Int. J. Hydrology Science and Technology, Vol. 13, No. 1, 2022

Loss methods in HEC-HMS model for streamflow projection under climate change: a review

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Abstract: Hydrologic models are tools used extensively for the simulation of various processes of the hydrological cycle, depending majorly on their characteristics. These models are classified as event-based, simulating a short-term hydrological event and continuous, which simulate hydrological processes for long-term. Among the various factors that characterise the models is a loss method that accounts for the volume of precipitation that falls in the watershed. Thus, certain loss methods are limited only to event-based while others can simulate event and continuous hydrological processes. Appropriate selection of these methods requires knowledge of the watershed, goals of the hydrologic study and engineering judgment. The aim of this paper is to review loss methods in HEC-HMS model for streamflow simulation under climate change, with a view to highlighting their advantages, weaknesses and suitability in watershed development and climate change study. The result of the review showed that despite simplicity and accuracy of deficit and constant loss method of HEC-HMS, studies on climate change impacts using the method are still very few and has not yet been studied in Malaysia.

Keywords: hydrologic model; HEC-HMS; loss methods; climate change.

Reference to this paper should be made as follows: Ismail, H., Kamal, M.R., Mojid, M.A., Bin Abdullah, A.F. and Hin, L.S. (2022) ‘Loss methods in HEC-HMS model for streamflow projection under climate change: a review’, *Int. J. Hydrology Science and Technology*, Vol. 13, No. 1, pp.23–42.

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1 Introduction

Hydrology is a significant element of the study dealing with earth's water, how it occurs, circulates and distributed, its chemical and physical characteristics and its reaction with the environment. It also relates water to the surroundings in each hydrological process (Devia et al., 2015). The hydrological processes such as changes in land cover patterns, streamflow from rivers, irrigation etc., have been affected by the rapid urbanisation and industrialisation.

Models are tools which can demonstrate a system in the real world (Devia et al., 2015). They are commonly used to predict the efficiency and interpretation of various hydrological procedures. Several hydrological models have been developed around the globe, to study watershed reaction to processes and evaluate the impact of climate change. Thus, they can be deterministic or stochastic, empirical, conceptual or physically-based (Awan et al., 2016; Refsgaard and Knudsen, 1996). The application of these models is in very complex and large basins. Complexity of certain models has been a major setback, which consequently affects their performances. There are no specific criteria for choosing the best model for a specific location (Ali et al., 2018).

Notably, some of the factors lead to the selection of the hydrological model in that aspect includes the uniqueness of the model characteristics, availability and experience among others. Moreover, some models are more reliable particularly when handling ungauged stations or stations with poor input data, which is a common situation in most of the watersheds. However, the best model results in the use of the least realistic parameters. Abdulkareem et al. (2018) reported that out of the 65% of the physical-based modelling studies, 60% applied HEC-HMS model due to its least input parameters compared to the SWAT model, with 20%. There are six attributes that characterise a computationally effective hydrological model; high spatial detail; easily accessible inputs ; continuous time depiction; the capacity to simulate various land management conditions; and the capacity to produce sensible outputs (Fukunaga et al., 2015). Among the major factors for good results in hydrologic simulation is the reliability of the input data. The information used by various models includes rainfall, soil properties, temperature, slope, vegetation, hydrogeology, and other physical parameters.

Climate change brings a severe impact on water resources, which affects the watershed. Changes in rainfall and temperature patterns threaten phases of the hydrological cycle, disturb the ecosystem, affect agricultural production and increase the vulnerability (Schlenker et al., 2007). The temperature has greatest effect on the estimation of evapotranspiration (Goodarzi and Eslamian, 2018). As pressure on the world's freshwater resources increase, many river basins will face both increasing freshwater scarcity and increasing pollution. Therefore, adaptation strategies under the new realities of climate change are one of the most important challenges globally in the

21st century for water and food security. The spatial and temporal variations in climate have affected water availability in different water catchments in the world. Water scarcity is a major issue globally (Paudel et al., 2018).

Climate change and the response of hydrologic systems are the two main issues involved in modelling the hydrologic impacts of global climate change (Jiang et al., 2007). Currently, general circulation models (GCMs) seem to be the most credible models to study and assess climate change. However, regional hydrological changes can only be predicted by using hydrological models that later simulate hydrological effects of climate change at basin scales, by using downscaling methods to relate climate models with catchment-scale hydrological models or by providing catchment-scale climate scenarios as input to hydrological models (Jiang et al., 2007).

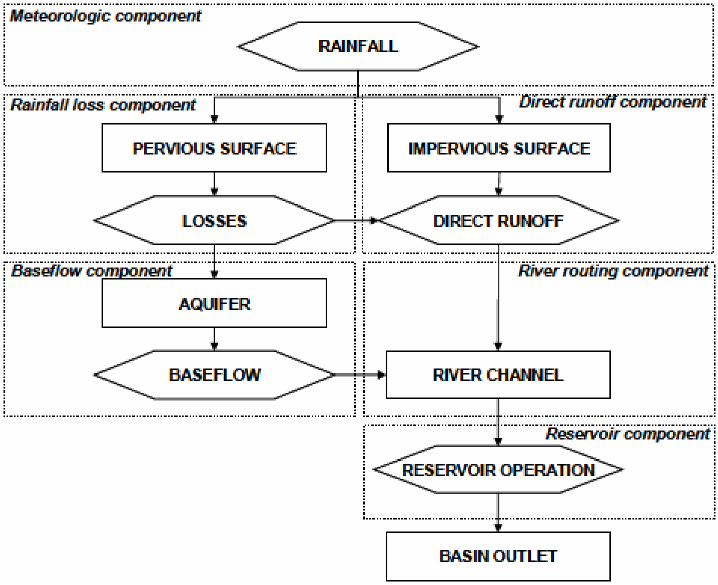
Hydrologic models have been extensively used in the simulation of various processes of the hydrological cycle, depending majorly on their characteristics and availability. These models use various inputs, process and predict the hydrological response to changes in different elements such as land use, rainfall and temperature among others. However, some models are event-based, that can only simulate a short-term hydrologic event while others are continuous, which are applied mostly in a long-term simulation. Among the various factors that characterises the models is the method of computing runoff volume i.e. loss method. The method accounts for the volume of precipitation that falls in the watershed. Thus, certain infiltration loss methods are limited to event-based simulations while others can simulate continuous hydrological processes. In addition, some loss methods require high number of input parameters, which make them complex and difficult to use, especially during calibration while others are simple with minimum parameters. Appropriate choice of these techniques requires watershed understanding, hydrological research objectives and engineering judgement.

Geographic and information system (GIS) has been widely used to preprocess hydrological data in watershed modelling. The system is not only for processing hydrological processes but also for aid in obtaining reliable information, which is later used as input data to hydrological models. Recent versions of hydrological models are incorporated with GIS extension to prepare and obtain information for the modelling processes. This information is used as input data to the modelling process (Jung et al., 2017; Manap et al., 2014; Pradhan and Youssef, 2010; Youssef et al., 2015). The aim of this paper is to review loss methods in HEC-HMS model for streamflow simulation under climate change, with a view to highlighting their advantages, weaknesses and suitability in watershed development and climate change study.

2 HEC-HMS model

The Hydrologic Engineering Centers Hydrologic Modelling System (HEC-HMS) is hydrologic modelling software developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC) for simulating precipitation-runoff processes of watershed systems. The model is publicly available and can be cooperated with GIS tool for effective simulation of most hydrological processes and hydraulic characterisation (Ghorbani et al., 2016; Kabiri, 2014; Mohammed et al., 2011; Razi et al., 2010; Yusop et al., 2007). Figure 1 illustrates various components of the model.

Figure 1 Schematic of rainfall-runoff process in HEC-HMS



Source: Adopted from Cunderlik and Simonovic (2004)

The simplification of hydrologic cycle in HEC-HMS has led to its division into four components in the program. In addition, each component is modelled separately. The model needs three parts of input:

1 Basin model, which describes the different elements of the hydrologic system. It consists of the following methods:
  a Infiltration loss method: this is used to compute runoff volume. It estimates losses resulting from infiltration and evapotranspiration during rainfall event. The loss technique calculates the quantity of water contributing to the runoff in the river for each moment interval in the modelling cycle. There are eleven different methods in HEC-HMS (USACE-HEC, 2016b):
    1 initial and constant method: the fundamental principle of this method is that the precipitation losses at a maximum potential rate is constant throughout an event
    2 deficit and constant method: this method differs from the initial and constant loss method in that after an extended period of no rainfall, the initial loss will recover
    3 exponential method: this method is a function of cumulative precipitation, which represents incremental infiltration as a logarithmically decreasing function and it does not involve any kind of recovery
    4 Green-Ampt method: this method includes initial condition, which represents surface ponding and the precipitation loss on the previous area is computed at time interval
    5 Smith Parlange method: this method assumes wetting front to be represented by an exponential scaling of saturated hydraulic conductivity

6 soil moisture accounting method: the method simulates the water movement and its storage on plants, soil surface, soil profile and groundwater layers

7 soil conservation service (SCS) curve number (CN) method: this method considers the precipitation loss as a function of the cumulative rainfall, land use patterns, soil cover and antecedent moisture

8 gridded soil moisture accounting method: this method is similar to the soil moisture accounting method, however, the catchment is subdivided into grid cells

9 gridded SCS-CN method: this method subdivides the catchment into grid cells, computes the precipitation loss for each cell independently and finally routes the excess to the outlet of the catchment

10 gridded deficit and constant method: this method is similar to the deficit and constant method, however, the catchment is subdivided into grid cells

11 gridded Green-Ampt method: this method is similar to the Green and Ampt method, however, the catchment is subdivided into grid cells.

Noticeably, the most acceptable and widely used is the SCS curve Number method (Abushandi and Merkel, 2013; Ibrahim-Bathis and Ahmed, 2016; Kabiri, 2014; Tripathi et al., 2014). This is because of its predictability, simplicity and stability and also relies only on a single parameter that varies as a function of soil group, land use, surface condition and antecedent moisture condition (USACE, 2016). Nevertheless, among the eleven methods for runoff volume computation in HEC-HMS, only deficit and constant method and soil moisture accounting method are appropriate for continuous simulation (USACE, 2016). However, studies have also found comparable results for long-term simulations using the SCS-CN loss method (Chu and Steinman, 2009).

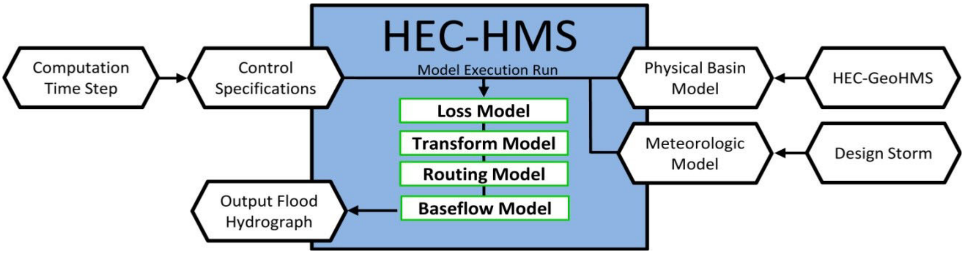
b Transform method: direct runoff technique, which transforms the excess precipitation at the watershed into a hydrograph at the outlet. This method accounts for the surface roughness and geometry of the watershed. There are seven methods of transformation in HEC-HMS: SCS unit hydrograph method, Clark unit hydrograph method, Snyder unit hydrograph method, kinematic wave method, ModClark method, user specified unit hydrograph method and user specified S-Graph method (USACE-HEC, 2016b).

c Baseflow method: this technique simulates portion of the runoff that groundwater contributes. A total of five different baseflow methods are provided in HEC-HMS: bounded recession method, constant monthly method, linear reservoir method, nonlinear Boussinesq method and recession method (USACE-HEC, 2016b). However, recession method is widely used (Ali et al., 2011; Oleyiblo and Li, 2010) to model the baseflow within the catchment for event simulation. Constant monthly method is the most suitable method for simulation of long period data (USACE-HEC, 2016b). The main difference between Bounded recession method and recession method is that, monthly baseflow limit can be specified using the latter. In addition, the bounded recession method does not reset baseflow after a storm event.

d Routing method: this technique normally routes the flow into sub-basins at the outlet of some upstream watersheds through the downstream river stream. A total of six methods are included in HEC-HMS: Muskingum method, kinematic wave method, Lag method, Modified Puls method, Muskingum-Cunge method and Straddle Stagger method (USACE-HEC, 2016b).

e Loss/gain method: conducts supplementary simulations of sub-surface relations within reach. It reflects channel losses, groundwater channel losses, or bi-directional water movements. There are two different methods in HEC-HMS: constant method and percolation method. However, the loss / gain techniques are only suitable with some chosen routing techniques due to different information requirements (USACE-HEC, 2016b). The technique of constant loss is combined with any routing technique while the percolation method is only used with the modified Puls or Muskingum-Cunge techniques. Figure 2 shows the schematic overview of the HEC-HMS software environment.

Figure 2 HEC-HMS software components (see online version for colours)



Source: Adopted from Heimhuber (2013)

2.1 GIS software: HEC-GeoHMS

Geographical information system (GIS) software is a tool used to perform GIS related tasks. GIS has recently been introduced in hydrological research because of the spatial character of the parameters governing hydrological processes. It plays a significant part in the parameterisation of the distributed hydrological model within ArcMap. ArcMap is a software developed by the Environmental Systems Research Institute (ESRI) for performing different kind of GIS related functions (USACE-HEC, 2016a, 2016b). Most of the GIS tasks in HEC-HMS (e.g., terrain processing, stream and sub basin delineation, etc.) are usually performed based on the functionality of the ArcMap extensions, Hydrologic Engineering Center-Geospatial Hydrologic Modelling System (HEC-GeoHMS). These GIS extensions are to prepare a consistent model input file for HEC-HMS within the ArcMap software environment.

3 HEC-HMS model for watershed development

HMS is relevant in a broad spectrum of geographical regions to solve as many issues as possible, including large river basin water supply and flood hydrology, and small urban river flow. HMS-produced hydrographs are applicable in wider scopes of studies (Guo, 2006; Gyori et al., 2013, 2016; Gyori and Haidu, 2011; Haidu and Ivan, 2016; Khaddor and Alaoui, 2014; Latha et al., 2012; Malekani et al., 2014; Shadeed and Almasri, 2010; Xiaoyong and Min-Lang, 2004).

Yusop et al. (2007) used HEC-HMS to determine the runoff and hydrograph-characteristic for an oil palm plantation in the Skudai River watershed. The model used initial and constant loss method to compute the evaporation and infiltration processes in the catchment and successfully simulated the hydrograph and suggested for the missing runoff from rainfall data. The selection of the loss method for the study was because of its simplicity and the simulation was event-based. To predict patterns of land use, McColl and Aggett (2007) implemented the HEC-HMS model. The features of the watershed were obtained using HEC-GeoHMS. They used SCS CN loss technique due to the ease with which new land-use allocation patterns and related curve number parameters can be established and evaluated hydrologically. The results showed that HEC-HMS model has high predictability. Study by Razi et al. (2010) using HEC-HMS at the Johor River to estimate flooding suggested the model as a tool to estimate peak discharge. He used the Curve number (CN) method of the Soil Conservation Service (SCS) to calculate the runoff amount. Shaghaeghi (2001) applied HEC-HMS model using SCS-CN method to simulate river flow in a watershed. The research results showed the model's reliability when comparing the simulated records with the observed. HEC-HMS model was also evaluated in Yellow River watershed in southwestern Iran, for computing peak discharge. The observed and simulated peak flows matched well (Radmanesh et al., 2006). A similar study carried out by Markus et al. (2007) used HEC-HMS with SCS-CN technique to evaluate changes in peak flow due to increases in precipitation at 12 stations using daily rainfall records. Results of the simulation indicated the model to be satisfactory.

A rainfall-runoff modelling by Al-Ahmadi (2005) provided a fitting comparison between simulated and observed records when HEC-HMS with GIS and remote sensing (RS) in three sub-basins was used in southwestern Saudi Arabia. Kabiri (2014) simulated flow using modified SCS-CN technique with GIS system in HEC-HMS. The simulated flows underestimated the observed discharges. Ghorbani et al. (2016) used SCS-CN method to compute runoff volume for simulation of flood risk area in Kelantan watershed. The profile of flood hydrograph in the most sub catchment was accurately fitted with measured profile, indicating the model was able to reproduce observed values for the sub basin. Oleyiblo and Li (2010) applied HEC-HMS model using initial and constant loss method with accurate prediction of peak flow based on the historical flood information. The research concluded that the complexity of the model structure does not ascertain its competency and effectiveness.

HEC-HMS model was applied to simulate runoff for long period in a tropical catchment and to identify the most appropriate simulation technique for the research catchment. Compared to the deficit and constant loss method, the soil conservation service curve loss method does not perform well. This is because the earlier is most suitable for long period simulation, as it accounts for evapotranspition from the catchment (Halwatura and Najim, 2013). However, Du et al. (2012), reported adequate long-term and event modelling outcomes when CN loss method. HEC-HMS was successfully applied to quantify the annual runoff and flood response to urbanisation for Qinhuai River basin, China using CN loss method.

Studies by Majidi and Shahedi (2012) simulated rainfall-runoff for five rainstorm events using Green-Ampt, loss method. The findings showed that the observed and simulated peak flows differed. In addition, sensitivity analysis revealed that lag time is a sensitive parameter during optimisation. Arekhi (2012) compared various techniques for assessment of runoff losses within HEC-HMS. Initial and constant loss method, in 70% of events used in the study had less percentage changes of simulated to observed discharges and it was chosen as the appropriate technique for simulating surface runoff.

4 Continuous HEC-HMS model for climate change study

HEC-HMS is a mathematical watershed tool that contains several methods with which to simulate various hydrological processes such as surface runoff and river/reservoir flow in river basins. It was first developed in 1967 at the Hydrologic Engineering Center, US Army Corps of Engineers for simulation of flood hydrographs in complex river basins (Singh and Littleton, 1982). Since then, there has been great expansion in its capabilities, to address the most current hydrological challenges. This leads to the release of different version of the program with additional features.

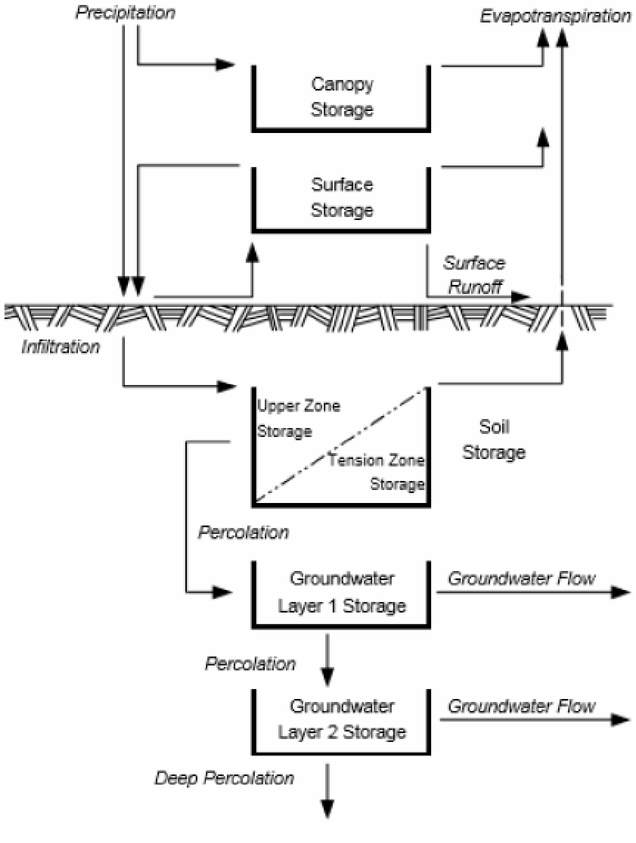
In its continuous version, HEC-HMS has been effectively applied in a broad spectrum of instances. Fleming and Neary (2004) for example, effectively used the model in the Cumberland River basin as a tool for continuous hydrological modelling. Continuous hydrological studies were conducted with SCS-CN in HEC-HMS for the watershed of Mona Lake in western Michigan (Chu and Steinman, 2009). Neary et al. (2004) used the HEC-HMS for continuous simulation with its soil-moisture-accounting (SMA) algorithm to compare streamflow simulations with basin-average radar estimates. Cunderlik and Simonovic (2005) used the HEC-HMS model's continuous simulation to portray the primary hydro-climate processes. Kabiri et al. (2015) used SCS-CN to evaluate the hydrological impact of climate change on the runoff pattern. Deb et al. (2018) used HEC-HMS with SCS-CN loss method to evaluate the effect of climate change on Thailand's water resources. They stated that the loss method could be applied for modelling both short and long-term processes. Recently, Ismail et al. (2020) applied HEC-HMS for the development of agro-hydrological model under climate change for a large scale irrigation scheme.

Among the advantages of HEC-HMS model over other hydrologic models is the various options in methods selection, to compute different hydrological responses for watershed development. The hydrologic model, together with loss methods for runoff computations (also included in the model), provides a basis for evaluation of climate change impacts. These methods are soil moisture accounting method and deficit and constant method, which are the most applicable methods for continuous simulation in the program.

4.1 Soil moisture accounting method

Soil moisture accounting (SMA) method is a loss method that simulates both wet and dry weather conditions in HEC-HMS model using three major layers as shown in Figure 3. The layers contribute to the dynamic flow of water in the soil (USACE-HEC, 2016b). The ability to calculate flows into, out and across storage volumes is one of its main benefits (USACE-HEC, 2016b). Conceptually, twelve parameters are required in SMA to model the hydrologic processes. The method has been widely used to compute continuous simulations in HEC-HMS (Roy et al., 2013; Yimer et al., 2009). In addition, it has been a great aid while studying the impacts of climate change using HEC-HMS. The major challenge with this method, despite its wider acceptance by the researches is, numerous input parameters, which are in one way or the other making the simulation tedious and consequently, affecting the accuracy of the model output. The parameters have to be determined through calibration processes (USACE-HEC, 2016b). However, Fleming and Neary (2004) successfully derived seven of the SMA parameters from GIS databases. Nevertheless, parameter values after model calibration in his study differed by an average of 37% from estimated values. Since climate change study is a continuous-based simulation, with predictions for long period that involves various parameters, choosing a suitable model with simple structure, minimum input data requirements and reasonable precision is essential.

Figure 3 Schematic of soil moisture accounting algorithm



Source: USACE (2000)

Roy et al. (2013) investigated the impact of climate change for a river basin in eastern India using SMA loss method. The research results showed strong efficiency of the model for streamflow analysis and thus, quantification of accessible water. Solomon (2007) applied HEC-HMS model with SMA algorithm to project streamflow. The findings showed that monthly calibration was satisfactory. SMA and the snowmelt models embodied in the HEC-HMS were used to reproduce historical streamflows, climate and land use of three watersheds of Lakes (Gyawali and Watkins, 2012). The result of the study showed that in late winter and early spring, the models had problem reproducing peak flows. Wang et al. (2016) employed HEC-HMS with SMA method to simulate runoff in the semi-arid region of northwestern China. The findings showed that the model underestimated hydrographs in winter and spring as well as some summer flows. This was due to the disparity between the watershed's nonlinear rainfall-runoff reaction and the SMA model used linear framework. Yimer et al. (2009) applied HEC-HMS with SMA algorithm to simulate the hydrological response of a catchment to change in climate. The research findings indicated that the performance of the model is good in predicting flows for periods beyond the calibration period. HEC-HMS with SMA loss method was used to model the impacts of climate change on water resources in ungauged and data-scarce watersheds in NE Spain (Candela et al., 2012). Kang and Ramírez (2007) applied SMA loss method with HEC-HMS to examine the response of streamflow to long-term rainfall variability under climate change in the Colorado Rockies.

4.2 Deficit and constant method

The deficit and constant (DC) method uses a single soil layer to account for continuous changes in moisture content. The method is simple and performed well in both event and continuous-based simulations (Babel et al., 2014; Bui, 2011; Halwatura and Najim, 2013; Meenu et al., 2013). In addition, it requires lesser-input parameters compare to SMA. The parameters in this method are initial deficit, maximum deficit, constant rate and percentage of impervious area, which can easily be obtained from the land use and soil grids, using GIS extension of HEC-HMS. Recent studies applied GIS to extract and process hydrological components. For instance, Pradhan and Youssef (2010) used a GIS and geospatial data to analyse landslide risk in Cameron, Malaysia. The combination of the DC method with a canopy method (which is also available in HEC-HMS) enables to extract water from the soil reference to potential evapotranspiration. This makes the method suitable for continuous simulation within the program. However, despite its simplicity and accuracy in simulation of long-term events, studies on climate change studies are still very few (Azmat et al., 2017; Mahmood et al., 2016). The most recent studies (Mahmood and Jia, 2016; Mahmood et al., 2016) successfully assessed the impact of climate change on water resources. For instance, 60% of the physically-based models used in Malaysia applied HEC-HMS model (Abdulkareem et al., 2018). However, almost none of those studies applied the DC method for climate change study. Among the few climate change studies utilised the method are highlighted below.

Bui (2011) used deficit and constant loss method in HEC-HMS to estimate the streamflow of the Rio Grande under impacts of climate change. The study highlighted the simplicity and accuracy in the DC loss method to accurately predict and simulate future scenarios. HEC-HMS with deficit and constant loss method was used to simulate streamflow for current and future periods in Mae Klong basin of Thailand. The simulated discharge from the model fit the observed discharge (Sharma and Babel, 2017). Meenu et al. (2013), successfully applied deficit and constant loss method in HEC-HMS to assess the impacts of potential future climatic changes on the hydrology of the catchment area of Tunga-Bhadra River. Furthermore, recent study by Mahmood et al. (2016) using DC loss method, indicated that the method is effective for continuous simulations. However, results of the study by Azmat et al. (2016) revealed that snowmelt-runoff model (SRM) performed better than HEC-HMS with DC method to predict runoff in a high-altitude, scarcely gaged basin.

Babel et al. (2014) applied HEC-HMS with deficit and constant loss method in the Bagmati River Basin, Nepal. The model was run successfully for a long period. Gebre and Ludwig (2015) successfully assessed the hydrological response of climate change of four catchments (Gilgel Abay, Gumer, Ribb, and Megech of the upper Blue Nile River basin) using DC loss method in HEC-HMS. Shrestha et al. (2014) used the HEC-HMS deficit and constant loss technique to evaluate flow variations due to climate change. HEC-HMS with DC method performed better with spatial representation when Aryal et al. (2018) compared it with SWAT model for uncertainty analysis under change in climate. The hydrologic modelling studies with various loss methods in HEC-HMS model are presented in Table 1.

Table 1 Hydrologic modelling studies with various loss methods in HEC-HMS model

No.	*Source*	*Loss method*	*Objective*	*Findings*
1	Azmat et al. (2020)	Soil moisture accounting method	To investigate the impacts of climate change on major hydrological components (precipitation-runoff, snow-and glacier-runoff, evapotranspiration and inter-annual change in streamflows)	The projections show that pre-monsoon and monsoon seasons are expected to be greatly influenced by climate change, snow-and-glacier accumulation through alterations and melt regimes with significant effects on the region's river runoff
2	Candela et al. (2012)	Soil moisture accounting method	To investigate traditional approach for the assessment of flow regime and groundwater recharge impacts, based on coupling general atmosphere-ocean circulation models (GCM) and hydrologic models	The projected climate change at the catchment will affect the entire hydrological system with a maximum of 56% reduction of water resources
3	Nyaupane et al. (2018)	SCS-CN method	To determine a suitable approach for prediction of peak flow based upon the available historical precipitation data and assess the impact of climate change on precipitation resulting the peak flow	The study found that 43% increase in peak flow was determined for 18% increase in storm depth. With the likely occurrence of extreme precipitation events in future and rapid urbanisation, existing structures for the stream may not be adequate in future to prevent flooding
4	Halwatura and Najim (2013)	SCS-CN method	To simulate runoff for long period in a tropical catchment and to identify the most appropriate simulation technique for the research catchment	Compared to the deficit and constant loss method, the soil conservation service curve loss method did not perform well in the flow simulation

Table 1 Hydrologic modelling studies with various loss methods in HEC-HMS model (continued)

No.	*Source*	*Loss method*	*Objective*	*Findings*
5	Meenu et al. (2013)	Deficit and constant method	To evaluate the impacts of possible future climate change scenarios on the hydrology of the catchment area of the Tunga-Bhadra River	Results of the study suggest increasing precipitation and runoff and decreasing actual evapotranspiration losses over the sub-basins in the study area
6	Azmat et al. (2017)	Deficit and constant method	To examine the most suitable combination of different methods (transfer and loss) in HEC-HMS, used for the event based and continuous streamflow simulations	The combination of Green-Ampt and Clark UH for event based and SMA and Snyder UH for continuous simulation showed best efficient results than any other combination. Further, the hypothetical climate change scenarios showed a significant increase of annual streamflows (21.87%) of the Jhelum River catchment by the increase of 20% precipitation in comparison with 3oC temperature increase (10.79%)
7	Kure et al. (2013)	Green and Ampt method	To evaluate the impact of climate change on the future hydrology and water resources of the Pyanj and Vaksh River basins in the republic of Tajikistan	The study found a gradual change in the hydrologic flow regime throughout a year, with the high flows occurring earlier in the hydrologic year, due to the warmer climate in the future
8	Majidi and Shahedi (2012)	Green and Ampt method	To evaluate HEC-HMS model using Green-Ampt method and GIS technique for streamflow estimation in Abnama watershed	The findings showed that the observed and simulated peak flows differed. In addition, sensitivity analysis revealed that lag time is a sensitive parameter during optimisation
9	Rosas et al. (2020)	Initial and constant method	To evaluate the potential impact of climate variability on the water storage capacity of hydroelectric reservoirs in Andean countries	Results of the study demonstrated the vulnerability of Andean hydroelectric reservoirs against future climate change. The average sediment load of the Cañete River was estimated at 981 kTon/yr upstream of the Capillucas reservoir and showed that the calculated life span of the Capillucas reservoir is about 17 years

Table 1 Hydrologic modelling studies with various loss methods in HEC-HMS model (continued)

No.	*Source*	*Loss method*	*Objective*	*Findings*
10	Arekhi (2012)	Initial and constant method	To compare various techniques for assessment of runoff losses within HEC-HMS	Initial and constant method, in 70 % of events used in the study had less percentage changes of simulated to observed discharges
11	Yener et al. (2007)	Exponential method	To calibrate HEC-HMS model and use it as a decision support tool in the operation and management of Yuvacik Dam Reservoir	The study found that no matter what the intensity position is, HEC-HMS highly underestimated the design discharge. Nearly, peaks of HEC-HMS hydrographs are two thirds of design hydrograph peak
12	Yavuz et al. (2012)	Exponential method	To develop a decision support system for the reservoir management of Yuvacık Dam Reservoir	The results of the study as volume and peak flow difference are in limits of ± 30 %.
13	Scharffenberg et al. (2010)	Smith Parlange method	To highlights and discuss hydrologic modelling system physically-based simulation components	The study highlighted that Smith Parlange method is less likely to over-estimate infiltration at early time during a storm event. And also has ability to adjust infiltration process according to the temperature
14	Šraj et al. (2010)	Initial and constant, Smith Parlange, Green-Ampt and SCS-CN methods	To evaluate the influence of patterns of effective rainfall on modelled hydrograph using different loss (Initial and Constant, Smith Parlange, Green and Ampt and SCS-CN) methods of HEC-HMS	The best results with the lowest root mean square error (RMSE) in the study was obtained with the SCS-CN method
15	Scharffenberg and Harris (2008)	Green-Ampt, SCS-CN, soil moisture accounting and deficit and constant methods	To assess the capability of HEC-HMS model for interior flood modelling	The HEC-HMS program includes a number of useful simulation capabilities that could be used to carry out several analysis procedures for the design of interior ponds used to protect a floodplain area from flooding on a primary river
16	Hu et al. (2006)	Gridded deficit and constant method	To present application of HEC-HMS in gridded snowmelt and rainfall-runoff modelling for reservoir operational forecasting	The study found that, the most important factor that contributes the model uncertainty and performance is the spatial and temporal representation of the precipitation, temperature, and snow water equivalent

Table 1 Hydrologic modelling studies with various loss methods in HEC-HMS model (continued)

No.	*Source*	*Loss method*	*Objective*	*Findings*
17	Knebl et al. (2005)	Gridded SCS-CN Method	To develop a framework for regional scale flood modelling that integrates GIS and a hydrological model (HEC-HMS/RAS) for the San Antonio River Basin	The modelling framework presented in the study incorporated a portion of developed GIS tool (Map to Map) that has been created on a local scale and extended it to a regional scale. It was revealed that gridded curve number (CN) technique enables spatially distributed infiltration calculations
18	Anderson et al. (2002)	Gridded Green and Ampt Method	To evaluate HEC-HMS model coupled with atmospheric models for prediction of watershed runoff	Calibration of the HEC-HMS model with distributed precipitation is necessary for translating precipitation forecasts into runoff forecasts

5 Conclusions

Different loss techniques have been used in distinct watershed development studies to account for the losses caused by infiltration and evapotranspiration during rainfall. The most widely used among them is the soil conservation service (SCS) curve number (CN) method. This is because of its predictability, simplicity and stability and relies on only a single parameter (curve number) that varies as a function of soil group, land use, surface condition and antecedent moisture condition. Nevertheless, among the eleven methods for runoff volume computation in HEC-HMS, only deficit and constant method and soil moisture accounting method are appropriate for continuous simulation.

The technique of soil moisture accounting has been effective in continuous simulations in HEC-HMS, especially in climate change studies. Numerous studies of climate change impact using the method have reported success. However, the major challenge is the much number of its input parameters, which usually make it complex and render the calibration tedious with less accuracy.

The deficit and constant method has recently been used for climate change studies with tremendous success. This is because of its simplicity, as it requires less input parameters and gives accurate results. In addition, the GIS extension of HEC-HMS helps a lot to compute the input parameters. This has made the calibration easier, especially when handling long period data. However, despite its simplicity and accuracy, researches related to climate change impact using the method are still very few and has not been conducted in Malaysia. This might be due to lack of GIS skills for reliable basic data such as digital elevation model (DEM), land use and soil grid of the study locations, which could be used to derive the input parameters for the DC method. Interestingly, with the GIS extension of HEC-HMS, the input for the DC method could be easily obtained.

References

Abdulkareem, J., Pradhan, B., Sulaiman, W. and Jamil, N. (2018) 'Review of studies on hydrological modelling in Malaysia', *Modeling Earth Systems and Environment*, Vol. 4, No. 1, pp.1–29.

Abushandi, E. and Merkel, B. (2013) 'Modelling rainfall runoff relations using HEC-HMS and IHACRES for a single rain event in an arid region of Jordan', *Water Resources Management*, Vol. 27, No. 7, pp.2391–2409.

Al-Ahmadi, F.S. (2005) *Rainfall-runoff Modeling in Arid Regions Using Geographic Information Systems and Remote Sensing: Case Study; Western Region of Saudi Arabia*, p.441, Dep. of Hydrology and Water Resources Management, King Abdulaziz University.

Ali, M., Khan, S.J., Aslam, I. and Khan, Z. (2011) 'Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan', *Landscape and Urban Planning*, Vol. 102, No. 4, pp.271–279.

Ali, M.H., Bhattacharya, B. and Katimon, A. (2018) 'Modelling surface runoff in a large-scale paddy field in Malaysia', *International Journal of Hydrology Science and Technology*, Vol. 8, No. 1, pp.69–90.

Anderson, M., Chen, Z-Q., Kavvas, M. and Feldman, A. (2002) 'Coupling HEC-HMS with atmospheric models for prediction of watershed runoff', *Journal of Hydrologic Engineering*, Vol. 7, No. 4, pp.312–318.

Arekhi, S. (2012) 'Runoff modeling by HEC-HMS model (case study: Kan watershed, Iran)', *International Journal of Agriculture and Crop Sciences*, Vol. 4, No. 23, pp.1807–1811.

Aryal, A., Shrestha, S. and Babel, M.S. (2018) 'Quantifying the sources of uncertainty in an ensemble of hydrological climate-impact projections', *Theoretical and Applied Climatology*, Vol. 135, No. 1, pp.1–17.

Awan, U.K., Liaqat, U.W., Choi, M. and Ismaeel, A. (2016) 'A SWAT modeling approach to assess the impact of climate change on consumptive water use in Lower Chenab Canal area of Indus basin', *Hydrology Research*, Vol. 47, No. 5, pp.1025–1037.

Azmat, M., Choi, M., Kim, T-W. and Liaqat, U.W. (2016) 'Hydrological modeling to simulate streamflow under changing climate in a scarcely gauged cryosphere catchment', *Environmental Earth Sciences*, Vol. 75, No. 3, p.186.

Azmat, M., Qamar, M., Ahmed, S., Hussain, E. and Umair, M. (2017) 'Application of HEC-HMS for the event and continuous simulation in high altitude scarcely-gauged catchment under changing climate', *Eur. Water*, Vol. 57, No. 1, pp.77–84.

Azmat, M., Wahab, A., Huggel, C., Qamar, M.U., Hussain, E., Ahmad, S. and Waheed, A. (2020) 'Climatic and hydrological projections to changing climate under CORDEX-South Asia experiments over the Karakoram-Hindukush-Himalayan water towers', *Science of the Total Environment*, Vol. 703, No. 1, p.135010.

Babel, M.S., Bhusal, S.P., Walid, S.M. and Agarwal, A. (2014) 'Climate change and water resources in the Bagmati River, Nepal', *RTheor Appl Climatol*, Vol. 115, pp.639–654.

Bui, C. (2011) *Application of HEC-HMS 3.4 in Estimating Streamflow of the Rio Grande under Impacts of Climate Change*, MSc, University of New Mexico.

Candela, L., Tamoh, K., Olivares, G. and Gomez, M. (2012) 'Modelling impacts of climate change on water resources in ungauged and data-scarce watersheds. Application to the Siurana catchment (NE Spain)', *Science of the Total Environment*, Vol. 440, No. 1, pp.253–260.

Chu, X. and Steinman, A. (2009) 'Event and continuous hydrologic modeling with HEC-HMS', *Journal of Irrigation and Drainage Engineering*, Vol. 135, No. 1, pp.119–124.

Cunderlik, J. and Simonovic, S.P. (2004) *Calibration, Verification and Sensitivity Analysis of the HEC-HMS Hydrologic Model*, Department of Civil and Environmental Engineering, The University of Western.

Cunderlik, J.M. and Simonovic, S.P. (2005) 'Hydrological extremes in a southwestern Ontario river basin under future climate conditions/Extrêmes hydrologiques dans un basin versant du sud-ouest de l'Ontario sous conditions climatiques futures', *Hydrological Sciences Journal*, Vol. 50, No. 4, pp.631–654.

Deb, P., Babel, M.S. and Denis, A.F. (2018) 'Multi-GCMs approach for assessing climate change impact on water resources in Thailand', *Modeling Earth Systems and Environment*, Vol. 4, No. 2, pp.825–839.

Devia, G.K., Ganasri, B.P. and Dwarkish, G.S. (2015) 'Review on hydrological models', Paper presented at the *International Conference on Water Resources, Coastal and Ocean Engineering (ICWRCOE)*.

Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y. and Xu, C-Y. (2012) 'Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China', *Journal of Hydrology*, Vol. 464, No. 27, pp.127–139.

Fleming, M. and Neary, V. (2004) 'Continuous hydrologic modeling study with the hydrologic modeling system', *Journal of Hydrologic Engineering*, Vol. 9, No. 3, pp.175–183.

Fukunaga, D.C., Cecílio, R.A., Zanetti, S.S., Oliveira, L.T. and Caiado, M.A.C. (2015) 'Application of the SWAT hydrologic model to a tropical watershed at Brazil', *Catena*, Vol. 125, No. 2, pp.206–213.

Gebre, S.L. and Ludwig, F. (2015) 'Hydrological response to climate change of the upper Blue Nile River Basin: based on IPCC Fifth Assessment Report (AR5)', *Journal of Climatology & Weather Forecasting*, Vol. 3, No. 1, p.121.

Ghorbani, K., Wayayok, A. and Abdullah, A.F. (2016) 'Simulation of flood risk area in Kelantan watershed, Malaysia using numerical model', *Jurnal Teknologi*, Vol. 78, Nos. 1–2, pp.51–57.

Goodarzi, M. and Eslamian, S. (2018) 'Performance evaluation of linear and nonlinear models for the estimation of reference evapotranspiration', *International Journal of Hydrology Science and Technology*, Vol. 8, No. 1, pp.1–15.

Guo, J.C-Y. (2006) *Urban Hydrology and Hydraulic Design*, Water Resources Publication, Highlands Ranch, Colorado, USA.

Gyawali, R. and Watkins, D.W. (2012) 'Continuous hydrologic modeling of snow-affected watersheds in the Great Lakes basin using HEC-HMS', *Journal of Hydrologic Engineering*, Vol. 18, No. 1, pp.29–39.

Gyori, M.M. and Haidu, I. (2011) 'Unit hydrograph generation for ungauged subwatersheds. Case study: the Monoroştia River, Arad County, Romania', *Geographia Technica*, Vol. 6, No. 2, pp.23–29.

Gyori, M.M., Haidu, I. and Humbert, J. (2016) 'Deriving the floodplain in rural areas for high exceedance probability having limited data source', *Environmental Engineering and Management Journal*, Vol. 15, No. 8, pp.1879–1887.

Gyori, M.M., Humbert, J. and Haidu, I. (2013) 'Deriving flash floods in the case of simulated precipitations', *Geographia Napocensis*, Vol. 7, No. 2, pp.11–18.

Haidu, I. and Ivan, K. (2016) 'Évolution du ruissellement et du volume d'eau ruisselé en surface urbaine. Étude de cas: Bordeaux 1984-2014, France', *La Houille Blanche*, Vol. 114, No. 5, pp.51–56.

Halwatura, D. and Najim, M. (2013) 'Application of the HEC-HMS model for runoff simulation in a tropical catchment', *Environmental Modelling & Software*, Vol. 46, No. 8, pp.155–162.

Heimhuber, V. (2013) 'GIS based flood modeling as part of an integrated development strategy for informal settlements: a case study in applying GIS (ArcMap) in combination with hydrologic (HEC-HMS) and hydraulic (HEC-RAS) modeling to estimate the flood hazard of Onaville-Canaan-Haiti', *Urban Water Systems Engineering*, Technische Universitat Munchen, Munich.

Hu, H.H., Kreymborg, L.R., Doeing, B.J., Baron, K.S. and Jutila, S.A. (2006) 'Gridded snowmelt and rainfall-runoff CWMS hydrologic modeling of the Red River of the North Basin', *Journal of Hydrologic Engineering*, Vol. 11, No. 2, pp.91–100.

Ibrahim-Bathis, K. and Ahmed, S. (2016) 'Rainfall-runoff modelling of Doddahalla watershed – an application of HEC-HMS and SCN-CN in ungauged agricultural watershed', *Arabian Journal of Geosciences*, Vol. 9, No. 3, p.170.

Ismail, H., Kamal, M.R., bin Abdullah, A.F. and bin Mohd, M.S.F. (2020) 'Climate-smart agro-hydrological model for a large scale rice irrigation scheme in Malaysia', *Applied Sciences*, Vol. 10, No. 11, p.3906.

Jiang, T., Chen, Y.D., Xu, C-Y., Chen, X., Chen, X. and Singh, V.P. (2007) 'Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China', *Journal of Hydrology*, Vol. 336, Nos. 3–4, pp.316–333.

Jung, K., Marpu, P.R. and Ouarda, T.B. (2017) 'Impact of river network type on the time of concentration', *Arabian Journal of Geosciences*, Vol. 10, No. 24, p.546.

Kabiri, R. (2014) 'Simulation of runoff using modified SCS-CN method using GIS system, case study: Klang watershed in Malaysia', *Research Journal of Environmental Sciences*, Vol. 8, No. 4, p.178.

Kabiri, R., Bai, V.R. and Chan, A. (2015) 'Assessment of hydrologic impacts of climate change on the runoff trend in Klang Watershed, Malaysia', *Environmental Earth Sciences*, Vol. 73, No. 1, pp.27–37.

Kang, B. and Ramírez, J.A. (2007) 'Response of streamflow to weather variability under climate change in the Colorado Rockies', *Journal of Hydrologic Engineering*, Vol. 12, No. 1, pp.63–72.

Khaddor, I. and Alaoui, A.H. (2014) 'Production of a curve number map for hydrological simulation – Case study: Kalaya Watershed located in Northern Morocco', *International Journal of Innovation and Applied Studies*, Vol. 9, No. 4, pp.1691–1699.

Knebl, M., Yang, Z-L., Hutchison, K. and Maidment, D. (2005) 'Regional scale flood modeling using NEXRAD rainfall, GIS, and HEC-HMS/RAS: a case study for the San Antonio River Basin Summer 2002 storm event', *Journal of Environmental Management*, Vol. 75, No. 4, pp.325–336.

Kure, S., Jang, S., Ohara, N., Kavvas, M. and Chen, Z. (2013) 'Hydrologic impact of regional climate change for the snowfed and glacierfed river basins in the Republic of Tajikistan: hydrological response of flow to climate change', *Hydrological Processes*, Vol. 27, No. 26, pp.4057–4070.

Latha, M., Rajendran, M. and Murugappan, A. (2012) 'Comparison of GIS based SCS-CN and Strange table Method of Rainfall-Runoff Models for Veeranam Tank, Tamil Nadu, India', *International Journal of Scientific & Engineering Research*, Vol. 3, No. 10, pp.1–5.

Mahmood, R. and Jia, S. (2016) 'Assessment of impacts of climate change on the water resources of the transboundary Jhelum River basin of Pakistan and India', *Water*, Vol. 8, No. 6, p.246.

Mahmood, R., Jia, S. and Babel, M.S. (2016) 'Potential impacts of climate change on water resources in the Kunhar River Basin, Pakistan', *Water*, Vol. 8, No. 1, p.23.

Majidi, A. and Shahedi, K. (2012) 'Simulation of rainfall-runoff process using Green-Ampt method and HEC-HMS model (Case study: Abnama Watershed, Iran)', *International Journal of Hydraulic Engineering*, Vol. 1, No. 1, pp.5–9.

Malekani, L., Khaleghi, S. and Mahmoodi, M. (2014) 'Application of GIS in modeling Zilberchai Basin runoff', *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 42, No. 3, pp.181–186.

Manap, M.A., Nampak, H., Pradhan, B., Lee, S., Sulaiman, W.N.A. and Ramli, M.F. (2014) 'Application of probabilistic-based frequency ratio model in groundwater potential mapping using remote sensing data and GIS', *Arabian Journal of Geosciences*, Vol. 7, No. 2, pp.711–724.

Markus, M., Angel, J.R., Yang, L. and Hejazi, M.I. (2007) 'Changing estimates of design precipitation in Northeastern Illinois: comparison between different sources and sensitivity analysis', *Journal of Hydrology*, Vol. 347, Nos. 1–2, pp.211–222.

McColl, C. and Aggett, G. (2007) 'Land-use forecasting and hydrologic model integration for improved land-use decision support', *Journal of Environmental Management*, Vol. 84, No. 4, pp.494–512.

Meenu, R., Rehana, S. and Mujumdar, P. (2013) 'Assessment of hydrologic impacts of climate change in Tunga-Bhadra river basin, India with HEC-HMS and SDSM', *Hydrological Processes*, Vol. 27, No. 11, pp.1572–1589.

Mohammed, T.A., Said, S., Bardaie, M.Z. and Basri, S.N. (2011) 'Numerical simulation of flood levels for tropical rivers', *IOP Conference Series: Materials Science and Engineering*, Vol. 17, pp.1–10.

Neary, V., Habib, E. and Fleming, M. (2004) 'Hydrologic modeling with NEXRAD precipitation in middle Tennessee', *Journal of Hydrologic Engineering*, Vol. 9, No. 5, pp.339–349.

Nyaupane, N., Mote, S.R., Bhandari, M., Kalra, A. and Ahmad, S. (2018) 'Rainfall-runoff simulation using climate change based precipitation prediction in HEC-HMS model for Irwin Creek, Charlotte, North Carolina', Paper presented at the *World Environmental and Water Resources Congress 2018: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management*.

Oleyiblo, J.O. and Li, Z-J. (2010) 'Application of HEC-HMS for flood forecasting in Misai and Wan'an catchments in China', *Water Science and Engineering*, Vol. 3, No. 1, pp.14–22.

Paudel, U., Imteaz, M.A. and Matos, C. (2018) 'Equations for potential water savings through rainwater harvesting for different climatic conditions in Adelaide (Australia)', *International Journal of Hydrology Science and Technology*, Vol. 8, No. 1, pp.91–104.

Pradhan, B. and Youssef, A.M. (2010) 'Manifestation of remote sensing data and GIS on landslide hazard analysis using spatial-based statistical models', *Arabian Journal of Geosciences*, Vol. 3, No. 3, pp.319–326.

Radmanesh, F., Hemat, J.P., Behnia, A., Khond, A. and Mohamad, B.A. (2006) 'Calibration and assessment of HEC-HMS model in Roodzard watershed', Paper presented at the *17th International Conference of River Engineering*, university of Shahid Chamran, Ahva.

Razi, M.A.M., Ariffin, J., Tahir, W. and Arish, N.A.M. (2010) 'Flood estimation studies using hydrologic system (HEC-HMS) for Johor River, Malaysia', *Journal of Applied Sciences*, Vol. 10, No. 11, pp.930–939.

Refsgaard, J.C. and Knudsen, J. (1996) 'Operational validation and intercomparison of different types of hydrological models', *Water Resources Research*, Vol. 32, No. 7, pp.2189–2202.

Rosas, M.A., Vanacker, V., Viveen, W., Gutierrez, R.R. and Huggel, C. (2020) 'The potential impact of climate variability on siltation of Andean reservoirs', *Journal of Hydrology*, Vol. 581, p.124396.

Roy, D., Begam, S., Ghosh, S. and Jana, S. (2013) 'Calibration and validation of HEC-HMS model for a river basin in Eastern India', *ARPN journal of Engineering and Applied Sciences*, Vol. 8, No. 1, pp.33–49.

Scharffenberg, W. and Harris, J. (2008) 'Hydrologic engineering center hydrologic modeling system, HEC-HMS: interior flood modeling', Paper presented at the *World Environmental and Water Resources Congress 2008*, Ahupua'A.

Scharffenberg, W., Ely, P., Daly, S., Fleming, M. and Pak, J. (2010) 'Hydrologic modeling system (HEC-HMS): physically-based simulation components', Paper presented at the *2nd Joint Federal Interagency Conference*, Las Vegas, NV.

Schlenker, W., Hanemann, W.M. and Fisher, A.C. (2007) 'Water availability, degree days, and the potential impact of climate change on irrigated agriculture in California', *Climatic Change*, Vol. 81, No. 1, pp.19–38.

Shadeed, S. and Almasri, M. (2010) 'Application of GIS-based SCS-CN method in West Bank catchments, Palestine', *Water Science and Engineering*, Vol. 3, No. 1, pp.1–13.

Shaghaeghi, F.R. (2001) *Simulation of Maximum Peak Discharge in River Tributaries Using HEC-HMS Model (Case Study: Mohammadabad Watershed, Golestan Province)*, Thesis of MSc, Natural Resources Faculty, University of Gorgan.

Sharma, D. and Babel, M.S. (2017) 'Assessing hydrological impacts of climate change using bias-corrected downscaled precipitation in Mae Klong basin of Thailand', *Meteorological Applications*, Vol. 25, No. 3, pp.384–393.

Shrestha, S., Khatiwada, M., Babel, M.S. and Parajuli, K. (2014) 'Impact of climate change on river flow and hydropower production in Kulekhani hydropower project of Nepal', *Environmental Processes*, Vol. 1, No. 3, pp.231–250.

Singh, V.P. and Littleton, C. (1982) *Applied Modeling in Catchment Hydrology*, Water Resources Publications, Highlands Ranch, Colorado, USA.

Solomon, S. (2007) *Climate Change 2007 – The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC*, Vol. 4, Cambridge University Press.

Šraj, M., Dirnbek, L. and Brilly, M. (2010) 'The influence of effective rainfall on modeled runoff hydrograph', *Journal of Hydrology and Hydromechanics*, Vol. 58, No. 1, pp.3–14.

Tripathi, R., Sengupta, S.K., Patra, A., Chang, H. and Jung, I.W. (2014) 'Climate change, urban development, and community perception of an extreme flood: a case study of Vernonia, Oregon, USA', *Applied Geography*, Vol. 46, No. 1, pp.137–146.

USACE (2000) *CPD-74B. Hydrologic Modeling System HEC-HMS, Technical Reference Manual*, Hydrologic Engineering Center, Davis, CA, USA.

USACE (2016) *HEC-HMS User's Manual*, Hydrologic Engineering Center, Davis, CA.

USACE-HEC (2016a) *Hydraulic Reference Manual*, US Army Corps of Engineers, Davis, CA.

USACE-HEC (2016b) *Hydrology Reference User's Manual*, US Army Corps of Engineers, Davis, CA.

Wang, M., Zhang, L. and Baddoo, T.D. (2016) 'Hydrological modeling in a semi-arid region using HEC-HMS', *Journal of Water Resource and Hydraulic Engineering*, September, Vol. 5, No. 3, pp.105–115.

Xiaoyong, Z. and Min-Lang, H. (2004) 'ArcCN-Runoff: an ArcG.I.S. tool for generating curve number and runoff maps', *Environmental Modelling & Software*, Vol. 19, No. 10, pp.875–879.

Yavuz, O., Uysal, G., Sensoy, A., Sorman, A., Akgun, T. and Gezgin, T. (2012) 'Using HEC-HMS as a decision support system to minimize the downstream flooding risk in Yuvacık Dam basin', Paper presented at the *Proc., Conf. on Water Observation and Information Systems, BALWOIS*, Ohrid, Macedonia.

Yener, M., Sorman, A., Sorman, A., Sensoy, A. and Gezgin, T. (2007) 'Modeling studies with HEC-HMS and runoff scenarios in Yuvacik Basin, Turkiye', *Int. Congr. River Basin Manage*, Vol. 4, No. 1, pp.621–634.

Yimer, G., Jonoski, A. and van Griensven, A. (2009) 'Hydrological response of a catchment to climate change in the upper Beles river basin, upper blue Nile, Ethiopia', *Nile Basin Water Engineering Scientific Magazine*, Vol. 2, No. 1, pp.49–59.

Youssef, A.M., Al-Kathery, M. and Pradhan, B. (2015) 'Landslide susceptibility mapping at Al-Hasher area, Jizan (Saudi Arabia) using GIS-based frequency ratio and index of entropy models', *Geosciences Journal*, Vol. 19, No. 1, pp.113–134.

Yusop, Z., Chan, C.H. and Katimon, A. (2007) 'Runoff characteristics and application of HEC-HMS for modeling stormflow hydrograph in oil palm catchment', *Water Science Technology*, Vol. 56, No. 8, pp.41–48.