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Application of a HEC-HMS model on event-based simulations in a tropical watershed

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Abstract

The upper reaches of the Seethawaka River in Sri Lanka lie in the highest rainfall region of the country. The development of a rainfall-runoff model for the Seethawaka River will essentially aid in reducing vulnerability to disasters that happen due to extreme rainfall events in the area. This research paper describes a case study of an event-based streamflow simulation approach for the Seethawaka River in the Kegalle administrative district of Sri Lanka using a conceptually-based, deterministic and semi-distributed Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). The main aim of this study was to examine the most reliable combination of precipitation loss and baseflow methods to simulate streamflow in the study area. Six combinations of precipitation loss methods, direct runoff methods, baseflow methods and routing methods were separately checked to determine the most effective method. Among the various combinations of precipitation loss and baseflow methods simulated, the Soil Conservation Service Curve Number method (SCS_CN) and the non-linear Boussinesq method performed fairly well with Clark unit hydrograph, Muskingum and lag methods. The values of statistical indicators and graphical observations revealed that the model developed through this study is capable of simulating peak discharges and timing the occurrence of peaks fairly well. Therefore, this model will greatly help in providing early warnings to the lower reaches of Seethawaka during extreme rainfall events.

Keywords: HEC-HMS, Seethawaka River, Event-based, Flood

1. Introduction

Physical, mathematical and analog models are important modeling approaches. Physical models express reduced dimensions of real world processes. A mathematical model with hydrological applications is “an equation or set of equations that represents the response of a hydrological system component change under hydro-meteorological conditions’’. An analog method is “the use of another physical system having properties similar to those of the prototype” [1]. Hydrological processes are considered explicitly in distributed modeling, whereas in lump-based modeling, they are averaged or ignored. In deterministic models “all parameters and processes are free of random variation and known with certainty” [2]. Even though distributed models require higher amounts of data when compared to lump-based models, they yield more accurate results. Mathematical models are considered the most extensively used and universally recognized due to their applications and scientific bases. Due to widespread knowledge of technology, computer modeling is a common approach in hydrological simulation studies today [3].

Due to the increased frequency of extreme rainfall events, flood alert applications are of vital importance [4]. Modeling rainfall-runoff processes is an essential component in estimating floods [5]. Understanding a catchment’s responses due to precipitation events during planning and construction phases is essential when designing hydraulic structures such as spillways and channels among others [6]. Topographical data, details of land cover and soil cover, observed hydro-meteorological data and information on soil properties are required in the watershed modeling process [3]. Reliable estimates of watershed modeling depend on the hydrologic data provided [7]. This is an especially crucial task which one needs to face in the Asian region. Recorded hydrological observations in this region are scarce, which limits the number of users in watershed modeling. The main factors that a modeler needs to consider when selecting a hydrological model are the objectives of the specific research and the availability of data in the selected study area.

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Nandalal and Ratnayake [3] noted the importance of analyzing a study watershed and obtaining sound knowledge of the particular study area before doing specific research related to hydrology. Prior to developing a hydrological model, data should be analyzed firsthand. In the past, rational methods, empirical methods and unit hydrograph were commonly used to estimate design floods [3, 8]. With the increased attention to rainfall-runoff processes, numerous tools and computer software have extensively evolved to model hydrological processes in a watershed. A conceptually based and semi-distributed hydrological model, the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) [2], was used in this study to model streamflow in the Seethawaka River, Sri Lanka. The HEC-HMS model has proven to be a valuable hydrologic modeling tool that has been extensively used in many parts of the world, in diverse climatic and topographical settings [9-16].

The HEC-HMS model has been applied in the major river basins of Sri Lanka to simulate streamflow under historical and projected future climatic conditions. De Silva et al. [5] reported that the HEC-HMS model was capable of both event and continuous simulations in the Kelani River Basin, Sri Lanka (drainage area: 2300 km^2). Halwatura and Najim [17] attempted to calibrate the HEC-HMS model for continuous simulations in the Attanagalu River Basin of the Western Province, Sri Lanka (drainage area: 337 km^2). Nandalal and Ratnayake [3] calibrated the HEC-HMS model on an event scale for the Kaluganga River Basin, Sri Lanka (drainage area: 2658 km^2). Sampath et al. [18] modeled the Deduru-Oya River Basin for continuous simulations with intrabasin diversions using the HEC-HMS model (drainage area: 2620 km^2). Ratnayake et al. [19] used the HEC-HMS model for event-based modeling in the Nilwala River Basin (drainage area: 1073 km^2). Hence, considering the suitability of HEC-HMS model in simulating watershed processes in the tropical climatic conditions, it was selected to model rainfall-runoff processes in the Seethawaka Watershed in this study.

The HEC-HMS model offers various methods to simulate precipitation, runoff and routing in a watershed. Depending on the availability of data and objectives of the study, a user can select various combinations of precipitation loss, direct runoff, baseflow methods and routing methods to simulate streamflow. Additionally, canopy cover and channel loss/gain simulation mechanisms are also available in the HEC-HMS model. Eleven precipitation loss, seven direct runoff, five baseflow and eight routing methods are available in the HEC-HMS model [2].

Various combinations of hydrologic processes have been evaluated through the HEC-HMS model to simulate streamflow in major river basins of Sri Lanka. Halwatura and Najim [17] used the SCS_CN method as well as deficit and constant loss methods to simulate precipitation losses with Clark unit hydrograph and Synder unit hydrograph. These were used to simulate direct runoff in the Attanagalu Oya catchment, Sri Lanka. Sampath et al. [18] used a soil moisture accounting model, Clark unit hydrograph, recession method and Muskingum method to model precipitation losses, direct runoff, baseflow and routing in the Deduru-Oya River Basin. The initial and constant loss method, Clark unit hydrograph, exponential recession method, Muskingum and lag methods were used to simulate precipitation losses, direct runoff, baseflow and routing in the Kalu Ganga River Basin by Nandalal and Ratnayake [3]. The Green and Ampt infiltration model was used to simulate precipitation losses with three direct runoff methods, the Synder unit hydrograph, Clark unit hydrograph and SCS transformation, while a recession method was used to simulate baseflow in the Nilwala River of the Sri Lanka Basin [19]. De Silva et al. [5] used the Green and Ampt infiltration model, Clark unit hydrograph, recession method and Muskingum method to simulate precipitation losses, direct runoff, baseflow and routing in an event-based study in the Kelani River of Sri Lanka. The Green and Ampt infiltration model was replaced by a soil moisture accounting model to simulate precipitation losses in the same study carried out by De Silva et al. [5] for continuous scale model simulations in the Kelani River Basin.

The main aim of the current study was to determine the most suitable combination of loss and baseflow methods available in the HEC-HMS model and thereby simulate streamflow of the Seethawaka River located in Sri Lanka. Therefore, the reliability of six different combinations of loss and baseflow methods were checked individually. Most of the precipitation loss methods recommended for event-based simulations in the HEC-HMS model, including the Soil Conservation Service Curve Number (SCS_CN) method as well as the initial and constant loss method. These methods are empirical without a thorough understanding of the governing physical processes of infiltration mechanisms [20]. The non-linear Boussinesq method was used to model baseflow in this study. It has no previous applications in the Sri Lankan River Basins. The hydrological model developed through this study will essentially serve as a flood prediction tool to provide early warnings to reduce the vulnerability to disasters during extreme rain events [5].

This paper is organized as follows. Section 2 describes the study area characteristics and the climate setting in the Seethawaka Region. This section also describes various methods and combinations adopted in the HEC-HMS model to simulate rainfall-runoff processes in the Seethawaka River Basin. Calibration and validation results are presented in Section 3. This section provides a detailed description of the parameters used and values assigned in the developed HEC-HMS model through this study. Finally, conclusions and recommendations based on this study are presented in Section 4. The methodology adopted in this study can be implemented for other watersheds that have similar topographic, land cover and climatic conditions.

2. Materials and methods

2.1. Study area

The Seethawaka River is a sub-basin of the Kelani River Basin. The studied watershed drains an area of 223 km^2. Figure 1 schematically represents the Seethawaka River in the Kegalle administrative district of the Sabaragamuwa Province, Sri Lanka. The main tributaries of the Seethawaka River are Magal and Panapura Streams. The Seethawaka River lies between latitudes of 6° 50’ and 7° 00’ N and longitudes of 80° 17’ and 80° 30’ E. The upper part of Seethawaka (Maliboda region) receives an average annual rainfall between 4000-5000 mm, which is also the highest rainfall receiving region of Sri Lanka [21]. The length of the Seethawaka main river is approximately 57 km. The mean temperature is around 27 °C throughout the year in this region [22]. The two dominant land use types in the study area are forests and rubber plantations (Figure 2b). The remaining land use mainly comprises homestead gardens, tea and paddy cultivations. The soil types in the area is of clay with a loamy nature characterized by moderate infiltration rates [23]. The altitude of the Seethawaka River Basin ranges between 50 to 1831 m above mean sea level (Figure 2a). The

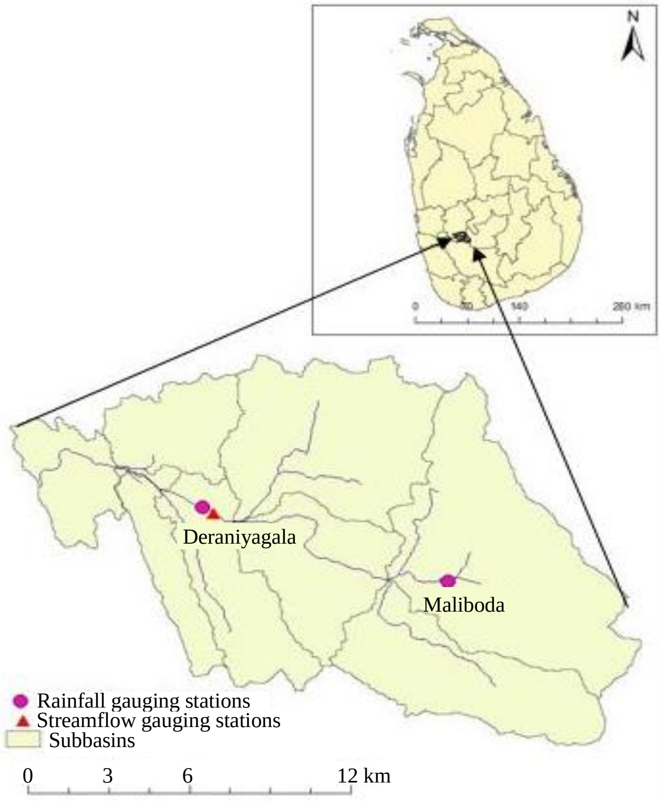

Figure 1 Rainfall and streamflow gauging stations located in the Seethawaka River Basin

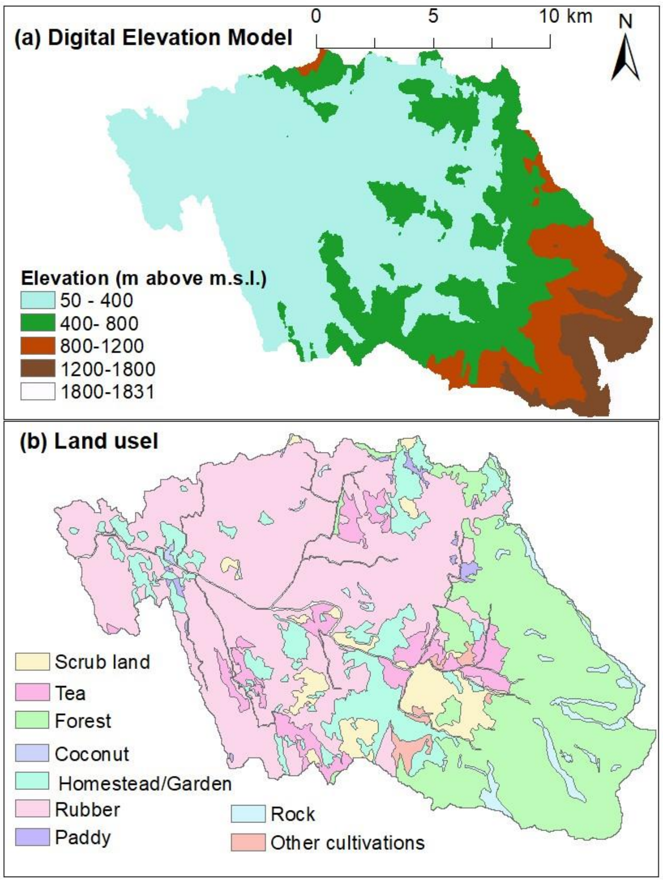

Figure 2 (a) DEM and (b) land use in the Seethawaka River Basin

Table 1 Description of temporal and spatial data

Data type	Stations	Resolution	Source
Rainfall	Deraniyagala Maliboda	Hourly Daily	Department of Meteorology, Sri Lanka
Streamflow	Deraniyagala	Hourly	Department of Irrigation, Sri Lanka
Topography	-	10 m×10 m	Global Mapper Website

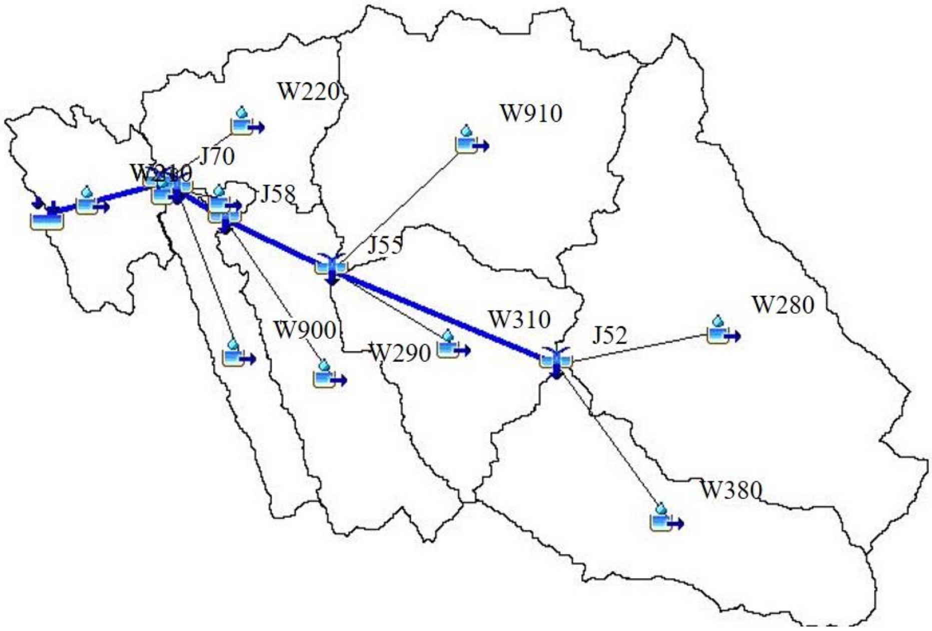

Figure 3 Delineated sub-basins in this study

steep slopes of the Seethawaka River Basin range between 20-25% grade. These steep areas are highly prone to soil erosion and land degradation. The impacts and associated risks are severe if proper soil and water conservation practices are not adopted. The upper part is characterized by tropical wet evergreen forests with dense canopies [22].

2.2 HEC-HMS model description

HEC-HMS software was developed by the United States (US) Army Corps of Engineers. The current HEC-HMS model is a successful outcome of continuous efforts by many scientists and researchers since its first version, HEC-1 developed by Leo R. Beard and released in 1967. HEC-1 was developed to simulate floods in complex river basins [6]. The current study utilizes HEC-HMS Version 4.3 to simulate rainfall-runoff processes on an event-based scale in the Seethawaka River Basin. The HEC-HMS model is capable of performing flood frequency studies, reservoir spillway capacity studies and of urban flooding, among others [24]. This model is comprised of four components, a basin model, meteorological model, specification control manager and time series data manager. The software in the public domain, providing a major advantage to HEC-HMS users worldwide. An extensive amount of studies have reported successful applications of HEC-HMS on event and continuous-based simulations in different regions of the world including Asia, Africa and America. Razi et al. [4] used HEC-HMS to simulate streamflow in the Johar River Basin, Malaysia. Oleyiblo and Li [6] developed the HEC-HMS model for the Misai and Wanan catchments in China. Chu and Steinman [10] used the HEC-HMS model to simulate streamflow in an American watershed. Chea and Oeurng [9] developed an HEC-HMS model for continuous simulations in a sub-basin of the Tonle Sap River Basin, Cambodia. Gebre [11] used the HEC-HMS model to simulate streamflow in the Upper Nile River Basin of Ethiopia. Shakti et al. [25] used radar rainfall to conduct simulations in an HEC-HMS model for an urbanized catchment in Japan. Skhakhfa and Ouerdachi [16] used an HEC-HMS model to simulate streamflow in an Algerian River Basin. Ouedraogo et al. [14] modeled a Kenyan catchment using the HEC-HMS model. Neary et al. [13] used HEC-HMS to model a Tennessee catchment in America employing satellite estimates as input rainfall data. This software poses an added advantage for users by offering a multitude of choices for selecting methods to simulate various parts of the hydrological cycle depending on the availability of data, topography and climate settings [26].

2.3 Data

Hourly rainfall data at the Deraniyagala rain gauging station and daily rainfall data at the Maliboda rain gauging station (see Figure 1) were obtained from the Department of Meteorology, Sri Lanka. Hourly streamflow data at the Deraniyagala streamflow gauging station were obtained from the Department of Irrigation, Sri Lanka. The Digital Elevation Model (DEM) with a 10 m×10 m resolution was downloaded from the Global Mapper website at https://www.bluemarblegeo.com/products/global-mapper.php. A description of obtained data types, stations used in the study, resolution of data and the sources obtained is provided in Table 1.

Table 2 Advantages and disadvantages of the precipitation loss methods used in this study [2, 20, 27]

Method	Advantages	Disadvantages
Initial and constant method	1) Mature method with successful applications across the world 2) Easy to setup	1) Difficulties in applications in ungauged watersheds 2) Model may be too simple to predict losses within an event
Green and Ampt infiltration model	1) Can be used in ungauged catchments after obtaining information of soils	1) Not widely adopted hence considered less mature
SCS_CN	1) Well established across US and elsewhere 2) This method relies only on one parameter that is a function of soil group, land use, treatment cover and antecedent moisture conditions 3) Relatively simple	1) Intensity of the rainfall is not accounted for 2) Infiltration will approach zero rather than a constant rate as expected after a rainfall event. 3) The model predicted values do not agree with classical unsaturated flow theory

Table 3 Values assigned to parameters in the initial and constant loss methods of this study

Parameter	Values
Initial loss (mm)	1.5
Constant loss (mm/hour)	0.5
Percent imperviousness	65

2.4 HEC-HMS model development

The user can either develop the basin model in the HEC-HMS itself or else by feeding the DEM into the HEC-Geospatial Hydrological Modeling Extension (HEC-GeoHMS), which is an extension tool of ArcGIS software. In this particular study, the basin model was developed using the HEC-GeoHMS tool. The Seethawaka River Basin was delineated into ten sub-basins in this study (see Figure 3). The sub-basin properties, including flow length, centroid locations and average slopes, were calculated using ArcGIS. Since hourly rainfall data was not available at the Maliboda rain gauging station, the same temporal distribution of rainfall throughout the day at the Deraniyagala rain gauging station was used to derive the hourly rainfall of Maliboda rain gauging station. In this study, precipitation was defined by the specified hyetograph method. This was done by taking the proximity of the rain gauge to the sub-basin into account. The developed model was simulated in hourly time steps.

2.4.1. Modeling precipitation losses

Canopy interception, retention and detention storages account for precipitation losses in a watershed. The precipitation loss rates depend on canopy cover and rainfall characteristics [24]. Eleven methods are available in HEC-HMS to simulate precipitation losses. They are the SCS_CN method, Green and Ampt infiltration model, initial and constant loss method, exponential loss method, initial and deficit method, Smith and Parlange, soil moisture accounting model (SMA), gridded deficit and constant loss method, gridded SMA, gridded Green and Ampt and gridded SCS_CN methods. Among the various loss models available in the HEC-HMS model, the SMA along with the initial and deficit methods are recommended for continuous simulations since these two methods simulate both dry and wet weather behaviors [2].

In this study, the reliability of initial and constant loss method, Green and Ampt infiltration model and SCS_CN methods were examined. The advantages and disadvantages of each precipitation loss methods are presented in Table 2.

Initial and constant loss method

The initial and constant loss method requires the values of initial loss, constant loss and percent imperviousness. The values used in this study are given in Table 3. The value for initial losses was assigned following the guidelines outlined by US Army Corps of Engineers [27] considering the vegetation characteristics of the Seethawaka River Basin. The values for constant loss rate and percent imperviousness were adjusted after obtaining the goodness-of-fit criteria between simulated and observed streamflow values.

Green and Ampt infiltration model

The Green and Ampt infiltration model requires values of initial loss, moisture deficit, suction head, hydraulic conductivity and percent imperviousness. The values used for this model in the current study are listed in Table 4. Suction head, saturated content and hydraulic conductivity values were obtained from a previous study conducted in Sri Lanka by De Silva et al. [5] which had soil types similar to those in Seethawaka. The values for initial moisture content and percent imperviousness were adjusted after obtaining goodness-of-fit criterion between observed and simulated streamflow values.

The Green and Ampt infiltration model, which calculates the infiltration rate for a particular soil, is given by Equation 1 [5].

$$f(t) = K[1 + \frac{\varphi\Delta\theta}{F(t)}] \quad (1)$$

where f(t), F(t), K, φ and Δθ are infiltration rate (mm/h), cumulative infiltration (mm), saturated hydraulic conductivity (mm/h), wetting front soil suction head (mm) and moisture content deficit, respectively.

Table 4 Values for Green and Ampt infiltration model parameters used in this study (data from [5])

Parameter	Value
Initial moisture content (ratio)	0.10
Saturated content (ratio)	0.40
Suction head	208.8 mm
Conductivity	2 mm/hr
Percent Imperviousness	65%

Table 5 Values used in the SCS_CN method of this study

Parameter	Value
SCS_CN	60
Initial abstraction	5 mm
Percent imperviousness	60%

SCS_CN method

This method requires values of SCS_CN, initial abstraction and percent imperviousness of the study watershed. The SCS_CN method uses functions of land use type, soil type and antecedent moisture conditions. The values of Curve Number (CN) range between 35-98 in the model. A CN value of 98 is attributed to water bodies whereas a value 35 indicates land under good hydrologic conditions. In this method, the SCS_CN value for major land use types in the Seethawaka River Basin, forest and rubber plantations, was fixed based on the guidelines adopted by Maidment et al. [1], Halwatura and Najim [17]. The value of initial abstraction was assigned based on the guidelines outlined by US Army Corps of Engineers [27]. The percent imperviousness was fixed by comparing simulated and observed streamflow volumes. The Table 5 lists the assigned values for SCS_CN, initial abstraction and percent imperviousness in the developed model.

The accumulated precipitation excess is given by Equation 2 [1]:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \tag{2}$$

where P_e is accumulated precipitation excess at time t, P unaccumulated rainfall depth at time t, I_a is initial abstraction and S is maximum potential retention.

The initial abstraction is approximated by Equation 3 [1]:

$$I_a = 0.2S \tag{3}$$

S is approximated by Equation 4 [1]:

$$S = \frac{25400 - 254\ CN}{CN} \tag{4}$$

2.4.2. Modeling direct runoff

The direct runoff is the portion of excess precipitation converted to point runoff in a watershed following a precipitation event. Direct runoff methods available in the HEC-HMS model fall under two categories, empirical and conceptual methods. The conceptual methods consider all physical mechanisms that govern precipitation movement, while empirical models develop relationship between precipitation and runoff without considering the internal processes. The parameters in empirical models are adjusted after obtaining goodness-of-fit criteria. The HEC-HMS model offers nine methods to calculate direct runoff. They include the Clark unit hydrograph, Synder's unit hydrograph, SCS_CN unit hydrograph, S curve, user specified unit hydrograph, Modclark and kinematic wave [2]. The Clark unit hydrograph [28] was used in this study since it requires fewer parameters compared to other direct runoff methods.

Clark unit hydrograph

The input parameters required for the Clark unit hydrograph method are time of concentration and storage coefficient. The time of concentration is defined as the time taken for a water particle to travel from the most hydraulically remote point to the catchment outlet. The time of concentration was calculated using the Kirpich formula [29]. The storage coefficient (R) can be calculated using the flow at the inflection point on the falling limb of the hydrograph divided by the time derivative of the flow. The unit of R is hours and the storage effects are reflected by the value of R [5].

The time of concentration calculated by Kirpich formula is given by Equation 5 [29]:

$$T_c = \frac{0.0179 \times L^{0.77}}{S^{0.385}} \tag{5}$$

where T_c is time of concentration (minutes), L is waterway length (meters) and S is slope (m/m).

2.4.3. Modeling baseflow

The baseflow is defined as the dry weather flow sustained during dry periods in a river or stream. The recession method, bounded recession method, non-linear Boussinesq, linear reservoir method and constant monthly flow are used to simulate baseflow in the HEC-HMS model. The constant monthly flow method represents baseflow as a user specified constant flow. Measurements of channel flow when rainfall is not occurring are required to estimate monthly baseflow in the model. The linear reservoir model is best recommended for use in conjunction with a soil moisture accounting model that is used to carry out continuous simulations [2]. In this study, the baseflow recession and non-linear Boussinesq methods are used to model baseflow as in previously studies by De Silva et al. [5].

Table 6 Various combinations adopted to simulate streamflow in the current study

Combination	Loss method	Direct runoff method	Baseflow method	Routing method
C1	Green and Ampt infiltration	Clark UH	non-linear Boussinesq	lag and Muskingum
C2	SCS_CN	Clark UH	non-linear Boussinesq	lag and Muskingum
C3	Initial and constant	Clark UH	non-linear Boussinesq	lag and Muskingum
C4	Green and Ampt infiltration	Clark UH	baseflow recession	lag and Muskingum
C5	Initial and constant	Clark UH	baseflow recession	lag and Muskingum
C6	SCS_CN	Clark UH	baseflow recession	lag and Muskingum

Recession method

The required parameters to model baseflow in the recession method are the initial discharge, recession constant and ratio to peak [5]. The initial conditions can be defined as initial discharge (m^3/s) or initial discharge per area ($\frac{m^3/s}{m^2}$). The initial discharge method was selected for this study. The recession method is designed to approximate the typical behavior observed in watersheds when the channel flow recedes exponentially after an event. The parameter "recession constant" describes the rate at which the baseflow recedes between storm events [3, 17, 19]. The values of the recession constant and ratio to peak in reaches of Seethawaka were 0.60 and 0.01. respectively. The values of initial discharge of in the reaches ranged between 12-30 (m^3/s). In this study the values corresponding to above parameters were adjusted after obtaining an acceptable goodness-of-fit criterion between observed and simulated streamflow values.

Non-linear Boussinesq method

The non-linear Boussinesq method requires values of initial discharge, ratio to peak, flow length, hydraulic conductivity and porosity of soils. The flow length of each reach in the Seethawaka River was extracted from the basin model created using HEC-GeoHMS in ArcGIS. Values for hydraulic conductivity and porosity of soils were assigned based on the soils in the study area. The values of hydraulic conductivity and porosity were based on the ranges suggested by Maidment et al. [1]. Hydraulic conductivity and porosity were assigned values of 0.50 mm/hr and 0.30, respectively. Initial discharge and the ratio to peak were adjusted after conducting several trials to obtain a goodness-of-fit between observed and simulated streamflow values [2]. The initial discharge values assigned for the reaches ranged between 5-9 (m^3/s), while the ratio to peak was set to 0.02 in this method.

2.4.4. Modeling channel routing

Routing is used to model channel flow from the upper catchment to basin outlet. A total of eight routing methods are available in the HEC-HMS to model channel flow. They are Muskingum, Muskingum Cunge, lag method, kinematic wave, Straddler Stagger, lag, lag and k and normal depth methods. These methods are used to route flow in main streams and tributaries of a watershed [2]. The selection of channel routing method depends on several factors including channel slope, availability of observed streamflow data, and the significance of backwater effects, among others. The modified-puls method is recommended if backwater effects will significantly influence the discharge hydrograph. The kinematic wave method and Muskingum-Cunge methods are normally used in channel routing if observed streamflow data is unavailable. Kinematic wave, Muskingum-Cunge methods and normal depth methods require information of channel properties including channel width, side slopes of channel, manning's n, the shape of the channel cross section, among others. The modified-puls method requires a storage discharge function relationship. Feldman [2] provides more detailed information on the criteria for selecting a routing technique.

In this study the Muskingum and lag methods were used to route the flow in the Seethawaka River Basin.

Lag method

Nandalal and Ratnayake [3] reported that the lag method is suitable for routing channel flow in steep reaches. The lag method was utilized to route streamflow in the steeper reaches of the upstream regions of the Seethawaka River. The lag time is the only required input for this method [2]. Since there is no attenuation, the shape of the ordinates does not change in the lag method [3]. The value of lag time in the reaches of the Seethawaka River was approximated as 0.70 of the time of concentration proposed by Overton and Brakensiek [30].

Muskingum method

The Muskingum method requires parameters "k" and "x". The parameter "k" is measured in hours and "x" is dimensionless. The value of parameter k ranges between 0.1 to 150 hours while x ranges between 0.1 and 0.5 [2]. In this study the values of k ranged between 0.1-150 (hours) while the value of x ranged between 0.20-0.25. The values for k and x were assigned within the recommended ranges. The Muskingum method was used to route flow in the mild slopes of the downstream reaches of the Seethawaka River.

The six different configurations of precipitation loss and baseflow methods are listed in Table 6. Clark UH, Green and Ampt infiltration model, non-linear Boussinesq, lag and Muskingum methods were used in combination C1. The SCS_CN method and initial and constant method were used respectively for modeling precipitation losses in combinations C2 and C3, while direct runoff, baseflow and routing techniques were similar to combination C1. In combinations C4, C5 and C6, baseflow recession methods were used, while for the Green and Ampt infiltration model, initial and constant method, and SCS_CN methods were used to model precipitation losses.

2.4.5. Model evaluation criteria

The Nash-Sutcliffe Efficiency ($N.S.E.$), percentage bias (δ_b), percentage error in volume (P.E.V) and ratio of root mean square to standard deviation (RSR) are recommended statistics to evaluate hydrologic performance [6, 9-10, 18, 31].

The Nash-Sutcliffe Efficiency (N.S.E.) is given by Equation 6:

Table 7 Performance evaluation criteria [data from 9, 14]

Performance rating	N.S.E.	P.E.V. (%)	RSR	δ_b(%)
Very good	0.75 to 1	<±10	0 to 0.5	≤±10
Good	0.65 to 0.75	±10 to ±15	0.5 to 0.6	±10 to ±15
Satisfactory	0.50 to 0.65	±15 to ±25	0.6 to 0.7	±15 to ±25
Unsatisfactory	<0.50	>±25	≥0.7	>±25

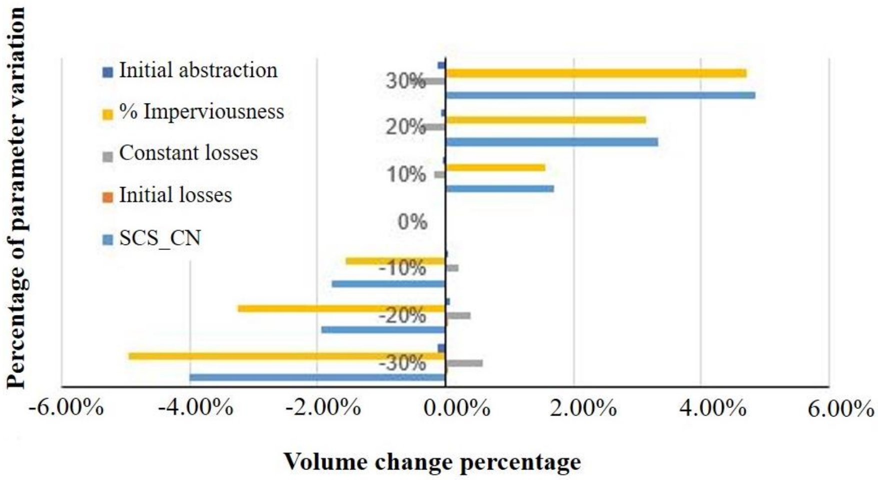

Figure 4 Percentage change in volume against percentage of parameter variation

$$\text{N.S.E} = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O_{mean})^2} \quad (6)$$

The percentage bias (δ_b) is given by Equation 7:

$$\delta_b = \left|\frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i}\right| \times 100\% \quad (7)$$

The percentage error in volume (P.E.V) is presented in Equation 8:

$$\text{PEV} = \left(\frac{vol_o - vol_s}{Vol_o}\right) \times 100\% \quad (8)$$

The ratio of root mean square error to standard deviation (RSR) is Equation 9:

$$\text{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}}{\sqrt{\sum_{i=1}^{n}(O_i - O_{mean})^2}} \quad (9)$$

where O_i, S_i, n, O_{mean} are observed discharge, simulated discharge, number of observational and mean values of observed values. The variables, vol_s and vol_o, are the total simulated streamflow volume and total observed streamflow volume. The ranges of values used for the performance evaluation criteria are tabulated in Table 7.

3. Results and discussion

3.1 Sensitivity analysis

The sensitivity of five paramaters, initial abstraction, percentage imperviousness, constant losses, initial losses, SCS_CN to streamflow volume and peak discharge were checked. Sensitivity analysis was done seperately by varying each parameter from -30% to +30% in increments of 10%. A one-parameter-at-a-time method was used for sensivity analysis in which one parameter was held constant while the others were changed. The percentage of variation in simulated volume and peak discharge were plotted against the percentage variation of each parameter, as illustrated in Figures 4 and 5, respectively. The SCS_CN and percent imperviousness were found to be the most sensitive parameters to streamflow volume and peak discharge.

3.2 Calibration and validation of the hydrological model

The hydrological model was calibrated at the Deraniyagala streamflow gauging station for a rainfall event that occurred between 14th May to 18th May 2016. A rainfall event between 25th May to 28th May 2017 was used for model validation.

The model parameters were optimized based on the Seethawaka River Basin characteristics. After obtaining initial estimates for the parameter ranges, several parameters were manually optimized. Values of parameters related to soil properties were obtained from the literature and secondary data sources. Several parameters required field observations, but with estimation from literature and secondary sources, the results obtained for streamflow simulations were satisfactory.

During the calibration process, parameters were adjusted within the acceptable ranges following the guidelines outlined by Feldman [2]. This was done to ensure that a physically meaningful set of parameter values was used in the developed model. De Silva et al. [5] specified that close values of observed and simulated streamflow volume, accurate estimates of time to peak and accurate simulation of peak discharge are important performance indicators of an event-based modeling study. In addition to these indicators, model performance was evaluated through N.S.E., RSR and Pbias. Use of these parameters is recommended for hydrological model evaluation [6, 9-10, 18, 31].

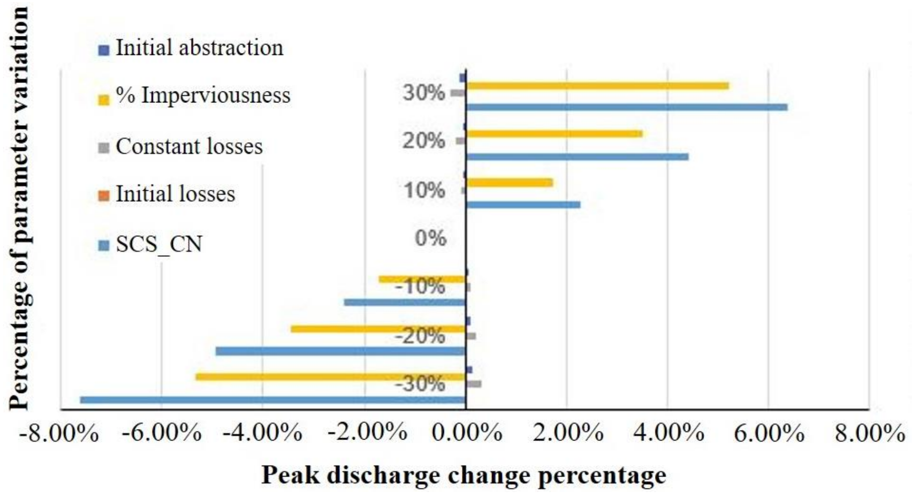

Figure 5 Percentage change in peak discharge against percentage of parameter variation

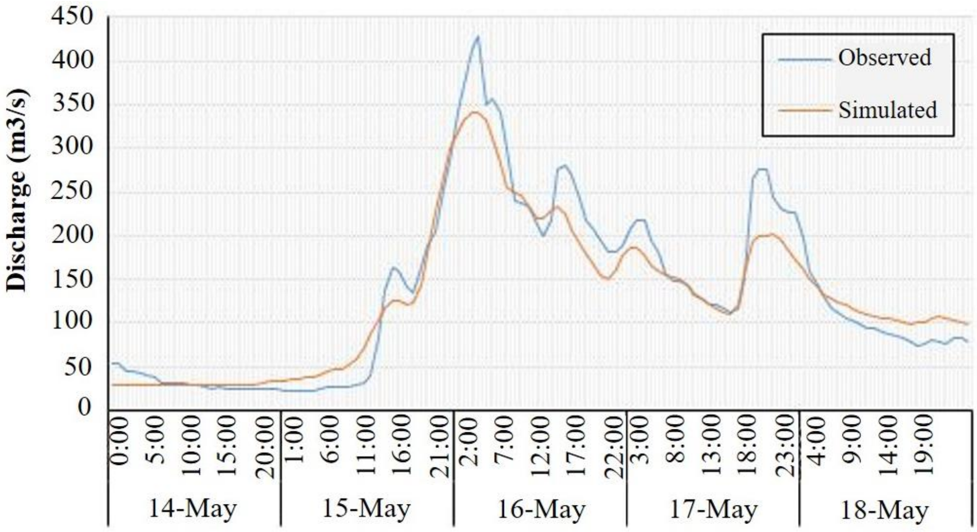

Figure 6 Hydrograph for the combination C2 during calibration (14th May-18th May 2016) at Deraniyagala streamflow gauging station

The statistical values computed for N.S.E., P.E.V, RSR and δ_b during the calibration and validation time periods for the six different combinations of precipitation loss and baseflow methods are presented in Tables 8 and 9. Table 10 gives details of events used for calibration and validation.

During calibration, for C1 values of N.S.E., P.E.V, RSR and δ_b were reported to be 0.87, 16%, 0.40 and -16% (Table 8). For the same case during validation, these values were found to be 0.77, 18%, 0.50 and 18%, respectively (Table 9). The Green and Ampt infiltration model and non-linear Boussinesq methods were used with a Clark unit hydrograph, Muskingum and lag methods to simulate hydrological processes for this combination. Combination C2, which used non-linear Boussinesq and SCS_CN methods, showed the best results among all cases examined as depicted in Figures 6 and 7. The statistical descriptors, N.S.E., P.E.V., RSR and δ_b, were 0.89, 14%, 0.30 and -15% during calibration and 0.81, 12%, 0.40 and 12% during validation. In calibration for combination C3, which used a Clark unit hydrograph, non-linear Boussinesq, initial and constant method, Muskingum and lag methods, N.S.E, P.V.E., RSR and δ_b values of 0.88, 14%, 0.30 and -14% were respectively found. During validation for combination C3, these values were 0.74, 22%, 0.50 and 21%, respectively. Although the statistical indicators showed very good performance during calibration for C4, C5 and C6 combinations at the Deraniyagala streamflow gauging station, the corresponding values during validation were not satisfactory according to model performance evaluation criteria. The results of model simulations indicate that the combination of SCS_CN and non-linear Boussinesq with a Clark unit hydrograph, Muskingum and lag methods provided more reliable estimates when compared to other loss methods, i.e., initial and constant methods, Green and Ampt infiltration and baseflow methods for baseflow recession in streamflow forecasting in the Kelani River.

Ratnayake et al. [19] obtained N.S.E. values between 0.83 and 0.91 for calibration and validation for an event-based simulation using HEC-HMS in the Nilawala River Basin, Sri Lanka. De Silva et al. [5] reported that for event-based simulations, the N.S.E. ranged between 0.80 and 0.90 in the Kelani River, Sri Lanka. The percentage bias varied between 9-17% during calibration and validation in the same study. Hence model performance ranges obtained through

Table 8 Statistical values during the calibration time period

Combination	NSE	PEV (%)	RSR	δ_b (%)
C1	0.87	16	0.40	-16
C2	0.89	14	0.30	-15
C3	0.88	14	0.30	-14
C4	0.86	8	0.40	-9
C5	0.90	-1	0.30	1
C6	0.88	7	0.30	-7

Table 9 Statistical values during the validation time period

Combination	NSE	PEV (%)	RSR	δ_b (%)
C1	0.77	18	0.50	18
C2	0.81	12	0.40	12
C3	0.74	22	0.50	21
C4	0.69	-31	0.60	30
C5	0.58	-40	0.60	39
C6	0.76	20	0.50	25

Table 10 The description of rainfall events used for calibration and validation of the model

	Time Period	Duration (days)
Calibration	14^{th} May-18^{th} May 2016	5
Validation	25^{th} May-28^{th} May 2017	4

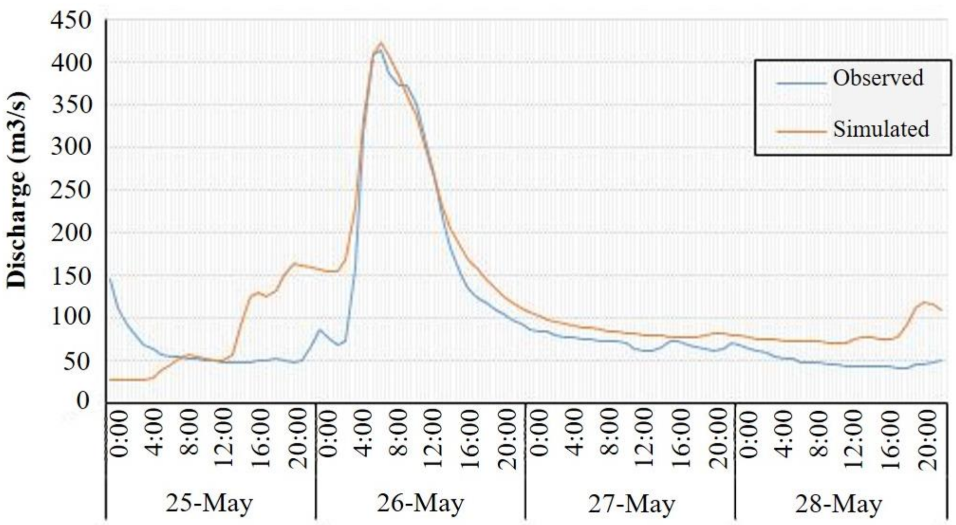

Figure 7 Hydrograph for the combination C2 during validation (25^{th}-28^{th} May 2017) at the Deraniyagala streamflow gauging station

this study are reasonable when compared with previous efforts using the HEC-HMS model in event-based modeling applications in Sri Lanka.

From graphical observations, it is evident that simulated streamflow values follow the same trend as the observed data. Since the Curve Number method was developed for temperate climatic conditions in the US, there remains an uncertainty when applying it to tropical watersheds. One study reported that decreasing CN values resulted from increased groundwater recharge rates of St. Antonia River Basin of America [12]. The land use of the Seethawaka Watershed is dominated by evergreen forests in its upper regions and rubber plantations downstream, which result in greater interception storage due to dense canopy cover. Underestimation of streamflow was reported in another forest dominated watershed conducted by Halwatura and Najim [17] in the Attanagalu River Basin in the Western Province, Sri Lanka. Halwatura and Najim [17] reported that the SCS_CN method performs well in agricultural watersheds when compared to forested watersheds. Even though the SCS_CN loss method performs well compared to other loss methods for the aforementioned reasons, this might be attributed to under-prediction of runoff during calibration in this study.

The first loss parameter defines the basin initial condition. Under basin saturation conditions, the initial loss will reach zero. Therefore, it is evident that antecedent moisture conditions will significantly affect the values of initial loss. The constant rate in this method is defined as the ultimate infiltration capacity of soils [17]. The results could have been improved when simulating losses using this method if field measured values for ultimate infiltration rates were available. This is because values used in this study were obtained from literature and other secondary data sources [1, 5].

The mismatches in the peak discharges during calibration might be attributed to localized storm events. The results of calibration and validation could have been improved if a dense network of rain gauges were available in the Seethawaka catchment.

4. Conclusions

The HEC-HMS model developed through this study used rainfall data of two rain gauges: Maliboda and Deraniyagala located within the Seethawaka River Basin. The model was calibrated and validated using observed streamflow data sets of Deraniyagala streamflow gauging stations for a historical 5 day-extreme rainfall event that occurred in May 2016 and for a 4 day extreme rainfall event in May 2017, respectively. Different combinations of precipitation losses and baseflow methods were separately checked with routing and direct runoff methods. From the results obtained, the SCS_CN method and non-linear Boussinesq methods can be recommended to use with a Clark unit hydrograph, Muskingum and lag in the Seethawaka River. The graphical observations and values of statistical indicators reveal that the developed model can simulate streamflow in the catchment fairly well. The model’s ability to predict peak discharges and timing of peak occurrences is an essential in applications of early warning systems and as a flood prediction tool [5]. Hence, possible adaptation measures can be taken beforehand to reduce the damages caused. The authors recommend the use of the HEC-HMS model in various other catchments in the wet zone of Sri Lanka to simulate rainfall-runoff processes. The output hydrographs of HEC-HMS of this study can be used in HEC-RAS to determine the areas under inundation. This will be useful in the planning of reservoirs and other hydraulic structures in the Seethawaka River Basin. The results of this study can serve as an input for flood risk assessment studies as well.

5. References

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