A Review: Contribution of HEC-HMS Model

Mukul Kumar Sahu, H. R. Shwetha, and G. S. Dwarakish

Abstract The rapid increase of population worldwide, urbanization, and industrialization significantly impact hydrologic processes locally and globally. Thus, development planning and managing various water resources are required to meet multiple water demands. However, acquiring gauge discharge data has always been difficult since measurements cannot be taken at every point along the river. Thus, HEC-HMS (Hydrologic Modeling System) is the hydrological model that can transform rainfall into a runoff by using known parameters, data, and appropriate mathematical equations to simulate flow records at the desired location. HEC-HMS was developed by the USACE and is freely accessible. It can estimate runoff from rainfall. In this paper, we review the studies carried out by researchers on the HEC-HMS model worldwide to ascertain its ability to simulate runoff with accuracy and use for making decisions. It could be seen that many researchers compared different modelling methods to obtain the best model suitable under different hydrological conditions and found HEC-HMS as a good model over others and recommended it for simulation of runoff. The reviews show that the HEC-HMS rainfall-runoff model has many flood modelling and water resource planning and management applications. In most studies, HEC-HMS rainfall-runoff modelling was found to be efficient and dependable in predicting runoff accuracy in various river basins. As a result, the model can simulate runoff in an ungauged basin for water resource planning, development, management, and decision-making.

Keywords HEC-HMS · Rainfall-Runoff Modelling · Simulation Model

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P. V. Timbadiya et al. (eds.), *Hydrology and Hydrologic Modelling*,
Lecture Notes in Civil Engineering 312,
https://doi.org/10.1007/978-981-19-9147-9_16

1 Introduction

Watershed models are required for proper assessment, development, and management of water resources. Computer simulation of rainfall-runoff began in early 1960 [5]. However, calculating runoff from an ungauged or poorly gauged watershed is problematic in developing nations like India. Hydrologic models help us in better understanding hydrological phenomenon occurring in the watershed. There are several components of the hydrologic cycle like surface runoff, infiltration, evaporation, sub-surface flow, depression storage, and baseflow. Integration of various hydrological processes helps in the management of water resources and also in the design of the hydraulic structure. The hydrological processes depend on rainfall patterns and land use land cover of the basin and vary in spatial and temporal scales.

To simulate the various hydrological process of the basin, the development of the model came into existence in, 1992 [30]. In 1967, Leo R Beard and other Hydrological Engineers Circle staff members, with the US Army Corps of Engineers, developed a mathematical watershed model HEC-1 to simulate the flood hydrograph. HEC-1 was upgraded to increase its capabilities [31]. The initial release of HEC-HMS was known as version 1.0, and it included all the features of HEC-1 with minor improvements. The second release, version 2.0, introduced the Soil Moisture Accounting (SMA) approach, which expanded the programme's capabilities from event-based simulation to continuous simulation. The third major update, version 3.0, introduced a new graphical interface to develop potential and snowmelt evapotranspiration methods. In addition, some new infiltration representation approaches were introduced in the model. The fourth, version 4.0, adds sediment movement, and surface erosion to the computation is an important update. After the fourth version, 4.0 of HEC-HMS, the 4.1 series of performances started, and HEC-HMS 4.9 is the latest version of the HEC-HMS programme and had the advantage that it does not overwrite the observed stage data with observed flow data as it done in its previous version 4.8.

HEC-HMS is made up of four primary parts as follows. (a) An analytical model for calculating runoff and channel routing from overland flows, (b) an innovative graphical user interface with interactive elements for demonstrating hydrological system components, (c) massive time-variable datasets require a framework for storing and managing them, and (d) a standard for showing and reporting model output in rainfall-runoff simulations. Many alternatives are available in HEC-HMS, such as the basin model, which consists of three processes: loss, transform, and base flow. Runoff prediction and its response at the outlet are very challenging in hydrology. In any watershed modelling, its calibration and validation require many spatial and temporal data. There is a great challenge to assure modelling quality due to the non-availability of high-resolution data utilized in the model's development, calibration, and validation. So, choosing a model that requires minimum input data is structured and highly precise for the present scenario. HEC-HMS is one of those models that require less data. Rainfall-runoff modelling can be done on an event-by-event basis or on a continuous basis. It can be utilized in both lumped and distributed parameter-based modelling scenarios. It can be used to investigate urban flooding, flood frequency, flood warning systems, reservoir spillway capacity, and stream restoration, amongst other things. This paper summarizes the literature reviews of the HEC-HMS model to depict rainfall-runoff dynamics in basins.

2 Overview of Reviewed Papers

The papers published across different journals from 1971 to 2021 were reviewed in this study. The areas of reviewed watersheds simulated using the HEC-HMS model were mainly between 100–5000 km^2. The paper reviewed was fifty.

The performance of HEC-HMS model outputs was assessed using several indices such as Nash–Sutcliffe Efficiency (NSE), Pearson's Correlation Coefficient (R), Root Mean Square Error (RMSE), and Coefficient of Determination (R^2). These were the most commonly used indices. Index of Agreement (IA), Relative Volume Error (RVE), Relative bias (r bias), Volume Ratio (VR), and Index of Volumetric Fit (IVF) were least used.

The data required for the river basin modelling is divided into three groups, (i) basin information like the channel or the river's topography, (ii) hydro-meteorological data, and (iii) data on flow rates and stages over time for model calibration and validation. These are used to establish model input and output boundary conditions. Recent advancements in remote sensing have enabled the acquisition of some of this data. Satellites and airborne remote sensing allow for the collection of spatially scattered data across broad areas and eliminate the need for expensive ground surveys. On the other hand, ground measurements are essential for validating satellite products. More and more geospatial datasets linked to hydrology such as topography, soil, and land use have become available through numerous open sources due to advancements in remote sensing in recent decades.

The review was broadly categorized into two summary sections, based on the applications of the HEC-HMS model: (i) streamflow simulation, (ii) flood modelling.

3 Application of HEC-HMS Model

3.1 Application for Streamflow Simulation

At various regional and national scales, research on water resources concentrated on extreme weather events (floods and droughts), rainfall-runoff models, streamflow modelling, and agriculture water ungauged basins. The HEC-HMS model was considered as adequately capable of simulating stream flows in ungauged basins [14] and to analyze runoff processes for the development and management of water resources [6, 16, 26, 28].

In several river basins, the HEC-HMS model was employed in this research to understand hydrological processes better. Models are categorized based on how the representation of catchment processes (deterministic or stochastic), and how the catchment is spatially detached (lumped or distributed). The continuity, momentum, and data-driven techniques have been used to build routing models that estimate wave propagation along a river channel [27].

The Hydrologic Modeling System (HEC-HMS) is intended to simulate the precipitation runoff process of the dendritic watershed system. The system incorporates traditional hydrologic processes such as unit hydrographs, infiltration, hydrologic routing, and procedures for continuous simulation such as snowmelt, evapotranspiration, and soil moisture accounting.

Before developing HEC-HMS software, the researchers used Geographic Information Systems (GIS) with HEC-1 software. GIS handles the datasets (raster or grid-based data, triangular irregular networks, vector, or contour-based line networks) used in hydrologic modelling. Grid cell or raster storage of information was used in the initial GIS applications in hydrologic modelling [24]. In other cases, infiltration, interflow, and overland flow processes in a sub-basin were regarded as discrete contributing processes. As a result, the processes in difficult terrain are physically considered as simple plane processes that happen on their own. The Soil Conservation Service Curve Numbers (SCS-CN) were created by evaluating small, reasonably uniform attribute watersheds, with the assumption of continuous rainfall [9]. After the release of HEC-HMS software, the researchers in their studies had used different methods to simulate the rainfall-runoff process using the soil conservation service curve number method and SCS-UH (Unit Hydrograph) to convert precipitation excess into direct runoff [3, 6, 18]. Hamdan et al. [16] developed a hydrological model combining HEC-HMS, the Geospatial Hydrologic modeling Extension (HEC-GeoHMS), and Geographical Information Systems to simulate the rainfall-runoff process over the Al Adaim river basin and embankment dam in Iraq (GIS). The SCS-CN method was used to calculate loss parameters, the SCS-UH for runoff transformation, and the Muskingum method for routing purposes. For the embankment dam, reservoir modelling was done. Both actual and simulated hydrographs were found to be strongly related, according to the findings. The dam's discharge was successfully simulated for the period under consideration but slightly overstated.

Combining the fine-scale event and coarse-scale continuous hydrologic modelling systems for Mona Lake watershed, West Michigan, Chu et al. [8] developed a strategy. The SCS-CN and Soil Moisture Accounting (SMA) methods were used as a loss model for the event and continuous hydrologic modelling. The Clark-UH (Unit Hydrograph) for excess precipitation into direct hydrographs and the Watershed Modelling System (WMS) model developed basin model. For continuous modelling, they had used the parameters of event modelling. Took five-minute time steps for event-based modelling, and hourly time steps were taken for continuous hourly modelling. The results of their model imply that fine-scale (5 min time step) event hydrologic modelling, aided by extensive field data, aids coarse-scale (hourly time step) continuous modelling. De Silva et al. [11] also developed an event-based and continuous hydrological model for the Kelani river basin, Sri Lanka. The study considered the Green and Ampt loss methods in event-based modelling and a five-layer SMA method for continuous modelling. The Clark-UH and the recession base flow method simulated direct runoff. Extremely high precipitation events in November 2005 were utilized to calibrate model parameters, and extremely high rainfall events were used to test the event model in April–May 2008, May–June 2008, and May 2010. Their results also concluded that event-based hydrologic modelling supported with intensive field data helps to improve continuous modelling.

Majidi et al. [22] utilized the HEC-HMS software version 3.4 to simulate the rainfall-runoff mechanism in the Abnama watershed in southern Iran. The Green-Ampt method for loss estimation, SCS Unit Hydrograph for transforming excess rainfall into the direct runoff, and Muskingum method for routing purposes. Considered five rainstorm events for the rainfall-runoff simulation and initially found that their results were not up to the requirement. So, they had used the optimization method for calibration, and sensitivity analysis was carried out. After that, the correlation between the observed and simulated discharges indicated a good match and revealed that lag time was a susceptible component. Alhan et al. [20] developed the hydrological model to simulate an event that occurred over the Ayamama watershed, Istanbul, Turkey, on September 9, 2009. The methods used in basin modelling were the Green-Ampt method for infiltration loss, the Clark-UH method, and Kinematic wave routing. The Rational method was used to compare the outcomes (WMS). It was emphasized that the HEC-HMS model outperformed the Rational method.

3.2 Application for Flood Modelling

Flood modelling is essential to understand the possible impacts of floods of a given magnitude and initiate on the ground efforts to mitigate the effect. Progress in hydrodynamic modelling (HEC-HMS) during the last decade has led to considerable improvement to simulate flooding scenarios [27]. Changes in land use in a basin affect hydrological processes on various temporal and spatial dimensions. It can influence the frequency and intensity of floods by affecting runoff generation and flow patterns by changing hydrological parameters as interception, infiltration, and evaporation. At a watershed size, such affects on hydrological processes will have a considerable impact on the ecology, environment, and local economy. Therefore, it is critical to understand and assess the impacts of land use change on the watershed hydrologic process for anticipating flood potential and hazard reduction. These have become a crucial concern for watershed planning, management, and long-term development [7, 10, 32, 33].

The integrated GIS module, Watershed Modelling System (WMS), Hydrological Modeling System (HEC-HMS), and River Analysis System (HEC-RAS) models have been utilized in flood mapping and modelling [1, 2, 15, 21, 23, 25, 29]. GIS components handle DEM processing and morphometric analysis, as well as producing inputs for the WMS programme. The WMS is in charge of delineations and model scenarios that are used as digital input data for the HEC-HMS. The hydrologic equations that manage the interactions between rainfall and runoff are controlled by the HEC-HMS, which generates hydrographs for various scenarios and rainfall return times. The HEC-RAS deals with hydraulic equations to calculate depth of flow and flood area and helps develop flood plains. Pistocchi and Mazzoli [25] performed their study on Romagna river basins; Knebel et al. [21] developed the San Antonio river basin framework. Gul et al. [15] introduced a combined hydrologic and hydraulic modelling approach for the Bostanli river basin in Izmir, Turkey, for testing the efficiency of structural flood control measures. Thakur et al. [29] developed the hydrologic model and flood plain for Copper Slough Watershed (CSW), Champaign. Abdelkarim et al. [1] evaluated the impact of flash flood hazards on the Tabuk City, Kingdom of Saudi Arabia (KSA). Abdessamed and Abderrazak [2] studied the inundation behaviour during extreme flood events by considering concrete retaining walls developed by local authorities and without it for the Ain Sefra watershed in the southwest of Algeria. Niyazi et al. [23] evaluated the hydrological characteristics and mapped the flood-prone areas for different return periods over the Jazan basin in Jazan Province, Saudi Arabia. The aforementioned researchers' findings demonstrated the importance of employing an integrated modelling method to assess and minimize flash flood dangers in arid regions around the world. Dukic and Eric [13] compared the Systeme Hydrologique European Transport (SHETRAN) and Hydrologic Modeling System (HEC-HMS) models to simulate flash floods and to examine whether or not using a complicated hydrological model yields more accurate results. The SHETRAN and HEC-HMS models were calibrated for the storm in September 2007 and validated the runoff results for the storm events in June 2009, May 2010, and June 2010. The St. Venant equation and SCS-CN method in the SHETRAN and HEC-HMS models were utilized, respectively. The results show that the SHETRAN model, which is more sophisticated, beats the simpler HEC-HMS model in the runoff but not for soil moisture. They came to the conclusion that more complex models do not always yield greater model performance. Depending on the hydrological variable under consideration, the dependability of hydrological model simulations can vary.

Ali et al. [4] simulated rainfall-runoff to observe the effect of land use land cover (LULC) over the Lai Nullah basin. They used the SCS-CN method to estimate losses, the SCS-UH method for transformation, and the recession method for base flow development of a model. They considered five rainstorm events for calibration and validation. They forecasted the LULC using the calibrated result obtained by HEC-HMS, based on the Islamabad master plan and growth pattern. Hejagi and Markus [17] highlighted the flood issues due to urbanization on 12 Northeastern Illunois, Chicago watershed. The percentage change of urbanization in the study area was very significant. Design peak flood was obtained with the help of the design storm method and HEC-HMS modelling. Sensitivity analyzes suggested that urbanization caused to arise in peak flow compared to that obtained due to climate variability, and discharge increased more than regular discharge. By including urbanization on annual runoff and flood events for the Quinhuai River watershed in Jiangsu Province, China, Du et al. [12] built a distributed hydrologic model and a dynamic land use change model. Future land use maps were created using a Markov chain and a

Cellular Automata model (CA–Markov model), and HEC-HMS was used to compute the runoff. Flood volume also increases due to imperviousness for all flood events. Potential changes in the peak were linearly related to flood volume. Kabeja et al. [19] investigated the effect of land cover change on flash flood peak discharge using HEC-HMS in two medium-sized mountainous watersheds in China. The first one was the Yanhe catchment, and the second one was the Guangyuan catchment. Series of Landsat images were utilized to evaluate the land use changes between 1990 and 2016. Hydrologic response of the basin and sub-basin scale was generated using Hydrologic Modeling System (HEC-HMS) under four LULC scenarios. The change in LULC occurred due to an increase in forest area resulted in a decrease in flood peak discharge. The results concluded that the LULC is vital in estimating peak discharge. As imperviousness increases, runoff increases. Developed models could evaluate the hydrological impacts and thus prove helpful in watershed management, water resources planning, and flood management.

4 Limitations

The limitations of HEC-HMS are as follows:

- Stream networks with branching or looping cannot be modelled.
- In the stream network, there is no way to model backwater.
- ArcGIS with the Spatial Analyst Extension is required for the additional tool HEC-GeoHMS.
- Other than the US Army Corps of Engineers, no support is offered.
- The model code is not available to the general public.

5 Conclusions

In general, Rainfall-runoff models are the most commonly used instruments for studying hydrological processes. The extensive review of the HEC-HMS rainfall-runoff model concluded that intended output (hydrological variable) and data availability primarily determine the modelling method and approach. Researchers analyzed various modelling methods to find the optimum model for diverse hydrological circumstances, found HEC-HMS superior to others, and recommended runoff simulation due to its automatic calibration technique. Many researchers evaluated using the HEC-GeoHMS tool for basin model construction and acquiring basin features. Some researchers used formulae to find model parameters value, while others optimized it during calibration. The majority of the researchers employed the auto-calibration technique in HEC-HMS to calibrate the model. The statistical analysis of HEC-HMS rainfall-runoff modelling indicates that the model is robust and capable of simulating accurate runoff in the best agreement with observed hydrograph in many watersheds. The HEC-GeoHMS tool may be used to construct river basin models and find basin characteristics. The auto-calibration and manual calibration both functions better in HEC-HMS. The soil moisture accounting loss method works more accurately for continuous modelling.

Further research is going on to improve runoff predictions and face significant challenges like climate change, soil erosion, and floods. LULC is vital in calculating curve numbers, which helps calculate initial losses during precipitation. Due to urbanization, there is a significant change in land use patterns, which directly affects the peak of the hydrograph. Therefore, it is necessary to know at what rate the hydrograph peaks are changing and develop IDF curves for precipitation. Finally, import them into the model for learning peak hydrographs for different return periods. So that various measures can be taken according to peak hydrographs for safety purposes. Also, remote sensing and field data can be used in the HEC-HMS model. Each model has its strengths and weaknesses. Hence, the model should be chosen based on the research's final purpose.

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