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Simulation of the rainfall–runoff relationship using an HEC-HMS hydrological model for Dabus Subbasin, Blue Nile Basin, Ethiopia

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ABSTRACT

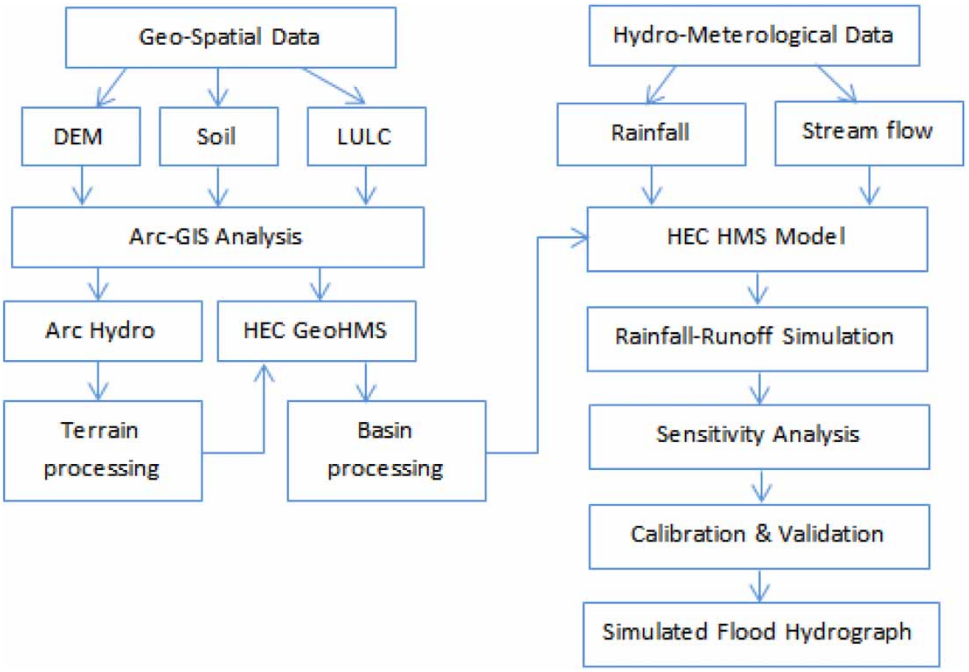
Hydrological modeling is important to provide relevant hydrologic information from limited data. In this study, Hydrologic Modeling System (HEC-HMS) was used to simulate the rainfall–runoff relationship for the Dabus subbasin of the Blue Nile Basin. Daily precipitation and stream flow data from 2002 to 2019 were used as key input data for the model, together with soil and land use/land cover data, and a digital elevation model of the study area. Arc-GIS was employed in combination with Arc Hydro and HEC-GeoHMS tools for terrain processing and translating spatial information into model files for HEC-HMS, respectively. Model calibration was done with data from 2002 to 2014, while the validation was done from 2015 to 2019. Nash-Sutcliffe simulation efficiency (NSE), observation standardized ratio (RSR), and coefficient of correlation (R^2) were used to assess the performance of the model. With NSE, RSR, and R^2 values of 0.784, 0.334, and 0.816 for calibration, and 0.793, 0.323, and 0.875 for validation, the model simulation of stream flows was found in good agreement with the observed values. Therefore, the HEC-HMS model can be utilized to predict stream flows in ungauged catchments in the Dabus subbasin from measured rainfall data for proper water resource planning and management.

Key words: Dabus, HEC-HMS, Nile basin, rainfall vs. streamflow

HIGHLIGHTS

- Rainfall–runoff relationship for data-scarce subbasin in the Blue Nile Basin was developed using HEC-HMS hydrological model.
- Arc-GIS was combined with ARC hydro and HEC-GEoHMS tools for terrain and basin processing to provide suitable inputs to the HEC-HMS model.
- The HEC-HMS hydrological model to simulate stream flow from rainfall data for the ungauged catchments in the subbasin is reliable and acceptable.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The derivation of relationships between the rainfall over a catchment area and the resulting flow in a river is a fundamental problem for the hydrologist. In most countries, there are usually plenty of rainfall records, but the more elaborate and expensive stream flow measurements, which are what the engineer needs for the assessment of water resources or damaging flood peaks, are often limited. Evaluating river discharges from rainfall has stimulated the imagination and ingenuity of engineers for many years, and more recently has been the inspiration of many researchers (Sarminingsih *et al.* 2019; Hamdan *et al.* 2021; Ranjan & Singh 2022; Guduru *et al.* 2023).

The surface subsystem of the hydrologic cycle is where the rainfall and runoff interaction takes place. The input to this system is the rainfall and the output is taken as the stream flow at the outlet of the system (Neitsch *et al.* 2002). Hydrological modeling is a typical approach for predicting the hydrological response of a basin to rainfall. It enables the prediction of the hydrologic response to various watershed management methods as well as a better understanding of their implications (Kadem 2011).

The wide analysis of the literature reveals that studies on the use of watershed models for hydrologic simulations in underdeveloped countries are severely restricted due to the limitation of data (Kumar & Bhattacharya 2011; Derdour *et al.* 2018). As a result, a study of hydrologic simulation through the development of an appropriate watershed model is very necessary. Since it is impossible to assess all characteristics that affect runoff, selecting a model with a basic structure, minimal input data needs, and adequate precision is critical (Ramesh 2017). Hydrologic Modeling System (HEC_HMS), which has been used extensively in many research works, is one of the hydrologic models that meet these criteria.

HEC-HMS is a physically based semidistributed hydrological model that represents a basin with interconnected hydrologic and hydraulic components to simulate the surface runoff response to precipitation. The HEC-HMS model uses three basic data sets for the modeling work, viz. meteorological data (rainfall, temperature, evapotranspiration); hydrological data (streamflow); and geospatial data (digital elevation model (DEM), soil, land use land cover). The computation of stream flow hydrographs at the basin outlet is the result of the modeling process.

The HEC-HMS model has been applied in wide geographical areas (Majidi & Shahedi 2012; Haddad 2022; Ranjan & Singh 2022; Guduru *et al.* 2023). The current version of HEC-HMS 4.2.1 is a highly flexible package. It includes different methods to simulate runoff volume, transforming excess precipitation, base flow estimation, and channel routing. The user can choose a suitable combination of models depending on the availability of data, the purpose of modeling; and the required spatial and temporal scales.

This study was, therefore, conducted to simulate the rainfall–runoff relationship for the Dabus subbasin in the Blue Nile Basin using HEC-HMS hydrological model to give useful information for future water resource planning and management. As the meteorological and gauging stations installed in the Blue Nile Basin in particular and in the country, in general, are very limited, the main motive of the study was to investigate hydrologic responses to precipitation under these data-scarce conditions.

2. METHODS

2.1. Description of the study area

The Dabus subbasin is located in Ethiopia between 10°0′0″ and 7°42′2.9″ north latitude and 31°8′53.6″ and 36°3′42.4″ east longitude in the Blue Nile Basin (Figure 1). The subbasin covers an area of 14,785 km^2. The highest and lowest points of the subbasin are 3,117 and 557 m above mean sea level, respectively. A single monsoon rainy season that lasts from May to September characterizes the climate of the study area. The subbasin receives an average annual rainfall of 1,236 mm. It has a mean annual air temperature of 28 °C in the lowland and 17 °C in the highland part of the area (Alkasim 2016).

2.2. Data acquisition

The daily historical hydrological and meteorological data for the subbasin were obtained from the Department of Hydrology and National Meteorological Agency of the Ministry of Water, Irrigation and Energy (MoWIE) for the period from 2002 to 2019. The data were collected from 10 rainfall stations (Table 1). The hydrologic gauging stations in the Dabus subbasin with automatic water level recordings are very limited. There are seven gauged stations but the stream flow data used in the model are from three stations, namely Dabus, Aleltu, and Dilla owing to the availability of rainfall recording stations in or near the boundary of the stream-gauged catchments (Table 2).

A DEM of resolution 30 m × 30 m which was downloaded from the United States Geological Survey Website was used for topographic analysis (Figure 2), and GIS was used to define drainage patterns and delineate the

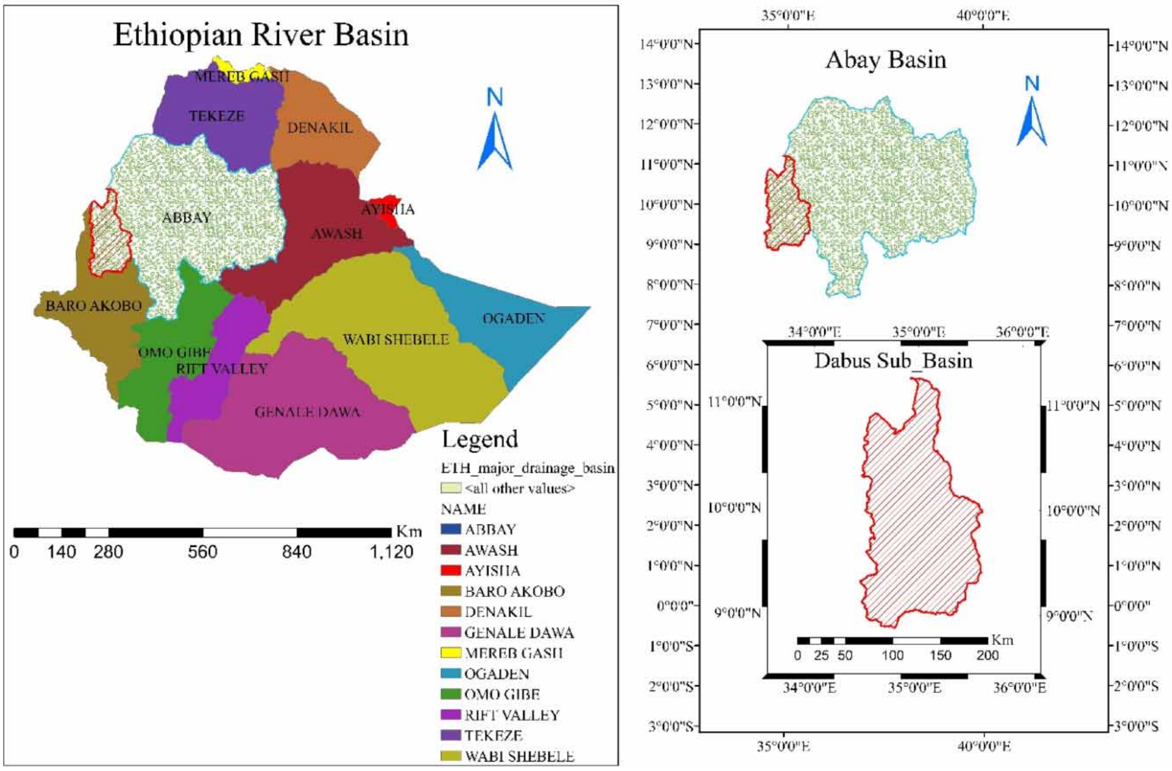


Figure 1 | Location map of the study area.

Table 1 | Description of the rainfall stations

Station name	Region	Latitude (°)	Longitude (°)	Year of data used
Abadi	Oromia	10.62	34.75	2002–2019
Amba 10	Oromia	9.75	34.6	2002–2019
Amba 16	Oromia	9.92	34.65	2002–2019
Asosa	Benishangul	10	34.52	2002–2019
Gidame	Oromia	9	34.15	2002–2019
Jarso	Oromia	9.45	35.32	2002–2019
Kamashe	Benishangul	9.47	35.83	2002–2019
Kiltukara	Oromia	9.72	35.22	2002–2019
Mendi	Oromia	9.78	35.1	2002–2019
Nedjo	Oromia	9.5	35.45	2002–2019

Table 2 | Description of the stream flow recording stations

Station name	River	Location	Latitude (°)	Longitude (°)	Drainage area (km^2)
Dabus	Dabus	Asosa	9.87	34.9	10,139
Aleltu	Aleltu	Nedjo	9.5	35	168
Dilla	Dilla	Asosa	9.45	35.88	69

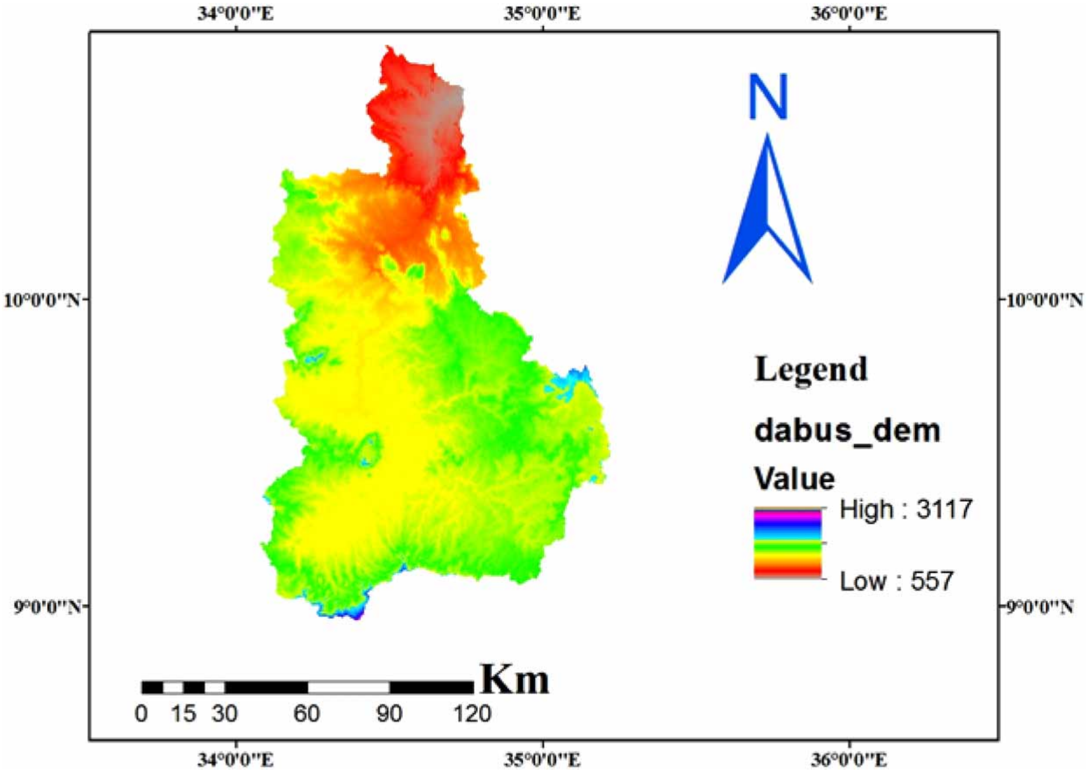


Figure 2 | DEM of the study area.

watershed boundary. Other data pertinent to the modeling process which include land use land cover and soil maps were obtained from the GIS department in the MoWIE (Figures 3 and 4). HEC-HMS hydrological model was used for rainfall–runoff simulation analysis (USACE-HEC 2008).

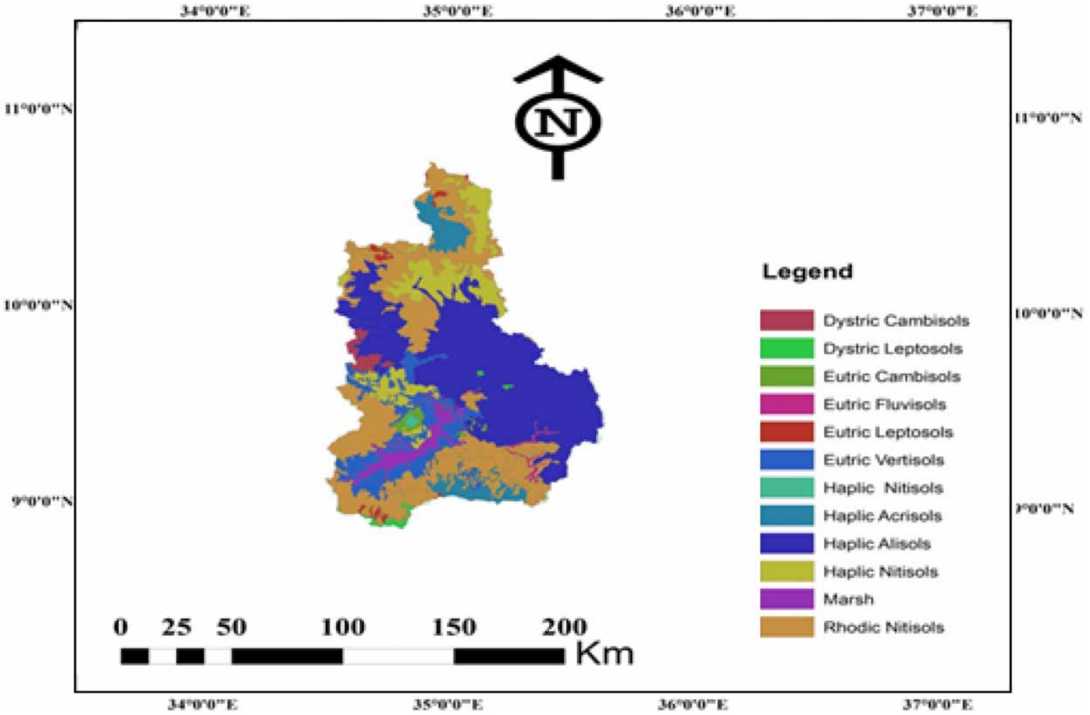


Figure 3 | Soil map of the study area.

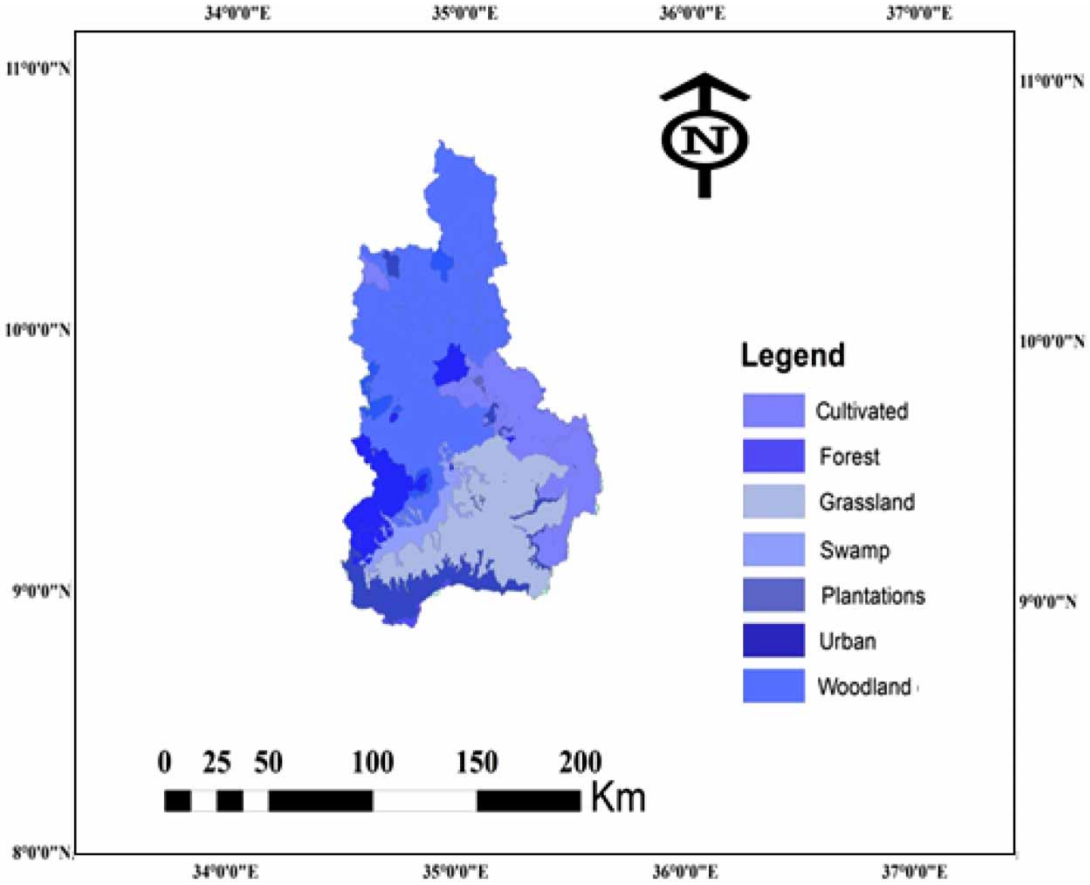


Figure 4 | Land use land cover map of the study area.

2.3. Data quality control

The reliability of the collected raw meteorological and hydrological data significantly affects the quality of the model input data and, consequently, the model simulation. Screening of the daily rainfall and stream flow data was first done by visual inspection. Filling of missed data and consistent checking were then made using the normal ratio and double mass curve analysis, respectively (Wang *et al.* 2002).

2.4. Preparation of the model input data

The collected spatial and time series hydrological and metrological data were arranged in a manner suited to HEC-HMS hydrological model for rainfall–runoff modeling.

The first step in doing any kind of hydrologic modeling is terrain preprocessing which involves delineating streams and watersheds and getting some basic watershed properties such as area, slope, flow length, and stream network density. Arc Hydro (a tool that works with Arc-GIS) was used to process a DEM to delineate the subbasin, watersheds, stream network, and drainage patterns of the subbasin. The results from terrain preprocessing were used to create input files for the HEC-HMS model using HEC-GeoHMS. HEC-GeoHMS provides the connection for translating GIS spatial information into model files for HEC-HMS.

Areal rainfall, humidity, wind speed, minimum and maximum temperatures, and solar radiation are the key meteorological input data used for the HEC-HMS model. Areal rainfall was calculated by the Thiessen polygon method. This method gives weight to stations in proportion to the space between the stations (USACE-HEC 2008). Other meteorological parameters are used to compute potential evapotranspiration. However, all those data are not available in most of the stations in the study area. Since the available weather parameters in all stations are only maximum and minimum temperatures, potential evapotranspiration was calculated by using the Hargreaves method (Equation (1)):

$$ET_O = 0.0023 \times R_a(T_{\text{mean}} + 17.8) \times (T_{\max} - T_{\min})^{0.5} \tag{1}$$

where R_a is extraterrestrial radiation in mm/d and T_{mean}, $T_{\max}$, and $T_{\min}$ are the mean, maximum, and minimum daily temperatures in °C.

2.5. Simulation of the model

Diverse methods are included in HEC-HMS to simulate various hydrologic processes (USACE-HEC 2008). In this study, the deficit constant loss method was employed to calculate rainfall losses by infiltration; the Clark unit hydrograph transformation method to compute direct runoff; the exponential recession method to estimate base flow; and the Muskingum method for channel routing. These methods were selected based on the applicability and limitations of each method, availability of data, suitability for the same hydrologic condition, well-established, stable, and widely acceptable, and recommendation by various studies (Ramesh 2017; Trivedi *et al.* 2019; Jaiswal 2020).

The deficit constant loss method assumes a single soil layer to account for continuous changes in moisture content. The potential evapotranspiration computed by the model was used to dry out the soil layer between precipitation events. Infiltration is assumed to occur only when the soil layer is saturated.

Runoff transformations convert excess precipitation on a subbasin to direct runoff at the subbasin outlet. The HEC-HMS is a conceptual model in which the process during simulation cannot be observed. It only gives the final output from the given input. The surface runoff calculations were performed using the Clark Unit Hydrograph method which requires time of concentration and storage coefficient to be computed for implementation.

Base flow is a portion of stream flow that is not directly generated from excess rainfall during a storm event. Base flow can be separated from a total stream flow hydrograph by using an exponential recession model based on the following relationship:

$$Q_t = Q_0^{Rt} \tag{2}$$

where Q_0 is the initial base flow at time t is the 0, Q_t is the threshold flow at time t, and R is the exponential decay constant. The exponential constant can be defined in many ways. A reasonable definition (as used in the HEC-HMS model) is that R is the ratio of the base flow at time t_0 to the base flow one day earlier. Initial base flow (Q_0) is estimated by field inspection. The recession constant (R) is estimated from the observed flow hydrograph which depends upon the source of base flow. The threshold flow (Q_t) is estimated from observed flows hydrograph, where the flow at which the recession limb is approximated well by a straight line (USACE-HEC 2008).

The Muskingum method for channel routing was chosen. In this method, X and K parameters must be evaluated. Theoretically, the K parameter is the time of passing of a wave in reach length and the X parameter is a constant coefficient and its value varies between 0 and 0.5. Therefore, parameters can be estimated with the help of observed inflow and outflow hydrographs. Parameter K was estimated as the interval between similar points on the inflow and outflow hydrographs. Once K was estimated, X was estimated by trial and error method (USACE-HEC 2008).

2.6. Sensitivity analysis of the model

Sensitivity analysis in hydrological modeling helps to reduce uncertainty by identifying the factors that have the greatest influence on output variation as a result of input variability. It also offers suggestions for parameter estimates at the model's calibration step (Haibo *et al.* 2018). The HEC-HMS model's built-in sensitivity analysis tool offers suggested parameter adjustment ranges. To improve the simulation result and thus understand the behavior of hydrologic systems in Dabus subbasin, sensitivity analyses were conducted using the entire flow parameters for HEC-HMS model. While all other parameters stayed constant at their nominal starting values, the model was run repeatedly with each parameter's initial baseline value increasing and decreasing by 25% (Lenhart *et al.* 2002). The hydrographs generated by the various model parameter values were then compared with the hydrograph from the base model. The effect of each model parameter was analyzed based on the objective function (model performance). Those model parameters having steep slopes (having high variation between intervals) were considered most sensitive, while those having moderate to gentle slopes (having low variation between intervals) were considered as less sensitive.

To add to the understanding of how the parameter change flow rates, the percentage of change in the resulting peak flow rate of each simulation was compared. The sensitivity of the model may be described in the relative percent change in peak flow rates, with higher sensitivity being associated with a greater percent change. The percentage change was calculated by Equation (3):

$$\Delta(\%) = \frac{V_p - V_i}{V_i} \times 100 \tag{3}$$

where Δ is the percentage change of peak flow; V_p and V_i are the peak flow rate values at each parameter change and initial simulation, respectively.

2.7. Calibration and validation of the model

Model calibration is a process of changing model parameter values until the output of the model satisfactorily corresponds to the observed data (Madsen 2000). In this study, a peak-weighted root mean square error (PWRMSE) function was used to assess the degree of fit between the computed and observed hydrographs. Two search methods are available in the HEC-HMS model to find the best parameter value (USACE-HEC 2008). The first is known as the univariate gradient method, which only evaluates and modifies one parameter at a time while maintaining the other parameter values constant. The second technique is the Nelder and Mead (NM) method, which uses a downhill simplex to assess all parameters simultaneously and decide which one should be changed. For this study, PWRMSE with NM method was used to search for the optimal parameter value.

The comparison of the model outputs with an independent data set without any further alterations is known as model validation. The values of calibrated model parameters are neither changed nor remain constant during this process. The degree of variation between estimated and observed hydrographs is the quantitative measure of the match.

Based on 18 years of historical streamflow data from 2002 to 2019, the HEC-HMS model was calibrated and validated. Data from 2002 to 2014 were utilized for calibration, and data from 2015 to 2019 were used for validation.

2.8. Performance evaluation of the model

To evaluate the performance of the HEC-HMS model, the quality and dependability of simulated values were compared with observed values using statistical tools. The Nash-Sutcliffe simulation efficiency (NSE), the observation standard deviation ratio (RSR), and the coefficient of determination (R^2) were applied for the purpose.

The NSE was obtained by Equation (4) (Nash & Sutcliffe 1970):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} (Q_o - \bar{Q}_s)^2}{\sum_{i=1}^{n} (Q_o - \bar{Q}_o)^2} \tag{4}$$

where Q_o is the observed flow, Q_s is the simulated flow, and $\bar{Q}_o$ is the average of observed flow. The NSE value ranges between 0 and 1. It is 1 if the measured value perfectly matches all forecasts. The forecasts are poor if the NSE is negative, indicating that the average output value is a better estimate than the model forecast (Sahu & Pyasi 2020). Moriasi *et al.* (2007) stated that an NSE value between 0.75 and 1 is excellent for daily time steps and an NSE value between 0.65 and 0.75 is adequate.

RSR standardizes root mean square error (RMSE) using the observations' standard deviation. It incorporates the benefits of error index statistics and includes a normalization factor so that the resulting statistic and reported values can apply to various constituents (Moriasi *et al.* 2007). RSR is calculated as the ratio of the RMSE and standard deviation of measured data (Equation (5)):

$$\mathrm{RSR} = \frac{\left[\sum_{i=1}^{n} (Q_o - Q_s)^2\right]^{1/2}}{\left[\sum_{i=1}^{n} (Q_o - \bar{Q}_o)^2\right]^{1/2}} \tag{5}$$

where Q_o is the observed flow; Q_s is the simulated flow, and $\bar{Q}_o$ is the average of observed flow. RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation to a large positive value.

The R^2 number indicates the degree to which the observed and simulated values are related. R^2 was obtained by using Equation (6):

$$R^2 = \frac{\sum_{i=1}^{n} (Q_s - \bar{Q}_s)[(Q_o - \bar{Q}_o)]^2}{\left[\sum_{i=1}^{n} (Q_s - \bar{Q}_s)\right]^2 \left[\sum_{i=1}^{n} (Q_o - \bar{Q}_o)\right]^2} \tag{6}$$

R^2 values again range between 0 and 1, with higher values suggesting less error variance and values larger than 0.5 are commonly regarded as acceptable (Moriasi *et al.* 2007).

3. RESULTS AND DISCUSSION

3.1. Sensitivity analysis

The sensitivity analysis was performed on two event model parameters (loss method and transform method). Parameters such as the base flow and relative loss percentages were not included in the sensitivity analysis due to their linear relationship with runoff production.

The model was run repeatedly by increasing and decreasing by +25 and −25% from the baseline value of each parameter while keeping all other parameters constant at their nominal starting values. The hydrographs resulting from the scenarios of adjusted model parameters were then compared with the baseline model hydrograph. The sensitivity analysis showed that two parameters (time of concentration and storage coefficient) have higher sensitivity (Figures 5 and 6). However, the initial deficit, maximum deficit, and constant flow rate were found to be the least sensitive parameters (lowest change in flow rates). This is in agreement with the study by Gebre (2015) who found the storage coefficient as the most sensitive parameter for the simulation of runoff in the Upper Blue Nile Basin.

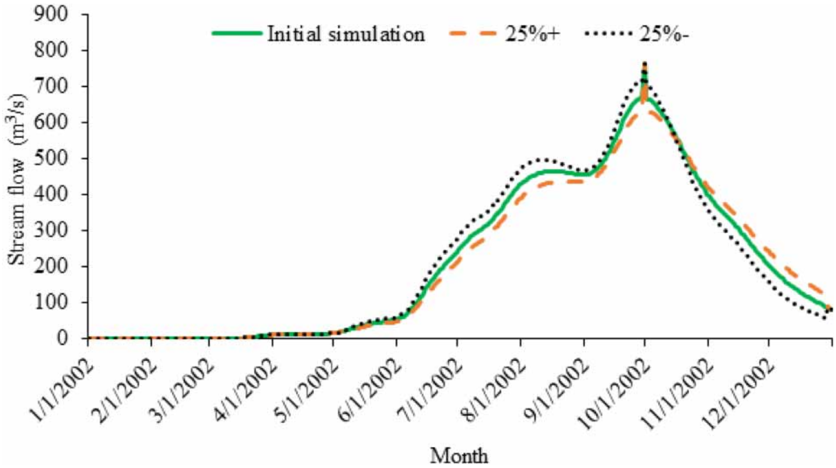


Figure 5 | Event model sensitivity to time of concentration.

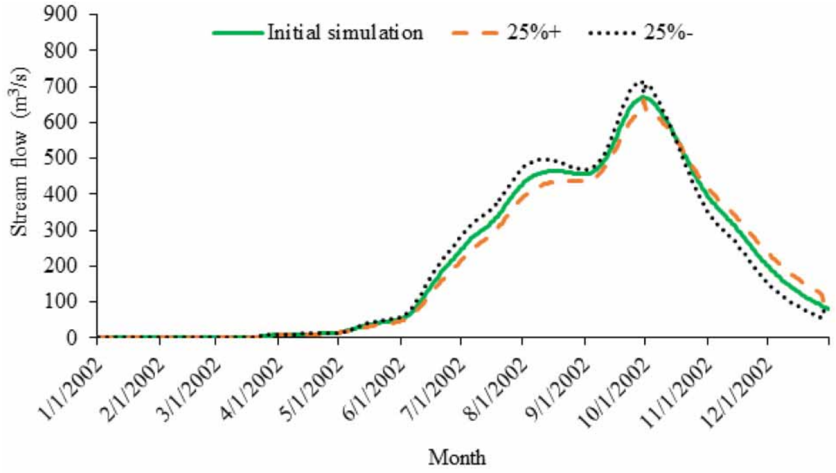


Figure 6 | Event model sensitivity to storage coefficient.

3.3. Calibration and validation of the model

3.3.1. Calibration of the model

The model automatically calibrated the flow based on observed areal precipitation, evapotranspiration, temperature, and flow. The calibration results revealed that the simulated and observed daily flows do agree quite well with NSE of 0.784, RSR of 0.334, and R^2 of 0.818 (Figures 7 and 8).

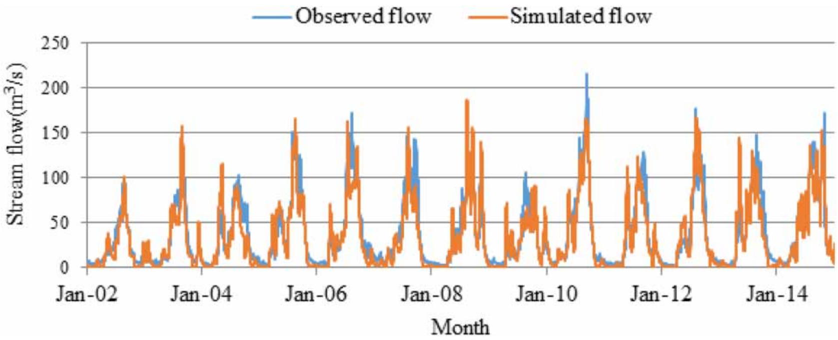


Figure 7 | Comparison of observed and simulated flows during calibration.

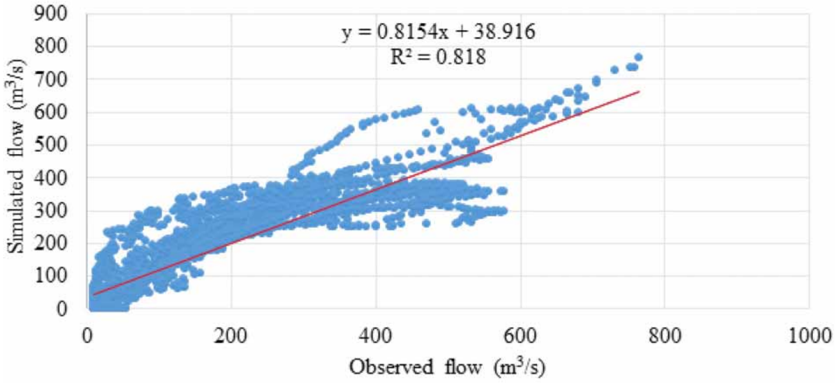


Figure 8 | Relationship between observed and simulated flows during calibration.

3.3.2. Validation of the model

A calibrated model should be validated before it is recommended for use. To validate the model, the simulated data were compared to another set of observed data, and statistical tests of error functions were carried out. The model was validated when the error functions have very small values. The validation period was chosen using the flow data from 2015 to 2019. The model performance was improved with NSE, RSR, and R^2 values of 0.793, 0.323, and 0.875, respectively (Figures 9 and 10). The observed and generated flow hydrographs agree quite well, demonstrating the model's capacity to estimate flow based on measured rainfall data in similar

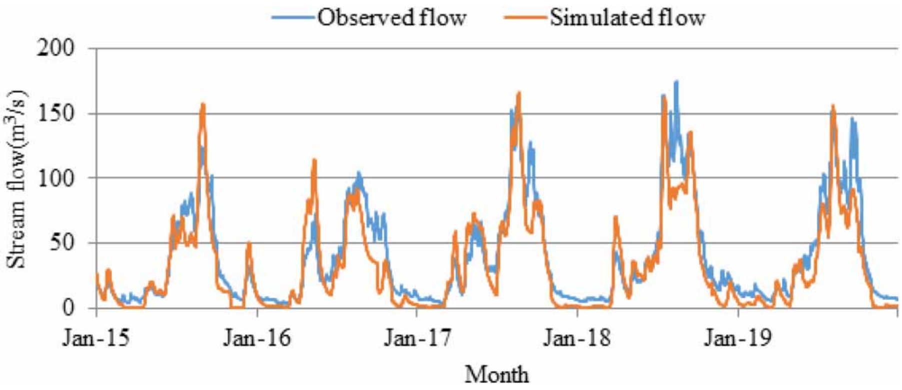


Figure 9 | Comparison of observed and simulated flows during validation.

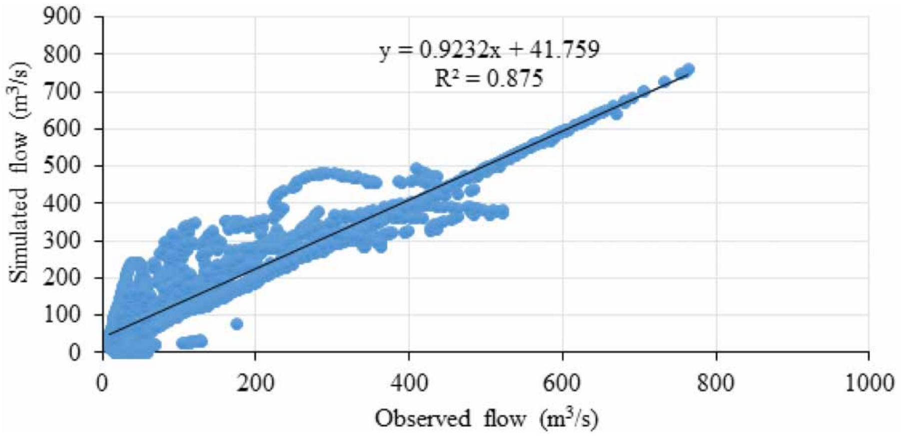


Figure 10 | Relationship between observed and simulated flows during validation.

watershed characteristics. The studies by Tassew *et al.* (2019) and Gebre (2015) also found the HEC-HMS model as the appropriate model for hydrological simulations for the catchments in the Upper Blue Nile Basin.

4. CONCLUSIONS

In the current study, the rainfall–runoff relationship was simulated for the data-scarce Dabus subbasin of the Blue Nile River Basin using the HEC-HMS hydrologic model. Daily precipitation and stream flow data from 2002 to 2019 were used as input data for the model, together with soil and land use/land cover data, and a DEM of the study area. When model parameters were subjected to sensitivity analysis, parameters like time of concentration and storage coefficient were found much more sensitive than loss parameters like initial deficit, maximum deficit, and constant rate. The model was calibrated and validated for its simulation of stream flow. The model predicted stream flow with reasonable accuracy with NSE, RSR, and R^2 values of 0.784, 0.334, and 0.818 during calibration, and 0.793, 0.323, and 0.875 during validation, respectively. This suggests that HEC-HMS modeling for daily stream flow in the Dabus subbasin is reliable and acceptable. As a result, the model can be used to obtain runoff data from measured precipitation on the studied subbasin. It can also be used to model runoff in ungauged watersheds having similar features to the study area.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper and any supplementary information, if required, can be provided upon reasonable request.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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