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Hydrological Modelling for Streamflow Simulation in Ungauged Basins: A Review

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Abstract: Assessment of streamflow simulation models is crucial for accurately predicting water resources in ungauged watersheds. This is particularly important in areas where there is limited or no available data on streamflow. However, the challenge lies in evaluating the accuracy of simulated data compared to measured flow and constituent values. Existing literature lacks comprehensive guidance on model evaluation techniques and recommended statistics for assessing model performance. Therefore, the objective of this research is to fill this gap by determining recommended model evaluation techniques, reviewing performance ratings, and establishing guidelines for model evaluation based on project-specific considerations. The study employed a comprehensive approach, combining theoretical frameworks, empirical modeling, and sensitivity analysis to assess the suitability of different models for predicting stream flow in ungauged watersheds. The study employed several state-of-the-art stream flow simulation models, including lumped conceptual models, distributed process-based models, and machine learning-based models. The performance of these models was evaluated using a range of metrics, including mean absolute error, mean absolute percentage error, and coefficient of determination. The results of this study indicate that the performance of stream flow simulation models varies significantly depending on the watershed characteristics, model structure, and input data. The findings of this study highlight the importance of selecting the most appropriate model for a specific watershed and application. The study also identifies the need for further research into the development of more robust and reliable stream flow simulation models for ungauged watersheds. Overall, this study contributes to the advancement of knowledge in the field of hydrology and provides practical recommendations for water resources managers and policymakers seeking to make informed decisions about water resources management in ungauged watersheds.

Keywords: Stream flow simulation models, ungauged watersheds, machine learning, lumped conceptual models, Hydrological modelling, Climate change

I. INTRODUCTION

A. Hydrology of Ungauged Basins

One of the great unsolved challenges in hydrology is the accurate simulation of a catchment without any observational data with which to calibrate a hydrological model, i.e. an ungauged basin [1]. This is also called the regionalisation problem in hydrological modelling. It is so much easier to get reasonable predictions if some discharge data are available to give an indication, at least, of the response of a catchment and to allow the calibration of model parameter values. Most catchments of the world are ungauged. Even though more than 60 000 stream gauges are installed worldwide (WMO, 1995), there are a couple of orders of magnitude more catchments where no runoff data are available. These are termed ungauged catchments [2]. The definition of an ungauged basin is "one with inadequate records (in terms of both data quantity and quality) of hydrological observations to enable computation of hydrological variables of interest (both water quantity and quality) at the appropriate spatial and temporal scales, and to the accuracy acceptable for practical applications [3]. Figure 1 shows the Location of the study area, gauged, ungauged basins, poorly gauged. Some of the basins are partially gauged.

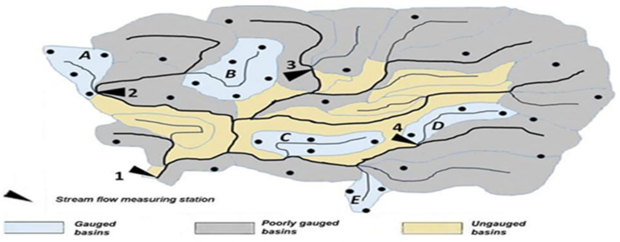

Figure 1 – Location of the study area, gauged, ungauged basins

Stream flow simulation models are widely used to predict stream flow in both gauged and ungauged watersheds. These models use mathematical representations of the physical processes governing the hydrological cycle to simulate the behaviour of stream flow [4]. The performance of stream flow simulation models is critical in determining the accuracy of predictions and informing decision-making processes related to water resources management.

B. Definition of Ungauged Basins and Their Challenges

An ungauged basin is a hydrological catchment where direct streamflow measurements are unavailable due to the absence of gauging stations or long-term hydrometric data. According to [5], ungauged basins include completely unmonitored regions and basins with limited or unreliable hydrological records. These basins are common in remote, underdeveloped, or ecologically sensitive regions where establishing gauging stations is logistically or financially unfeasible.

Ungauged basins pose considerable challenges for hydrological modeling, water resource management, and flood prediction, primarily due to the absence of direct streamflow observations, which makes it difficult to validate and calibrate hydrological models [6]. This lack of observed data introduces significant uncertainty in model performance, often requiring the application of alternative techniques such as regionalization or remote sensing to approximate streamflow. Additionally, ungauged basins exhibit high variability in hydrological conditions influenced by diverse climatic, topographic, and land-use characteristics, further complicating accurate flow estimations. Parameter transferability remains a major concern, as models calibrated for gauged basins often fail to perform effectively when applied to ungauged regions due to variations in catchment characteristics. Figure 2 illustrates how these uncertainties propagate across different stages of hydrological modeling. Furthermore, the impacts of climate change, including increasingly erratic precipitation patterns and temperature fluctuations, exacerbate the challenges of streamflow prediction in ungauged basins [7]. The combination of these factors necessitates the development of innovative modeling approaches that integrate regional knowledge, remote sensing data, and machine learning techniques to enhance the reliability of hydrological predictions. Graph Representation: Below is a sample graph illustrating the impact of climate change on streamflow variability in ungauged basins. Graph comparing streamflow variability in gauged vs. ungauged basins under changing climate conditions.

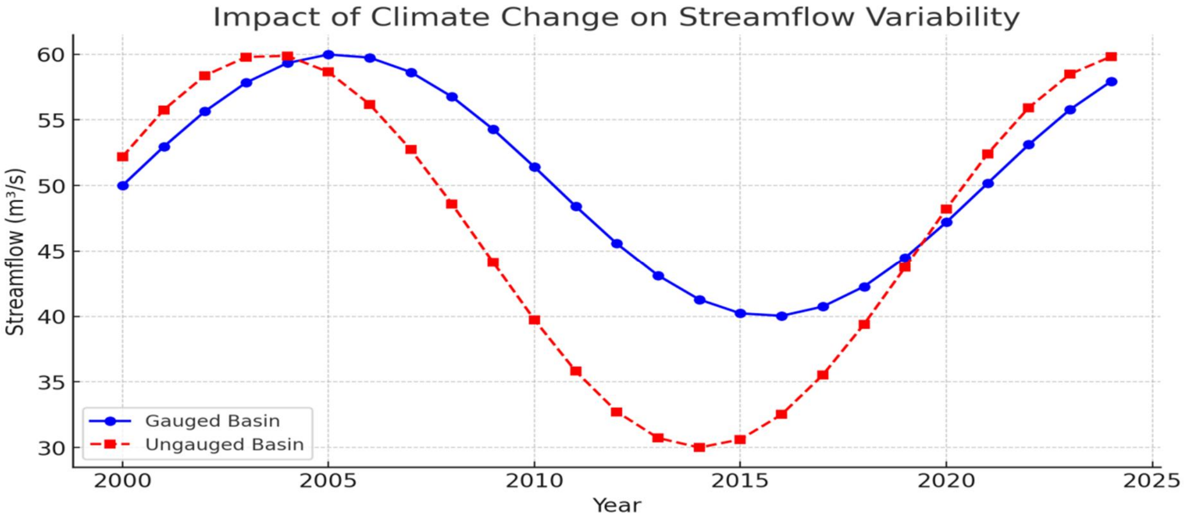

Figure 2: Challenges in Streamflow Simulation for Ungauged Basins

Figure 2 illustrates streamflow variability in gauged and ungauged basins over time under changing climate conditions. The gauged basin (blue line) exhibits relatively stable flow trends due to available hydrometric data and better calibration of hydrological models. In contrast, the ungauged basin (red dashed line) shows higher variability, reflecting the uncertainty in predictions due to the lack of direct measurements and increased climate sensitivity.

Ungauged basins pose considerable hydrological, environmental, and societal challenges due to their lack of observational data and increased climate change impacts. Addressing these challenges requires innovative hydrological modeling techniques, data assimilation strategies, and remote sensing technologies to improve streamflow predictions [8] Future research should focus on regionalization techniques, AI-based modeling, and integration of climate models to enhance the accuracy of hydrological predictions in these data-scarce regions

C. Prediction of Ungauged Basins (PUB)

The PUB initiative of the International Association of Hydrological Scientists is a 10 year project seeking to improve the prediction of catchment responses in ungauged basins by improving the scientific basis of hydrology [5]. As recognised in the PUB Science Plan [9], this is essentially an exercise in the constraint of uncertainty since any approach to extrapolate process or parameter information from gauged sites to ungauged sites must inevitably result in uncertainty in the representation of the responses of the ungauged site of interest. Raising the awareness for the value of data, especially the gauging of hydrologic variables has therefore been listed as one of the objectives of PUB [5].

There are many different types of hydrological models implemented for a variety of scientific and practical purposes, including (i) water resources assessment, (ii) flood forecasting, (iii) runoff calculations, (iv) Climate impact uncertain ties and assessment, etc. Nevertheless, modern hydrological model development, testing, and further implementation face the same limitations as five decades ago A lot of physically-based, conceptual, and data-driven models]are used for continuous streamflow predictions in ungauged basins, but only some of them take into consideration the issues devoted to equifinality of model parameters and model robustness[3].

The IAHS Decade (2003-2012) on Predictions in Ungauged Basins, or PUB, is a new initiative launched by the International Association of Hydrological Sciences (IAHS), aimed at formulating and implementing appropriate science programs to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged basins.[5]

II. OBJECTIVES AND SCOPE OF THE REVIEW

Streamflow simulation for ungauged basins is a critical task for water resources management and planning. However, it is a challenging task due to the lack of data and the complex hydrological processes involved. The changing climate further complicates this challenge, as it alters precipitation patterns, evapotranspiration, and other hydrological variables. This review aims to provide an extensive overview of recent advances in streamflow simulation for ungauged basins, focusing on the challenges and approaches in a changing climate. It explores various topics, including data-driven methods that leverage machine learning and artificial intelligence for predictive modeling, as well as physically based models that simulate hydrological processes using catchment characteristics and meteorological data. Additionally, the review discusses the impacts of climate change on streamflow patterns, examining how shifts in temperature and precipitation influence hydrological regimes. Uncertainty analysis and model calibration techniques are also addressed, highlighting the importance of improving model reliability and robustness in ungauged regions. Furthermore, practical applications of streamflow simulation for water resource management, flood forecasting, and ecological assessments are explored. This comprehensive synthesis will be valuable for researchers, practitioners, and policymakers seeking to understand and mitigate the challenges associated with streamflow simulation in ungauged basins, especially under the uncertainties of a changing climate.

A. Objectives

The primary objectives of this review are to comprehensively examine the current state-of-the-art methods used for streamflow simulation in ungauged basins, providing an in-depth understanding of the various approaches and techniques applied in hydrological modeling. Additionally, this review aims to assess the challenges associated with streamflow simulation in the context of a changing climate, including the impacts of climate variability, data scarcity, and model uncertainties. By identifying promising methodologies and emerging technologies, the review will explore innovative solutions that can enhance the accuracy and reliability of streamflow predictions. Furthermore, the applications of streamflow simulation in water resources management and planning will be highlighted, emphasizing its significance in decision-making processes related to flood forecasting, drought management, infrastructure design, and sustainable water allocation. This comprehensive analysis will offer valuable insights for researchers, practitioners, and policymakers seeking to advance the field of hydrological modeling and address the pressing challenges of water resource management in ungauged regions.

B. Scope

This review will focus on streamflow simulation for ungauged basins using both data-driven and physically based models. The review will also cover the impacts of climate change on streamflow and the challenges of incorporating climate change into streamflow simulation models. Finally, the review will discuss the applications of streamflow simulation for ungauged basins in water resources management and planning.

C. Challenges

Streamflow simulation for ungauged basins in a changing climate presents several challenges. The primary issue is the lack of observed data, which hinders accurate model calibration and validation. Additionally, the complexity of hydrological processes, including interactions between surface water, groundwater, and vegetation, adds to the difficulty of developing reliable models. Climate change further exacerbates these challenges by altering precipitation patterns, temperature, and evapotranspiration rates, leading to uncertainties in future streamflow projections. Furthermore, conducting comprehensive uncertainty analysis and model calibration becomes particularly challenging in data-scarce regions, making it essential to explore alternative approaches such as remote sensing, machine learning, and regionalization techniques to improve simulation accuracy.

D. Approaches

Various approaches have been developed to tackle the challenges of streamflow simulation for ungauged basins in a changing climate. Data-driven methods, such as regionalization and regression analysis, are widely used to estimate streamflow by transferring information from gauged to ungauged basins. Physically based models, including the Budyko framework and the HBV model, simulate hydrological processes using catchment characteristics and meteorological data[10]. Climate change impact assessment methods, like downscaling and bias correction, are employed to assess future streamflow scenarios under different climate conditions. Additionally, uncertainty analysis and model calibration techniques, such as Bayesian inference and Monte Carlo simulation, are applied to improve model reliability and quantify uncertainties. The applications of streamflow simulation in ungauged basins span a variety of fields, including water supply planning, flood risk assessment, hydropower development, environmental flow assessment, and ecosystem management. These simulations play a critical role in supporting decision-making processes and ensuring sustainable water resources management in regions lacking direct hydrological observations.

III. HYDROLOGICAL MODELING FOR UNGAUGED BASINS & ITS IMPORTANCE

Hydrological modeling is a powerful technique of hydrologic system investigation for both the research hydrologists and practicing water resources engineer involved in the planning and development of integrated approach for management of water resources. Hydrologic models are symbolic or mathematical representation of known or assumed functions expressing various components of the hydrologic cycle[11] .The term hydrological model is often misunderstood to be only as a computer based mathematical model. The main function of these models are hydrologic prediction and to understand various hydrologic processes. Hydrologic models for ungauged basins try to simulate the catchment behaviour by solving the equations that govern the physical processes occurring within the catchment. Therefore hydrologic models are usually used to simulate the catchment response for a given input. The hydrologic models take time series data and produce another time series as output.

Stream flow prediction in ungauged basins (PUB) is a significant challenge in hydrology due to the lack of direct measurement data. Ungauged basins are those where no or insufficient stream flow records are available, making it difficult to apply traditional hydrological models directly. The accurate prediction of stream flow in these basins is crucial for water resource management, flood forecasting, and environmental protection. Various soft computing techniques, including artificial neural networks, fuzzy logic systems, and genetic algorithms, have been developed to address these challenges and improve prediction accuracy [12].

Hydrological modeling is a crucial scientific approach used to understand and predict the movement, distribution, and quality of water within a watershed. It serves as a foundation for managing water resources, mitigating flood risks, and supporting sustainable development. By simulating the water cycle's processes, hydrological models offer insights into streamflow, groundwater levels, soil moisture, and other hydrological parameters. These models are essential for assessing the impacts of climate change and human activities on water systems [13]

A. Types of Hydrological Models

Hydrological models can be broadly classified into three categories:

1) Empirical Models: These are data-driven and rely on observed data to establish statistical relationships between input and output variables. They are often used for short-term predictions.
2) Conceptual Models: These models represent the physical components of a watershed using simplified mathematical formulations. They require calibration using observed data.
3) Physical-Based Models: These models simulate hydrological processes using physical laws, such as conservation of mass and momentum. They are particularly useful for studying the effects of climate change on hydrological systems [14]

IV. TRADITIONAL HYDROLOGICAL MODELS FOR STREAMFLOW SIMULATION

Hydrological models are essential tools for simulating streamflow, particularly in ungauged basins where direct observations are unavailable. Traditional hydrological models are primarily classified into three categories: conceptual models, empirical models, and physically-based models. These models rely on various mathematical representations of the hydrological cycle to estimate streamflow. Despite advancements in data-driven techniques, traditional models remain crucial due to their physical interpretability and established methodologies.

A. Conceptual Hydrological Models

Conceptual models represent the hydrological system using simplified, lumped equations based on physical processes. These models generally divide the watershed into compartments (e.g., soil, groundwater, and surface water) with parameters estimated through calibration.

The HBV model is a widely used conceptual model developed in Sweden, designed to simulate runoff from rainfall and snowmelt. It applies storage components representing soil moisture, snowpack, and groundwater, providing reliable streamflow predictions in both gauged and ungauged basins [15]. Figure 3 illustrates the structure of the HBV model.

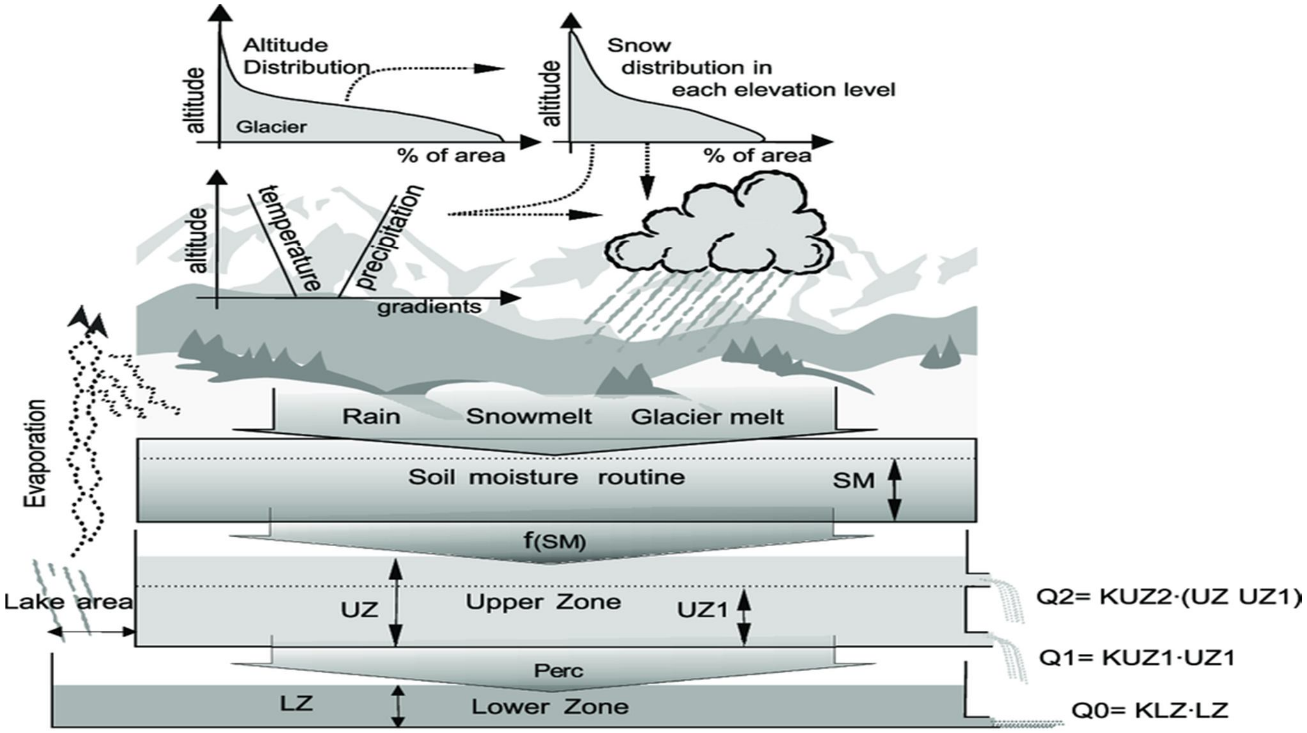

Figure 3 represents the Conceptual representation of the HBV model components.

B. Empirical Models

Empirical models establish direct relationships between observed hydrological variables (e.g., rainfall and runoff) using statistical or regression-based methods. These models are often used for short-term predictions and are data-driven without detailed physical interpretations. The Rational Method is a commonly applied empirical model used for estimating peak discharge in small watersheds. It uses a simple formula:

$$Q = C\ I\ A$$

Where: Q = Peak discharge (m^3/s)
C = Runoff coefficient
I = Rainfall intensity (mm/h)
A = Drainage area (ha)

While the Rational Method is easy to apply, its applicability is limited to small basins with uniform rainfall distribution.

C. Physically-Based Models

Physically-based models simulate hydrological processes using mathematical representations of physical laws such as the conservation of mass, momentum, and energy. These models require detailed data on soil properties, topography, land use, and meteorological conditions. The SWAT model is a semi-distributed, physically-based model used globally for predicting streamflow and assessing land management impacts on water resources. It divides watersheds into sub-basins and hydrological response units (HRUs) for detailed simulation [16]. Figure 4 shows the workflow of SWAT modeling.

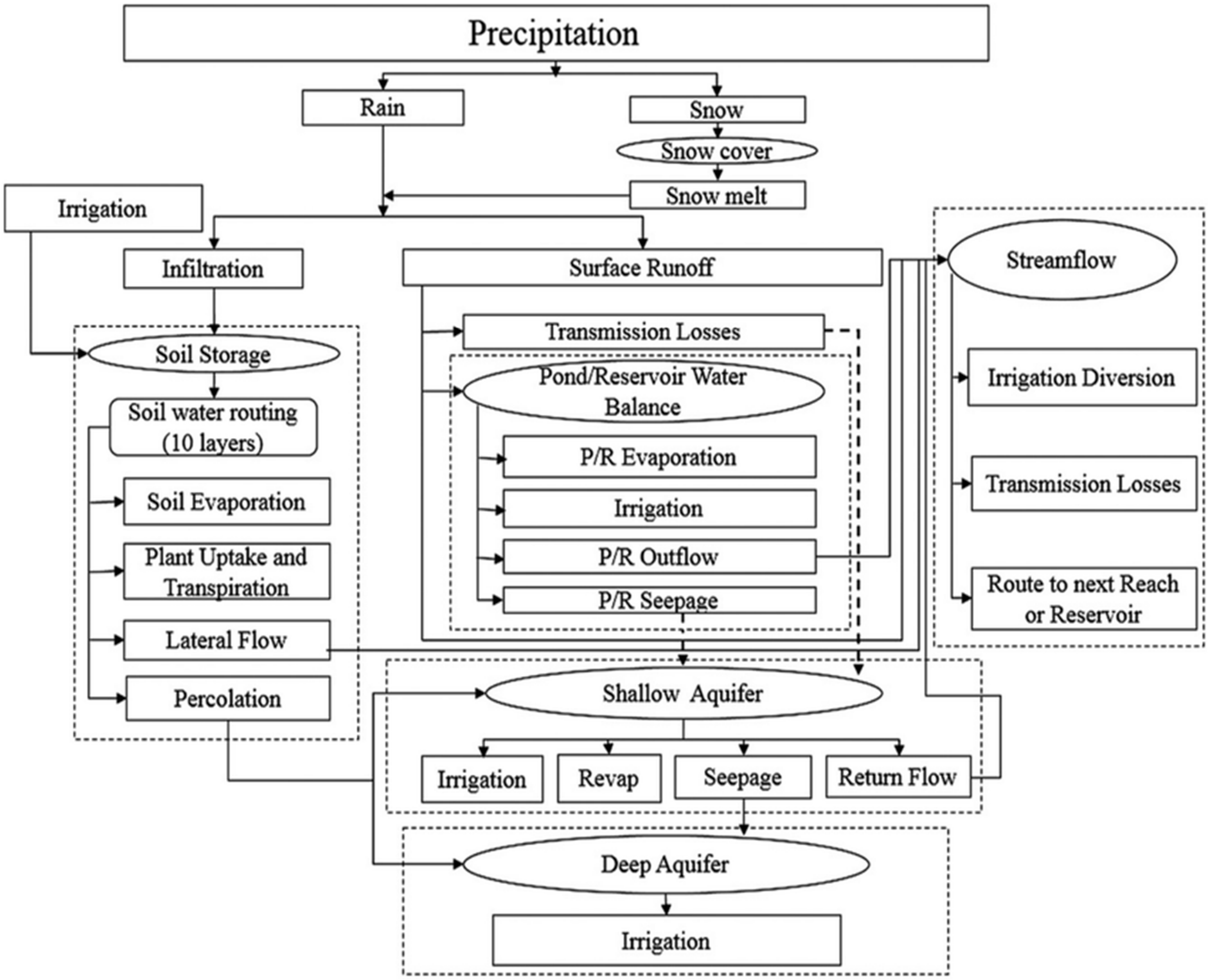

Figure 4 represents Schematic representation of SWAT model structure

D. Comparative Analysis of Traditional Models

To better understand the applicability of these models, a comparative analysis is presented in

Table 1. Comparison of traditional hydrological models for streamflow simulation.

Model	Type	Strengths	Limitations	Best Use Case
HBV	Conceptual	Simple, requires limited data	Requires calibration	Seasonal and annual streamflow simulation
Rational Method	Empirical	Easy to apply, minimal data needed	Limited to small basins	Peak flow estimation for small watersheds
SWAT	Physically-Based	Detailed process simulation	Data-intensive, complex calibration	Land-use management and long-term simulations

Traditional hydrological models provide a robust foundation for streamflow simulation in ungauged basins. While empirical models offer simplicity and ease of application, conceptual models such as HBV strike a balance between physical realism and computational efficiency. On the other hand, physically-based models like SWAT deliver detailed insights into hydrological processes, making them suitable for long-term assessments and climate change studies. The choice of model depends on the availability of data, the spatial and temporal scale of interest, and the specific objectives of the study.

Future advancements in hydrological modeling will likely involve the integration of these traditional approaches with machine learning algorithms and remote sensing data to enhance predictive accuracy under changing climatic conditions.

V. CONCLUSION

Hydrological modeling in ungauged basins has seen significant advancements in recent years, with the integration of remote sensing data, machine learning algorithms, and improved regionalization techniques. Physically-based models, while offering detailed process-based simulations, often face challenges in data-scarce regions. Conversely, data-driven models provide robust predictions using minimal input data, but they may lack interpretability [17]

Traditional models, while robust, often require substantial calibration, making data-driven methods more attractive for regions with limited hydrological data. Furthermore, the integration of remote sensing and GIS has expanded the scope of data acquisition, contributing to improved model performance. However, uncertainties associated with parameter estimation, climate variability, and land use changes continue to pose challenges. Future research should focus on developing hybrid modeling frameworks that combine the strengths of physics-based and data-driven models, ensuring more robust and transferable predictions. Additionally, the application of ensemble modeling techniques and uncertainty quantification methods can further enhance the reliability of streamflow simulations. Collaborative efforts in data sharing, model intercomparison studies, and the use of emerging technologies will be crucial in advancing hydrological modeling for ungauged basins. Ultimately, improving model accuracy and adaptability will support more informed decision-making in water resource management and climate change adaptation. Studies have shown that hybrid approaches, combining physical models with data-driven algorithms, enhance model accuracy and reliability [18]. Moreover, advances in satellite remote sensing offer comprehensive datasets that bridge the gap in observation scarcity.

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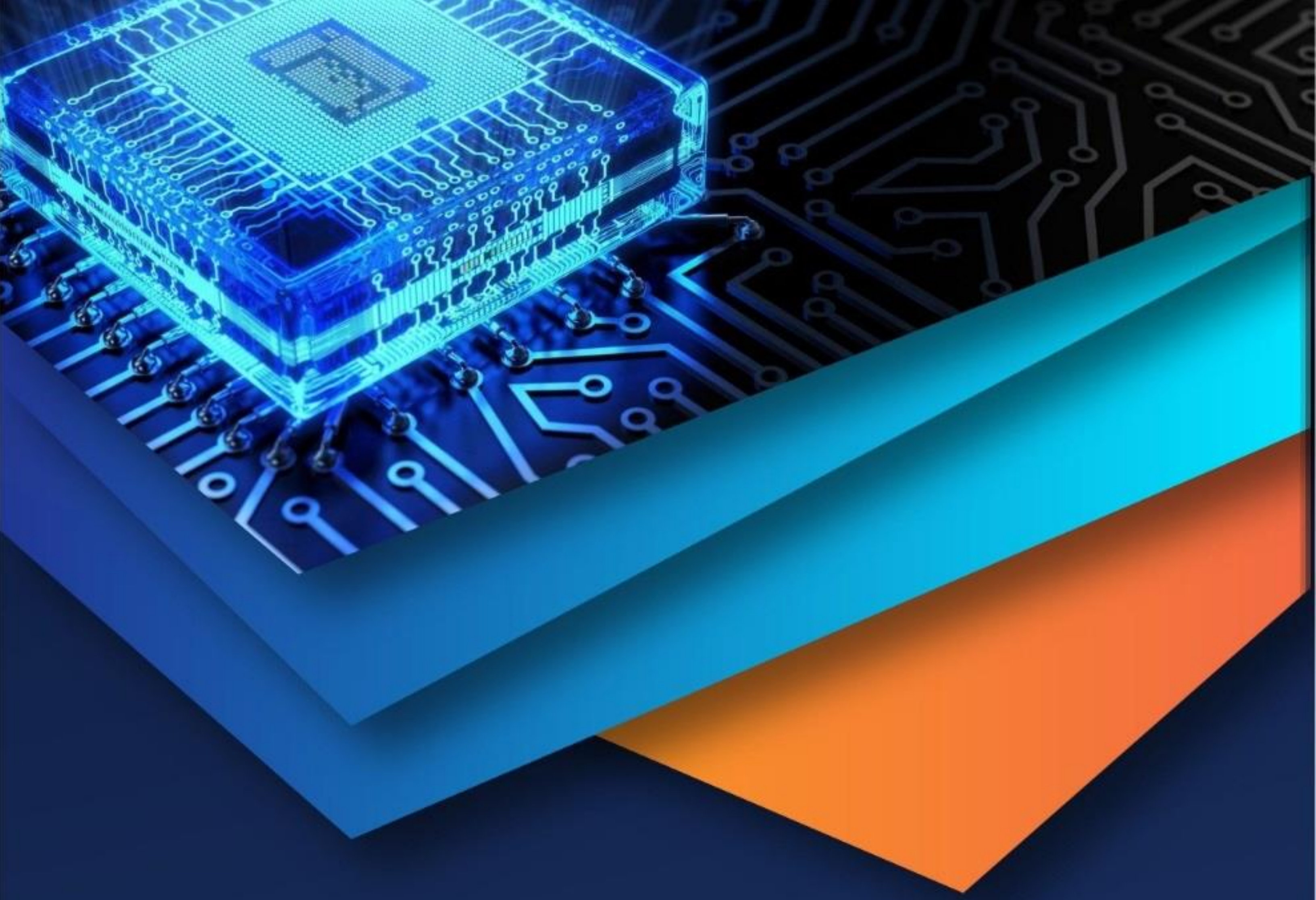

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