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HEC-HMS model in watershed hydrology: A review of methods, calibration, and real-world applications

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Abstract

The Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) is a widely used tool for simulating precipitation-runoff processes in dendritic watershed systems. This review outlines current literature on HEC-HMS with a focus on its development, core components, calibration approaches, and integration with geospatial technologies such as GIS and remote sensing. Thorough review of applications in Indian watersheds, which present diverse hydrological and climatic conditions. The model's effectiveness in event-based and continuous simulations is evaluated using performance metrics such as the Nash-Sutcliffe Efficiency (NSE). Case studies reveal its suitability for flood forecasting, water resource management, and climate change impact assessments. Despite challenges like data scarcity and calibration complexity, HEC-HMS remains a robust and adaptable modelling platform when supported by high-quality input data and interdisciplinary integration.

Keywords: HEC-HMS, hydrologic modelling, rainfall-runoff simulation, calibration, GIS, Indian watersheds, flood forecasting, water resource management

Introduction

'Water is essential for sustaining ecosystems, agriculture, and human life. Global climate change is increasing the frequency of extreme events such as floods and droughts, this causes extremities in weather conditions like droughts and flood more frequently. This can have greater impact on agriculture, natural resources, overall ecosystem and livelihood. Rainfall- runoff are the components contributing significantly to the hydrological cycle. In surface hydrology, rainfall-runoff processes play a important role. The rainfall-runoff relationship is one of the most important phenomena in hydrologic design of hydrological structures and drainage systems. The estimation of runoff volume of a catchment is an important aspect in engineering planning, environmental impact assessment, flood forecasting and water balance calculations (Balvanshi and Tiwari, 2014)^[6].

Hydrological modelling plays a important role in water resource planning, flood forecasting, and environmental management. Hydrologic models also allow us to predict the hydrologic response to various watershed management practices and to have a better understanding of the impacts of these practices (Srinivas *et al.*, 1999). Among the various hydrological models developed globally, the Hydrologic Engineering Center's Hydrologic Modelling System (HEC-HMS), developed by the U.S. Army Corps of Engineers, is widely adopted due to its flexibility, modular design, and ability to simulate complex watershed hydrology (Anderson *et al.*, 2013; Visweshwaran, 2016)^[51, 57].

HEC-HMS is capable of model different type of hydrological components, including precipitation, infiltration, surface runoff, baseflow, and channel routing. It supports both event and continuous flow analysis, making it suitable for a wide range of applications in both urban and rural settings (Kumar *et al.*, 2010; Shrivastava, 2020). The model's compatibility with GIS and remote sensing tools has further increased its utility, enabling spatial parameterization and watershed delineation even in data-scarce regions (Putty & Prasad, 2010; Kumar & Bhattacharya, 2011)^[3, 7, 28, 40, 48].

Country like India have, massive variation in climatic zones and monsoon-driven hydrology, presents numerous challenges for hydrological modelling. Quantitative description of the land phase of the hydrologic cycle is often complex and indefinite. Variations in climate, geography, and watershed properties cause different basin responses to rainfall events. As a consequence of limited rainfall runoff data, it has not been able to understand hydrological condition of the basin. Thus, it has become inevitable to determine rainfall-runoff model and the model parameters for a particular watershed (Halwatura and Najim, 2013). Numerous studies have evaluated HEC-HMS in this context, demonstrating its capacity to simulate rainfall-runoff processes effectively in various watershed types from tropical forests in the Western Ghats to semi-arid basins in Gujarat (Trivedi & Yadav, 2020; Masoud, 2016). The SCS-CN method is the most frequently used loss estimation technique within Indian studies, due to its simplicity and adaptability (Patil *et al.*, 2019; Paul *et al.*, 2014)^[22, 31, 35, 36, 55, 60].

This paper provides a comprehensive review of the structure, calibration techniques, and real-world applications of HEC-HMS, with a particular focus on Indian watersheds. By analyzing case studies from various climatic and geographical regions, this study aims to highlight the model's strengths, limitations, and areas for improvement. The goal is to support researchers and practitioners in making informed decisions regarding the model's use in water resource assessments and hydrological forecasting.

The computer advances in the 1960's made possible the integration of models of different components of hydrologic cycle and the simulation of virtually entire watershed with a development of Stanford Watershed Model (SWM) presently known as Hydrological Simulation Program Fortran (HSPF) by Crawford and Linsley in 1966 (Singh and Fervert, 2006). At present, there are well-established conceptual as well as physically based modelling approaches which have been employed for the simulation of rainfall-runoff processes in different watersheds of India (Putty and Prasad, 2000) and abroad (Anderson *et al.*, 2002). At present several hydrological models are available, but a choice of suitable hydrological model is important for accurate prediction of watershed runoff. The selection of the model depends on the basin and the objective of the hydrological prediction in the basin. Therefore, comparative evaluation-based studies are needed to assess the applicability and limitations of watershed models and to provide a basis for selecting a model that will perform adequately in a specific application. Compared to other empirical models, physically based models do not require long hydrological records for their calibration since their input parameters are directly related to the watersheds physical characteristics. Several studies have been conducted using the Hydrologic Engineering Center's Hydrologic Modelling System (HEC-HMS) model in different regions under different soil and climatic conditions. Chu and Steinman (2009) used HEC-HMS model for both event and continuous hydrological modelling in Monalack watershed in west Michigan. Anderson *et al.* (2002), Abed *et al.* (2005), Clay *et al.* (2005), Kneble *et al.* (2005), Hu *et al.* (2006), McColl and Aggett (2006), Yusop *et al.* (2007), Yener *et al.* (2008), Arekhi (2012), Majidi and Shahedi (2012), Sardoii *et al.* (2012), Halwatura and Najim (2013), Majidi and Vagharfard (2013) used HEC-HMS model with geo-informatics and atmospheric models for flood forecasting and early warnings in different regions of the world. Putty and Prasad (2000), Kumar and Bhattacharya (2011), Bhatt *et al.* (2012) also used HEC-HMS model to simulate of rainfall-runoff process for

watershed management in different parts of India. The model was found accurate in spatially and temporally predicting watershed response in event based and continuous simulation as well as simulating various scenarios in flood forecasting and early warnings. The previous studies reveals that HEC-HMS model has been used effectively in several water resources studies, where conventional rainfall-runoff model or lumped catchment model do not meet the criteria. Compared to other watershed models, the HEC-HMS is a physical based, semi-distributed watershed model that incorporates both single event as well as continuous rainfall-runoff simulation. It is one of the only hydrologic simulation products ever to place such an equal value on either natural and urbanized watersheds or mixture of both conditions. This flexibility allows a watershed model developed for one purpose, to be reconfigured with a minimal amount of effort. The model is a completely unified work environment including a database, data entry utilities, computation engine, graphical user interface and results reporting tools^[1, 2, 5, 7, 9, 22, 26, 27, 29, 30, 32, 39, 52, 62].

Core Modeling Capabilities

HEC-HMS can replicate a variety of hydrological processes, including baseflow, channel routing, rainfall, and loss estimates. The SCS-Curve Number (SCS-CN) (Patil *et al.*, 2019; Kumar *et al.*, 2010), Green-Ampt infiltration (Reshma *et al.*, 2015; Majidi & Shahedi, 2012), and Soil Moisture Accounting (SMA) for continuous simulations (Gyawali & Watkins, 2013; Putty, 2014) are among the loss methods supported by the model. The frequency storm method is used to run the meteorological model. Indian watershed studies often use transformation techniques like the Clark unit hydrograph (Paul *et al.*, 2014; Dwivedi, 2015), the Snyder method (Trivedi & Yadav, 2020; Mohamedmaroof & Yadav, 2019), and routing techniques like Muskingum (Verma *et al.*, 2025; Visweshwaran, 2016)^[12, 20, 28, 29, 33, 35, 36, 38, 43, 50, 55, 56, 57, 59, 60].

SCS-Curve Number (SCS-CN)

For rainfall runoff processes, the Soil Conservation Services and Curve Number (SCS-CN) technique is a highly significant, well-known, and straightforward method. Hydrologic modeling uses land cover data to calculate the amount of surface roughness or friction, which influences the water's overland flow velocity (Ara, Z. 2018; Zakwan & Muzzammil 2016). In the semi-arid region of southwest Algeria, Derdour *et al.* (2018) used the HEC-HMS hydrological model to simulate runoff. They used the SCS unit hydrograph model to simulate the runoff rate and the soil conversation service (SCS) curve number (CN) to determine the loss rate. (El-Bagoury, & Gad 2024) calculated the hydrologic loss rate using the SCS curve number (CN) loss method, the runoff rate using the SCS unit hydrograph (HU) method, and the meteorological model was simulated using frequency storm^[4, 11, 14, 63].

Hec-HMS Model Capabilities

1. Integration with GIS and Remote Sensing

By offering spatially distributed inputs for rainfall, soil type, and land use, GIS and remote sensing technologies greatly improve HEC-HMS performance (Kumar & Bhattacharya, 2011; Kumar *et al.*, 2010). Particularly in regions with limited data, several studies have effectively parameterized models using GIS-based delineation and precipitation derived from remote sensing (Masoud, 2016; Putty & Prasad, 2010). Visweshwaran (2016) showed how to use HEC-GeoHMS for automated watershed characterization, which decreased human error and increased calibration accuracy^[7, 27, 28, 31, 40, 57].

2. Calibration and Validation Techniques

Careful calibration is required for HEC-HMS models in order to modify determinant factors such as the curve number, initial abstraction, and lag time. High simulation accuracy is indicated by Nash-Sutcliffe Efficiency (NSE) values exceeding 0.75-0.85 in a variety of Indian case studies. For instance, Paul *et al.* (2014) reported $NSE > 0.75$ for 24 storm events in the Balijore Nala watershed, while Patil *et al.* (2019) obtained an NSE above 0.80 for event-based modeling in the Upper Godavari Basin ^[35, 36].

Similarly, Trivedi and Yadav (2020) observed NSE is 0.823 in the Rel watershed, Gujarat. Reshma *et al.* (2015) and Ghosh (2015) ^[15] indicated the impact of repetitive calibration and incorporation of soil and land use data to refine model accuracy ^[43, 55, 60].

3. Application in Indian Watersheds

a. Monsoon-Dominated Basins

HEC-HMS has proven effective in modeling rainfall-runoff processes in monsoon-influenced watersheds. Patil *et al.* (2019) demonstrated strong agreement between observed and simulated runoff in the Upper Godavari Basin using the SCS-CN and Muskingum methods. Similarly, Verma *et al.* (2025) used HEC-HMS integrated with HEC-RAS to model flood inundation in the Kharkai River Basin, achieving NSE values above 0.80. Visweshwaran (2016) and Shrivastava (2020) also confirmed the model's accuracy for large-scale monsoon-driven hydrology ^[35, 48, 56, 57].

b. Semi-Arid and Tropical Watersheds

In semi-arid watersheds, such as the Rel (Trivedi & Yadav, 2020) and Sabarmati basins (Kumar & Bhattacharya, 2011), HEC-HMS effectively simulated runoff patterns under variable rainfall conditions. Mohamed maroof and Yadav (2019) reported an NSE of 0.83, underscoring the model's reliability. In tropical regions like the Nethravathi Basin, Masoud (2016) demonstrated successful application with high NSE values, supported by GIS-based inputs. Putty and Prasad (2010) showed that the model could also simulate runoff from steep and rugged terrain in the Western Ghats ^[7, 27, 31, 40, 55, 60].

c. Urban and Agricultural Catchments

HEC-HMS performs well in small-scale agricultural and urban watersheds where data may be limited. Paul *et al.* (2014) simulated 24 storm events in the Balijore Nala watershed with strong agreement to observed data. Chunale *et al.* (2013) validated the model in a small agricultural watershed in Maharashtra, confirming its suitability for rural applications. Saleh (2012) adapted the model for urban runoff in the Koraiyar basin, accounting for complex drainage patterns with satisfactory performance ($NSE = 0.80$) ^[8, 36, 45].

d. Comparative Studies and Hybrid Applications

Kumar *et al.* (2010) compared HEC-HMS with the WEPP model and found that HEC-HMS delivered better performance for Indian storm events. Mokhtari *et al.* (2017) integrated HEC-HMS outputs with HEC-FIA for infrastructure damage assessment, while Anderson *et al.* (2013) demonstrated coupling with atmospheric models for improved runoff prediction. These hybrid approaches reflect the growing versatility of HEC-HMS in research and operational use ^[3, 28, 34].

Conclusion

The Hydrologic Engineering Center-Hydrologic Modelling

System (HEC-HMS) has come out as a strong, easily adaptable, and widely validated tool for hydrological simulation across diverse watershed conditions. Through this review of over twenty years of literature, especially from the Indian subcontinent, it is apparent that HEC-HMS offers exceptional versatility in simulating both event-based and continuous rainfall-runoff processes. Its modular design, compatibility with geospatial technologies, and capacity to integrate with other hydrological models make it highly suitable for a broad range of applications from flood forecasting and urban drainage design to climate change impact assessments and water resource planning. Kinds of case studies shows the model's performance in estimating the hydrological responses of tropical, semi-arid, monsoon-driven, and urban watersheds in India. Calibration and validation studies regularly show high performance metrics such as NSE values exceeding 0.75, despite the low availability of hydrological input data. The merging of GIS and remote sensing technologies has been particularly transformative, enabling spatially distributed modelling even in Data-poor regions.

However, HEC-HMS is also with limitations. The accuracy of simulations is often bounded by the availability and quality of input data, the complexity of calibration processes, and the assumptions driving empirical methods like the SCS-CN curve number approach. To address and overcome these limitations, recent advances have included coupling HEC-HMS with hydraulic models, atmospheric prediction systems, and flood impact analysis tools, significantly expanding its utility.

Now a days challenge of grow in climate variability, rapid urbanization, and the growing need for resilient water infrastructure, HEC-HMS considered a reliable and optimal solution. HEC-HMS will depend on enhanced data collection systems, integration with real-time forecasting platforms, and the execution of advanced calibration methods including AI and machine learning.

This review presents HEC-HMS as a noteworthy model of modern watershed modelling one that boost abilities to understand rainfall runoff processes of the researchers, engineers, and policymakers to make informed, science-based decisions for sustainable water management in both developing and developed regions.

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