



Modeling of rainfall–runoff events using HEC-HMS model in southern catchments of Jerusalem Desert-Palestine

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Abstract

The current study aimed to simulate the rainfall–runoff events in two catchments (Daraja and Al-Ghar) of Palestine using HEC-HMS model during 1990–2010 data period. Main inputs to the model included soil properties, land use land cover, stream network, slope in addition to rainfall data, and physical catchment characteristics. The model was calibrated and validated on total of 20 rainfall–runoff events from both catchments. Model efficiency was estimated through accuracy percentage, Nash–Sutcliffe (NS), and coefficient of determination (R^2). Simulation indicated acceptable model efficiency with NS (R^2) value ranged between 0.78–0.96 (0.79–0.98) and 0.88–0.94 (0.91–0.98) for Daraja and Al-Ghar catchments, respectively, over entire data period. Outcomes of the study suggested that HEC-HMS model calibrated during this study may be used for forecasting the flows on short time-step with future climatic scenario in the similar environments and may be helpful for water resources manager to predict and mitigate the flood risk.

Keywords HEC-HMS model · Rainfall–runoff modeling · Geographic information systems (GIS) · Water resource management · Flood risk · Jerusalem Desert-Palestine

Introduction

Water is an essential component of global life sustenance; therefore, the freshwater scarcity and quality is major concern that must be addressed for the socioeconomic

development process. Water availability is the main driver of agriculture-based economy of Palestinian territories. According to Hammad and Salameh (2019) and Rozalis et al. (2010), the climate crisis is coming hard and heavy to the region. The historical Palestine is expected to have prolonged summers and a decline in precipitation (by as much as 25%) in future, resulting in triggering a frightening leap in water scarcity (Alpert et al. 2002). The Palestinian Water Authority (PWA) also believes that Palestinians will be the most vulnerable in the region to the potential climate disasters to come (PWA 2013). In addition, although the total rainfall amounts are projected to decrease, the numbers of extreme events are expected to increase, causing prolonged droughts or frequent floods and storm surges, posing potential threat to agriculture, infrastructure, and human life.

Growing water pollution and increase in demand of domestic water (in wake of Israeli expansion policies) is further exacerbating the situation of water availability. In addition, the threat of declining amounts of available rainfall water and the risk of more frequent floods in future are the major challenges for the Palestinian Authority. Despite being an extremely precious resource, a valuable proportion of the surface runoff generated from rainfall events in Palestine

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(estimated as 5%) is lost without any exploitation (El-Naser et al. 1998). The estimation, organization, and planning of water resources and flood protection had to be adapted robustly, particularly in the areas where rainfall is inadequate and groundwater recharge is underachieved (Gontia and Patil 2012; Jaber et al. 2017).

The Daraja and Al-Ghar catchments located in western Dead Sea Basin are prone to a higher flood risk (Belachsen et al. 2017). While the expected higher risk of floods can be attributed to the stronger runoff curve numbers observed in the West Bank area, with an average value of about 70 (Shadeed et al. 2019). Overall, the issues with climate data availability and restriction on the access to the area had hindered any hydro-meteorological investigations as well as water resource development and management, particularly in these arid catchments of the Jerusalem Desert and over the whole western Dead Sea Basin in general. The result is that despite increasing need for water accessibility, particularly for the Bedouins cattle sector, the threats of diminishing recharges and the projected increase in flood risks is emerging. On the other hand, Israel took full sovereignty of all the land and natural resources of the Palestinians. Israel has either seized or declared over 55% of the West Bank as closed areas and thus put them out of Palestinian control and not accessible and Palestinians have less than 15% of the total water supplies of the West Bank available to them (Isaac and Sabbah 1994). Therefore, the Palestinian water resources researchers have limitations due to the unavailability of complete hydrologic data or accessibility to research fields. These circumstances have led to a growing awareness about the need and importance of water research and management, among both researchers and policy makers in Palestine and neighbor states over the past decade (Abushandi and Merkel 2013). Similarly, the importance of collecting the flood water over the catchment domain, to serve as available water for farming, groundwater replenishment and as flood mitigation tool cannot be over emphasized (Abdulla et al. 2002; Alkhaddar et al. 2005; Al-Adamat et al. 2010; Abushandi and Merkel 2013).

Modeling the rainfall–runoff in such arid catchments can though assist in investigating the watershed characteristic and subsequently required for better planning and water resources management (Jaber et al. 2017). However, executing such modeling is difficult in such regions due to scarcity of measured data (Pilgrim et al. 1988), specifically rainfall or (as witnessed in the current case) field inaccessibility due to physical, administrative, or geo-political hurdles. Such limitations may diminish the applicability, reliability and scope of such efforts but also add to results uncertainties (Nakatani et al. 2019). Despite these issues, exploring hydrological dynamics of watersheds in arid and semiarid sectors using hydrological modeling techniques is of utmost importance (Abdulla et al. 2002).

There are two main categories of hydrological or rainfall–runoff models: conceptual-lumped rainfall–runoff models and distributed or semi-distributed rainfall–runoff model. The later typically need higher data input than conceptual-lumped models (Kunnath-Poovakka and Eldho 2019) but may be capable of providing a better representation of the responses to the heterogeneity of rainfall spreading (Abushandi and Merkel 2013; Yu and Jeng 1997). The added data needs for such distributed models may though pose a challenge (Hayat et al. 2019). With the technological advancement over the past couple of decades, the absence of in situ observational data could be mitigated by the use of remotely sensed data (i.e., weather radar or satellite data, elevation models, soil, etc.). Similarly, the increase in computational capabilities and availability of geographic information systems (GIS) make the application of distributed models a more feasible option. The benefit of utilizing the GIS in hydrological management has been obviously specified by numerous researchers (Jayakrishnan et al. 2005; Martin et al. 2005; Reinelt et al. 1991; Ahmad et al. 2020). Trials have also been carried globally and regionally to assimilate a number of hydrological models in a GIS environment, such as Soil and Water Assessment Tool (SWAT), Water Erosion Prediction Project (WEPP), Système Hydrologique Européen (MIKE SHE), Areal Non-Point Source Watershed Environment Simulation (ANSWERS), Topography-based hydrological MODEL (TOPMODEL), as well as Hydrologic Engineering Center's Hydrologic Model System (HEC-HMS) (Tiwari et al. 2013; Abushandi and Merkel 2013). The use of such models permits evaluation and assess the expected influence of catchment management methods on the hydrological responses (Arnold et al. 1998; Verma et al. 2010; Wheeler et al. 1999; Zhang et al. 2008). Other studies have used a variety of well-established hydrologic models to investigate the rainfall–runoff relationship to study flood generation throughout modeling process (Romali et al. 2018; Bhuiyan et al. 2017; Zhang et al. 2013; Nandalal and Ratmayake 2010; Oleyiblo and Li 2010). Despite the promises these models can offer and their track record in other geographic regions, these approaches (mainly the rainfall–runoff modeling) have not been investigated enough in the Palestinian territory so far. Furthermore, it was indicated that every specific set of climatic and environmental conditions require specific hydrological models (Todini 1988). In fact, the rainfall and runoff processes in arid, semi-arid, or hyper-arid regions being more complex than those in exclusively humid regions (Pilgrim et al. 1988).

Preceding research on HEC-HMS application showed its capability to simulate and forecast low and high flows resulting from rainfall events based on different datasets and catchment characteristics in various catchments (Anderson et al. 2002; Bournaski et al. 2009; Chu and Steinman 2009; Cydzik and Hogue 2009; Knebl et al. 2005; Yusop et al.

2007). El Alfy (2016) analyzed the influence of urbanization on flash floods in arid regions in the Jazan region of southwestern Saudi Arabia. This study used an integrated approach that included a GIS, remote sensing data, and rainfall–runoff modeling by HEC-HMS. Study concluded that expansion in urban areas reduced infiltration and increased runoff, leading to increasing flood peaks and water even for low intensity rainfall during short time-period. Hamidon et al. (2020) designed a hydrologic model based on HEC-HMS for Bukit Merah region of Malaysia and anticipated flood magnitude for the next twenty years while taking climate change and land use changes into account. High and low rainfall scenarios were both modeled, and peak discharges were projected in both circumstances. Agarwal et al. (2020) evaluated the operational flood forecasting efficiency based on a novel Web-based Decision Support System (DSS) coupled with HEC-HMS and Weather and Research (WRF) rainfall forecast data. It was found that system has performed very well in forecasting flows and floods by providing additional lead time for issuing the flood advisories within Aye-yarwady river basin (ARB) of Myanmar provides.

This study focused on simulating the rainfall-runoff events (including low and high flows, and flood volume) in the two catchments (Daraja and Al-Ghar catchments) in Jerusalem Desert-Palestine. Regions such as our study area needs a customized and targeted modeling effort, specifically suited for it. Therefore, we opted to apply HEC-HMS model to simulate the rainfall-runoff events owing to its suitability in similar catchments. Performance of the HEC-HMS model was assessed on total discharge volume and peak flows (may be categorized as flood events).

Study area

The current study was conducted on two catchments, Daraja and Al-Ghar, located in the Jerusalem Desert of Palestine within the eastern rain Shadow Mountains of West Bank near Dead Sea (Fig. 1). The desert plateau is located to the east of the divider anticline water (the West Bank Mountains). Both catchments are located at ~ 30 km south-east of Jerusalem, the capital of Palestine, between 35.1 and 35.4 (decimal degree) East longitude and 31.4 and 31.7 (decimal degree) north latitude (Fig. 1), with a mean elevation of 895 m above sea level (m asl). The study area is characterized by different climatic zones mainly arid and hyper arid. Both catchments are distinguished by very hot summer and high steep topography and deep conduits; therefore, the inhabitants are very few and in sparse distribution (Eshel et al. 2017). Both catchments together occupy approximately 467 km² area up to both hydrometric stations at the fan top, draining the eastern slopes of the Jerusalem Desert to the Dead Sea (~ 439 m below sea level). Due to the rain-shadow

effect, the annual rainfall gradient in the area is very sharp: the northwest part of the catchment receives ~ 480 mm/year while near the shore of the Dead Sea, called a hyper-arid zone, less than 50 mm/year (Morin et al. 2009). The horizontal distance from the uppermost section to the catchment outlet is just around 20 km.

Geologically, the study area is situated in dense and resistant Upper Cretaceous carbonate rocks which has resulted in the formation of irregular, steep narrow gorges with bedrock channels (Greenbaum et al. 2010). The stream channels in sub basins are steeply sloped, rocky with very few sediments and less bending and meandering. Both catchments are characterized by large sections of exposed rock, shallow soils, absence of vegetation, presence of debris cover and desert pavement. Coverage of the vegetation is uncommon, discontinuous, and occurs mainly in canals. Some of the causes of the sparse distribution of the population include the arid to hyper-arid climate, high summer temperatures, and steep topography (Eshel et al. 2017). These catchments drain their intermittent waterflow into the Dead Sea and sometimes in the form of flash floods generated from high-intensity rainfall events. Waterflows are often exacerbated in these areas by short-term strong rain episodes triggering to regionally low infiltration capacity of thin soil layer, exposed bedrock, sealing surfaces, and extremely steep topography (Shamir et al. 2013; Yair and Kossovsky 2002). The main loss of flow from the catchments is done by infiltration into the channel alluvial bed and banks (i.e., transmission losses) which is a prominent hydrologic mechanism that affects stream-flow generation (Shentsis et al. 1999). The dominant soil extends from reddish carbonate soil (Terra Rosa) in the west to desert soil on the plateau. Soil cover varies as a result of rainfall gradients (Lavee et al. 1991). The lower section of both catchments contributes in the Dead Sea Fault Escarpment formation, which rises up to 650 m above the Dead Sea level and borders the desert plateau. Colluvial and Lacustrine sediments primarily marl, coarse colluvial, and river deposits cover mostly these slopes in the bottom half of the hills (David-Novak et al. 2004). Owing to the topography and soil properties, both of these catchments (Daraja and Al-Ghar) are insecure for flash floods generated through rainfall which often resulted in severe casualties and intense smashing.

Methodology

The fundamental technique in hydrological modeling is computing the water flux throughout the channels related to meteorological information and watershed distinctiveness, which are accessible from the study area (Ye et al. 2013). This study used HEC-HMS model to simulate runoff generated from the study area in response of rainfall events during

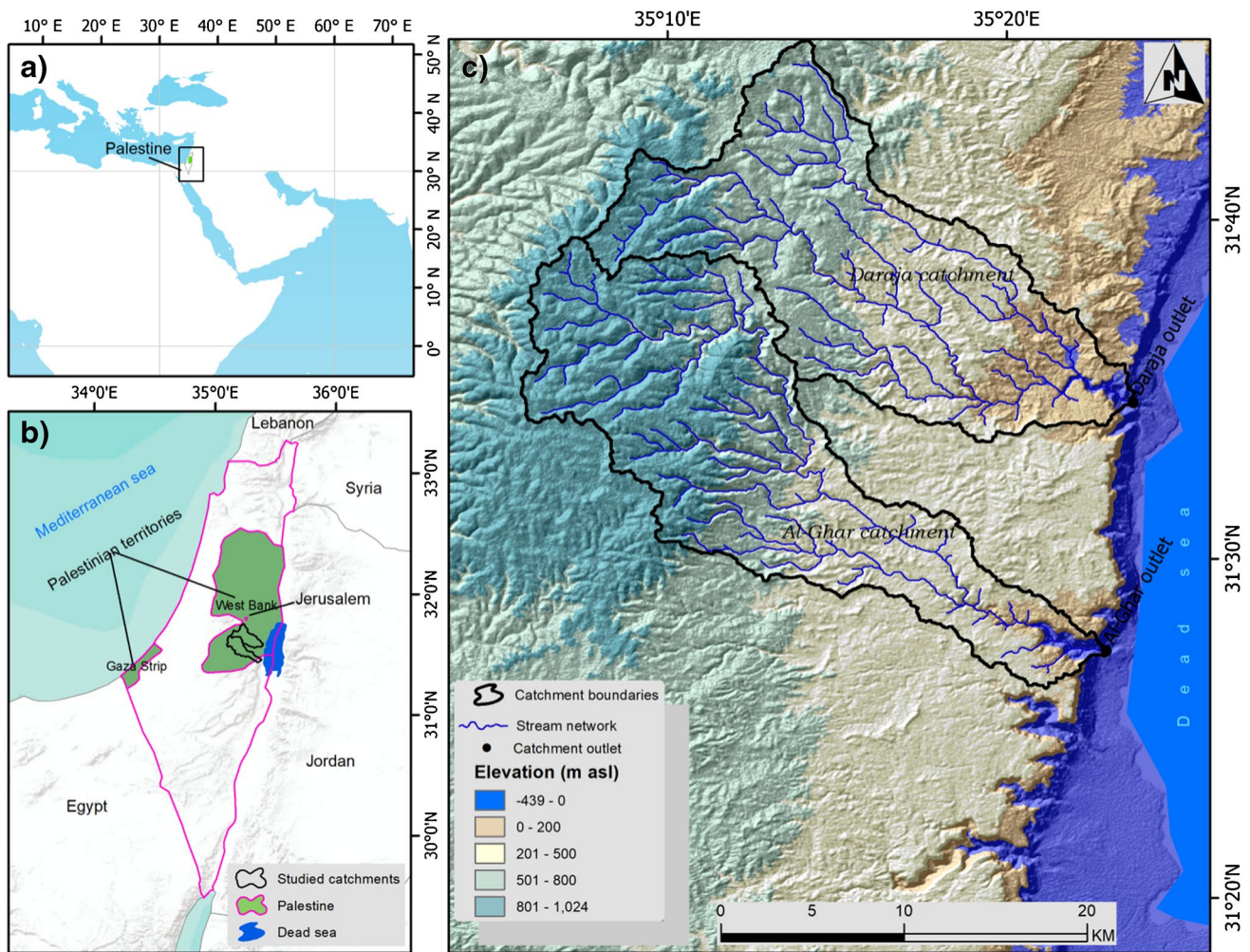


Fig. 1 a Geographical location (in degrees longitude and latitude) of the Palestine. b Location of studied catchments (in degrees and decimal minutes) within the Palestinian territories. c Boundaries of the

catchments, Daraja and Al-Ghar, spatial extent, stream network, flow outlets, and elevation variation

1990–2010 data period. The methodology is composed of two major sections. First section described the remote sensing and other datasets obtained to set up the HEC-HMS model. Second section detailed the working principle of HEC-HMS model and its run during this study. A flowchart describing the methodological approach is presented in Fig. 2.

Datasets and model inputs

Four types of data sets were obtained to run the HEC-HMS model. These data sets include digital elevation model (DEM), hydro-meteorological (stream flow and rainfall), soil type, and land use land cover (LULC) datasets.

Ministry of Local Government (MOLG) has developed and operated the first integrated spatial information system in Palestine known as GeoMOLG (2019). Computer

Network Information Center in Palestinian Polytechnic University provided the accessibility to GeoMOLG. Digitally generated elevation maps in form of DEM were obtained from GeoMOLG data portal. DEM data was used to extract catchment characteristics, the drainage network and the related drainage divisions of both catchments. The watershed and sub-basins were also delineated from DEM data. Stream network and the topographic attributes of each sub-basin were characterized based on a 1:50,000 scale topographical maps. State of the art ArcHydro Tools 2.0, an extension of ArcGIS software, was used for the delineation of catchments and sub-basins and the description of drainage networks (natural streams). A total of 13 and 15 sub-basins were delineated for Daraja and Al-Ghar, respectively, with different areas. Objective was to quantify the flow generation from each sub-basin specifically and then from the entire catchment. Topographical data (contour lines, altitude

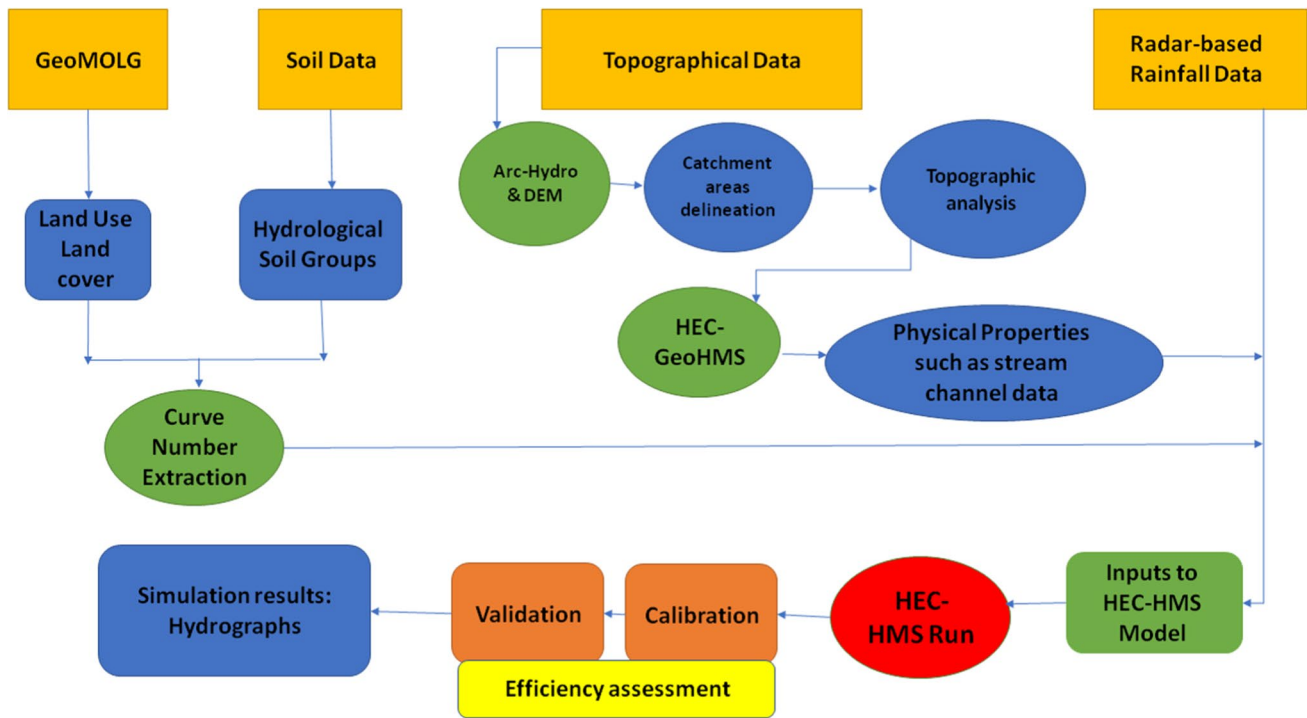


Fig. 2 Methodological flowchart showing the steps followed from data input to model simulation

points, and slopes) was resultant from the cartographic system created by GeoMOLG.

The main input data for any hydrological model is rainfall data. High spatial and temporal variability is the main characteristics of rainfall. There was no rain gauge data available from the study area so weather radar remote sensing rainfall data was used as basic input. Weather radar rainfall data with high temporal resolution of 5-min time interval was obtained from the Physical Geography and Climatology Department (PGCD) of Hebrew University. This data was recorded using Shacham weather radar, located in the Ben Gurion Airport. Some researchers working on the radar rainfall data quality in the state included the study area (Morin et al. 2003; Morin and Gabella 2007). They mentioned that meteorological radar data-based quantitative precipitation estimation theoretically offers continuous, high-resolution large-coverage data necessary for meteorological and hydrological research (Sun et al. 2018). For this reason, the radar based rainfall data was utilized in this research as an input data for the proposed hydrological model. Rainfall events data and the flow discharge at the outlet of each catchment were obtained for the study area for a period extending over two decades from 1990 to 2010.

Flow event and physical characteristics data of stream channels in both catchment was obtained from the hydrometric stations of the Israel Hydrological Service (IHS) by the PGCD of Hebrew University. Flow data was obtained for the same dates as for the rainfall events. These information and

data were examined in order to identify their accuracy. Some differences were revealed mainly in stream channel characteristics between the GeoMOLG and IHS data. These data were corrected for various streams in both catchments by keeping the GeoMOLG information as a reference. Manning roughness coefficient values were estimated by PGCD of Hebrew University in 2014 and found that both catchments have similar values such as 0.1 for floodplain and stream banks along the hill slopes and 0.035 for the stream channels. These values were used in current HEC-HMS model application. LULC data along the water divide in upstream of catchments was obtained from GeoMOLG and Google Earth mapping. These data were utilized to determine the impervious area percentage and to determine the soil curve number (CN) properties of the study area. Different maps have been extracted such as rainfall map, contour map, geological map, topographical map, LULC map, and soil map for both catchments using HEC-GeoHMS.

Throughout the rainfall event cycle, water will dissipate in different routes such as infiltrate to replenish groundwater, interception, evapotranspiration, and runoff. Many methods have been proposed to simulate rainfall–runoff. HEC-HMS model used in this study is based on loss method. Loss method estimates the losses from catchment during the rainfall–runoff generation process. Many loss methods can be adopted by the proposed model such as the Soil and Conservation Service (SCS), Green and Ampt (G.A.), Initial-Constant (I.C.), Deficit-Constant

(D.C.), Constant Fraction (C.F.), Exponential (Exp.), and Soil Moisture Accounting (SMA) (Razmkhah 2016). For a watershed with a mixture of soils and land uses, a single runoff curve number can be created (USDA 1989). In the present research, the SCS-CN was adopted as a loss method during the modeling process. It is a simple, widely used and efficient method for determining the approximate amount of runoff from a rainfall event in a particular area (Schulze et al. 1992; Shadeed and Almasri, 2010; Khader et al. 2019). The loss method required following parameters to be defined: initial abstraction, CN, and impervious percent. The former is considered zero in the current research.

CN was derived by using rainfall pattern suggested by Natural Resource Conservation Service (NRCS) (Cronshy 1986). NRCS method proposed a CN technique known as CN-NRCS (Kumar et al. 2013). This method reported that CN can be computed by LULC map. To describe these curve numbers mathematically, NRCS assumed that surface runoff depth, Q (mm) is related to rainfall quantity, P (mm), initial abstraction, I_a (mm), and potential maximum retention or soil water storage, S (mm) as given in Eq. 1:

$$Q = (P - I_a)^2 / (P - I_a + S) \quad (1)$$

Initial abstractions (I_a) related to water losses are associated with interception, soil surface storage, and infiltration (Jiao et al. 2015). The CN-NRCS technique determined initial abstraction as given in Eq. 2:

$$I_a = 0.2S \quad (2)$$

However, the value of I_a for each event was determined based on the observed radar precipitation data in this study. Potential soil water storage (S) was transformed to the CN by the linear formula in Eq. 3:

$$CN = (25400)/(254 + S) \quad (3)$$

The soil type data were obtained from Dudeen et al. (2001). The dominant soils in the region are the Tertiary and Cretaceous deposits of limestone (Dudeen et al. 2001). The impervious percent (Imp %) can be determined through the GeoMOLG by extracted LULC maps using the Eq. 4:

$$\text{Imp}\% = \sum_{k=1}^n \left(\frac{a}{A} \times \% \right) \quad (4)$$

where A is the catchment area, a is the impervious area, and n is the number of sub-basins.

The Clarks unit hydrograph (CUH) method was selected to calculate the effective rainfall-runoff transformation. This method required time of concentration

and storage coefficient values. This model highlighted two significant procedures in the conversion of effective rainfall into direct surface runoff (Ahmad et al. 2009). First, the reduction which indicated the decline in the stream flows created by effective rainfall due to storage in the catchment and identified by the storage coefficient of each sub-basin. The storage coefficient, R , was calculated for every sub-basin by using the Eq. 5:

$$R = \frac{T_c}{\left[\left(1.46 - \left(0.0867 \left(\frac{0.0867L^2}{A} \right) \right) \right) \right]} \quad (5)$$

where T_c is the time of concentration (in hours), A is the catchment area (in km^2), and L is the longest flow length (in km) of a basin.

Second, the transformation, reflected by the lag time ($Lag_{(t)}$). It is the required time taken by effective rainfall in the hydrological basin to reach to the outlet. The lag time was calculated after deriving time of concentration (Woodward 2010; Che et al. 2014). The time of concentration, T_c , was determined by applying the Kirpich formula (Kirpich 1940) as given in Eq. 6:

$$T_c = 0.01947L^{0.77}S^{-0.385} \quad (6)$$

where L is the longest flow length (in meters) of a basin and S is the potential soil water storage (in mm). T_c was then used to estimate the lag time (in hours), $Lag_{(t)}$ using Eq. 7.

$$Lag_{(t)} = 0.6T_c \quad (7)$$

T_c , $Lag_{(t)}$ and R were calculated for each sub-basin in both catchments by applying the equations mentioned previously.

All the parametric values found by using the equations mentioned above or extracted from GeoMOLG database were modified slightly during calibration process of the model to better simulate the flow from the catchments. CN and imperviousness percent values initially calculated from previously mentioned equations were used in trial-error method and modified until the best suited values for simulation were found. Impervious area percent values found through trial were approximately similar as found through GeoMOLG and CN values optimized during trial-error method were similar to those presented by Shadeed and Almasri (2010) for the same area.

HEC-HMS model description and working principle

Like any hydrological model build on physical parameters, HEC-HMS simulates nearly all of the major catchment hydrologic functions. Simulation process by HEC-HMS

model can be achieved on sub-basin, entire river watersheds, and small urban and natural catchment water system. Furthermore, the model has a benefit to display spatial hydrological characteristics of the intended study areas using HEC-GeoHMS extension system in ArcGIS. Model has the capability to estimate flow discharge, flow volume and generating hydrographs as indicated by various researches (Oleyiblo and Li 2010; Halwatura and Najim 2013; Azam et al. 2017). Romali et al. (2018) applied HEC-HMS in the Segamat River flood with the goal to assess the flooding risk by providing the stakeholders with peak inundation maps.

Catchment and sub-basin boundaries, areas, water channel network, as well as diversions and junctions are used as physical characteristics input. HEC-HMS model needs a variety of input datasets involving field and remote sensing sources: DEM, rainfall data, soil type, and LULC datasets. User manual (Scharffenberg 2013) offers a description of all the variables and physical parameters used in HEC-HMS processing. In conjunction with the ArcHydro extension in ArcGIS, the Geospatial Hydrologic Modeling Extension (HEC-GeoHMS) was incorporated to demarcate the physical properties of both catchments using GeoMOLG data and to generate a stream system in the study area. HEC-HMS model involved individual modules, which are obtainable to correspond to each element of the runoff such as quantify the volume of runoff (loss methods), direct runoff (transforming techniques), and base flow (Feldman 2000; Ford et al. 2008). All the input data sources, parameter calculations, and pre-processing used in this study to run HEC-HMS is explained in the “[Datasets and model inputs](#)” section. The results of HEC-HMS were obtained in the form of hydrograph, hyetograph, flood volume, peak discharge and time of peaks. The efficiency of the model, in terms of match between observed and simulated flow, was tested using the percent accuracy, Nash–Sutcliffe (NS) efficiency coefficient (Nash and Sutcliffe 1970), and the coefficient of determination (R^2). Available rainfall and stream flow data was spanned over two decades from 1990 to 2010 with 10 rainfall–runoff events happening in each of the catchments. Five of the events in each catchment were used for calibrating the model and rest of the events for validation process. Calibration process was carried out to find the best values of model parameters which can simulate the flow from catchment in a better way. These parameters were then used in validation stage to check if the calibrated parameters worked fine. Methodology of current research was adopted from the study of Eljack et al. (2015) and modified according to the catchment characteristics of our study area.

Results and discussion

Physical and hydrological characteristics of the study area and parameters' values used during simulation

Topographic, geologic, soil, rainfall aridity, land cover, and land use maps for the study area were generated to be used as input in the HEC-HMS model. DEM was used to extract physical characteristics such as basin and sub-basin boundaries, surface areas, stream or channel network longest flow route, slope and flow direction. Daraja catchment is bit larger and has more desert characteristics than Al-Ghar (Morin et al. 2009), while it has lower elevation in the upper limit as compared to the lower limit. In order to develop a range of hydrological model inputs, ArcGIS-based HEC-GeoHMS and Spatial Analyst extensions were used. Assessing digital landscape data, HEC-GeoHMS transformed watershed routes and drainage borders into a hydrological data system that reflected the response of the catchment to rainfall. The consequences created by HEC-GeoHMS were then introduced into the Hydrological Modeling Structure, HEC-HMS 4.2.1, where simulation was executed. Some of these physical and hydrological characteristics for both studied catchments are presented in Tables 1, 2, and 3.

Tables 2 and 3 show the physical and hydrological properties of each sub-basin in each catchment and the channel stream system. Some of these data were obtained from the Hebrew university during spring 2014; others were extracted from GeoMOLG and GIS techniques. The data included physical properties like sub-basin areas, gradients of the hillslopes and channels, length of hillslopes and channels, channel width and sub-basin order for each sub-basin in every catchment.

Catchment boundaries, stream network, their elevation variation, and outlets are shown in Fig. 1 while soil types distributed among both catchments are shown in Fig. 3. Both catchments described many similarities in their geographical and physical characteristics with little differences. Similarities were found in aridity with similar climatic zones, orientation from west to east. Both have steep topography, desert and mountain soil (Fig. 3), and have nearly the same

Table 1 Physical characteristics of Daraja and Al-Ghar catchments

| Physical parameter | Daraja | Al-Ghar |
|---------------------------------------|--------|---------|
| Area (km ²) | 235 | 232 |
| Maximum elevation above sea level (m) | 940.3 | 985.2 |
| Minimum elevation below sea level (m) | -413 | -435.2 |
| Percent of desert soil (%) | 45 | 39 |

Table 2 Physical and hydrological characteristics of sub-basin wise channel stream system in Daraja catchment

| Sub-basin | Sub-basin area (km ²) | Hillslope length (m) | Hillslope gradient (degrees) | Channel length (m) | Channel width (m) | Channel gradient (degrees) | Sub-basin next Id | Sub-basin order |
|-----------|-----------------------------------|----------------------|------------------------------|--------------------|-------------------|----------------------------|-------------------|-----------------|
| 1 | 23.58371 | 707.01 | 9.58 | 5277.97 | 6.89 | 2.43 | 8 | 1 |
| 2 | 13.30215 | 1226.37 | 11.88 | 1716.26 | 5.85 | 2.91 | 7 | 1 |
| 3 | 10.84016 | 922.97 | 11.3 | 1858.36 | 5.52 | 3.5 | 4 | 1 |
| 4 | 1.470699 | 257.27 | 11.56 | 904.51 | 6.7 | 2.21 | 7 | 2 |
| 5 | 8.996899 | 4619.41 | 11.78 | 308.17 | 5.23 | 2.27 | 4 | 1 |
| 6 | 6.733233 | 2003.32 | 10.47 | 531.81 | 4.81 | 2.82 | 8 | 1 |
| 7 | 5.694352 | 481.72 | 9.92 | 1870.39 | 8.04 | 1.66 | 9 | 3 |
| 8 | 0.140374 | 175.59 | 6.27 | 126.49 | 7.42 | 3.16 | 9 | 2 |
| 9 | 2.783189 | 310.24 | 11.47 | 1419.46 | 9.55 | 1.41 | 11 | 5 |
| 10 | 28.66202 | 1020.1 | 11.01 | 4445.78 | 7.29 | 2.92 | 11 | 1 |
| 11 | 80.6451 | 786.98 | 15.11 | 16,214.2 | 12.39 | 2.4 | 13 | 6 |
| 12 | 24.4231 | 1054.54 | 12.67 | 3664.55 | 6.96 | 5.05 | 13 | 1 |
| 13 | 27.93892 | 835.66 | 15.83 | 5290.06 | 13.32 | 2.42 | | 7 |

Table 3 Physical and hydrological characteristics of sub-basin wise channel stream system in Al-Ghar catchment

| Sub-basin | Sub-basin area (km ²) | Hillslope length (m) | Hillslope gradient (degrees) | Channel length (m) | Channel width (m) | Channel gradient (°) | Sub-basin next Id | Sub-basin order |
|-----------|-----------------------------------|----------------------|------------------------------|--------------------|-------------------|----------------------|-------------------|-----------------|
| 1 | 15.339 | 5513.0 | 11.194 | 1391.2 | 8.47 | 2.13 | 4 | 1 |
| 2 | 17.8879 | 3705.3 | 7.853 | 2548.8 | 8.99 | 1.96 | 5 | 1 |
| 3 | 1.86413 | 525.3 | 14.054 | 1774.3 | 12.59 | 1.18 | 4 | 3 |
| 4 | 20.1075 | 734.2 | 16.269 | 13,694.1 | 14.35 | 1.94 | 10 | 4 |
| 5 | 7.92199 | 704.8 | 13.799 | 5620.2 | 10.85 | 1.29 | 3 | 2 |
| 6 | 9.57659 | 2871.3 | 10.663 | 1667.7 | 7.40 | 3.08 | 5 | 1 |
| 7 | 22.9692 | 1733.9 | 10.956 | 6623.7 | 9.51 | 2.13 | 3 | 1 |
| 8 | 12.7149 | 2338.2 | 15.355 | 2718.9 | 8.03 | 4.55 | 10 | 1 |
| 9 | 21.4458 | 1520.0 | 14.982 | 7054.7 | 9.33 | 5.11 | 11 | 1 |
| 10 | 0.452312 | 332.9 | 18.301 | 679.4 | 14.89 | 2.01 | 11 | 5 |
| 11 | 4.12051 | 607.5 | 15.088 | 3391.4 | 15.81 | 1.80 | 13 | 6 |
| 12 | 11.5491 | 1888.6 | 14.569 | 3057.6 | 7.81 | 4.90 | 13 | 1 |
| 13 | 21.1391 | 953.3 | 12.675 | 11,087.8 | 16.82 | 1.52 | 15 | 7 |
| 14 | 40.5495 | 1570.6 | 13.031 | 12,909.2 | 11.19 | 2.22 | 15 | 1 |
| 15 | 24.3774 | 1136.5 | 15.078 | 11,165.1 | 18.49 | 5.14 | | 8 |

area. Moreover, the geographical watershed shape is the same and can be described as elongated elliptical catchment shape (Fig. 1).

The longest distance between upper and lower point from east to west for Daraja is 29 km and that of its width from south to north is 12 km. The longest distance between upper and lower point from the east to the west of Al-Ghar is 35 km and that of its width from south to north is 13 km.

The impervious percentage, CN, time of concentration, lag time and storage coefficient for both catchments were calculated as described in methodology section or estimated

through trial–error method during calibration. Tables 4 and 5 show the final values of all these parameters used for the calibration and validation of HEC-HMS model in both catchments. Values for time of concentration, storage coefficient, and lag time were incorporated sub-basin wise (Table 4) while other parameters' values were used catchment wise (Table 5).

The values of CN and imperviousness percent were extracted from GeoMOLG, GIS, and Hydrology Soil Group (HSG) for soils of arid region and the mathematical formulas mentioned in methodology. CN (related to land use and

Fig. 3 Map showing soil types of both catchments, Al-Ghar and Daraja. Soil type data was obtained from Ministry of Local Government (MOLG) in Palestine (GeoMOLG 2019)

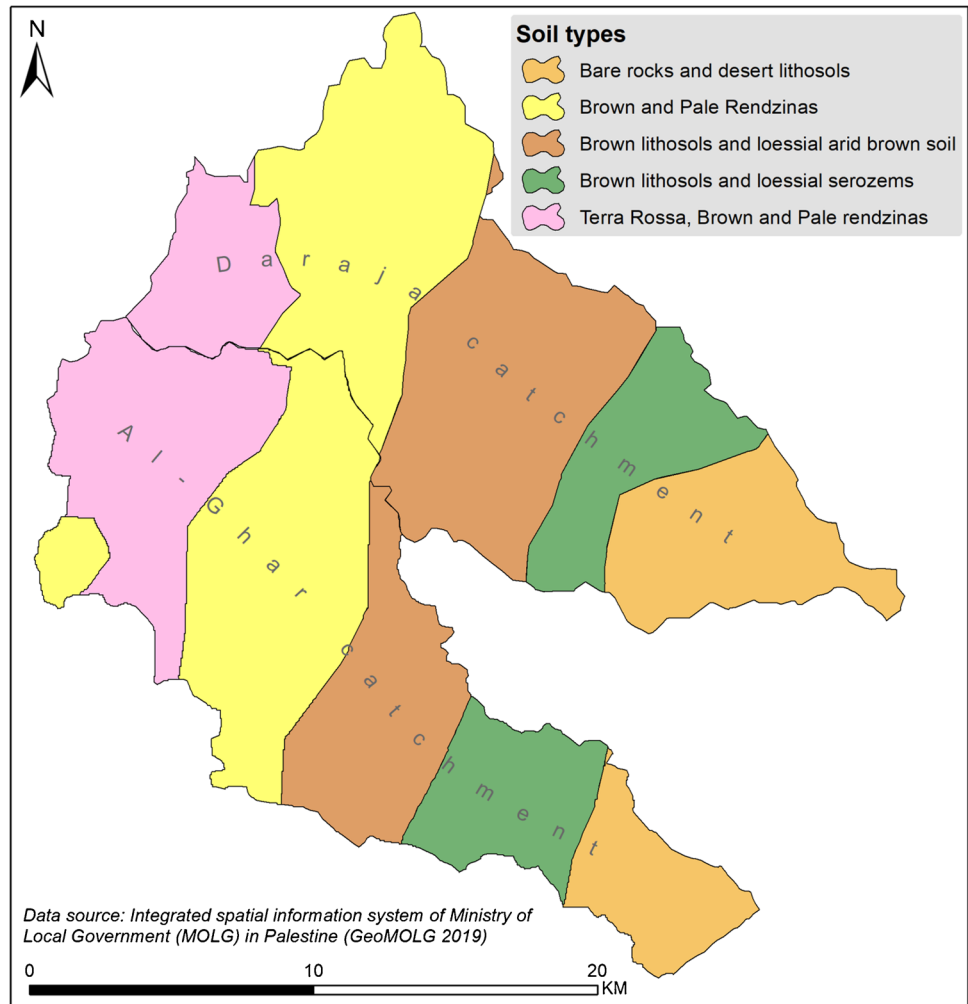


Table 4 Time of concentration, storage coefficient and lag time values for each sub-basin of Al-Ghar and Daraja catchments used during calibration and validation of HEC-HMS model

| Sub-basin number | Time of concentration, T_c (h) | | Storage coefficient, R (h) | | Lag time, $Lag_{(t)}$ (h) | |
|------------------|----------------------------------|--------|------------------------------|--------|---------------------------|--------|
| | Al-Ghar | Daraja | Al-Ghar | Daraja | Al-Ghar | Daraja |
| 1 | 0.38 | 0.99 | 0.26 | 0.88 | 0.23 | 0.59 |
| 2 | 0.62 | 0.39 | 0.43 | 0.28 | 0.37 | 0.23 |
| 3 | 0.38 | 0.35 | 0.26 | 0.26 | 0.33 | 0.21 |
| 4 | 1.5 | 0.26 | 0.96 | 0.2 | 0.9 | 0.16 |
| 5 | 0.47 | 0.11 | 0.33 | 0.08 | 0.28 | 0.06 |
| 6 | 0.94 | 0.16 | 0.74 | 0.11 | 0.56 | 0.09 |
| 7 | 0.5 | 0.52 | 0.36 | 0.41 | 0.3 | 0.31 |
| 8 | 2.1 | 0.05 | 1.8 | 0.03 | 1.26 | 0.03 |
| 9 | 1.34 | 0.44 | 1.2 | 0.35 | 0.8 | 0.26 |
| 10 | 0.57 | 0.8 | 0.43 | 0.64 | 0.34 | 0.48 |
| 11 | 2.37 | 2.3 | 3.4 | 1.8 | 1.42 | 1.38 |
| 12 | 0.22 | 0.56 | 0.16 | 0.43 | 0.13 | 0.33 |
| 13 | 0.8 | 1 | 0.65 | 0.84 | 0.48 | 0.6 |
| 14 | 2.12 | | 2.21 | | 1.27 | |
| 15 | 1.33 | | 1.28 | | 0.79 | |

Table 5 Catchment wise parameters' values used for calibration and validation of HEC-HMS in both catchments of the study area

| Catchment | Curve number (CN) | Impervious area % | Ratio to peak | Recession | Hillslope Manning (n) | Channel Manning (n) |
|-----------|-------------------|-------------------|---------------|-----------|-----------------------|---------------------|
| Daraja | 67 | 14.0 | 0.1 | 0.8 | 0.1 | 0.035 |
| Al-Ghar | 67 | 12.33 | 0.1 | 0.8 | 0.1 | 0.035 |

Table 6 Estimation of CN and impervious area percent during trial-error method to simulate peak discharge and flood volume for both catchments

| Trial | CN | Impervious area (%) | Simulated peak discharge (m ³ /s) | Simulated flood volume (m ³) | Flood volume difference (%) |
|---|-----------|---------------------|--|--|-----------------------------|
| Al-Ghar catchment (Event: 31 December 1991) | | | | | |
| Observed peak discharge = 25 m ³ /s, Observed flood volume = 1344836.35 m ³ | | | | | |
| 1 | 75 | 12.33 | 38.5 | 3,125,900 | 132.4 |
| 2 | 73 | 9 | 27.7 | 2,390,098 | 77.7 |
| 3 | 67 | 12.33 | 22.5 | 1,916,900 | 42.5 |
| 4 | 67 | 9 | 19.4 | 1,695,120 | 26 |
| 5 | 65 | 12.33 | 17.8 | 1,873,640 | 39.3 |
| Daraja catchment (Event: 28 October 2004) | | | | | |
| Observed peak discharge = 3.6 m ³ /s, Observed flood volume = 28016.77 m ³ | | | | | |
| 1 | 65 | 9 | 2.2 | 15,500 | 44.7 |
| 2 | 67 | 9 | 2.3 | 15,500 | 44.7 |
| 3 | 67 | 14 | 3.2 | 22,900 | 18.3 |
| 4 | 73 | 12 | 3 | 20,100 | 28.3 |
| 5 | 75 | 13 | 3.1 | 22,210 | 20.7 |

land cover) and impervious area (depends on urbanization) values were then modified by using the trial-error method during calibration process to achieve the best simulation results. The estimated optimum CN value for both catchments Daraja and Al-Ghar was 67. This value was slightly different than GeoMOLG database but very close to the values estimated for the same region by Shaded and Almasri (2010). Imperviousness percent was 12.33% and 14% for the Al-Ghar and Daraja catchments, respectively, which is similar to the values presented in GeoMOLG for the study area. Table 6 shows few of many trials that have been carried out during calibration process to find the optimum values of CN and impervious area percentage for the event of 31 December 1991 in Al-Ghar catchment and 28 October 2004 in Daraja catchment. Efficiency of these trials was estimated using difference in peak discharge and flood water volume percentages on the said events (Table 6).

Calibration of the HEC-HMS model to simulate rainfall-runoff from the study area

The calibration process is an essential stage to confirm the suitability of the parametric values to simulate the flow as efficiently as possible by the hydrological models. The

Table 7 Accuracy of the HEC-HMS model during calibration period to simulate five rainfall-runoff events (events 1 to 5) each from Al-Ghar and Daraja catchments

| Event # | Event date | Peak discharge (m ³ /s) | | | Flood volume (m ³) | | |
|----------------------|------------|------------------------------------|-----------|--------------|--------------------------------|-----------|--------------|
| | | Observed | Simulated | Accuracy (%) | Observed | Simulated | Accuracy (%) |
| Al-Ghar catchment | | | | | | | |
| 1 | 31/12/1991 | 25 | 22.5 | 90 | 1,344,836.4 | 1,916,900 | 70.15 |
| 2 | 5/11/1994 | 54.2 | 40.43 | 74.6 | 874,721.1 | 599,700 | 68.5 |
| 3 | 24/3/1996 | 6.75 | 11.1 | 60.8 | 309,367.5 | 229,100 | 74.1 |
| 4 | 17/11/1996 | 7 | 5.7 | 81.4 | 214,821.6 | 228,100 | 94.2 |
| 5 | 18/3/1997 | 10.5 | 12.2 | 86.1 | 311,600.4 | 223,400 | 71.7 |
| Average accuracy (%) | | | | 78.58 | Average accuracy (%) | | 75.73 |
| Daraja catchment | | | | | | | |
| 1 | 31/12/1991 | 0.65 | 1.0 | 65 | 15,900.7 | 18,700 | 85 |
| 2 | 6/3/1996 | 4.3 | 4.7 | 91.5 | 77,398.94 | 120,700 | 64.1 |
| 3 | 22/1/1997 | 2.35 | 4.1 | 57.3 | 95,310 | 78,100 | 81.9 |
| 4 | 28/10/2004 | 3.6 | 3.2 | 88.9 | 28,016.77 | 22,900 | 81.7 |
| 5 | 1/4/2006 | 4.48 | 6.2 | 72.9 | 33,868.33 | 50,300 | 67.3 |
| Average accuracy (%) | | | | 75.12 | Average accuracy (%) | | 76 |

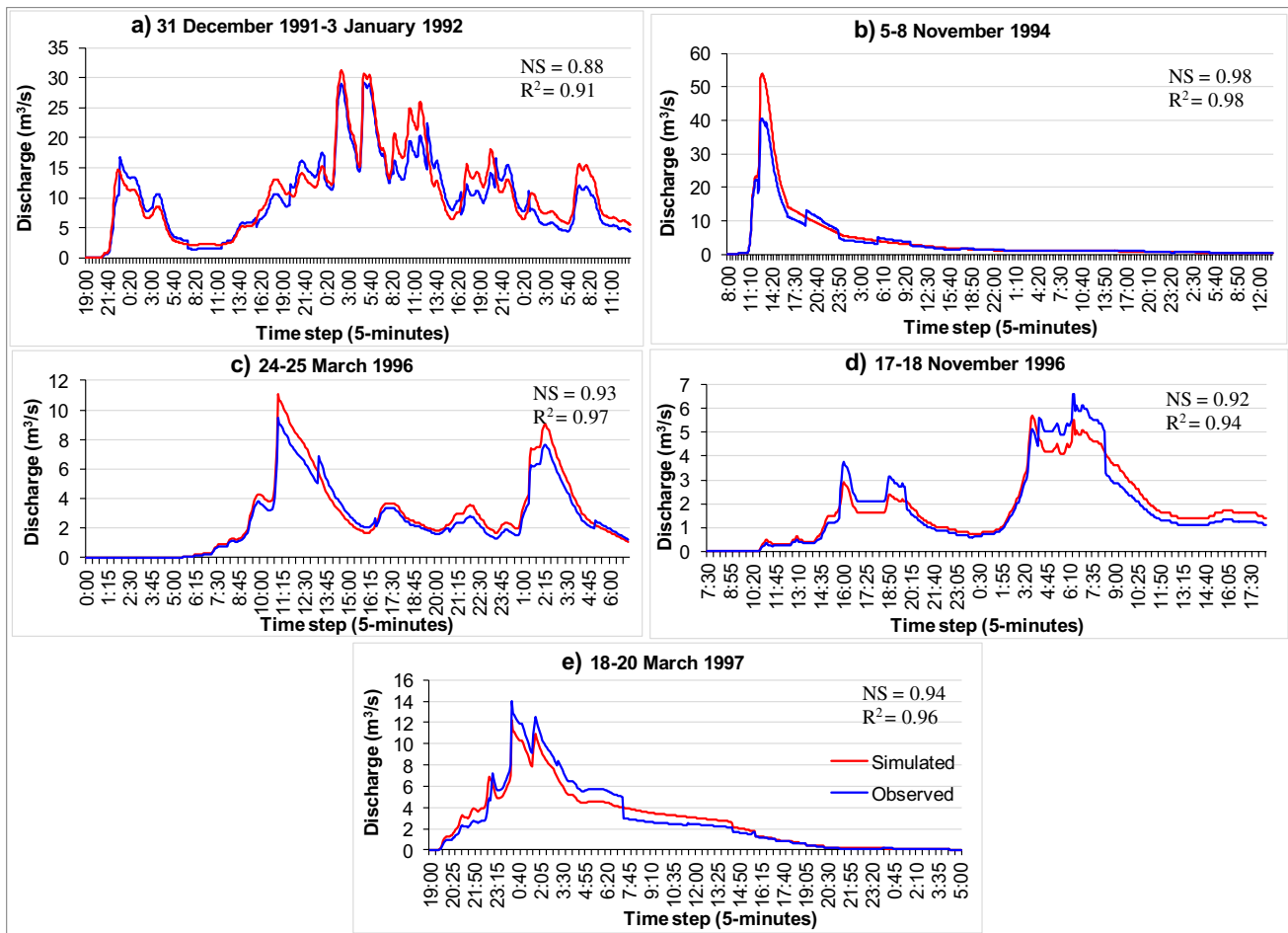


Fig. 4 Simulation of rainfall–runoff events of Al-Ghar catchment using HEC-HMS model during calibration period. Efficiency of model is presented in terms of NS and R^2 value

parameters and characteristics that were derived from previously mentioned techniques or obtained from different sources were essential input data to simulate the flows from the HEC-HMS model. The model parameters were modified in successive calibrated process till the simulated and measured flow correlated with good efficiency. These parametric values were presented in Tables 4 and 5. Results for the calibration of HEC-HMS model to simulate the peak flow and total flood volume for five rainfall–runoff events (events 1 to 5) out of total 10 events from Al-Ghar and Daraja catchments are presented in Table 7 (in terms of percent accuracy of simulated flow) and Figs. 4 and 5 (in terms of NS and R^2 values). These coefficients together determine the efficiency of model to simulate various characteristics of hydrograph such as total flood volume, peak discharge, and timing of peaks.

Highest accuracy to simulate peak discharge of Al-Ghar catchment during calibration period was on event#1 followed by events#5, 4, 2, and 3, respectively (Table 7). Accuracy of simulating peak discharges was not less

than ~61% for all events in this catchment. Highest accuracy to simulate peak discharge in this catchment was found as 90% for the event#1. In terms of flood volume accuracy, highest value was achieved by the model for event#4 followed by the events#3, 5, 1, and 2, respectively. Volume was over-estimated by the model in events#1 and 3 while under-estimated in events#2, 4, and 5 during calibration period in Al-Ghar catchment. Minimum and maximum accuracy for flood volume simulation was found as 68.5% and 94.2% for events#2 and 4, respectively. Average accuracy for entire calibration period was found as ~79% for peak discharge and ~76% for flood volume simulation. Figure 4 represents the observed and simulated hydrographs for the Al-Ghar catchment. It was evident that the model has simulated the low flows, peak discharges, as well as timing of peaks with a good efficiency. Statistical analysis showed that NS coefficient and R^2 values were 0.88–0.98 and 0.91–0.98, respectively, for all the five events during calibration period. Highest NS and R^2 values were found for event#2 (Fig. 4). Average efficiency

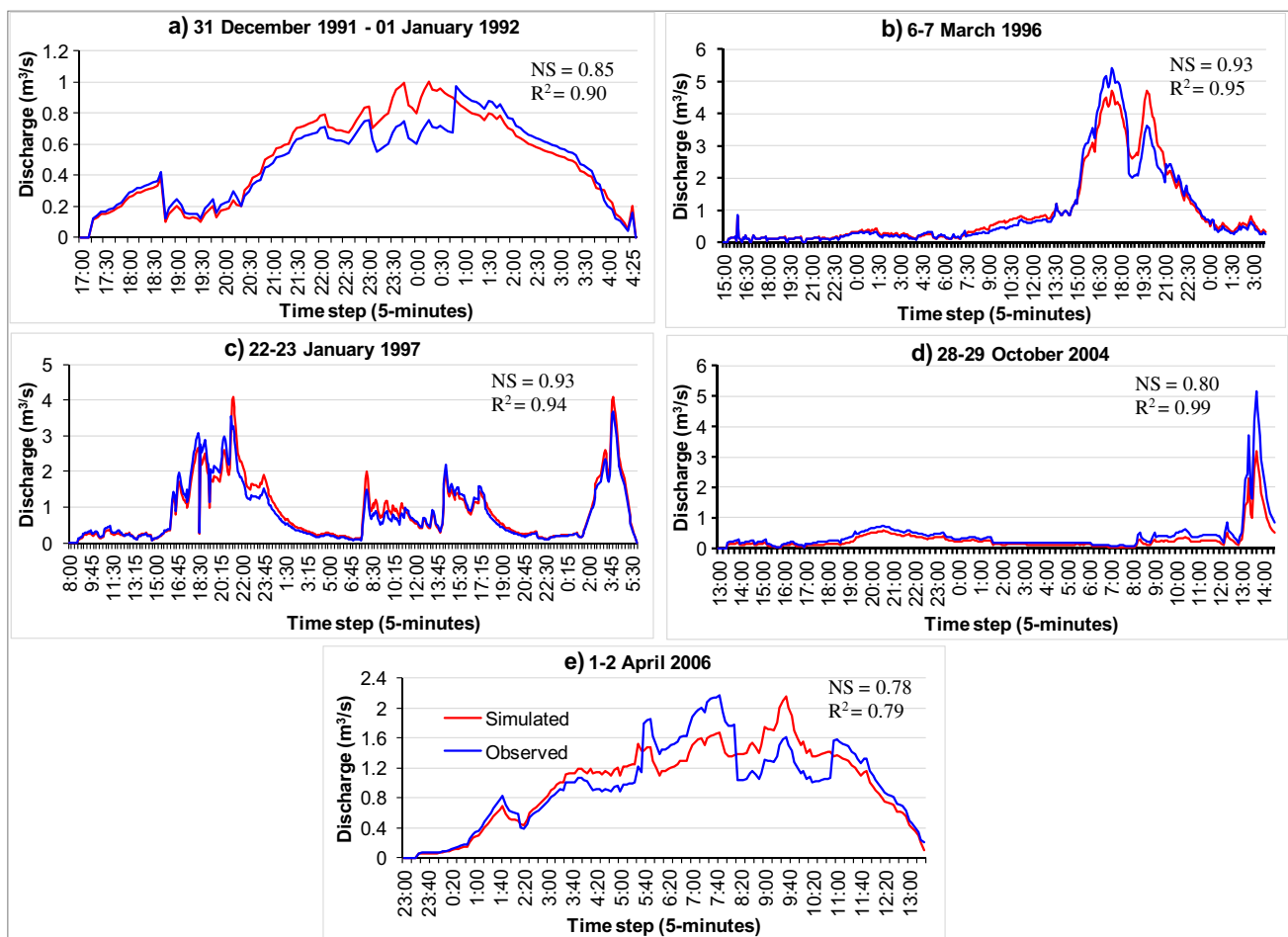


Fig. 5 Simulation of rainfall–runoff events of Daraja catchment using HEC-HMS model during calibration period. Efficiency of model is presented in terms of NS and R^2 value

of the model for entire calibration period in Al-Ghar catchment was found as ~ 0.93 and ~ 0.95 in terms of NS and R^2 values, respectively.

For Daraja catchment, the highest accuracy to simulate peak discharge during calibration period was on event#2 followed by events#4, 5, 1, and 3, respectively (Table 7). Accuracy of simulating peak discharges was not less than $\sim 57\%$ (event 3) in this catchment. Highest accuracy to simulate peak discharge in this catchment was found as 91.5% for the event#2. In terms of flood volume accuracy, highest value was achieved by the model for event#1 followed by the events#3, 4, 5, and 2, respectively. Volume was over-estimated by the model in events#1, 2, and 5 while under-estimated in rest of two events during calibration period in Daraja catchment. Minimum and maximum accuracy for flood volume simulation was found as 64.1% and 85% for events#2 and 1, respectively. Average accuracy for entire calibration period was found as $\sim 75\%$ for peak discharge and 76% for flood volume simulation.

Figure 5 represents the observed and simulated hydrographs for the Daraja catchment. Model has simulated the low flows, peak discharges as well as timing of peaks with a good efficiency in this catchment as well like in Al-Ghar. Statistical analysis showed that NS coefficient and R^2 values were 0.78–0.93 and 0.79–0.99, respectively, for all the five events during calibration period. Highest NS and R^2 values were found for event#2 and 4, respectively (Fig. 5). Average efficiency of the model for entire calibration period in Daraja catchment was found as ~ 0.86 and ~ 0.91 in terms of NS and R^2 values, respectively.

Statistical tests in terms of percent accuracy, NS coefficient, and R^2 values indicated that the model's performance to simulate the rainfall–runoff events (events 1 to 5) during the calibration period in both catchments was satisfactory. This calibrated model was then applied on rest of five rainfall–runoff events (events 6 to 10) in both catchments to validate the parameter values and model's efficiency.

Table 8 Accuracy of the HEC-HMS model during validation to simulate five rainfall-runoff events (events 6 to 10) each from Al-Ghar and Daraja catchments

| Event # | Event date | Peak discharge (m ³ /s) | | | Flood volume (m ³) | | | |
|--------------------------|------------|------------------------------------|-----------|--------------|--------------------------------|----------------------|--------------|-------|
| | | Observed | Simulated | Accuracy (%) | Observed | Simulated | Accuracy (%) | |
| Al-Ghar catchment | | | | | | | | |
| 6 | 19/12/1997 | 6.25 | 7.8 | 80.1 | 3,295,562.3 | 3,212,000 | 97.4 | |
| 7 | 14/2/1998 | 4.4 | 3.6 | 81.8 | 115,372.2 | 69,200 | 60 | |
| 8 | 7/2/2001 | 7.25 | 8.0 | 90.6 | 193,716.6 | 110,700 | 57.4 | |
| 9 | 23/3/2001 | 7.25 | 8.1 | 89.5 | 157,281.9 | 115,500 | 73.4 | |
| 10 | 2/5/2001 | 418.1 | 455.6 | 91.8 | 3,626,338.2 | 5,804,900 | 62.5 | |
| Average accuracy (%) | | | 86.8 | | | Average accuracy (%) | | 70.14 |
| Daraja catchment | | | | | | | | |
| 6 | 5/11/1994 | 4.52 | 6.2 | 72.9 | 165,792.24 | 153,400 | 92.52 | |
| 7 | 1/11/1995 | 12.36 | 10.86 | 87.86 | 148,250.72 | 196,300 | 75.5 | |
| 8 | 9/1/2000 | 8.18 | 6.03 | 73.72 | 60,674.97 | 38,500 | 63.5 | |
| 9 | 24/1/2001 | 5.4 | 4.93 | 91.30 | 467,412.3 | 285,800 | 61.1 | |
| 10 | 29/1/2008 | 0.62 | 0.56 | 90.32 | 15,162.24 | 23,200 | 65.4 | |
| Average accuracy (%) | | | 83.22 | | | Average accuracy (%) | | 71.6 |

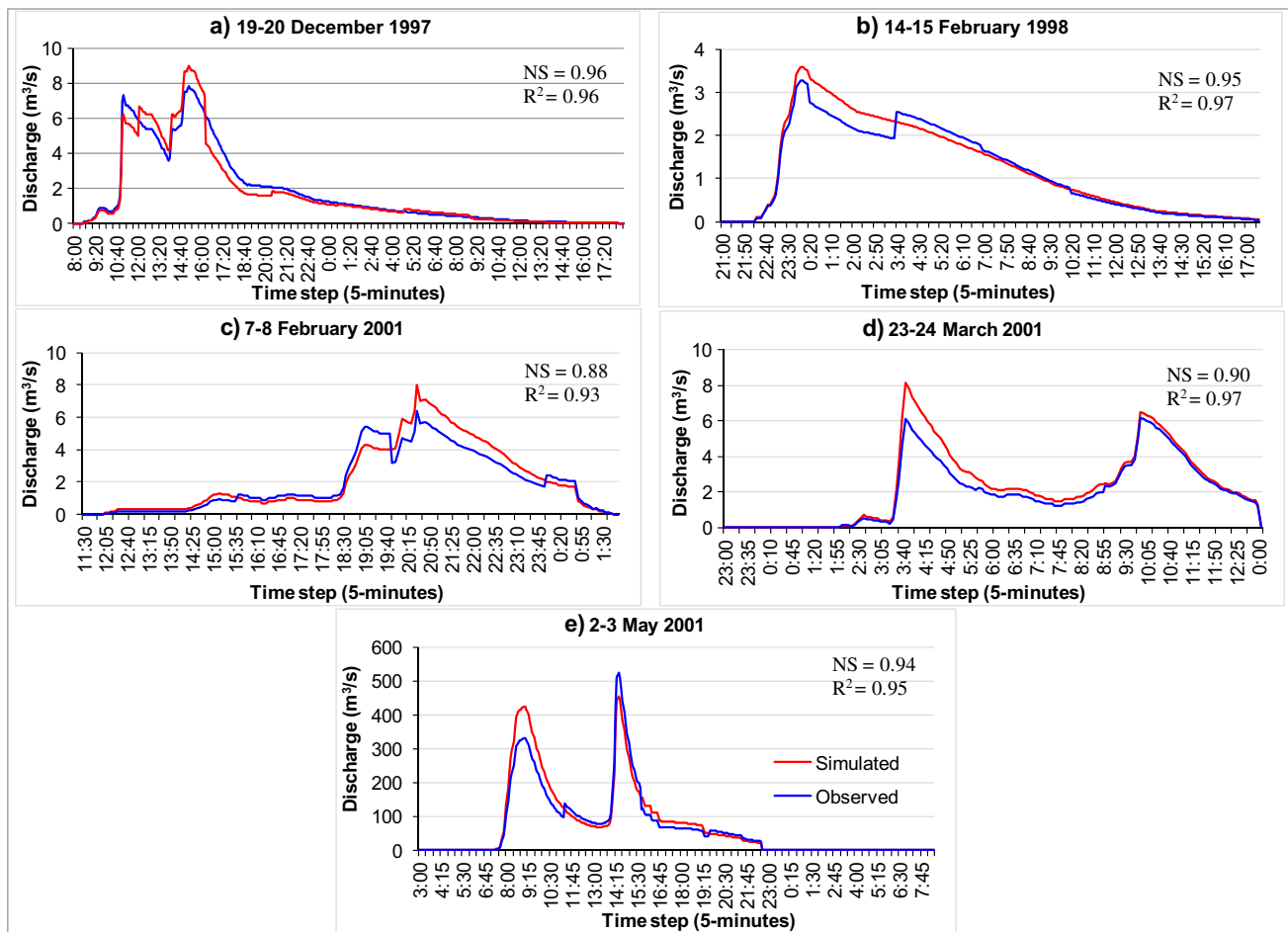


Fig. 6 Simulation of rainfall-runoff events of Al-Ghar catchment using HEC-HMS model during validation period. Efficiency of model is presented in terms of NS and R² value

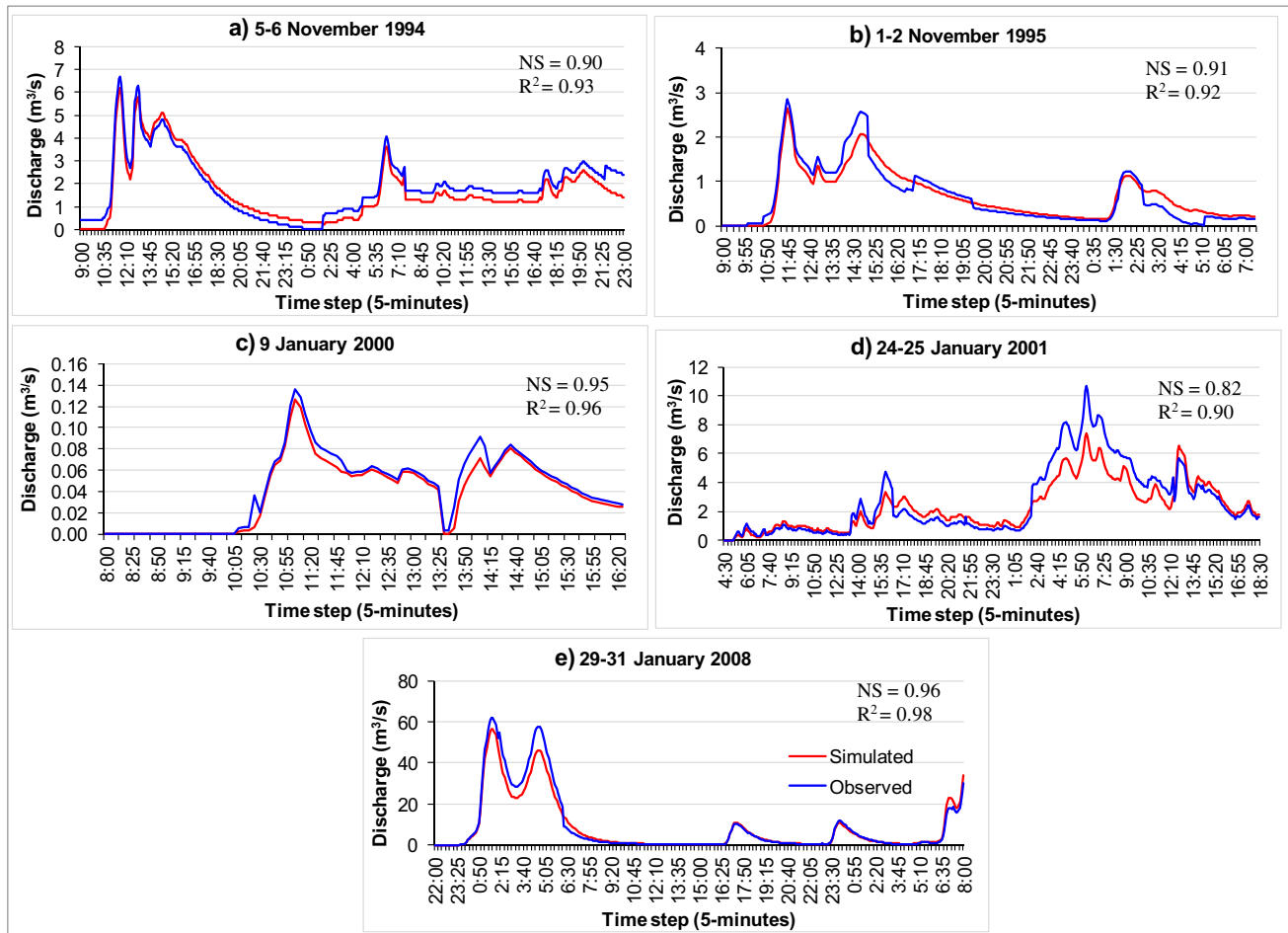


Fig. 7 Simulation of rainfall-runoff events of Daraja catchment using HEC-HMS model during validation period. Efficiency of model is presented in terms of NS and R^2 value

Validation of the HEC-HMS model to simulate rainfall-runoff from the study area

Results of HEC-HMS model to simulate the peak flow and total flood volume for five rainfall-runoff events (events 6 to 10) for the validation period from Al-Ghar and Daraja catchments are presented in Table 8 (in terms of percent accuracy of simulated flow) and Figs. 6 and 7 (in terms of NS and R^2 values).

Table 8 shows the accuracy with date of events used for the validation of HEC-HMS model for both catchments. The calculated hydrograph is one of the main HEC-HMS model results which is resulted from input radar rainfall data time series for certain event, while the observed hydrograph was obtained from measured water flow at outlet. Both rainfall and water flow were measured at 5 min time step. Many researchers have suggested that the time period of input data should be as short as possible so that there is greater accuracy in the data that feeds the model

(Thakur et al. 2017; Abushandi 2016); therefore, 5-min interval was chosen in this research.

Highest accuracy to simulate peak discharge of Al-Ghar catchment during validation period was on event# 10 followed by events#8, 9, 7, and 6, respectively (Table 8). Accuracy of simulating peak discharges was not less than ~80% in this catchment. Highest accuracy to simulate peak discharge in this catchment was found as ~92% for the event#10. In terms of flood volume accuracy, highest value was achieved by the model for event#6 followed by the events#9, 10, 7, and 8, respectively. Flood volume was over-estimated by the model in event#10 while under-estimated in rest of the events during validation period in Al-Ghar catchment. Minimum and maximum accuracy for flood volume simulation was found as ~57% and ~97% for events#8 and 6, respectively. Average accuracy for entire validation period was found as ~87% and ~70% for peak discharge and flood volume simulation, respectively. Figure 6 represents the observed and simulated hydrographs for the Al-Ghar

catchment. It was indicated that the model has simulated the low flows, peak discharges as well as timing of peaks with a good efficiency. Highest peaks were slightly over-estimated by the model in almost all the events. Statistical analysis showed that NS coefficient and R^2 values were 0.88–0.96 and 0.93–0.97, respectively, for all the five events during validation period. Highest NS (event#6) and R^2 (events#7 and 9) values were found as 0.96 and 0.97, respectively (Fig. 6). Average efficiency of the model for entire validation period was found as ~0.93 and ~0.96 in terms of NS and R^2 values, respectively.

Highest accuracy to simulate peak discharge of Daraja catchment during validation period was on event#9 followed by events#10, 7, 8, and 6, respectively (Table 8). Accuracy of simulating peak discharges was not less than ~72% in this catchment. Highest accuracy to simulate peak discharge in this catchment was found as ~91% for the event#9. In terms of flood volume accuracy, highest value was achieved by the model for event#6 followed by the events#7, 10, 8 and 9, respectively. Flood volume was over-estimated by the model in events#7 and 10 while under-estimated in rest of the events during validation period in Daraja catchment. Minimum and maximum accuracy for flood volume simulation was found as ~61% and ~93% for events#9 and 6, respectively. Average accuracy for entire validation period was found as ~83% and ~72% for peak discharge and flood volume simulation, respectively. Figure 7 represents the observed and simulated hydrographs for the Daraja catchment. It was indicated that the model has simulated the low flows, peak discharges as well as timing of peaks with a good efficiency. Model detected and estimated all the peaks in flow events with very good efficiency except in event#9 where highest peaks were slightly under-estimated (Fig. 7). Statistical analysis showed that NS coefficient and R^2 values were 0.82–0.96 and 0.90–0.98, respectively, for all the five events during validation period. Highest NS and R^2 values were found as 0.96 and 0.98, respectively, for event#10 (Fig. 7). Average efficiency of the model for entire validation period was found as ~0.91 and ~0.94 in terms of NS and R^2 values, respectively.

An average accuracy on entire data period containing ten flow events was ~83% and ~73% for the peak discharge and flood volume, respectively, for the Al-Ghar catchment and this value was ~79% and ~74% for the Daraja catchment. NS coefficient and R^2 values were 0.93 and 0.95, respectively, over entire data period of ten events for the Al-Ghar catchment. These values were 0.88 and 0.93, respectively, for the Daraja catchment. These statistics showed that the HEC-HMS model simulated the peak discharges, flood volume and timing of peaks with good efficiency and indicated its capability to forecast the floods at short time steps like the ones used in this study. This model proved to be reliable with calibrated parameters to simulate the flows from the studied

region. It can further be explored to assess the flood prone areas if furnished with modeled rainfall events under climate change scenarios.

Discussion

Accuracy of simulations may be attributed to several factors but mainly to the rainfall data quality, the curve number approximation and impervious percentage calculations. In the validation stage, 60% of the events occurred in the first decade of the twenty-first century. Results indicated that the average accuracy percent to simulate peak discharges during validation stage of HEC-HMS application in both catchments was higher than those in calibration stage. This can be explained through the change in land use and land cover, which consequently affected the soil structure and texture, topography, and geology of the sub-basins and the sub-stream channels. These variations in land use land cover tend to change the value of the CN and imperviousness percent parameters, and thus the surface runoff simulation in the region (Abushandi and Merkel 2013). Moreover, every sub-basin should be considered an independent unit (distributed modeling approach) with its own CN and impervious percent.

In the current application of the model, it dealt with most parameters by taking their values catchment wise rather than sub-basin wise. The study area was characterized with its heterogeneity in elevation leading to the difference in climatic conditions within the catchment areas. Rainfall data was collected and listed regarding to sub-basins of each catchment. Most of the rainfall events generating the surface runoff in the study area belong to convective rainfall clouds, which were characterized by heavy rainfall with short duration and unevenly distributed (spotty) among the same catchment (Belachsen et al. 2017) and some of them created floods. Therefore, some sub-basins have about zero value of rainfall data for the same event, while others have higher rainfall volumes. The location distributions of each sub-basin affected the model hydrograph shape and calculated results by increasing or decreasing the values related to active or inactive sub-basin's participation in runoff formation in the hydrological system of the catchment. Also, both catchments contained temporary ponds and swamps, but with less percentage in Al-Ghar compared to Daraja. These small water bodies in some sub-basins affected the flood water volume, velocity and depth in stream channels. Accumulated water in these temporary ponds did not contribute to the total running water towards the main channel feeding the catchment outlet. This water is considered missing from the total surface runoff and delayed the time of water flow in stream channels. The water accumulation process required much more time and it was subjected to evaporation or seepage into the groundwater in the region.

These processing often reduced the total amount of water flowing and negatively affected the model results. For these mentioned reasons, the time of concentration, storage coefficients and lag time values were taken sub-basin wise for the runoff simulation to adjust the model results by some extent.

After studying the hydrograph shapes derived by the HEC-HMS model for the events, most of them can be categorized as major single or double peak discharges because the majority of surface area was paved, compact, and rocky preventing percolation and promoting more runoff. The outcome was high peak discharge and short lag time. To discuss this result of hydrograph, one event from each catchment was taken as example. Event#10 (Table 8) from both catchments occurred on 2 May 2001 in Al-Ghar catchment (Fig. 6) and on 29 January 2008 in Daraja catchment (Fig. 7). Both of these events were high flow events and included in validation period of model simulations.

First, the hydrograph of flow event in Daraja occurred on 29 January 2008 (Fig. 7) offers many characteristics to be studied. This event can be described as heavy, sudden bursts of rainfalls, which guided to steep increasing limbs of hydrograph and short lag times (Table 4) (Shamir et al. 2013; Yair and Kossovsky 2002), because water is not given enough time to percolate thoroughly which can also be explained due to the rocky watershed nature and steep hilly topography that enhanced water running to accumulation quickly to generate surface runoff. It was noticed that there were two major successive peaks with other minor peaks. In addition to the rainfall event nature which started suddenly with two successive high intensity showers over the sub-basins close to the outlet produced short time of concentration. From the hydrograph, it can be seen that the peak time for the observed and simulated flow on 29 January 2008 was very close to each other at 01:35 AM. Flow started to rise at 12:20AM, and it reached the peak after one hour and fifteen minutes approximately.

Second, the flow event for Al-Ghar occurred on 2 May 2001, was characterized with high peak discharge and huge flow volume comparatively to other flow events (Fig. 6) hitting the area. Event seems hundred times higher in magnitude than average rainfall-runoff events in terms of discharge presented in Fig. 6. First peak of flow appeared at approximately 9:00 AM and the second peak occurred on approximately 14:25 PM. This event had two major peak discharges. This represents primarily high rainfall intensities with heavy spotty showers, which characterized flash runoff (Yair and Kossovsky 2002; Frostick and Reid 1979).

In both events of Daraja and Al-Ghar, high flows were efficiently simulated by the model in terms of timing to reach the peak however first peak was slightly over-estimated in terms of discharge value in Al-Ghar while low flows were slightly under-estimated in Daraja. In all other flood events, presented in calibration and validation graphs, model has

successfully simulated the flows (in terms of peak flows and their timings) with exception of few peaks where there was difference of few minutes time between observed and simulated peaks. Therefore, it can be safely argued that the HEC-HMS model has ability to predict the peak discharge and the time of peak with a good efficiency. Moreover, the technique could be recommended as an early warning system of potential flood risk hazards by coupling it with reliable ground and satellite data as reported by Agarwal et al. (2020) and Hamidon et al. (2020).

Both catchments are characterized by surface runoff which is highest and fast on steep rocky slopes because infiltration is reduced, therefore water reaches the stream channels fast (short lag time) and discharge is higher (Shamir et al. 2013; Yair and Kossovsky 2002). Both of catchments have high elevated sub-basins in upstream areas and results in high runoff rates which shorten the lag time values. The study area was characterized by flooding phenomena. Li et al. (2019) reported that region including Palestine will be under the risk of flash floods formation that have been more frequent and extreme as a result of climate change and pose a danger to society, especially in the ungauged catchments. The climate change has affected the precipitation characteristics and transformed in extreme runoff and sometimes flood generation resulting (Karamouz et al. 2009). For minimizing the effects of floods, it is required to forecast precisely extreme runoff and its behavior in the study area on short time steps. Some examples of these types of forecasting mechanisms are being used effectively in various regions such as in Myanmar as reported by Agarwal et al. (2020) and in Malaysia reported by Hamidon et al. (2020). The results of this study are in agreement with the findings of other researchers who used the model for similar climatic and hydrological conditions (Thakur et al. 2017; Abushandi 2016; El Alfy 2016).

Conclusions

This study was carried out to simulate the selected rainfall-runoff events spread over two decades from the Al-Ghar and Daraja catchments of Palestine. HEC-HMS model was used as a tool to compute the hydrographs of the study area by using the input data from various sources. Different parameters were calibrated catchment-wise and sub-basin wise before the model was validated. It can be concluded from the results that:

- Curve number and impervious percent are two parameters that highly effected the HEC-HMS model calibration.
- In un-gauged or data-scarce watersheds, HEC-HMS can be coupled with remote sensing datasets such as land use

land cover and radar rainfall data to compute the runoff efficiently over shorter time steps.

- HEC-HMS model was effective in imitating the runoff hydrographs for both catchments. Model showed a good efficiency for simulating the flood volume, peak discharges and overall hydrographs in nearly all flow events in both catchments. Statistical coefficients such as Nash–Sutcliffe coefficient and R^2 values showed a reliable performance of HEC-HMS model to simulate the rainfall-runoff from both catchments for almost all the events.

This study may be further expanded to forecast the future high flow events by furnishing the HEC-HMS model with the projected future rainfall data such as that by Alpert et al. (2002). HEC-HMS model calibrated in this study may be used to simulate the flood events in similar environments if input datasets are available. Hence, the extreme rainfall events that may generate huge runoff or even floods may be predicted and transformed into beneficial use and water resources management.

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Data availability The data that support the findings of this study are available on request from the corresponding author, AAT. Some of the data are not publicly available due to restrictions by the data providing agency.

Declarations

Conflict of interest The authors declare no competing interests.

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