoff modeling and flood forecasts.

In 2017, Jan *et al*. reviewed various rainfall-runoff models to help modelers understand their types and applications. They grouped these models into empirical, conceptual, and physical categories, and classified them as lumped, semi-distributed, or distributed.

In 2011, Hosseini *et al.* used the SWAT Model to estimate runoff in the Taleghan Catchment, Tehran, Iran. They found that surface runoff was 21% of rainfall in the upper part and 33% at the outlet. Groundwater and lateral flows were higher in the mountainous upper area, contributing 23% and 17%, respectively.

Evgenia *et al.*, 2023 researched hydrological modeling in Athens, Greece, using the Soil and Water Assessment Tool. They looked at runoff in urban areas, finding that daily rainfall predictions were more accurate than hourly ones when using different methods to estimate surface runoff.

In 2011, Kumar created a method to model how rainfall causes runoff in a catchment. The catchment was divided into sections that aligned with the number of rain gauge stations. Rainfall recorded at each station was assumed to evenly distribute across its respective section of the catchment.

Tramblay *et al.*, 2011 investigated how using rainfall data from specific locations, rather than average rainfall across an area, enhances flood prediction models. They found that this approach improves the accuracy of predicting major flood events.

In 2014, Choudhari used a computer model called HEC-HMS to see how rain in the Balijore Nala area of Odisha, India, turns into water flowing in streams. They measured how much water flows, how fast it flows, and used different ways to calculate these, like looking at the shape of the land and how water flows downhill. They studied rainfall from 24 storms between 2010 and 2013 to understand these processes better.

Meng *et al.,* 2019 explored how the MIKE SHE Model works in the Jialingjiang River Basin. They described how this model is structured and its key features for understanding water flow in the area.

Tian *et al;* 2016 investigated how accurately the MIKE SHE model simulated runoff in the Bahe River Basin. They found that the model performed well in predicting annual runoff for the basin.

In 2017, Liu and his team used satellite data to create a computer model for predicting daily water flow in the Yarkant River Basin. Their model performed well, accurately matching real-world measurements using MIKE SHE model.

Lu *et al.,* 2014 simulated the hydrological process in Bajiang River Basin by MIKE SHE. The outputs depict that the model is capable of modeling temporal origin of water flow.

In 2017, Fei and colleagues used a computer model called PRMS to predict how much water would flow each day in the Zamask-Yingluoxia area of the Heihe River Basin. Their model did a good job matching actual river flows at Yinglouxia station, showing it could be useful for managing floods and water resources in that area.

In 2005, *Xia et al.* used a computer model to simulate how rain and melted snow create runoff in the upper Heihe River mountains.

In 2015, Li and Wu applied the SWAT model to predict daily rainfall runoff in various parts of the Heihe River Basin, achieving improved accuracy with a correlation coefficient of 0.89.

Li *et al.*,2015 conducted hydrological modeling across both the upper and middle reaches, comparing the performance of a distributed hydrological model.

In 2016, Imene and colleagues used a computer model called HEC-HMS to study how water behaves in the Wadi Ressoul watershed in Algeria. They found that the model accurately predicted how much water flowed, with a very small difference between their predictions and actual measurements. Their model's results were quite close to what they observed, showing it worked well for studying water in that area.

In 2012, Santosh and his team examined various algorithms for forecasting rainfall-runoff to enhance water management. They reviewed the strengths and weaknesses of these algorithms and suggested a new framework for improving water consumption predictions in runoff models.

In 2018, Ayushi and others looked into how rainfall turns into runoff. They found it's hard to predict runoff accurately for planning water resources in areas with rivers and streams. They suggested that developing and testing different models could help us figure out how much water we have and use it better in those places.

In their study, Carpenter *et al.* (2001) looked at how a water model responds to different factors like rainfall data. They found that using radar data like NEXRAD gave results similar to simpler models that use rain gauges. They also found that the effects of model settings and radar rainfall data varied depending on the size of the area they studied.

Katerina and Daniel (2019) studied how rainfall affects river flow in the Morava river basin, Czech Republic, using Runoff Prophet Software. They found that the software is good at predicting long-term changes in water levels. It's useful for figuring out how landscapes balance water and for planning how much water future reservoirs will have.

Gayathri *et al.,* (2015) looked at different hydrological models to see how well they work in wet areas for managing water in agriculture. They compared models like SWAT, VIC, MIKE SHE, HVB, and TOPMODEL to see how they simulate rainfall and runoff, and how useful they are in various situations.

Tripti *et al.* (2022) used the HEC-HMS model to study the Bhagirathi River Basin from 2010 to 2015. They found that the model closely matched the actual data, showing it can accurately simulate river conditions.

Michal Jeníček (2007) looked into how rainfall causes runoff in small and medium-large catchments. The review categorized models by how they explain this process: some are deterministic or stochastic, and they vary in how they handle time and space-whether continuously or during events, and whether they model the entire area or just parts of it.

Comparative Analysis of the Hydrological Models

In this, only the conceptual and physically based models were compared because the hydrological models are strictly categorized into two major types based on the data requirement, complexity in computation, accuracy and precision, flexibility and applicability and based on these characteristics, comparative assessment of different hydrological models was done(Table 2).

Data Requirements

The conceptual models specifically required fewer data inputs for simulation, thus enabling the models more adequate for regions with few data availability while the physically based models required large datasets including land use, properties of the soil, and data on topography.

Complexity in computation

The conceptual models are less computationally intensive and easier to use for a particular modelling while the physically based models are more computationally demanding owing to the complexity of the processes simulated.

Accuracy and Precision

The conceptual models give a tangible for large-scale and long-term predictions but may precision in fine-scale applications. The physically-based models offer higher precision and exactness for small scale and even based predictions owing to detailed process representation.

Flexibility and Applicability

The conceptual models required more flexible in terms of parameters adjustment and are used to a large spans of scenarios with minimal calibration while the physically-based models required less flexible but more robust in terms of representing physical processes, enabling the models adequate for elaborate studies in well-monitored catchments.

Table 2:Comparative assessment of different hydrological models

Model Types	Data Requirements	Complexity in Computation	Accuracy and Precision	Flexibility and Applicability	Application in Different Climatic Regions	Scale of Application
HEC-HMS	Moderate: Requires meteorological, land use, soil data	Moderate to High: Uses multiple algorithms	High: Depends on data quality and calibration	Flexible: Suitable for various hydrologic problems	Versatile: Applicable in diverse climates	Watershed to regional scale
SWAT	High: Needs extensive data (weather, soil, topography)	High: Involves complex processes	High: Effective for long-term simulations	Highly flexible: Agricultural management, land use changes	Widely used: Effective in varied climates	Basin to regional scale
MIKE-SHE	High: Requires detailed spatial and temporal data	Very High: Physically based, comprehensive	Very High: Detailed physical representation	Very flexible: Integrated surface water and groundwater, ecohydrological studies	Effective in complex, varied climate	Field to watershed scale
PRMS	High: Requires meteorological, hydrological, topographic data	High: Modular and complex	High: Effective for distributed watershed models	Flexible: Modelling of distributed hydrologic processes	Suitable for different climates	Watershed scale
Runoff Prophet	Low to Moderate: Depends on available data sources	Low to Moderate: Machine learning based	Variable: Depends on training data and model	Flexible: Machine learning adapts to various data inputs	Emerging: Applicability expanding to various climates	Local to regional scale, depending on training data
VIC	High: Needs meteorological, land cover, and soil data	High: Energy and water balance computations	High: Robust for large-scale hydrologic studies	Flexible: Suitable for large-scale water and energy balance studies	Effective in different climates	Regional to global scale
HVB	Moderate to High: Hydrological and meteorological data	Moderate to High: Conceptual model	Moderate to High: Depends on model calibration	Flexible: Can be adapted for various hydrologic conditions	Effective in various climates	Watershed to regional scale
TOPMODEL	Moderate: Requires topographic and hydrologic data	Moderate: Based on topographic index theory	Moderate: Effective for humid, temperate climates	Moderate flexibility: Suited for topography-driven hydrology studies	Best in humid, temperate regions	Watershed scale

Scale of Application

Conceptual models are applied in large river basins such as HEC-HMS are regionally used for basin-wide proactive management while the physically-based models such as MIKE –SHE which provide detailed insights into localized hydrological process are applied in small

Application in different climatic regions

In the tropical regions, the physically based models tend to perform better due to the complex hydrological processes influenced by intense rainfall while in the arid and semi-arid areas, the conceptual models are often used owing to the simplicity and limited data requirement.

Scale of Application

Conceptual models are applied in large river basins such as HEC-HMS are regionally used for basin-wide proactive management while the physically-based models such as MIKE –SHE which provide detailed insights into localized hydrological process are applied in small watersheds.

Conclusion

Review of numerous hydrological models for rainfall runoff modeling has been critically done. It was seen that all the different hydrological models reviewed belongs to a specific type or class of hydrological models and in this review, the characteristics of the models differs in operation, merit and demerits, types of data used, complexity in computation, accuracy and precision, flexibility and applicability, application in different Climatic regions, principles and application scales. Data for simulating an extreme condition for rainfall runoff modeling for water use efficiency are scares and often lack reliability and not often detailed. Because of data scarcity globally especially in areas where the modelers can hardly get data, the hydrological model is thus not suitable for such environmental modelling for water resources management. This review showed that there are need for more elaborate studies for rainfall runoff modeling since there are several emergence hydrological models that are still coming up for future optimization of water resources in Nigeria, Africa in particular and global world. It is of interest to note that during the review, it was deduced that, to perform a more elaborate hydrological modeling, an integrated modelling approach is adequately encouraged. However, the choice of hydrological models for rainfall-runoff simulation relied heavily on particular objectives, availability of the data to be used for the modeling and the application extent. It was concluded that based on the review, for large scale modeling, conceptual models are highly encouraged to be used in a data scarce region, while the physically-based models are preferably utilized for elaborate, miniature scale research. For a vibrant water resources modeling and management, comprehending the strength and weakness of the model is very crucial. The conceptual models are easier to calibrate but may overshoot the simulation which might affect the modeling output while the physically-based models require elaborate calibration data and are more prone to parameter uncertainty.

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