Application of Rainfall Runoff Distributed Model Using HEC-HMS for Al-Faria Catchment, West Bank, Palestine

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Abstract

The arid and semi-arid regions, such as the West Bank, have its own properties in the hydrological processes as a response to rainfall. Extreme rainfall events and accompanied floods have higher probability in these regions compared to other regions. So, the floods occurrence has become more predictable and the risk of these floods has increased. As such, the importance of rainfall-runoff modeling becomes more challenging in such regions not only to predict the catchment response to these extreme rainfall events but also to be able to produce a more reliable infrastructure designs. This in turn will facilitate the development of proper mitigation measures to reduce its impacts on the surrounding environment.

This study aims to model rainfall-runoff response in Al-Faria catchment, which is located in the northeastern part of the West Bank with a total area of about 320 km^2 and drains into the Jordan River. The HEC-HMS was used to simulate the rainfall-runoff response in the catchment based on single events. The GIS tools were utilized to prepare some gridded input data (e.g. land use, soil) whereas, MS excel was used to prepare some time series data (e.g. rainfall, runoff). Model performance was evaluated based on two major rainfall events. The storm of February (8-9), 2006 was used to calibrate the model while the storm of February (4-8), 2005 was used for model validation.

The observed flow data from the runoff flumes in the upper part of the catchment were used to calibrate and validate the model. The model performance was tested statistically using both the *root mean square error* (RMSE) and the Nash-*Sutcliffe efficiency* (NSE). Results showed that the model was quite good in simulating the single rainfall event response and thus it can be used for further modeling of single rainfall event in the Faria catchment specifically and in the West Bank catchments generally.

Keywords: Semi-arid regions, Rainfall Runoff Model, Al-Faria catchment, and Surface runoff.

I. INTRODUCTION (*HEADING 1*)

Rainfall runoff modeling has been used as one of the environmental and urban supporting prediction, planning and management tools [1], [22], [23] and [20]. The rainfall runoff models are used as tools for determining the catchment response due to rainfall [4] and [7]. These models are used for different purposes that might be complex or simple ones [18] and [6]. As an example of the simple purposes, in case of floods, it can be used for the quantification of a flood in addition to the time and location determination of that flood. The model selection process should depend on the modeling objective and the modeled catchment itself [4]. In general, the simplest model that is capable to achieve the needed purposes should be chosen [21] and [12]. HEC-HMS (Hydrologic Engineering Center – Hydrologic Modeling System) model was developed by the US Army Corps of Engineers [3] and it can be used for many hydrological simulations. The HEC-HMS consists of four main components. Those are: 1) The analytical model that calculates the channel routing in addition to the overland flow, 2) storing and managing data system for time series data sets and large ones, 3) friendly graphical user interface that illustrates the system components with interactive features, and 4) a means for displaying and reporting model results [2].

In this study, the model is calibrated and validated for the Faria catchment with respect to the local observed stream-flow measurements. So, the model has some degree of greater confidence in its reliability [9].

An assortment of different loss methods are available in HEC-HMS, some are suitable for continuous simulations such as The one-layer deficit constant method and the others are intended for the event based ones like initial constant, SCS curve number and exponential loss method. In this study, the SCS curve number method was selected to simulate the excess rainfall and losses. Seven different transformation methods are also available in HEC-HMS, some of them are complicated because it needs a lot of input parameters and some are simpler. In our case, the dimensionless SCS unit hydrograph method was chosen to transform the excess rainfall to runoff. Moreover, among the six routing methods available in the software, Muskingum method was used in our hydrologic model. A brief description about the model is described in the model application and calibration sections below.

II. METHODOLOGY

A. Study Area

Al-Faria catchment, which is located in the eastern part of the West Bank, Palestine, was selected for this study. The catchment area is about 320 km^2 starting from Nablus Mountains in the Northwestern part and drains its water to Jordan River to the West of the West Bank. The regional location of Al-Faria catchment is shown in Regional location map of Al-Faria catchment Figure 1 below. Considering the catchment topography, it changes significantly throughout the catchment from about 900 meters above the mean sea level in the north western part of the catchment to about 350 meters below the mean sea level in the south eastern part. For the land use of the catchment, it can be generally divided into several parts, including: built-up areas, natural forests, agricultural areas, natural grassy hill slopes, olive plantations, and scattered olive plantations. The rainfall distribution within Al-Faria catchment ranges from about 640mm in the headwater to 150mm at the outlet in proximity to the Jordan River.

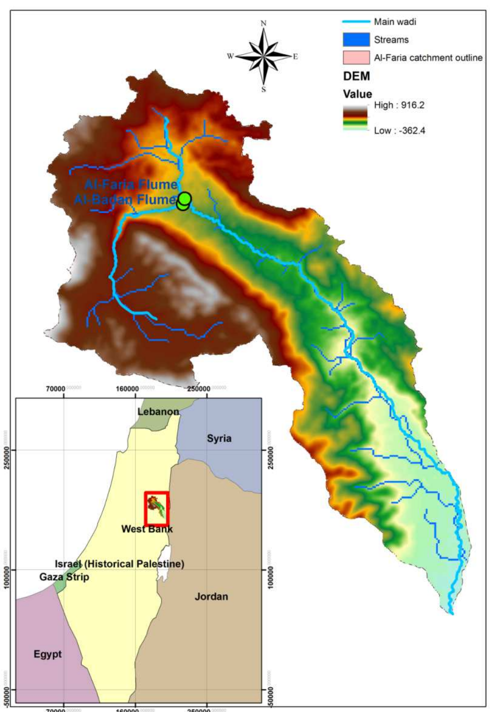

Figure 2: Regional location map of Al-Faria catchment

B. Data Collection

a) Rainfall Data

The rainfall data were collected from seven rainfall stations, four of them are tipping buckets and others are daily gauges. Another seven stations were assumed in different locations throughout the catchment in order to capture the rainfall gradient in the catchment. The following spatial-oriented formula was used to quantify the topography effect on the rainfall amount in Al-Faria catchment [17]:

$$R = 8285 - 39.41X - 2.46\,Y - 0.34\,Z \qquad (1)$$

Where, R is the annual average rainfall in mm, X is the x-coordinate in km, Y is the y coordinate in km and Z is the elevation in m.

The hourly rainfall data was computed for the 10 stations rather than the tipping buckets using the following formula:

$$P_x^y = \frac{P_{avx}}{n} \sum_{i=1}^{n} \frac{P_i^y}{P_{avi}} \qquad (2)$$

Where:-

P_x^y is the missing rainfall value at station x at time step y;

P_{avx} is the long term annual average of station x;

P_i^y is rainfall value at station i at time step y;

Pavi is the long term annual average of station i.

b) Runoff Data

For the runoff data, it was collected from the two flumes which are located approximately at the outlets of both Al-Badan an Al-Faria sub-catchments as shown in Figure 2. So that the summation of the rainfall from both streams represents the total runoff from the upper faria catchment part. The flumes data are recorded every ten minutes, and represents the flow amount among the flume body. These data were used in the calibration process of the model simulated flows and later on it was used evaluate the model efficiency.

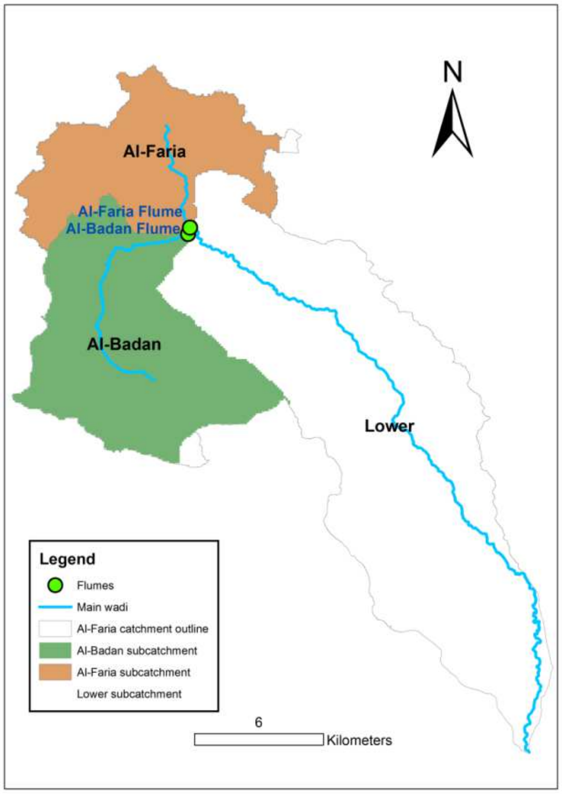

Figure 3: Flow measuring flumes in Al-Faria catchment

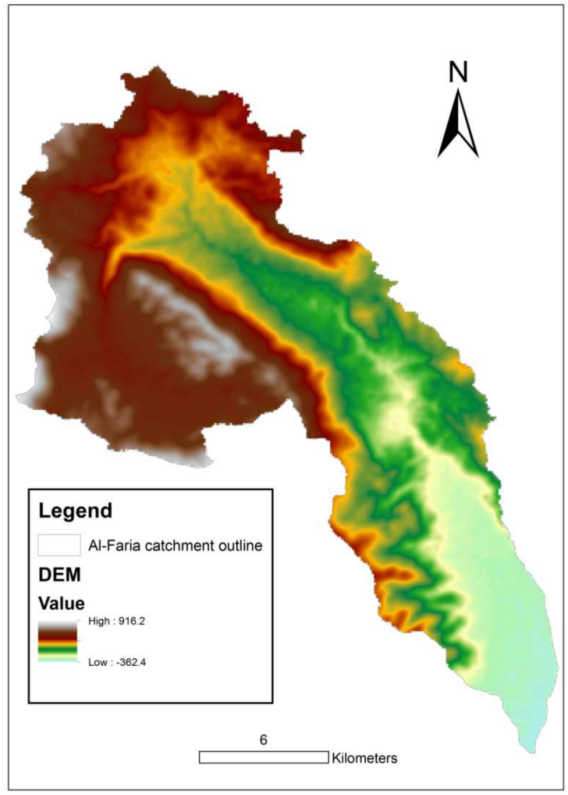

Figure 4: Al-Faria catchment Digital Elevation Model (DEM)

C. *Maps Preparation*

Arc GIS 10.1 software package was used in order to prepare all the spatial data required for the modeling. In addition to doing some spatial-related manipulations, the developing of the Digital Elevation Model (DEM), flow direction and flow accumulation grids, stream definition, watersheds delineation and many others were done using Arc GIS. The Digital Elevation Model, which is the most important map from which all the other maps were originated, was developed for the catchment from the contour map of the West Bank and it shows the topographic elevation all over the catchment. The DEM of Al-Faria catchment is shown in Figure 3.

Moreover, after defining the stream network of the catchment, the catchment was divided into 20 sub-catchments as shown in Figure 4. And from the figure it is shown that the sub-catchments number 1, 2, 3 and 4 belongs to Al-Faria sub-catchment which drains its surface runoff into Al-Faria flume and the ones having the numbers 6, 8, 9, 10 and 11 belongs to Al-Badan sub-catchment and drains into Al-Badan flume.

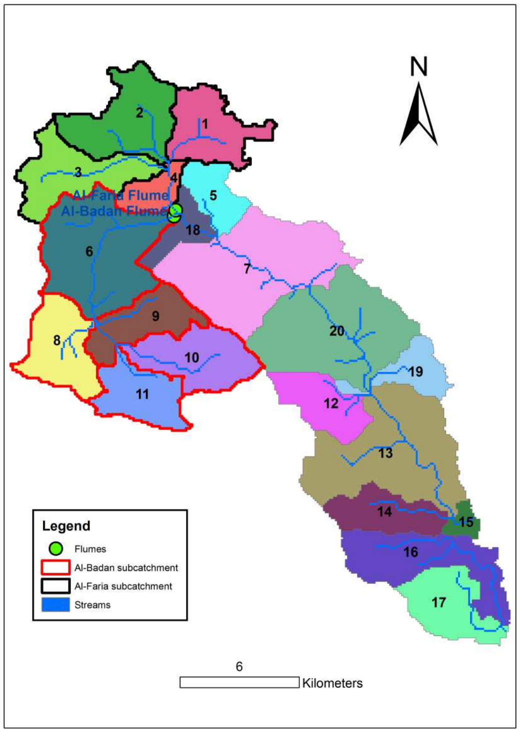

Figure 5: Model Sub-catchments

D. *Model Application*

The HEC-HMS (version 4.0) model was used in order to simulate the flood volumes, peaks and timing. The prepared maps were used in the model. In addition, the hydrologic modeling related data for the catchment were entered to the model, such as: the sub-catchments areas and land use patterns, initial losses, time of concentration, curve numbers, imperviousness, and sub-catchments initial abstractions in addition to Muskingum parameters for the routing process for the streams. These values were computed depending on the permanent soil types in the catchment. Figure 5 below illustrates the developed model in HEC-HMS 4.0.

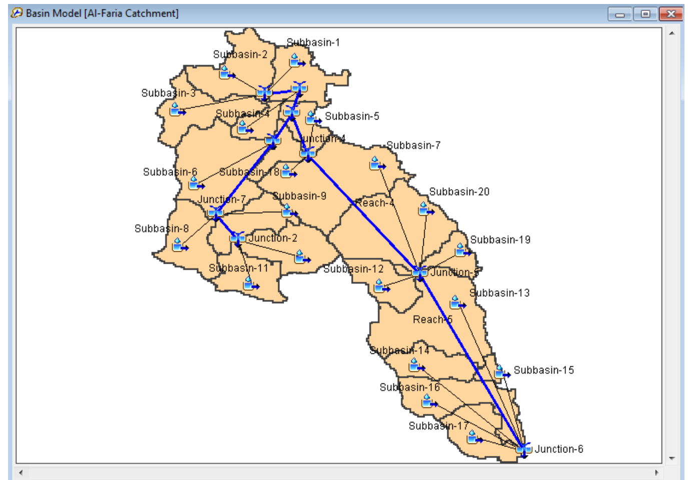

Figure 6: Al-Faria catchment model developed using HEC-HMS

For the rainfall data applied to the HEC-HMS model, Thiessen Polygon method was used in order to find the average rainfall values overall the catchment. Then, for each sub-catchment, the gage weights method were used to find the weights of the gages which their polygons intersect that sub-catchment. After that, the total rainfall recorded by each station is multiplied by its weight for every sub-catchment. Figure 6 below illustrates the distribution of the existing and the assumed rainfall stations among the catchment and Thiessen polygon for each of them. The weights of the gages for each sub-catchment are calculated according to the following equation:

$$w_{i,j} = \frac{A_{i,j}}{A_j} \qquad \textbf{(3)}$$

Where:

$w_{i,j}$ is the weight of rainfall station i in sub-catchment j;

$A_{i,j}$ is the area of Thiessen polygon of station i that intersects sub-catchment j;

A_j is the area of sub-catchment j.

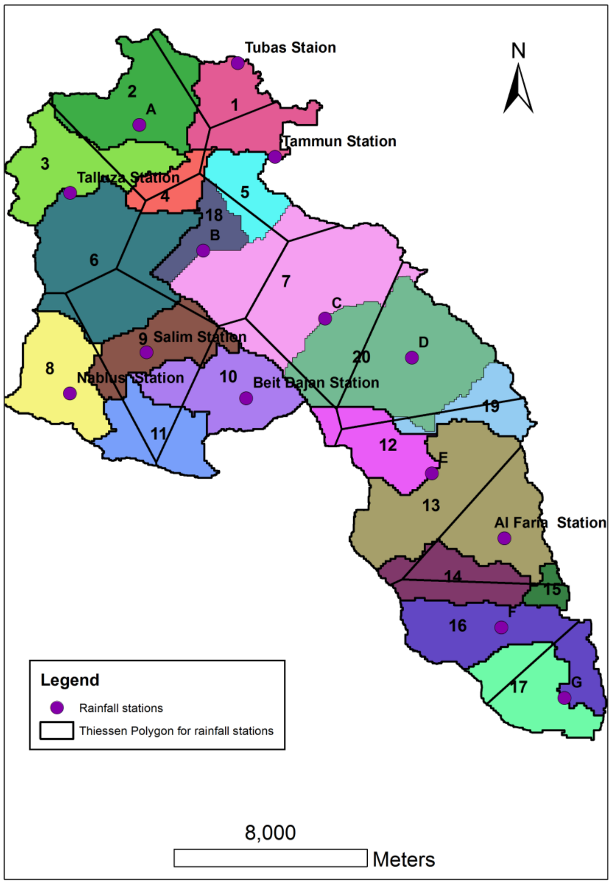

Figure 7: Thiessen Polygons for the existing and assumed rainfall stations

E. Model Calibration

The successful rainfall-runoff modeling for any catchment depends on how well the model calibration is. So, HEC-HMS catchment model was calibrated. The available runoff data at the upper parts of the catchment, which gauged by the flumes, were used mainly to calibrate the model. The model was calibrated for different parameters including: curve number, initial abstractions, loss/gain fractions and flows for the streams. The calibration process was mainly the traditional method that depends on trial and error and it continued until a good correlation between the simulated and the observed flows for both the magnitude of the peaks and time to peak had been achieved.

a) CN Calibration

The Soil Conservation Service (SCS) Curve Number (CN) loss method was used in the calibration. This method can estimate the excess rainfall as a function of many parameters, including: land use, land cover, and antecedent moisture content [3]. The CN in this method was computed as a weighted value according to the land use types in each sub-catchment. The following formula was used to calculate CN each sub-catchment:

$$CN(\text{subcatchment}) = \frac{A_i \times CN_i}{\sum_{i=0}^{n} A_i} \quad (4)$$

Where:

$CN(\text{subbasin})$ is the weighted average CN of the sub-catchment;

A_i is the area of the ith part of the sub-catchment;

CN_i is the CN of the ith part of the sub-catchment, where taken from standard curve number tables [14].

The CN values ranges from about 30 for soil with high infiltration rate to 100 for the water bodies [19]. The calculated weighted CNs for the sub-catchment were used in the calibration. It was changed consecutively, and each time the model simulation was performed until the most suitable CN set for the study area were selected.

b) Sub-Catchments Initial Abstraction Calibration

SCS-CN loss method was used as stated before. So, the initial abstraction for each sub-catchment had to be entered to the model. The initial abstractions are computed according to the following formula:

$$I_i = \lambda S \quad (5)$$

Where:

$$S = \frac{25400}{CN} - 254 \quad (6)$$

Where:

I_i is the initial abstraction;

λ is factor varies from 0.2 to 0.4;

S is the maximum potential retention;

Since the value of the initial abstractions for any sub-catchment depends on the value of the CN for that sub-catchment, as shown in the equation above, the model calibration for the CN included the initial abstractions calibration by default.

c) Loss/Gain Method Calibration

For this part in the model, the constant method was selected to present the loss/gain from/to the streams in the streams network. This method uses an empirical relationship in order to calculate the channel loss using both a fixed reduction flow rate and a ratio of the flow. The fixed flow rate is subtracted from the routed flow and then the reminder is multiplied by the fixed ratio [5]. The values of the reduction flow rate amount and ratio were calibrated in the light of transition losses amounts for the streams in the catchment from a previous rainfall-runoff modeling study using TRAIN-ZIN model [16].

d) Transform method Calibration

For each sub-catchment in the model, there is a transform method that is responsible for the calculation of surface runoff. In this case, the SCS Unit Hydrograph method was selected as a transform method. Research by the SCS suggests equations by which the peak flow rate amount and timing can be calculated. In these equations the lag time for every sub-catchment is used. In this case, the lag time was computed according to the following formula [15]:

$$t_l = 0.6 \times t_c \qquad (7)$$

Where t_c is the time of concentration in seconds. It can be expressed as:

$$t_c = \sum_{i=1}^{n} \frac{L}{v} \qquad (8)$$

Where:

L is the length of one segment of the longest flow path in the catchment in meters;

v is the flow velocity (m/s);

n is number of flow path elements.

III. Performance Evaluation

In this study, two measures of the performance of the HEC-HMS model were used. The first one is Nash-Sutcliffe efficiency (E); it is used as a predictive power of the hydrological models. It is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the same period [10]. It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^{n} (Oi - Si)^2}{\sum_{i=1}^{n} (Oi - \bar{O})^2} \qquad (9)$$

Where O observed and S simulated values.

The value of E ranges from -∞ to 1 (perfect fit). A value of lower than zero indicates that the mean value of the observations would have been a better predictor than the model [8].

Nash-Sutcliffe efficiency (E) implicitly compares the performance of the particular model to that of perhaps the simplest imaginable model, one that uses as its prediction the mean value of the observed target. Which means that an NSE value of 1.0 indicates that the performance of the model is perfect (the model perfectly simulates the target output), an E value of 0 indicates that the model is, on average, performing only as good as the use of the mean target value as prediction, and an E value less than 0 indicates an altogether questionable choice of a model. Therefore, it is preferred to have E values to be larger than 0·0 and approaching 1·0 [13].

The second efficiency criteria used in this study is the coefficient of determination (r^2). This is defined as the squared ratio between the covariance and multiplied standard deviations of the observed and predicted values. So, it estimates the combined dispersion against the single dispersion of the observed and predicted series [8]. It is calculated as:

$$r^2 = \left(\frac{\sum_{i=1}^{n} (Oi - \bar{O})(Si - \bar{S})}{\sqrt{\sum_{i=1}^{n} (Oi - \bar{O})^2} \sqrt{\sum_{i=1}^{n} (Si - \bar{S})^2}} \right)^2 \qquad (10)$$

The value of r^2 ranges from 0 to 1. A value of zero means that there is no correlation between the observed and simulated values whereas a value of one means that the dispersion of the predicted values is the same as the once of the observed values.

IV. Results and Discussion

The rainfall and runoff data recorded in Al-Faria catchment have been used to calibrate and validate the developed model. Figures 7 and 8 illustrate a comparison between the observed and simulated flows for both Al-Badan and Al-Faria sub-catchments for the events of 4-8 February, 2005 and 8-9 February, 2006, respectively.

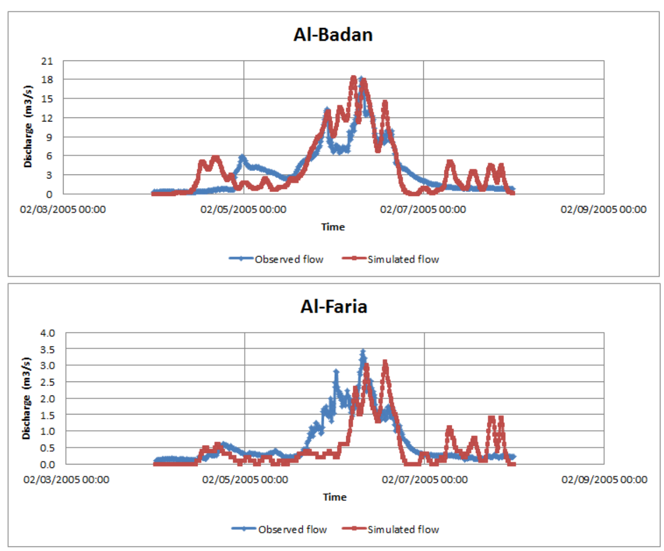

Figure 8: Observed and Simulated flows for 4-8, February, 2005

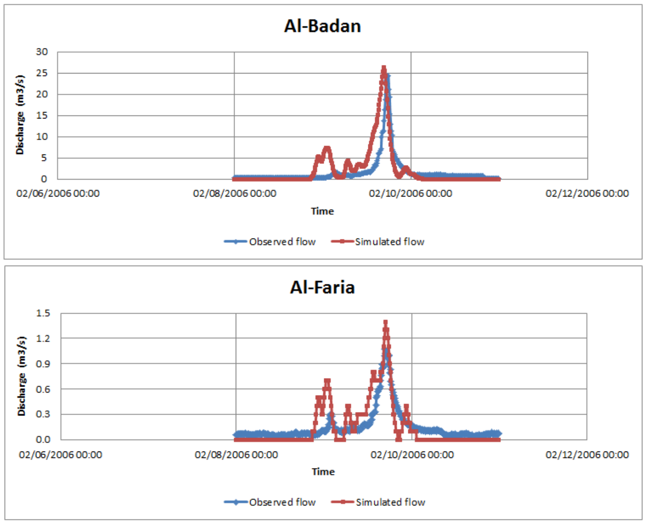

Figure 9: Observed and Simulated flows for 8-10, February, 2006

Both efficiency criteria mentioned above were determined for the gauged sub-catchments, Al-Badan and Al-Faria, to check the model response efficiency for both events. The values of Nash- Sutcliffe and coefficient of determination are shown in the following tables:

Table 1: Efficiency Criteria for the Event of 8-10 February, 2006

Catchment	Nash-Sutcliffe E	Coefficient of Determination r2
Badan	0.14	0.53
Faria	-0.36	0.20

Table 2: Efficiency Criteria for the Event of 4-8 February, 2005

Catchment	Nash-Sutcliffe E	Coefficient of Determination r^2
Al-Badan	0.17	0.63
Al-Faria	0.71	0.52

From the numbers in both tables above, it can be concluded that Nash-Sutcliffe and the Coefficient of Determination had given different impressions about the simulation for each case. For example, for the event of February, 2006, Nash-Sutcliffe efficiency coefficient for Al-Faria sub-catchment is higher than the once of Al-Badan while it is the other way round for the Coefficient of determination. Moreover, the negative value of Nash-Sutcliffe efficiency for Al-Faria sub-catchment for February, 2005 event indicates that the model predictions are weaker than the mean value of the observations.

Although the coefficient of determination r^2 reflects a good performance efficiency of the model for all cases (except the once of Al-Faria for February, 2005), Nash-Sutcliffe efficiency seems to have relatively small values. The reason may refer to the disadvantage of Nash-Sutcliffe efficiency measure, which is the differences between the observed and the simulated values are calculated as squared values (Legates, 1999). As a result, larger values are highly overestimated while the lower ones are neglected.

V. Conclusions

Based on the above results, it is fair to say that the HEC-HMS model was capable to model the single rainfall events in a semi-arid environment. In addition, the model was able to represent the different hydrological processes that take place in the catchment during a rainfall event and the resulted hydrographs. This reflects the goodness of the model and the suitability of the using of HEC-HMS as a tool to build rainfall-run off models for single events in semi-arid climates. Overall, it can be concluded that the developed HEC-HMS model for Al-Faria catchment is a valid runoff prediction tool from rainfall data. However, it needs further modifications and calibration in order to get higher efficiency and reliability degrees.

For future work on this model, it is recommended to recalibrate the model for more events in order to get more accurate results and best simulations.

VI. References

[1] Arnold JG, Srinivasan, R., Muttiah, R., & Williams, J. (1998). Large area hydrologic modeling and assessment Part 1: model development. *Water Resour Assoc 34*, 73-89.

[2] Bajwa, H., & Tim, U. (2002). Toward immersive virtual environments for GIS-based floodplain modeling and visualisation. *22nd ESRI User Conference.* San Diego, TX, USA.

[3] Feldman, A. (2000). *Hydrologic Modeling System HEC-HMS, Technical Reference Manual.* CA, USA: U.S. Army Corps of Engineers, Hydrologic Engineering Center,HEC.

[4] Hunukumbara, P., Weerakon, S., & Herath, S. (2008). Runoff modeling in the upper Kotmale Basin. *Interdisiplinary Essays in Honor of Professor Madduma Bandara, University of Peradeniya*, 169-184.

[5] Hydrologic Engineering Center. (2013). *Hydrologic Modeling System HEC-HMS, User's Manual.* Davis, US Army Corps of Engineers.

[6] Kobierska, F., Jonas, T., Zappa, M., Bavay, M., Magnusson, J., & Bernasconi, S. M. (2013). Future runoff from a partly glacierized watershed in Central Switzerland: a 2 model approach. *Advances in Water Resources, 55*, 204-214.

[7] Kotsifakis, K., Psomas, A., Feloni, E., & Baltas, E. (2015). Rainfall Runoff Modeling In An Experimental Watershed In Greece. *14th International Conference on Environmental Science and Technology.* Rhodes.

[8] Krause, P., Boyle, D. P., & Base, F. (2005). Comparison of different efficiency criteria for hydrological model assesment. *Advances in Geosciences*, 89-97.

[9] Muthukrishnan, S., Harbor, J., Lim, K., & Bernard, A. (2006). Calibration of a simple rainfall-runoff model for long-term hydrological impact evaluation. *Urban and Reigonal Information System Assosiation (URISA) Journal*, 35-42.

[10] Nash, J. E. (1970). River flow forecasting through conceptual models, Part I-A discussion of principles. *J. Hydrology*, 282-290.

[11] Nash, J., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models. *J. Hydrology*, 282-290.

[12] Paniconi, C., & Putti, M. (2015). Physically based modeling in catchment hydrology at 50: Survey and outlook. *Water Resources Research*, 7090-7129.

[13] Schaefli, B., & Gupta, H. V. (2007 , May 10). *Wiley InterScience*. Retrieved December 28, 2015, from John Willy & Sons: www.interscience.wiley.com

[14] Schweb, G., Fangmeier, D., Elliot, W., & Frevert, K. (2005). In *Soil and Water Conservation Engineering* (p. 508). New York: John Wiley and Sons.

[15] Service, U. S. (1973). *Hydrology. Nat. Eng. Handb., sec. 4*, p. 547.

[16] Shadeed. (2008). *Up To Date Hydrological Modeling in Arid and Semi-arid Catchment,The Case of Faria Catchment, West Bank, Palestine*. Freiburg im Breisgau, Germany.

[17] Shadeed, S. (2005). GIS-Based Hydrological Modeling of Semi-arid Catchment: The Case of Faria Catchment. *M.Sc. Thesis*. Nablus, Palestine.

[18] Singh, V. P., Seo, I. W., & Sonu, J. H. (1999). Hydrologic Modeling. *International Conference on Water, Environment, Ecology, Socio-economics, and Health Engineering (WEESHE)* (pp. 232-234). Seoul, Korea: Water Resources Puplications, LLC.

[19] USDA-SCS. (1985). *National Engineering Handbook. Section 4-Hydrology*. Washington, D.C.

[20] Verma, A., Jha, M., & Mahana, R. (2010). Evaluation of HEC-HMS and WEPP for simulating watershed runoff using remote sensing and geographical information system. *Paddy Water Environ 8*, 131-144.

[21] Viessman, W., Lewis, G., & J.W., K. (2003). *Introduction to Hydrology*. Harper Collins.

[22] Wheater, H., Jolley, T., Onof, C., Mackay, N., & Chandler, R. (1999). Analysis of aggregation and disaggregation effects for grid-based hydrological models and the development of improved precipitation disaggregation procedures for GCMs. *Hydrol Earth Syst Sci 3*, 95-108.

[23] Zhang, X., Srinivasan, R., Debele, B., & Hao, F. (2008). Runoff simulation of the headwaters of the Yellow River using the SWAT model with three snowmelt algorithms. *J Am Water Res Assoc 44*, 48-61.