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Comparative Review of Hydrological Models for Runoff Estimation: A Focus on SCS-CN, TOPMODEL, and VIC Approaches– A Review

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Abstract: Accurate runoff estimation is essential for effective watershed management, flood risk mitigation, and sustainable water resource planning. Over the decades, a wide range of hydrological models have been developed, differing in complexity, data requirements, and spatial–temporal resolution. This review provides a comparative evaluation of three widely used models—*the SCS-Curve Number (SCS-CN) method*, *TOPMODEL*, and the *Variable Infiltration Capacity (VIC) model* with emphasis on their underlying structure, hydrological processes, applicability, and performance across various hydro-climatic and land use scenarios. The SCS-CN method, although empirical in nature, remains a preferred tool for event-based runoff estimation due to its simplicity and minimal data demands. *TOPMODEL*, a semi-distributed conceptual model, links runoff generation to terrain-driven saturation dynamics, making it well-suited for humid and sloped watersheds. On the other hand, *VIC*, a semi-distributed, physically-based model, enables large-scale and climate-sensitive hydrological simulations by coupling water and energy balances within a grid-based framework. This review synthesizes recent literature to outline the strengths and limitations of each model, offering guidance for researchers and water managers in selecting appropriate runoff modeling tools based on watershed characteristics, modeling objectives, and available data resources.

Keywords: Runoff Estimation, SCS-Curve Number, TOPMODEL, VIC Model, Hydrological Modeling, Watershed Management, Rainfall–Runoff Simulation, Model Comparison, Remote Sensing, GIS Integration

Introduction

Background & Significance of Runoff Estimation: Surface runoff is a key component of the hydrological cycle, and its estimation plays a central role in watershed hydrology and sustainable water resource management. Runoff refers to the portion of rainfall that flows over the land surface, eventually reaching streams, rivers, or other water bodies, and its accurate assessment is essential for flood forecasting, soil conservation planning, and the design of hydraulic structures (Chow, Maidment, & Mays, 1988). Changes in land use, such as urbanization and deforestation, significantly influence runoff generation by altering infiltration rates and increasing impervious surfaces. Additionally, increased variability in rainfall due to climate change has made runoff modeling more challenging and more essential (Bronstert, 2003). These dynamics have driven the development and application of hydrological models that simulate surface runoff under a variety of environmental and climatic conditions. Several models are available for estimating runoff, ranging from simple empirical approaches to complex physically-based systems. The SCS-Curve Number (SCS-CN) method remains popular for its ease of use and minimal data requirements, particularly in data-scarce or small watershed conditions. In contrast, more advanced models such as TOPMODEL and the Variable Infiltration Capacity (VIC) model provide deeper insights into hydrological processes through spatially and physically-based formulations. TOPMODEL emphasizes topographic control on runoff generation, making it suitable for humid, sloping terrains where saturation-excess flow dominates (Beven & Kirkby, 1979), while VIC integrates water and energy balance components across large-scale gridded domains, supporting applications in climate-sensitive and data-rich regions (Liang et al., 1994). Evaluating and comparing these models is essential for selecting the most suitable approach based on study goals, watershed conditions, data availability, and the spatial and temporal complexity of the hydrological system.

Role of Hydrological Models in Watershed Management: Hydrological models serve as powerful tools in understanding, managing, and predicting water-related processes within a watershed. These models simulate the complex interactions between climatic inputs, land surface conditions, soil characteristics, and hydrologic responses such as runoff, infiltration, evapotranspiration, and groundwater recharge. Their role in watershed management has become increasingly vital due to growing concerns about water scarcity, land degradation, and climate variability. At the core of watershed management lies the need to assess how land use and land cover changes, soil types, slope, and rainfall patterns influence hydrological processes. Hydrological models help quantify these effects by transforming rainfall into runoff and tracing water movement across the landscape. This simulation capacity allows decision-makers to evaluate the impacts of various land management scenarios, such as deforestation, agricultural intensification, or urban expansion, on the quantity and timing of surface water flows (Beven, 2012).Furthermore, models like SCS-CN, TOPMODEL, and VCI assist in identifying critical source areas of runoff and sediment yield, enabling targeted interventions such as check dams, afforestation, or rainwater harvesting. Hydrological models also play a crucial role in integrating spatial data from remote sensing and GIS. These geospatial tools enhance model input accuracy by providing updated information on land use, soil texture, elevation, and vegetation indices (Fohrer et al., 2001). As a result, watershed-scale planning becomes more data-driven and scenario-based, leading to more effective and sustainable management strategies. In summary, hydrological models act as decision-support systems, enabling the analysis of watershed behavior under various land and climate scenarios. They support the design of effective water conservation measures, flood control infrastructure, and sustainable land use plans by providing a scientific basis for intervention.

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Aim and Scope of the Review: The aim of this review is to critically evaluate and compare the functional capacities, methodological structures, and application domains of three widely used hydrological models—SCS-CN, TOPMODEL, and VIC with a special focus on their effectiveness in runoff estimation and watershed-scale water resource planning. These models, though differing in their data requirements and modeling approaches, serve as foundational tools in understanding how rainfall is transformed into surface runoff under varying physiographic, climatic, and land use conditions. This review is driven by the increasing need for precision in runoff modeling, particularly considering shifting land use patterns, urbanization pressures, and more frequent hydrometeorological extremes. The core objective is not only to delineate the conceptual and technical differences between these models but also to highlight their respective strengths, limitations, and suitability under different watershed scenarios. Each model will be analyzed based on criteria such as spatial resolution, temporal scale, input sensitivity, ease of calibration, integration with GIS and remote sensing, and adaptability for future land use and climate projections. The scope of this review also includes exploring how these models contribute to evidence-based watershed management—whether for planning flood mitigation measures, evaluating water balance, or implementing sustainable land management strategies. By including case studies and published applications, the review extends its relevance beyond theoretical understanding to practical implications, helping researchers and planners make informed decisions on model selection and deployment. Furthermore, the review seeks to address existing research gaps by identifying conditions where model accuracy diverges, such as in data-scarce regions, steep or flat terrains, and urban versus agricultural landscapes. Another unique dimension of this review is the integration of model comparison with land use impact assessment, showcasing how runoff modeling not only forecasts hydrologic responses but also quantifies human-induced environmental change. Ultimately, this review offers a technical and comparative lens for researchers, practitioners, and students in hydrology, water resources engineering, and geoinformatics, equipping them with a clearer understanding of when, where, and how these models can be optimally applied for robust runoff estimation and holistic watershed development planning.

Overview of Runoff Estimation Approaches:

Rainfall–Runoff Process: The rainfall–runoff process is a fundamental component of the hydrologic cycle, representing the transformation of precipitation into surface flow that travels over the land and eventually contributes to streamflow, groundwater recharge, or evapotranspiration. When precipitation falls on the Earth's surface, it follows multiple pathways: a portion infiltrates into the soil, some is intercepted by vegetation or stored in surface depressions, while the remaining part flows overland as runoff. The quantity and rate of this surface runoff are influenced by several physical factors, including rainfall intensity, land use, soil properties, antecedent moisture conditions, and topographic slope (Dingman, 2015). Understanding this process is essential not only for predicting streamflow but also for managing floods, planning water resources, and mitigating soil erosion. In hydrological studies, the conversion of rainfall to runoff is typically modeled through mathematical or conceptual frameworks, which simulate how water moves through the landscape. These models are indispensable for the development of infrastructure, agricultural planning, and designing climate adaptation strategies at the watershed level (Beven, 2012).The complexity of the rainfall–runoff process varies depending on the temporal and spatial scale of analysis. At smaller scales or shorter durations, the response of a watershed to rainfall can be rapid and nonlinear, especially in urbanized or steep terrains. Conversely, over larger areas or prolonged periods, processes such as infiltration, storage, and delayed subsurface flow become more influential (Singh & Woolhiser, 2002). As such, runoff modeling serves as a bridge between climate inputs and hydrologic outputs, enabling scientific understanding and practical decision-making in watershed management.

Classification of hydrological models: Empirical, Conceptual, Physically-based: Hydrological models are tools designed to simulate the movement, distribution, and quality of water within a watershed. These models vary in terms of their structure, input requirements, and level of physical representation. The classification of hydrological models broadly falls into three major categories: empirical (black-box)**,** conceptual (grey-box) and physically-based (white-box) models, depending on how they represent the processes involved in the rainfall–runoff transformation.

Empirical Models: Empirical models rely on statistical relationships between observed inputs and outputs, without simulating physical hydrological processes. The SCS-Curve Number (SCS-CN) method is a widely used example, estimating runoff based on land use, soil type, and rainfall depth (Mishra & Singh, 2003). These models are valued for their simplicity and low data requirements, making them useful in ungauged basins. However, they are limited to the conditions under which they were calibrated and are less effective in dynamic or complex hydrologic settings.

Conceptual Models: Conceptual hydrological models use simplified yet physically meaningful representations to simulate water flow and storage processes. They often model interception, infiltration, baseflow, and runoff through interconnected reservoirs. While not fully physically based, they offer greater realism than empirical models and require calibration with historical data. TOPMODEL is a prominent example that links runoff generation to topographic saturation patterns. It performs well in humid, sloped watersheds where saturation-excess flow dominates (Beven & Kirkby, 1979).

Physically-Based: Physically-based models simulate hydrologic processes using fundamental laws of mass, momentum, and energy conservation. They require detailed spatial and climatic data and solve complex equations over time and space. The VIC model exemplifies this approach, offering high-resolution, grid-based water and energy balance simulations (Liang et al., 1994). While accurate and comprehensive, VIC demands extensive calibration and computational resources. Model choice ultimately depends on objectives, data availability, watershed scale, and required accuracy**.**

Key Model Selection Criteria in Hydrological Modelling: The selection of an appropriate hydrological model is a critical step in any water resources study, as it directly affects the accuracy, applicability, and reliability of the results. Choosing a model involves careful evaluation of multiple factors, including the scale of analysis**,** purpose of study**,** data availability**,** model complexity, and user expertise. These criteria are interconnected and must be assessed contextually based on watershed characteristics and project objectives (Singh & Woolhiser, 2002).

Spatial and Temporal Scale: The spatial and temporal scale plays a critical role in selecting an appropriate hydrological model. Physically-based models like VIC are ideal for large-scale, long-term simulations, effectively capturing regional water balances and climate variability due to their grid-based structure (Liang et al., 1994). In contrast, conceptual models such as TOPMODEL are better suited for small to medium watersheds**,** using topographic indices to simulate saturation-excess runoff efficiently (Beven & Kirkby, 1979). While VIC may overlook localized flow dynamics, TOPMODEL can become computationally intensive at broader scales. Therefore, matching model resolution with watershed processes and data availability is essential for accurate runoff simulation.

Data Availability and Quality: Another fundamental criterion is the availability of hydrological, meteorological, and spatial datasets**.** Physically-based models typically require extensive datasets, including daily precipitation, temperature, soil characteristics, land use, and topographic information. If such data are sparse, as in many developing regions, simpler models with fewer input requirements may be preferable (Refsgaard & Storm, 1995). Furthermore, the quality and resolution of input data can significantly influence model outputs, especially in runoff estimation and calibration processes.

Purpose and Objectives of the Study: Hydrological model selection depends on the study's purpose. **TOPMODEL** is effective for event-based runoff in terrain-influenced, humid catchments due to its topographic focus. For long-term, large-scale simulations involving land use or climate change, **VIC** provides a detailed, continuous framework. **SCS-CN** remains useful for quick runoff estimates where data is limited (Mishra & Singh, 2003). Aligning model complexity with study goals ensures appropriate application.

Model Structure and Complexity*:* The complexity of a model often determines its suitability. While physically-based models simulate real-world processes in greater detail, they are also more demanding in terms of input preparation, calibration, and computation. Simpler models offer faster results with fewer resources, making them attractive for operational applications or regions with limited technical capacity. However, simplification may also lead to increased uncertainty and reduced generalizability (Gupta et al., 1998).

Calibration and Validation Requirements: Hydrological models vary in calibration demands and data intensity. Physically-based models like VIC require extensive parameterization of soil, vegetation, and baseflow, necessitating long-term streamflow and climate data for reliable performance. TOPMODEL, though conceptual, involves calibration of transmissivity and saturation deficit parameters but is less computationally intensive, making it suitable for moderate-scale applications. In contrast, empirical models like SCS-CN require minimal calibration, relying on preset curve numbers based on land use and soil types. This simplicity favors rapid application in data-scarce regions but compromises physical realism and adaptability to complex hydrologic settings (Arnold et al., 2012).

Technical Expertise and Software Availability: Model selection is influenced by user expertise, software accessibility, and institutional support. **VIC**, being code-driven and data-intensive, demands proficiency in hydrology, programming, and geospatial analysis—posing challenges for beginners or resource-limited institutions. **TOPMODEL**, though conceptually robust, is computationally light and implementable via open-source tools, making it suitable for academic or moderate-scale use. In contrast, **SCS-CN** offers user-friendly execution through common GIS or spreadsheet platforms, requiring minimal technical training. Hence, the balance between model complexity and usability critically informs its adoption (Moriasi et al., 2007).

SCS-Curve Number (SCS-CN) Method:

Historical Background and Development: The SCS-Curve Number (SCS-CN) method, developed by the USDA-SCS in the 1950s and formalized in NEH-4 (1954), was conceived as a simplified empirical approach to estimate direct runoff from rainfall, using the Curve Number (CN) parameter to encapsulate land use**,** soil type and antecedent moisture (USDA-SCS, 1972). In contrast to physically-based models like **VIC**, which simulate complex hydrological fluxes through energy and water balance formulations, or conceptual models like TOPMODEL, which integrate topographic controls on subsurface flow, the SCS-CN method prioritizes operational simplicity and minimal data dependency. Despite its empirical limitations, its robustness in data-scarce and planning-level applications continues to ensure its relevance in hydrological modeling (Ponce & Hawkins, 1996).

Governing Equations and Assumptions of the SCS-CN Method: The SCS-Curve Number (CN) method, formulated by the USDA Soil Conservation Service, estimates direct runoff (Q) from a rainfall event (P) using an empirical relationship based on the watershed's ability to retain and infiltrate water. It is grounded in a simple water balance equation and a proportionality assumption relating runoff and retention.

Water Balance Equation: The fundamental principle of the SCS-CN method is based on conservation of mass for a rainfall event:

P=Q+F+Ia

P = total precipitation (mm)**; Q** = direct surface runoff (mm)**; F** = actual retention after runoff begins (mm)**; Ia** = initial abstraction (mm)**,** which includes surface storage, interception, and infiltration before runoff begins.

Proportionality Assumption: To link precipitation with runoff, the SCS method assumes that:

$$\frac{F}{S} = \frac{Q}{P-I_a}$$

S = potential maximum retention after runoff begins (mm)**.** This leads to the main governing runoff equation once the initial abstraction (I_a) is approximated.

Runoff Estimation Equation: Using the common assumption I_a=0.2S, the SCS-CN method expresses runoff as:

$$Q - \frac{(P-0.2s)^2}{P+0.8s} \text{ for } P > 0.2\,S$$

This equation is used to estimate event-based runoff from rainfall, provided the curve number is known.

Curve Number and Storage Relationship: The potential maximum retention (S) is related to the Curve Number (CN) by**:**

$$S - \frac{25400}{CN} - 254(mm)$$

Where: CN is a dimensionless value ranging from 30 to 100A higher CN indicates less infiltration and more runoff potential & vice-versa. This relationship allows the model to link land surface conditions to runoff capacity.

Curve Number Classification*:* The Curve Number is determined based on: Land use/land cover (LULC), Hydrologic Soil Group (A, B, C, D), Antecedent Moisture Condition (AMC). Values are typically obtained from SCS standard tables or derived using GIS-based land use and soil maps.

Antecedent Moisture Condition (AMC) Adjustments: For varying soil moisture conditions, Curve Numbers are adjusted for three AMC levels: **AMC I (dry), AMC II (average), AMC III (wet).** Empirical formulas are used to convert CN for average condition (CNII) into CN for dry or wet conditions:

$$CN_I - \frac{CN_{II}}{2.334 - 0.01334 * CN_{II}}$$

$$CN_{III} - \frac{CN_{II}}{0.4036 + 0.005964 * CN_{II}}$$

Assumptions of the SCS-CN Method: The SCS-CN method assumes that runoff is generated from a single rainfall event with uniform rainfall distribution across the watershed. It applies a fixed initial abstraction (typically 20% of maximum retention) and presumes homogeneous land use, soil type, and topography within each unit. The standard method does not account for slope or seasonal variability, though modifications exist to address these limitations.

Data Requirements for the SCS-CN Method: The effectiveness and reliability of the SCS-Curve Number method heavily rely on accurate input data representing the watershed's physical and hydrological characteristics. The method simplifies runoff estimation by integrating key variables into a single parameter—the Curve Number (CN). To compute this value appropriately, three essential datasets are required: Land Use/Land Cover (LULC), Hydrologic Soil Group (HSG), and Antecedent Moisture Condition (AMC).

Land Use/Land Cover (LULC): LULC classification is crucial as it directly affects the surface's infiltration capacity and runoff behavior. Different land use types such as urban areas, forests, croplands, or grasslands have varying imperviousness and vegetation cover, which influence water absorption. Urban areas (with impervious surfaces like roads and buildings) tend to produce high runoff and are assigned higher CN values, Forests and grasslands, due to higher vegetation cover and soil permeability, usually have lower CNs. LULC maps are typically derived from remote sensing data using classification techniques (e.g., supervised or unsupervised classification) and further refined in GIS environments. The classification must align with SCS land use categories to ensure correct CN assignment.

Hydrologic Soil Group (HSG)*:* Soils are categorized into four hydrologic groups (A, B, C, and D) based on their infiltration rate: Group A: High infiltration (sandy soils, minimal runoff),Group B: Moderate infiltration (loamy soils),Group C: Low infiltration (clay loams),Group D: Very low infiltration (clay soils, high runoff potential).HSG maps are often developed using soil texture data obtained from national or regional soil surveys. In a GIS framework, each soil unit is labeled with its respective HSG, and when overlaid with LULC data, it helps identify the appropriate CN values for combined land-soil units.

Antecedent Moisture Condition (AMC): AMC accounts for the soil's wetness prior to a rainfall event, which significantly influences runoff response. It represents the initial moisture status of the soil and is categorized into three levels: **AMC I**: Dry soil (lower runoff, lower CN), **AMC II**: Normal or average conditions (standard CN values), **AMC III**: Wet soil (higher runoff, higher CN).AMC levels are determined based on the total rainfall in the five days preceding the runoff event and whether the vegetation is in a growing or dormant season. The choice of AMC affects the CN value used in the runoff equation, and adjustments are made using empirical formulas if AMC-I or AMC-III are applicable instead of AMC-II.

Case Studies and Applicability of the SCS-CN Method: SCS-Curve Number method has demonstrated remarkable flexibility and utility across varying climatic, topographic, and land use settings. Several studies in India and abroad have effectively utilized the SCS-CN method to estimate surface runoff, leveraging the integration of remote sensing and GIS for spatial input generation.

Satheeshkumar et al. (2017) applied the SCS-CN method in the Pappiredipatti watershed, a sub-basin of the Vaniyar River in southern India. Utilizing satellite imagery (LISS III), DEM, and Survey of India toposheets, thematic layers for soil, LULC, and slope were developed. The watershed was characterized into various hydrologic soil groups and land use types, which were superimposed to assign CN values. Rainfall data from 2000 to 2014 were analyzed, and Thiessen polygon-based interpolation was used for rainfall distribution. The model outcomes supported the design of artificial recharge structures and informed water resource planning in the hard rock terrain of the region.

In a study by Rawat and Singh (2017), the SCS-CN method was employed to estimate runoff in the semi-arid Jhagrabaria watershed. Remote sensing data from LANDSAT-7 ETM+ and soil data from NBSS&LUP were integrated within a GIS environment. The study computed CN values for different AMC levels and reported an average annual runoff coefficient of 0.22 over 14 years, with a strong correlation ($R^2 = 0.91$) between estimated and observed runoff. This highlights the method's robustness in data-scarce agricultural regions for long-term runoff analysis.

Ebrahimian et al. (2012) evaluated the applicability of the SCS-CN method in the steeply sloped Kardeh watershed of northeastern Iran. The study compared standard and slope-adjusted CN equations and demonstrated that slope significantly influenced runoff estimates. Although the slope-adjusted CN method did not drastically improve accuracy, the standard method still provided acceptable results with 55% accuracy. This work emphasized the need for slope correction in high-relief terrains, where runoff behavior is more sensitive to topographic variations.

Garg et al. (2013) studied the impact of slope on runoff potential in the Solani watershed using a modified NRCS-CN method within a GIS framework. The region, encompassing diverse elevation zones from plains to hills, was modeled to analyze daily rainfall-runoff dynamics. The study revealed that incorporating slope factors improved runoff predictions, particularly in upper hilly areas. This approach validated the need to integrate topographic parameters into runoff modeling, particularly in physiographically heterogeneous basins.

In the Timmapur watershed study by Shwetha et al., the SCS-CN method was used in conjunction with hybrid LULC classification and soil mapping to estimate daily runoff using 11 years of rainfall data. GIS was used to overlay LULC and soil maps to generate CN grids. The results facilitated an understanding of how land cover and soil variability influence surface runoff, making the approach suitable for integrated watershed management and planning water conservation strategies.

These case studies collectively illustrate the adaptability and applicability of the SCS-CN method across a range of environments—from steep slope watersheds in Iran to semi-arid agricultural zones in India. They also underscore the importance of GIS integration**,** AMC adjustments, and where necessary, slope correction to enhance runoff estimations

TOPMODEL (Topography – Based Hydrological Model):

Origin and Development of TOPMODEL: Developed by **Beven and Kirkby** in the late 1970s, TOPMODEL introduced a paradigm shift in hydrological modeling by linking topographic control to saturation-excess runoff generation, particularly in humid and hilly terrains. Unlike earlier lumped or empirically driven models, it incorporated variable source area theory, simulating runoff from transiently saturated zones influenced by antecedent moisture and rising water tables. Its minimal parameterization and adaptability to Digital Elevation Models (DEMs) allowed spatial application across watersheds. Though conceptually simple, it has evolved to include snowmelt**,** land cover change**, and** climate variability, while retaining its foundational elegance and widespread applicability.

Model Structure and Components of TOPMODEL: TOPMODEL is a semi-distributed conceptual hydrological model designed to simulate the spatial variability of soil moisture and runoff generation, particularly in catchments where saturation-excess runoff is dominant. Its structure is built around the principle that topography governs subsurface flow convergence and soil saturation, which in turn influences surface runoff. The model operates on the assumption that the saturated hydraulic conductivity declines exponentially with depth, and that the water table is in equilibrium with surface topography. This allows the model to link local soil moisture dynamics with catchment-wide hydrologic response using topographic data.
At its core, TOPMODEL consists of the following main components:

Topographic Index Calculation*:* Using a Digital Elevation Model (DEM), the model calculates the topographic index (TI) for each grid cell, expressed as:

$$TI - ln\left(\frac{\alpha}{\tan\beta}\right)$$

Where: α = **local upslope contributing area per unit contour length (m²/m),** β **= local surface slope in radians.** This index determines the spatial distribution of potential saturation zones, it quantifies the tendency of a location to become saturated, assuming that areas with larger contributing areas and gentler slopes are more prone to saturation.

Saturated Zone Transmissivity (T): TOPMODEL assumes exponential decline in transmissivity with depth:

$$T_{(z)} - T_0 \cdot e^{-fz}$$

Where: $T_{(z)}$= transmissivity at depth z; $T_{(0)}$ = transmissivity at the surface (when the soil is saturated); f = decay constant (controls rate of decline), z = water table depth below the surface

Subsurface Flow at Catchment Scale: The catchment average soil moisture deficit is used to control the activation of saturated areas. Areas with higher TI values saturate first and contribute to surface runoff. Lateral subsurface flow is computed based on transmissivity and the water table gradient. The model assumes exponential decay of transmissivity with depth, which simplifies the representation of groundwater flow. The total lateral subsurface flow from the catchment is the sum of flows at each point:

$$Q_b - T_0 \cdot \tan\beta \cdot e^{-f\bar{z}}$$

Where: Q_b= baseflow (m³/s); $\bar{z}$ = average water table depth over the catchment; $\tan\beta$ = average slope of the catchment

Local Water Table Depth (z(x)): The local water table depth at a point x is related to the catchment-average depth:

$$z(x) - \bar{z} + \frac{1}{f}\left(ln\left(\frac{a(x)}{tan\beta(x)}\right) - \overline{TI}\right)$$

Where: $z(x)$ = water table depth at point x; $\overline{TI}$= average topographic index across the catchment

Surface Runoff Generation: Surface runoff is generated from areas where the soil becomes saturated (i.e., where local storage exceeds the deficit). The model captures the dynamic expansion and contraction of the variable source area contributing to streamflow. Surface runoff is generated from saturated areas**,** i.e., where $z(x) \leq 0$. The fraction of the catchment that is saturated is calculated as:

$$f_{sat} - P(TI \geq TI_{crit})$$

Where:$\mathbf{TI}_{\mathbf{crit}}$ = threshold topographic index where saturation begins; $\mathbf{f}_{\mathbf{sat}}$ = saturated area fraction; **P.** = proportion of the catchment area meeting the condition.

Total Streamflow: A simple linear reservoir approach is used to route the total discharge to the catchment outlet, combining both baseflow and surface runoff.The total discharge at the outlet is the sum of baseflow and saturation-excess surface runoff:

$$\boldsymbol{Q_{total} - Q_b + Q_{surf}}$$

Where:$\boldsymbol{Q_{surf}}$ = surface runoff from saturated areas; $\boldsymbol{Q_b}$ = base flow from unsaturated zones
Despite its simplicity, TOPMODEL effectively simulates spatial variability in hydrological response, making it a valuable tool for research and watershed-scale planning in sloping, humid regions.

Assumptions of TOPMODEL: TOPMODEL (Topography-based Hydrological Model) is grounded in a set of simplifying assumptions that allow it to represent the complex processes of runoff generation in a physically meaningful yet computationally efficient way. TOPMODEL operates on several foundational assumptions: it prioritizes saturation-excess runoff, making it most applicable in humid regions with shallow water tables. It presumes an exponential decline in soil transmissivity with depth, concentrating lateral flow near the surface. The model assumes spatial uniformity in subsurface parameters to ease calibration and adopts instantaneous hydraulic equilibrium, aligning water table depth with surface topography. Baseflow is considered to occur under steady-state conditions, limiting responsiveness to rapid hydrologic events. Crucially, it relies on the Topographic Index (TI) as a surrogate for spatial saturation distribution, enabling DEM-based runoff estimation despite ignoring soil heterogeneity and delayed groundwater dynamics.

Input Data Requirements for TOPMODEL: TOPMODEL requires a limited yet specific set of inputs to simulate hydrologic processes based on topographic control of soil moisture and saturation excess runoff. The model is designed to balance physical realism with computational simplicity, making it applicable even in data-scarce regions. The input data can be grouped into three main categories: topographic data**,** hydrological time series and model parameters**.**

Topographic Data: The cornerstone spatial input for TOPMODEL is a Digital Elevation Model (DEM), from which the Topographic Index (TI) is derived for each grid cell. TI quantifies saturation potential, with higher values denoting low-gradient zones with substantial upslope contribution, prone to saturation and runoff generation. The spatial fidelity of TI is highly contingent on DEM resolution, typically ranging between 10–30 meters, influencing the model's hydrological precision.

Hydrological Inputs: TOPMODEL requires daily or sub-daily time series of rainfall (P) and potential evapotranspiration (PET) as primary climatic inputs—rainfall drives soil moisture recharge, while ET determines moisture deficit. Optional streamflow observations (m^3/s) enhance calibration and validation accuracy. Simulations also necessitate an initial average water table depth to define antecedent conditions. These datasets are sourced from local meteorological stations or global repositories such as CHIRPS and ERA5, contingent on study scale and data availability.

Soil and Model Parameters: TOPMODEL relies on a concise set of calibrated parameters to represent soil and subsurface flow dynamics: (a) Surface Transmissivity—saturated hydraulic conductivity at the surface dictating lateral flow under saturation; (b) Decay Parameter—governs the exponential decline of transmissivity with depth; (c) Soil Moisture Scaling Parameter—links local and mean water table depth; (d) Recession Constant (optional)—controls baseflow decline in dry phases; and (e) Routing Delay Time (optional)—defines travel time to the catchment outlet. These parameters are typically derived via hydrograph calibration**,** borehole data or sensitivity analysis to assess their influence on runoff behavior. TOPMODEL's relatively low data demand makes it especially valuable in small- to medium-sized catchments where only basic climatic and terrain data are available. It avoids the need for detailed soil texture or land use classifications, relying instead on topographic variation to simulate the spatial pattern of runoff generation.

Case Studies and Applicability of the TOPMODEL: TOPMODEL has been applied in a wide range of hydrological and climatic settings, demonstrating its adaptability to different temporal and spatial scales. Its topographic index-based approach makes it especially effective in humid, sloped, and forested catchments, as well as in snow-dominated and data-scarce regions. The following case studies highlight how researchers have modified and implemented

TOPMODEL in various environmental contexts to improve runoff simulation and watershed analysis. Liu et al., 2010, In a study focusing on the arid and high-altitude **Manas River Basin**, a modified version of TOPMODEL was developed to include a **snowmelt module** based on solar radiation and topographic characteristics. This addition allowed the model to simulate runoff contributions from both rainfall and snowmelt. A combination of **Monte Carlo simulation** and **GLUE-based uncertainty analysis** was used for calibration, which demonstrated that the model captured daily flow variations effectively. This adaptation showed that integrating snow dynamics into TOPMODEL enhances its applicability in alpine catchments where snowmelt is a significant component of streamflow. Azari et al., 2017, TOPMODEL's sensitivity to flow direction algorithms was tested in the **Ammameh catchment** of the Alborz Mountains. The study compared runoff simulations using **D8** and **D∞** flow algorithms across event, daily, and monthly time scales. It was found that the model performed better at daily time steps, where it more accurately represented soil moisture and saturation zones.

Moreover, the **D∞ algorithm** yielded improved hydrograph simulations during high-flow events due to its better handling of multiple flow paths. This case confirmed the importance of high-resolution terrain representation and flow routing in enhancing model accuracy. Széles et al., 2012, In the **Jalovecky Creek** watershed located in the Western Carpathians, Slovakia, TOPMODEL was applied for both short- and long-term simulations. The region is characterized by steep slopes and deep, heterogeneous soil profiles. Despite the geological complexity, the model succeeded in simulating the spatial and temporal variation of saturated areas and streamflow. The results were validated through **isotopic analysis** of runoff components, which supported the model's assumptions regarding subsurface flow and water table fluctuations. The study demonstrated TOPMODEL's strength in capturing dominant hydrologic processes in forested mountainous landscapes. Chen et al., 2023, Recent advancements have introduced **hybrid models**, where TOPMODEL was dynamically coupled with **Long Short-Term Memory (LSTM)** networks and **Self-Organizing Maps (SOM)**. This integration allowed the model to adapt its parameters in real time, improving runoff predictions in catchments with rapidly changing hydrological behavior. The machine learning-enhanced model provided more accurate discharge estimates, particularly during peak flow conditions, and helped address limitations of static parameter assumptions in the original model structure. Niu et al., 2005, In large-scale land surface modeling, a simplified version of TOPMODEL known as **SIMTOP** was implemented within the **Community Land Model (CLM)** developed by the National Center for Atmospheric Research (NCAR). SIMTOP used an **exponential distribution** of the topographic index and fewer parameters, making it computationally efficient for global applications. It successfully reproduced realistic runoff patterns without the need for detailed soil and vegetation datasets, suggesting its usefulness in **climate impact studies** and **earth system modeling**. These diverse applications demonstrate that TOPMODEL remains a valuable and adaptable tool in hydrology. Its ability to simulate both surface and subsurface flow processes using topographic control makes it especially useful in sloping, humid, and forested regions. Moreover, the model's integration with modern tools such as machine learning and snowmelt modules shows that it can evolve to meet current hydrological modeling needs, from alpine catchments to global land surface simulations.

Variable Infiltration Capacity (VIC) Model

History and Development: The Variable Infiltration Capacity (VIC) model was introduced in the early 1990s by Lettenmaier et al. to overcome limitations in land surface hydrology models, particularly their inability to capture sub-grid heterogeneity in infiltration and runoff (Liang et al., 1994). By incorporating variable infiltration capacity, VIC enabled partial-area runoff simulation within each grid cell, enhancing hydrologic realism across heterogeneous landscapes. Originally a daily water balance model, it later evolved to include energy balance components, supporting simulations of land atmosphere exchanges, snow processes, and soil heat fluxes (Liang et al., 1996). Widely applied in systems like NLDAS, GLDAS, and climate impact studies (Nijssen et al., 2001), VIC's open-source structure and modular design have fostered a robust global user community, with ongoing enhancements including lake/reservoir modeling and bias correction (Hamman et al., 2018).

Model Structure and Components of the VIC Model: The Variable Infiltration Capacity (VIC) model is a semi-distributed, grid-based macroscale hydrologic model designed to simulate land–atmosphere water and energy exchanges across spatial scales ranging from watersheds to continents. It operates on independent grid cells, each partitioned into vegetation tiles to represent land cover heterogeneity, accounting for canopy processes, transpiration, and snow dynamics. The water balance module comprises a three-layer soil profile handling surface runoff, plant-available moisture, and baseflow, with infiltration governed by a variable capacity curve and delayed flow modeled via a nonlinear recession function. An optional energy balance module computes radiation fluxes and snowmelt, essential for climate-sensitive studies. Although VIC lacks internal streamflow routing, it interfaces with external routing models. Inputs include high-resolution meteorological forcing, soil**,** vegetation, and snow parameters for process-based hydrologic simulation.

Equations and Modeling Framework in the VIC Model: The VIC (Variable Infiltration Capacity) model represents a balance between physical realism and computational efficiency, enabling hydrologic simulations over large areas and long timeframes. It does so by breaking down the hydrologic system into modular components, each governed by physically-based or conceptual equations. VIC simulates both water and energy balances and can operate in either water balance mode or full energy balance mode**,** depending on user needs.

Water Balance Component: At its core, VIC solves the water balance for each grid cell and vegetation tile:

$$\Delta S = P - ET - R_{surf} - Q_{base}$$

Where: **ΔS** = change in soil moisture storage (mm); **P** = precipitation (mm/day); **ET** = evapotranspiration (mm/day); $\mathbf{R_{surf}}$ = surface runoff (mm/day); $\mathbf{Q_{base}}$ = baseflow from lower soil layer (mm/day).

Infiltration Modelling: VIC models the spatial variability of infiltration capacity within a grid cell using a variable infiltration curve**,** based on the idea that only a portion of the area becomes saturated during rainfall.

$$A_{(i)} = 1 - \left(\frac{i}{i_{max}}\right)^{1/b}$$

Where: $\mathbf{A_{(i)}}$ = fraction of area where infiltration is less than i, i = actual infiltration rate (mm/h); i_{max}= maximum infiltration capacity (when soil is dry); b = infiltration shape parameter (empirically defined).

Evapotranspiration Component: Evapotranspiration (ET) is broken into three components: a) Canopy evaporation (from intercepted rain), b) Vegetation transpiration &c) Soil evaporation. Each vegetation tile in VIC computes its own ET, and outputs are area-weighted to derive total ET for the grid cell. The **Penman-Monteith equation** is often used to estimate transpiration:

$$ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{VPD}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

Where: **ET** = evapotranspiration rate (mm/day); $\mathbf{R_n}$ = net radiation at the surface (W/m^2); **G** = soil heat flux (W/m^2); $\mathbf{\rho_a}$ = air density (kg/m^3); $\mathbf{c_p}$= specific heat of air (J/kg·K); **VPD** = vapor pressure deficit (kPa).

Snow and Energy Balance Component (optional): When energy balance mode is enabled, it solves a coupled set of equations that compute: Shortwave and longwave radiation exchange; Ground heat flux; Latent and sensible heat fluxes; Snow accumulation and melt using an energy balance or degree-day approach. The energy balance equation for a snowpack is:

$$Q_{net=}Q_{SW} + Q_{LW} + Q_{sens} + Q_{lat} + Q_{cond}$$

Where:$Q_{SW,}Q_{LW}$ = shortwave and longwave radiation; Q_{sens},Q_{lat} = sensible and latent heat; Q_{cond} = conductive heat into the snowpack.
Meltwater from snow contributes directly to the soil moisture and runoff generation process.

Routing Model (External Routing Component): While VIC computes runoff and baseflow at the grid cell level, it lacks internal streamflow routing. To estimate discharge at a watershed outlet, outputs are passed through an external routing model, commonly the Lohmann et al. (1996) scheme, which applies a unit hydrograph and linear reservoir approach to route flows across the basin. This approach captures the travel time and attenuation of flow through a river network and produces continuous hydrographs for comparison with observed streamflow data.

$$Q_{out}(t) = \sum_{i=1}^{N} [R_i(t) * U_i(t - \tau)]$$

Where: $Q_{out}(t)$ = streamflow at time ttt (m^3/s); $R_i(t)$ = runoff/baseflow from grid cell *i* at time *t*; U_i= unit hydrograph weighting function for delay τ; **∗** = convolution operator; **N** = number of contributing grid cells

Time Step and Spatial Discretization: VIC supports **sub-daily forcing** (e.g., 1- to 3-hour intervals) for simulating short-term rainfall, snowmelt, and ET processes. Outputs are typically aggregated to **daily or monthly scales**. Spatially, the model runs on an **independent grid-cell basis** (1 km to 1° resolution), with **multiple vegetation tiles** per cell to capture land surface heterogeneity. Water and energy balance is maintained within each cell as:

$$\boldsymbol{P = ET + Q + \Delta S}$$

Where: $\boldsymbol{P}$ = precipitation; $\boldsymbol{ET}$ = total evapotranspiration ; $\boldsymbol{Q}$ = total runoff (surface + baseflow); $\Delta\boldsymbol{S}$ = change in soil moisture storage.
This ensures mass balance continuity in both water and energy terms over time and space.

Assumptions of VIC Model: The VIC model assumes sub-grid heterogeneity in infiltration, using a variable infiltration curve to simulate partial saturation under varying rainfall. Each grid cell operates independently, with no lateral water exchange, enabling parallel processing but limiting subsurface connectivity representation. Land cover heterogeneity is modeled via vegetation tiles, which simulate fluxes independently. Baseflow is estimated empirically using an Arno-type formulation, and energy balance is closed within each tile. Soil properties are treated as uniform per layer within a cell. Inputs are derived from sources like ERA5, MODIS, and FAO, and must be pre-processed to match VIC's structure.

Case Studies and Applicability of VIC: The Variable Infiltration Capacity (VIC) model has been extensively applied in diverse hydrological and climatic regions, demonstrating its effectiveness in large-scale runoff estimation, streamflow simulation, and climate impact studies. Zhao et al., 2013, In China VIC-3L was implemented across 33 river basins, where 14 were used for calibration and the remaining for validation. The model showed high accuracy in reproducing streamflow, with improvements observed when using regionally adjusted parameters. This highlights VIC's strength in simulating runoff across data-scarce and climate-diverse basins, and its potential for national-scale hydrological forecasting . Banerjee & Mishra, 2022, In the Kangsabati catchment of India, the model was applied to simulate streamflow with the support of VIC-ASSIST for sensitivity analysis. Key parameters such as infiltration shape factor and soil depth were found to strongly influence runoff predictions. The model's performance was further enhanced by coupling with HEC-RAS to account for reservoir outflows, making it suitable for integrated watershed planning .Patil et al., 2022, A long-term application in the Ashti catchment (India) demonstrated VIC's ability to capture hydrologic variability over multi-decadal periods. The model was calibrated using data from 1971–1990 and validated for 1991–2010, resulting in NSE values of 0.94 and 0.86, respectively—indicating excellent performance in both historical flow reconstruction and trend detection. Zhao et al., 2012, In Europe, VIC was used in the Rhine River basin as part of a comparative study with other hydrological models. While conceptual models like HBV were more responsive to certain parameter changes, VIC more effectively simulated peak flows and water balance partitioning, reinforcing its applicability for climate change assessments and future runoff projections in complex river systems .

Comparative Methodology Analysis: Runoff estimation lies at the heart of hydrological modeling and watershed planning. The choice of model profoundly influences the accuracy, spatial representation, and applicability of runoff simulations. Below is a detailed analysis of the methodologies of three widely used hydrological models—SCS-CN, TOPMODEL, and VIC—which represent empirical, conceptual, and physically-based modeling philosophies, respectively.

SCS-Curve Number Method: The SCS-CN method is a rainfall-runoff model developed by the USDA's Soil Conservation Service. It is a simple empirical model that estimates direct runoff from rainfall events, primarily using land use/land cover (LULC), hydrologic soil group (HSG), and antecedent moisture condition (AMC) as governing variables.

Methodological Framework: The SCS-CN method estimates event-based runoff using Curve Numbers (CN) assigned from LULC and soil data, adjusted for antecedent moisture conditions (AMC). It assumes a fixed initial abstraction ($Ia = 0.2S$) before runoff begins. The method lacks continuous simulation**,** baseflow modeling**,** and streamflow routing, making it best suited for small or ungauged basins**.**

Methodological Strengths and Weaknesses:

- **Strengths:** Simplicity, minimal data needs, suitable for ungauged basins.

- **Limitations:** Static, lumped, and event-based; lacks soil moisture feedback and cannot simulate hydrologic memory or groundwater interactions.

TOPMODEL: TOPMODEL (Beven & Kirkby, 1979) is a conceptual and semi-distributed hydrological model that links topographic controls to runoff generation, especially saturation-excess flow. It assumes that saturated areas expand and contract with varying moisture conditions, influenced by local topography.

Methodological Framework: TOPMODEL **uses a** Topographic Index (TI) derived from DEM to represent spatial saturation potential, where higher TI areas saturate first. Runoff occurs when local saturation deficit**,** distributed via TI, reaches zero. Baseflow is modeled through an exponential decay of transmissivity with depth. Key calibration parameters include surface transmissivity (T_0)**,** decay factor (f)**,** and recession constants**,** adjusted using observed streamflow data.

Methodological Strengths and Weaknesses:

- **Strengths:** Captures spatial variability using topography; useful in humid, sloping catchments with saturation-dominated runoff.
- **Limitations:** Assumes equilibrium between water table and surface; less effective in arid or flat regions and lacks dynamic evapotranspiration and snow modules.

VIC (Variable Infiltration Capacity Model): The VIC model is a semi-distributed, physically-based hydrological model designed for large-scale water and energy balance simulation. It simulates both infiltration-excess and baseflow processes and can operate in water or energy balance modes.

Methodological Framework: The VIC model operates on a grid-based framework**,** with each cell containing multiple vegetation **tiles** and a three-layer soil profile for simulating runoff, root zone moisture, and baseflow. It uses a variable infiltration curve to capture sub-grid heterogeneity and an Arno-type algorithm for baseflow generation. Water balance is computed at sub-daily time steps**,** and an optional energy balance module accounts for radiation and snowmelt. Streamflow routing is handled externally via unit hydrograph and reservoir-based models.

Methodological Strengths and Weaknesses:

- **Strengths:** High process realism, scalability, climate coupling potential; simulates long-term, continuous hydrologic behavior.
- **Limitations:** High data and calibration demand; limited groundwater representation; assumes independence of grid cells (no lateral flow).

ASPECT	**SCS-CN**	**TOPMODEL**	**VIC**
Model Type	*Empirical*	*Conceptual/semi-distributed*	*Physically-based/semi-distributed*
Spatial Resolution	*Lumped or HRU-based*	*DEM-based TI grid*	*Grid-based (1 km or coarser), tile-based inside*
Runoff Mechanism	*Rainfall–runoff (curve number)*	*Saturation excess based on TI*	*Variable infiltration + baseflow*
Soil Moisture Dynamics	*Static (AMC class)*	*Dynamic saturation deficit*	*Multi-layer soil moisture computation*
Routing Method	*Not included*	*Conceptual lateral flow*	*External routing model (e.g., Lohmann)*
Calibration Needs	*Low*	*Moderate*	*High*
Snow and ET Simulation	*Not included*	*Minimal*	*Optional full energy balance module*
Best Use	*Small watersheds, ungauged areas*	*Mid-sized humid basins, terrain-driven flow*	*Large-scale climate-sensitive hydrologic studies*

Table 1: Comparative Methodological Analysis of SCS- CN, TOPMODEL & VIC.

Research Gaps in SCS-CN, TOPMODEL, and VIC Models: Despite their widespread application and proven utility, each of the three models—SCS-CN, TOPMODEL, and VIC—presents specific research limitations that warrant further investigation and refinement. These gaps arise due to conceptual assumptions, data sensitivity, model scalability, and the evolving needs of hydrologic modeling under changing climatic and land use conditions.

SCS-Curve Number (SCS-CN) Method: While the SCS-CN method remains widely used for rapid runoff estimation, several research gaps have been consistently identified:
a) **Static Parameterization:** The use of fixed curve numbers for different land use and soil combinations does not account for seasonal variability or soil moisture dynamics, limiting accuracy in continuous or climate-sensitive simulations.
b) **Lack of Physical Basis:** The method does not represent the physical processes of infiltration and runoff generation, making it unsuitable for process-based analysis or in complex terrain.
c) **Inadequate for Long-Term Simulation:** Its event-based nature restricts its application in continuous hydrological assessments or watershed-scale water balance studies.
d) **AMC Classification Limitations:** Antecedent moisture conditions are represented using coarse classifications (I, II, III), which may not align with actual hydrologic conditions on the ground.
Future Scope: Research is needed to develop dynamic CN frameworks, integrate remote sensing-based soil moisture for real-time adjustment, and enhance its adaptability for use in data-scarce developing regions with varying climate and land use patterns.

TOPMODEL: TOPMODEL is a widely accepted conceptual model, yet it has its own set of research and application limitations:
a) **Assumption of Hydrologic Equilibrium:** The model assumes a steady-state balance between recharge and discharge, which may not be valid in arid regions, urban environments, or areas with high rainfall variability.
b) **Topographic Control Assumption:** It assumes that runoff generation is primarily governed by topography and saturation excess, which is not universally applicable—particularly in infiltration-excess dominated basins or heavily managed landscapes.
c) **Limited Use in Snow or Glacial Basins:** The original model lacks snowmelt dynamics, limiting its application in cold or mountainous regions without custom adaptations.
d) **Parameter Transferability:** The catchment-specific calibration reduces transferability to ungauged basins unless reliable terrain and soil information is available.
Future Scope: Development of hybrid models that integrate TOPMODEL's terrain-based runoff logic with dynamic water table or infiltration modules could improve flexibility. There is also a need for topography-independent extensions suitable for flat or urbanized basins.

VIC (Variable Infiltration Capacity Model): Although VIC is among the most sophisticated macroscale hydrologic models, it also has limitations that present opportunities for advancement:
a) **No Lateral Flow Between Cells:** VIC treats each grid cell as hydrologically independent, excluding lateral subsurface flow and groundwater connectivity, which may lead to inaccuracies in regions with significant inter-cell interactions.
b) **High Calibration Demands:** The model involves many parameters, especially when operated in energy balance mode, requiring extensive calibration and validation datasets, which limits its use in data-scarce regions.
c) **Simplified Groundwater Representation:** Baseflow is modeled empirically rather than through fully coupled groundwater equations, reducing realism in groundwater-dependent systems.
d) **Computational Demands:** Full-resolution VIC simulations with routing can be computationally intensive, presenting a challenge for real-time forecasting or large ensemble climate simulations.
Future Scope: Research can focus on enhancing groundwater interaction modules, enabling cell-to-cell connectivity, and incorporating machine learning techniques for more efficient parameter calibration and uncertainty analysis.

Together, these research gaps suggest the need for:
a) More dynamic and flexible runoff models that integrate physical realism with operational simplicity,
b) Better adaptation to diverse watershed conditions, including urban, arid, and snow-dominated basins,
c) And the use of emerging technologies such as remote sensing, data assimilation, and AI-based calibration to overcome traditional data and modeling limitations.

Conclusion:

Understanding and accurately estimating runoff is essential for effective watershed management, flood forecasting, agricultural planning, and climate change adaptation. This review has examined and compared three widely used hydrological models—SCS-CN, TOPMODEL, and VIC—each representing a distinct modeling philosophy: empirical, conceptual, and physically-based, respectively. Through an in-depth methodological analysis, case studies, and model structure evaluation, it becomes evident that while all three models serve the common objective of runoff estimation, their approaches, assumptions, data needs, and applicability differ substantially. The SCS-CN method, with its simple empirical structure, remains a practical choice for event-based runoff estimation in small or ungauged catchments, especially where detailed spatial and temporal datasets are unavailable. Its ease of use and reliance on standard land use and soil classification tables make it valuable for preliminary assessments, rapid watershed prioritization, and surface water resource planning in data-scarce regions. However, the method's static nature and lack of soil moisture feedback mechanisms limit its effectiveness in long-term simulations and changing climatic scenarios. TOPMODEL bridges the gap between empirical and physical modeling by incorporating terrain-driven hydrologic processes, primarily using the topographic index to represent saturation-excess runoff dynamics. Its semi-distributed nature allows spatial representation of runoff generation while retaining computational simplicity. The model performs particularly well in humid, sloping catchments where topography and subsurface saturation strongly influence surface flow. However, its assumptions—such as hydraulic equilibrium between water table and terrain—can become limiting in flat or arid regions and where infiltration-excess processes dominate. In contrast, the VIC model offers a highly detailed, physically-based framework capable of simulating both water and energy balances at a range of spatial and temporal scales. Its ability to represent sub-grid land cover variability, multi-layer soil dynamics, and variable infiltration capacity makes it a powerful tool for large-scale and climate-sensitive hydrological modeling. VIC's modularity—such as its ability to include snowmelt, vegetation dynamics, and evapotranspiration components—enables its use in applications ranging from seasonal streamflow forecasting to long-term impact studies of land use and climate change. However, its complexity, high data requirements, and reliance on external routing models demand significant expertise and computational resources. Collectively, these models provide a spectrum of tools for hydrologists and water resource planners. The SCS-CN method is well-suited for localized applications with limited data, TOPMODEL serves intermediate scales with moderate terrain influence, and VIC is optimal for data-rich, basin-wide or continental-scale studies. The comparative analysis reinforces the notion that model selection should be context-specific, aligning with the study objectives, available data, and dominant hydrological processes of the watershed in question. In a rapidly changing climate, where the hydrological regime of many basins is becoming more dynamic and less predictable, integrating insights from these models—either through hybrid frameworks or multi-model ensembles—may offer a more resilient approach to runoff estimation. Continued research and development in model interoperability, machine learning integration, and open-access data assimilation are likely to enhance the reliability and applicability of hydrological models in the years ahead.

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