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Development of a Runoff Simulation Model in Data Scarce Semi-Arid Regions

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Abstract: The hydrological features of Wadis in arid and semi-arid regions are unique. The hydrological regime is characterized by high variability in temporal and spatial rainfall distributions, flash floods, absence of base flow in most cases, and high rates of evapotranspiration. There have been many efforts to estimate, analyse and predict the stream flow in Wadis either for water harvesting or flood control. The aim of this paperis to develop simulation model fora semi-arid basin in Sudan, using Hydrologic Modelling System of the Hydrologic Engineering Center(HEC-HMS)software, developed by the US Army Corps of Engineers. The HEC-HMS modelling was done in conjunction with the HEC-GeoH MS extension in Arc Map. The aridity index of United Nations Environment (UNEP), which is one of the most adopted indices, was used to estimate the aridity of the study area. Analysis of the rainfall records at stations with automatic gauges had shown that there is a similarity in the shape of the incremental rainfall depths hyetographs, for a particular climatic region. Accordingly, a new procedure for transforming the daily rainfall depths into incremental rainfall depths hyetographs, is developed. These incremental rainfall depths hyetographs and the corresponding single flood events in Wadi AbuFargha basin, were modelled using HEC-HMS. The results showed a very good similarity between the observed and the simulated flows. Nash and Sutcliffe efficiency criterion was used to evaluate the model performance. The overall model efficiencies were 92% and 88%, in the calibration and verification periods, respectively. Therefore, it is concluded that the HEC-HMS software offers a reliable tool for flash flood forecasting in data scare semi-arid regions.

Key words: *rainfall-runoff modelling, semi-arid region, HEC-HMS.*

1. INTRODUCTION:

Despite the critical importance of water in arid and semi-arid areas, hydrological data have historically been severely limited. It has been widely stated that the major limitation of the development of arid-zone hydrology is the lack of high quality observations (Wheatear et al, 2008). In such cases, the uncertainty should be taken into account. In the arid and semi-arid regions, water resources are scarce, and under continuous pressure from the growing population and their needs. The hydrological regime is characterized by the high variability of temporal and spatial rainfall distributions, flash floods, absence of base-flow and the high rates of evapotranspiration. There have been efforts to estimate, analyse and predict the stream flow in order to make stable water use and flood control under these conditions (Han, 2010). For this aim, Hydrologists used models to simulate the runoff and to generate synthetic data sets when actual data are unavailable. The major problem in modelling the hydrological processes based on their physical governing laws, is the variability in Space and time of the parameters that control these processes. Such models usually consist of a set of simultaneous equations or a logical set of operations contained within a computer program and should have parameters, which are numerical measures of a characteristic that are constant under specified conditions.

With the emergence of remote sensing techniques as potential sources of data of the hydrological processes and the improved capabilities of generating and processing Digital Elevation Model (DEM) data, GIS techniques have gained a prominent role in hydrological modelling. This role has developed from the traditional use of GIS as an interface to the hydrological models for pre-processing and post-processing of data into "rethinking hydrological models in spatial terms so that better GIS-based hydrological models can be created" (Maidment, 1993). Modelling methods have been widely used in the last decades for a variety of purposes.

However, almost all modelling tools have been primarily developed for humid. Areas. Arid and semi-arid areas have particular challenges and have received little attention. The Hydrologic Modelling System (HEC-HMS) is a hydrologic modelling software developed by the Hydrologic Engineering Center of the US Army Corps of Engineers (USACE). It is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in wide range of geographic areas for solving the widest possible range of problems. This includes large river basin, water supply and flood hydrology and small urban or natural watershed runoff (USACE, 2013). HEC-Geo HMS was developed to use Readily available digital geospatial information in order to construct hydrologic models more expediently than the Traditional manual methods. Also, the development of basic watershed information will aid the user in estimating hydrologic parameters (USACE, 2013).

The main objective of this study is to develop alumped rainfall-runoff model in a partially gauged catchment in a semi-arid region, using HEC-HMS.HEC-Geo HMS was used to delineate the physical properties of watershed. This model was carried out using Geographical Information System (GIS).

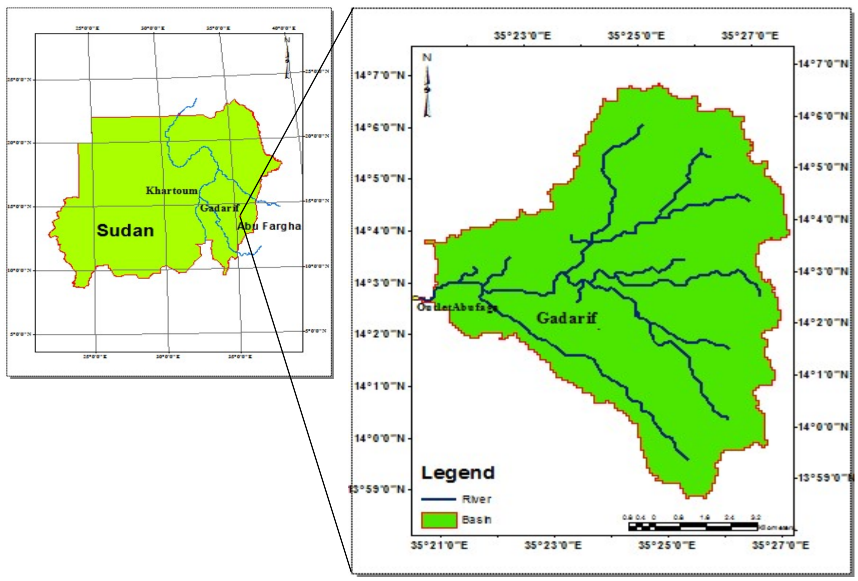

Fig. 1. Location of Abu Fargha Watershed

2. Material & Methods:

2.1 Study Area:

Wadi AbuFargha is located in the eastern part of Sudan. The study area is a sub-catchment of the RahadBasin. The watershed hasa drainage area of 102km^2.The total length of this wadi is about 18 km (see Fig1).AbuFargha watershed lies between latitudes 13°58'N and 14°07' N; and longitudes 35°21' E and 35°28' E, with elevations ranging from approximately 577m above mean sea level at the outlet to approximately 694 mat the catchment boundary. The average annual rainfall is 606 mm and the corresponding evapotranspiration is estimate2256 mm. The hydrology of the watershed is dominated by the ephemeral Wadis with a dry period extending between November and May. The basin parameters are calibrated and validated using the rainfall-runoff data of the basin for the period 1967-2000. After examining the rainfall and runoff records of several Wadis in Sudan (e,g, Nyala, Al-Ghala, Abu Habil, Arbabt), it was concluded that Wadi AbuFargha is the only ephemeral stream with credible data. Accordingly, the study was limited to this Wadi. However, the study will be extended tothe other Wadis, as soon as credible data become available. It is worth noting that automatic gauges had recently been installed in these Wadis, by the Ministry of Water Resources, Irrigation and Electricity.

2.2 Data:

2.2.1 Digital Elevation Model (SRTM DEM):

The Shuttle Radar Topography Mission (SRTM) dataset used in this study, were released in 2003by the National Aeronautics and Space Administration (NASA) for some regions, with 3 arc-second resolutions for the globe.

2.2.2 Observed Rainfall:

The rainfall which is the primary hydrological input, is commonly characterized by extremely high spatial and temporal variability, in arid and semi-arid areas (Wheater et al, 2008). In particular the rainfall in Wadi AbuFargha tends to vary significantly from year to year in time and space. There is one precipitation gauge located in ElGadarif town near the outlet of the basin. The average annual rainfall is 606 mm with standard error of 14.5mmfor the period 1904 to 2000.Fig 2, shows the annual rainfall amounts for the period 1904 to 2000. The high variability of annual rainfall is very evident in this Fig.

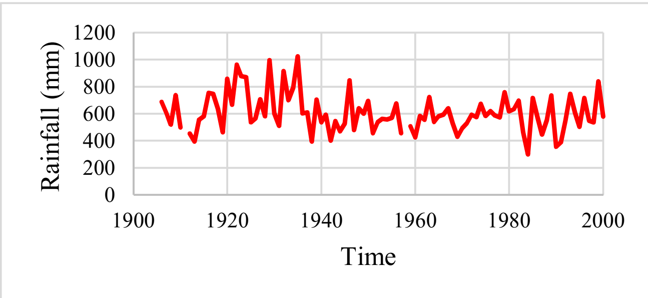

Fig.2. ElGadarif Annual Rainfall Series for the Period 1904 to 2000

The daily rainfall records in ElGadarif station for the period 1967 to 2000.**Fig.3.**Shows the time series of the daily rainfall. Apparently, there is an obvious fluctuation in the amount of daily rainfall during the period. The recorded maximum daily rainfall depth was 106 mm, in 1996 and 1999.

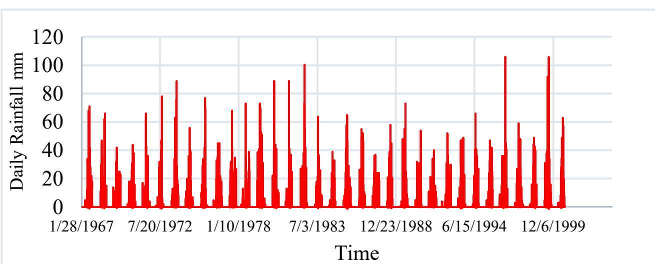

Fig.3. El Gadarif Daily Rainfall Series for the Period 1967 to 2000

2.2.3 Observed Wadi Runoff:

The runoff is the main watershed output and usually used in most water resources applications. Wadi AbuFargha is an ephemeral stream which runs for a short period, usually during and after heavy rain events. The Wadi is dry in most of the year. Flow hydrographs rise sharply to the peaks and some flow events show more than one peak during a single rainfall event. The maximum flow recorded in Wadi Abu Fargha was 871.5m^3/s in 1973. The mean annual runoff at the Wadi gauge is 4.0 Million m^3. The runoff data are available for the period 1967 to 2000in 15-minute intervals. However, there is some discontinuity in the record.

2.3 Methodology:

2.3.1 Aridity Index:

The aridity is a consequence of the climate variability. It is a growing problem in many parts of the world (Wallen, 1967). Many definitions of aridity have been developed based on climatological data. The identification of the different types of arid regimes is done by estimation of the aridity index. Among the most used indices is the Aridity Index of UNEP (AIU) which is a function of the precipitation and the potential evapotranspiration. The AIU is defined by the ratio of annual precipitation to the annual potential evapotranspiration.

$$AIU = \frac{P}{PET} \quad (1)$$

Where: P = annual rainfall

PET = annual potential evapotranspiration

Based on the AIU values five categories of arid regimes can be identified as shown below (Gao et al, 2008).

$$AIU = \left\{ \begin{array}{cc} AIU \geq 1 & humid \\ 0.65 \leq AIU < 1 & Dry\ \ subhumid \\ 0.02 \leq AIU < 0.5 & Semi\ Arid \\ 0.05 \leq AIU < 0.02 & Arid \\ AIU \leq 0.05 & Hyper\ Arid \end{array} \right\} \quad (2)$$

Table 1, shows the Aridity Index of UNEP for the stations within the study area.

Table 1. Aridity Index for the Study Area

Stations	Rainfall (P)mm	Evapo (PET) mm	AIU	Regio n
El Gadarif	607	2256	0.269	semi-arid
Kosti	355	2155	0.165	semi-arid
ElObied	345	2467	0.140	semi-arid
ElGenei na	474	2336	0.203	semi-arid

Therefore, the AbuFargha basin and the three other stations are located in the semi-arid belt of Sudan. Fig4, shows the location of these stations on the isohyetal map of Sudan.

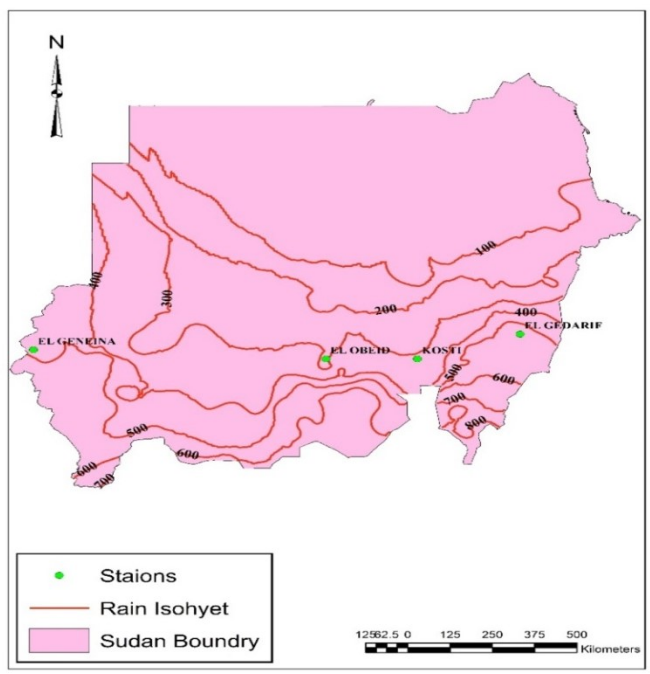

Fig. 4. Isohyetal map of Sudan and location of stations

2.3.2 Development of Rainfall Hyetographs:

In the semi-arid regions of tropical zones, the rainfall results from short duration convective storms, with duration ranging between 15 minutes to four hours. For this catchment, the daily rainfall records are available for the period 1967 to 2000. The runoff data are available for the same period, in 15-minute intervals.

The majority of the meteorological stations in Sudan, are not equipped with automatic rainfall gauges and only the daily rainfall depth is manually measured. Fortunately, for most of the cases, the rainfalls in semi-arid regions of Sudan are usually from a single event. Analysis of the rainfall records at stations with automatic gauges had shown that there is a similarity in the shape of the incremental rainfall depths hyetographs, for a particular climatic region. The incremental rainfall depths hyetograph is a plot of the rainfall as a function of time, shown in form of a histogram (Chow et al, 1988). Accordingly, the authors developed a new procedure for transforming the daily rainfall depths into the corresponding incremental rainfall depths hyetographs. The first step, is to divide the incremental rainfall depths, for any gauging station with an automatic gauge, by its corresponding total rainfall depth in order to convert them into percentages.

The second step is to calculate the average incremental rainfall depths percentages hyetograph for the particular station. The third step is to calculate the average incremental rainfall depths percentages hyetograph for the neighbouring gauging stations or for the climatic region. The fourth step, is to use the developed average incremental rainfall depths percentages hyetograph for the region, in order to transform the daily rainfall depths into the corresponding incremental rainfall depths hyetographs, for the stations without automatic gauges. These incremental rainfall depths hyetographs will be used during the rainfall-runoff modelling by HEC-HMS. The reliability of this transformation method will be tested when more data become available.

The study of the rainfall and the corresponding discharge hydrographs for Abu Fargha basin, showed that no runoff resulted from rainfall depths less than 20 mm. Such rainfalls are lost as initial and constant abstractions. Fig 5 shows the average depths and the corresponding average durations for the rainfall events for the semi-arid region of Sudan. From Fig 5, the rainfall depth of 20 mm, corresponds to a duration of two hours. Therefore, it is logical to conclude that the runoffs in the semi-arid region of Sudan, usually result from rainfalls with durations of three hours or more. Accordingly, the average incremental rainfall depths percentages hyetograph for the semi-arid region of Sudan is developed for a duration of three hours.

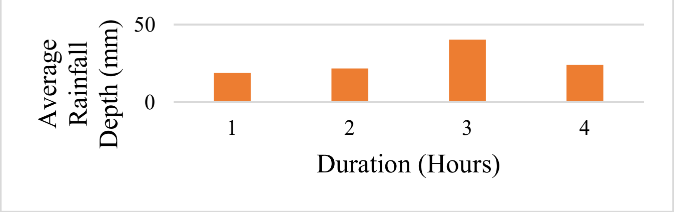

Fig.5. Average Rainfall Depths and Average Durations for the Semi-arid Region of Sudan

Thus, the observed daily rainfall data for Abu Fargha, are redistributed into 15-minutes intervals, using the developed average incremental rainfall depths percentages hyetograph.

2.3.3 Modeling:

Many components of hydrologic models depend strongly on spatial factors. Therefore, GIS will provide an effective tool in hydrologic modelling. In this paper, HEC-Geo HMS in GIS environment and HEC-HMS are used to develop a lumped rainfall runoff model for Wadi Abu Fargha.

2.3.3.1 Physiographic Characteristics of the Catchment:

HEC-Geo HMS in GIS environments is used to delineate the physical properties of the Abu Fargha watershed from a DEM of 90 m resolution. Characteristics such as the boundary of the watershed, contributing area, slope, and the wadi length are obtained.

The rainfall and runoff data are prepared and stored in Data Storage System (DSS) file format to facilitate their import into HEC-HMS model.

2.3.3.2 Model Setup and Modelling Procedure:

The developed catchment characteristics using HEC-Geo HMS are imported to the HEC-HMS environment. Many combinations of loss methods, transform methods and channel routing procedures were examined. It was found that the Initial Constant method, Clark unit hydrograph and the Lag method, provided the best results for losses, transformation and channel routing, respectively.

Initial parameter values are needed for the simulation phase. These initial parameter values are then refined during the calibration phase. According to USACE (2000), the initial loss was estimated as25 mm and the constant rate was estimated as7 mm/hr.

The time of concentration,T_c, was estimated as 4.3 hr using Kirpich equation (Chow et al, 1988):

$$T_c = 0.0195 * L^{0.77} * S^{-0.385} \quad (3)$$

Where:

L≡River length S≡ Catchment slope

Chow et al, (1988), estimated the time lag, $T_p$between the peak of rainfall and the peak of discharge is taken as 60% of the time of concentration.

$$T_p = 0.6\, T_c \quad (4)$$

The basin storage coefficient R was estimated through calibration.

The imported HEC-HMS model was prepared, setup, calibrated and verified using the data set which consists of 15rainfall events and their corresponding discharge records during the period 1967-2000.Several rainfall events which are less than 20 mm/day do not yield any runoff. The model was calibrated using 11 rainfall events and verified using the other four rainfall events.

3. Results and Discussion:

The physiographic characteristics of the Abu Fargha watershed are shown in Table 2.

Table 2. Important of Watershed Physiographic Characteristics for Wadi Abu Fargha

Characteristics	Value
Area (km^2)	102
Average Elevation (m)	603
Longest Flow Path (km)	18.0
Average Slope	0.0065

3.1 Rainfall Redistribution:

The rainfall percentage is calculated for three automatic weather stations located in the semi-arid region of Sudan, for several events. Figs6, 7 and 8 show the incremental rainfall percentages hyetographs for ElObied, Kosti and ElGeneina, respectively. These stations are equipped with automatic gauges. The average incremental rainfall percentages hyetograph, for the semi-arid region of Sudan is shown in Fig 9.

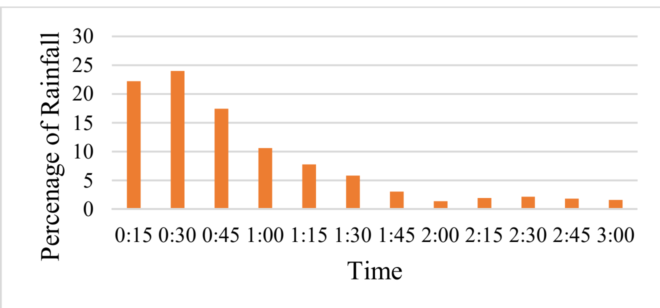

Fig.6. Rainfall Percentage Hyetograph for ElObied Station

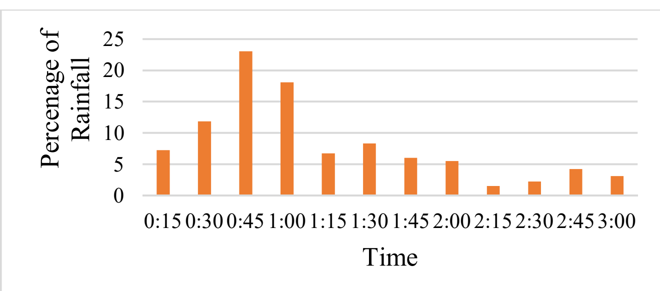

Fig 7: Rainfall Percentage Hyetograph for Kosti Station

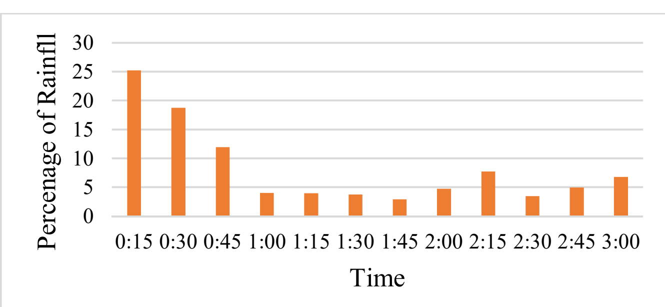

Fig.8. Rainfall Percentage Hyetograph for ELGeneina Station

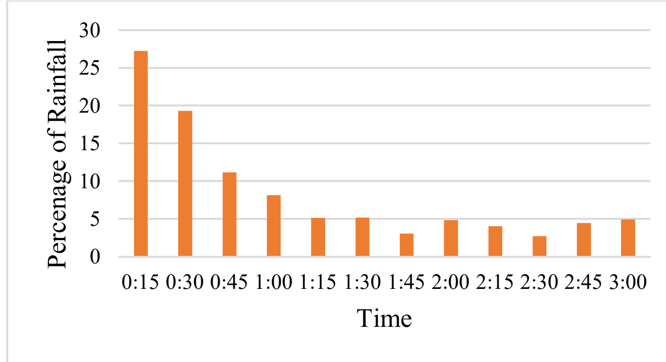

Fig.9. Average Rainfall Percentages Hyetograph for the Semi-arid Region of Sudan

Table 3 shows the average incremental rainfall percentages hyetograph, for the semi-arid region of Sudan,with 15-minute intervals.

Table 3. Average Rainfall Percentages Hyetograph for the Semi-arid Region of Sudan

Time (hrs)	0	0:15	0:30	0:45	1:00	1:15	1:30	1:45	2:00
Percentage	0	27.25	19.28	11.13	8.14	5.11	5.16	3.04	4.82
Time (hrs)	2:15	2:30	2:45	3:00	-	-	-	-	-
Percentage	4.02	2.72	4.44	4.90	-	-	-	-	-

3.2 Model Calibration:

The goal of calibration is to adjust the model's parameters in order to obtain the best fit between the observed and the simulated stream-flows. The calibration process was completed manually by repeatedly adjusting the parameters, computing, and inspecting the goodness of fit between the computed and observed hydrographs for each of the 11rainfallevents. Table 4 shows the date of the events used in calibration, the calibrated parameters and the coefficient of determination, R2. This coefficient is one of the measures of model efficiency (Nash and Sutcliffe, 1970).The last row in the table 4 shows the average calibrated parameters which are used for model verification. Figure 10 shows examples of the plots of the simulated and observed discharge hydrographs in the calibration period.

Table 4. Values of Calibrated Parameters for Abu Fargha Basin

Date	Loss			Transform		Routing	R^2
	Initial Constant			Clark UH		Lag	
	Initial Loss (mm)	Constant Rate (mm/hr)	Imp (%)	T_c (hr)	Storage Coef (hr)	Lag Tim (min)	
22/7/1967	44	10	4.3	1.6	1.2	450	0.91
19/8/1967	42	10	4.2	2	1.2	430	0.88
27/8/1968	46.7	12	6	1.6	0.5	430	0.83
12/9/1968	43.2	7	4.8	1.3	0.6	330	0.98
28/7/1971	31.2	6	6.4	1.3	1.1	440	0.92
15/8/1972	25.9	8	4.5	1.6	1	420	0.98
24/7/1977	43	9	5	2.7	1	380	0.99
2/7/1979	50	8	4	1.8	0.5	420	0.98
16/7/1979	35	8	4.17	1.86	0.85	420	0.91
16/8/1982	40.4	7.9	3.9	1	0.2	470	0.92
20/9/1990	36.2	8	4.17	1.86	0.85	415	0.85
Average	**39.78**	**8.53**	**4.69**	**1.69**	**0.82**	**418**	**0.92**

The model efficiency using Nash and Sutcliffe (1970) criterion, was ranging from 83% to 99%, with an average value of 92%, during the calibration period as shown in table 4.

In order to evaluate the model performance in estimating the peak discharge, the percentage error in the peak, is calculated. According to USACE (2000), the model Percentage Error in Peak (Z), is calculated through the following equation:

$$Z = 100\left|\frac{q_S(peak) - q_0(peak)}{q_0(peak)}\right| \qquad (5)$$

Where: $q_{s\,(peak)}$ = simulated peak discharge

$q_{0\,(peak)}$ = observed peak discharge.

Table 5, shows that the percentage error in the peak discharge (Z) is very low in the calibration period. In most cases this error is less than 1%.

Table 5. Model Efficiency Using Percent Error in Peak (Z)

Date	Time of Peak	Peak (m^3/s)		Z (%)
		Obs	Sim	
22/7/1967	02:45	122.48	122.3	0.15
19/8/1967	05:00	158.8	161.6	1.76
27/8/1968	23:45	61.69	62.8	1.80
12/9/1968	21:15	200.9	200.5	0.20
28/7/1971	01:15	56.16	56.1	0.11
15/8/1972	18:00	73.92	73.9	0.03
24/7/1977	22:15	126	126.8	0.63
2/7/1979	06:15	163.36	163.6	0.15
16/7/1979	20:45	291.2	289.7	0.52
16/8/1982	17:15	133.4	130	2.55
20/9/1990	18:30	93.2	93.3	0.11
Average	**0.73**			

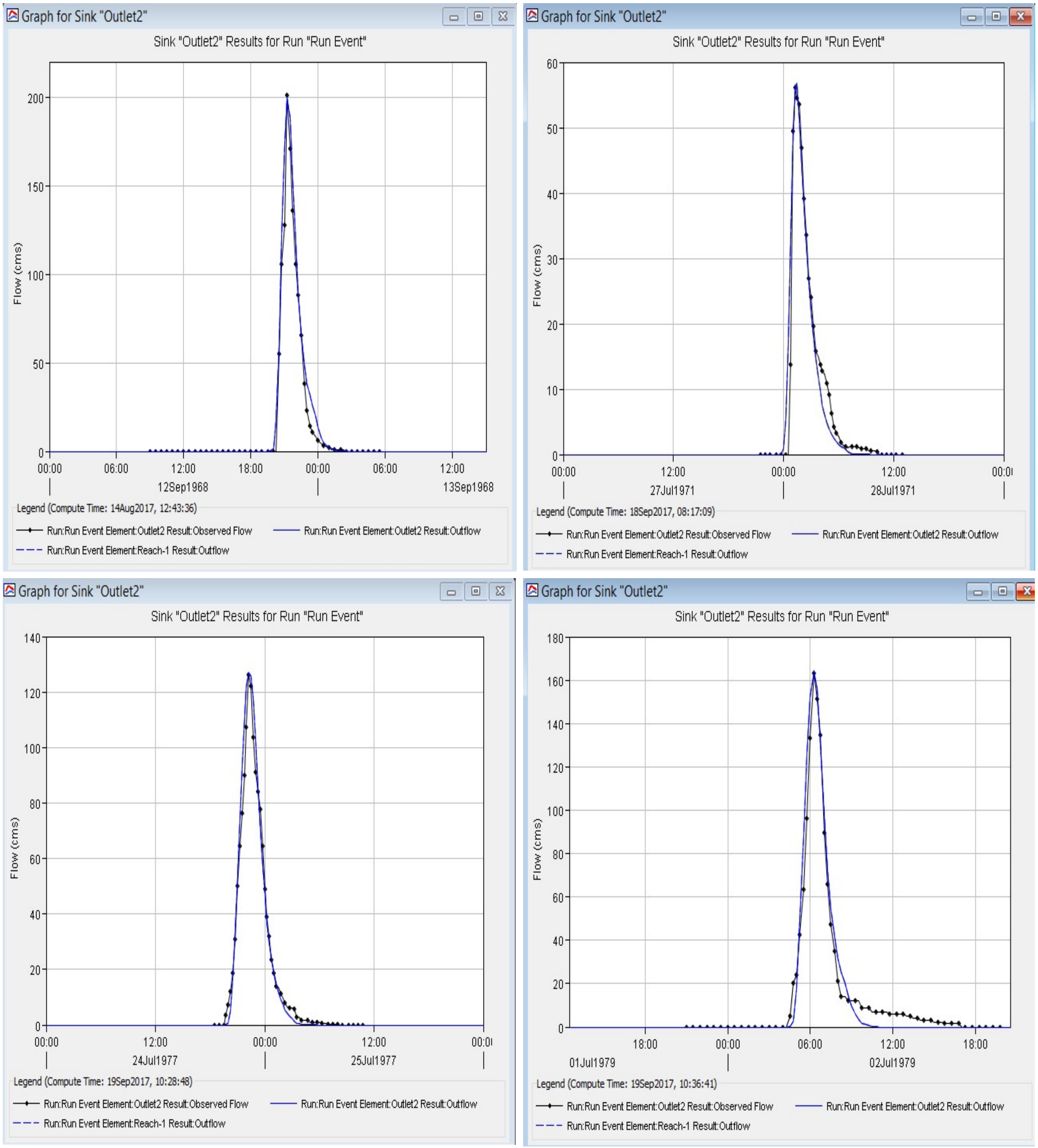

Fig 10: Simulated and Observed Discharge Hydrograph for Abu Fargha Watershed

3.3 Model Verification:

The model verification was used to determine the effectiveness of the calibrated parameters in predicting the runoff in the future. The verification period consists of four rainfall events during the period1995 to 2000.To test the model applicability, the average calibrated parameters were used in the verification period. Fig 11 shows a sample plot of the simulated and the observed discharge hydrographs for some validation events. The parameters used in the validation are the arithmetic average of the calibrated parameter values in table 4. The coefficient of determination (R^2) which represents the model efficiency is shown in table 6. The model efficiency using Nash and Sutcliffe (1970) criterion, was ranging from 78% to 94%, with an average value of 88%, during the verification period. These results are considered adequate and indicate that the model can reproduce the observed flows in a satisfactory manner, in the future.

Figs (11.a) and (11.b) show the simulated and observed flow in the verification period. The Figs clearly indicate that the peak and time to peak are well reproduced.

Table 6: Model Efficiency for Verification Using Coefficient of Determination (R^2) and Percent Error in Peak (Z) for the Verification Period for Wadi Abu Fargha

Date	Time of Peak	Peak (m^3/s)		R^2	Z(%)
		Obs	Sim		
10/7/1995	22:15	30.6	27.8	0.91	9.15
26/8/1997	20:00	33.3	28.4	0.90	14.71
18/7/2000	16:15	32	29	0.78	9.38
23/8/2000	00:15	100	87.9	0.94	12.1
Average	**0.8811.34**				

Table 6, shows that the percentage error in the peak (Z) is relatively low for three flood events out of four, in the verification period. In fourth case this error was relatively high (more than 11%).

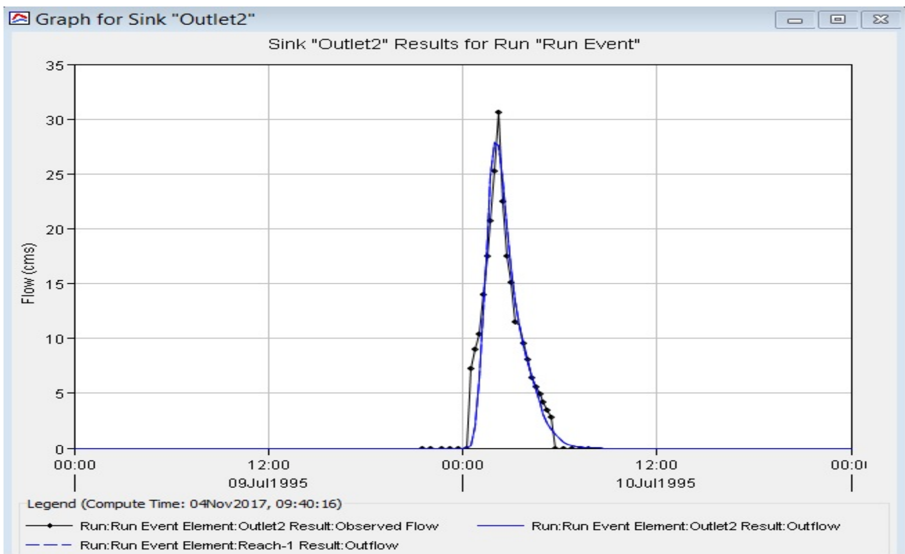

Fig. 11.a. Simulated and Observed Flow Hydrographs for the Rainfall Event on 10 Jul 1995

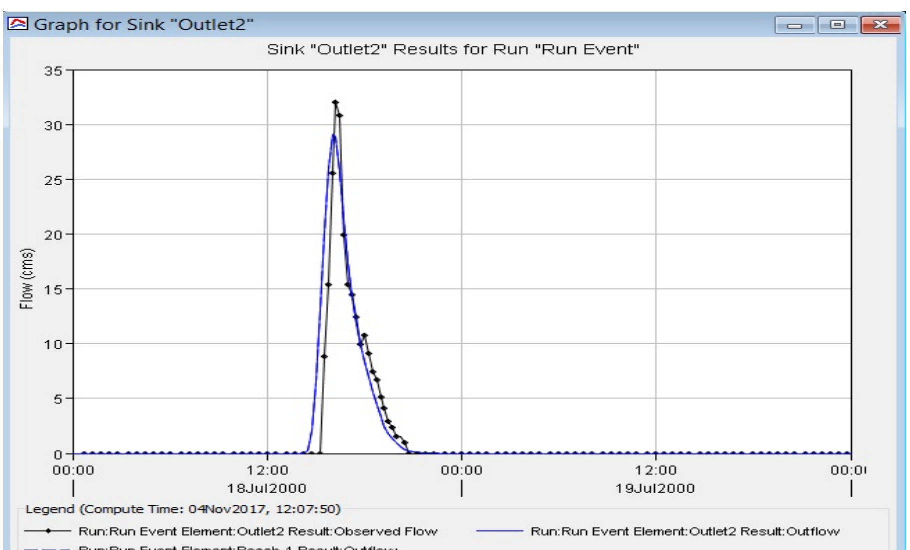

Fig.11.b. Simulated and Observed Flow Hydrographs for the Rainfall Event on19 Jul 2000

4. CONCLUSIONS:

The UNEP aridity index was used to estimate aridity of the study area. Using the indices, it was found that Abu Fargha watershed is located in the semi-arid region of Sudan. Analysis of the rainfall records at stations with automatic gauges had shown that there is a similarity in the shape of the incremental rainfall depths hyetographs, for a particular climatic region. Accordingly, a new procedure for transforming the daily rainfall depths into the corresponding incremental rainfall depths hyetographs is developed. This procedure involves the computation of the average incremental rainfall depths hyetograph for the climatic region. This average incremental rainfall depths hyetograph for the climatic region was used to transform the daily rainfall depth into the corresponding incremental rainfall depths hyetograph, with 15-minute time intervals. These incremental rainfall depths hyetographs were used during the rainfall-runoff modelling by HEC-HMS. The study of the rainfall and the corresponding discharge hydrographs for Abu Fargha basin showed that no runoff resulted from rainfall depths which are less than 20 mm/day. Such rainfalls are lost as initial and constant abstractions. It was concluded that the runoffs in Abu Fargha basin usually result from rainfalls with durations of three hours or more.

HEC-Geo HMS and HEC-HMS softwares were used to develop a lumped rainfall-runoff model for Abu Fargha basin. This model was calibrated and verified at the outlet of Abu Fargha watershed using many single rainfall events. The model verification was done using the average calibrated parameter values. The model efficiency using Nash and Sutcliffe (1970) criterion ranges from 78% to 94%, with an average value of 88%, during the verification period. These results are considered adequate and indicate that the model can reproduce the observed flows in a satisfactory manner. The developed procedure for transforming the daily rainfall depths into the corresponding incremental rainfall depths hyetographs, is very useful for rainfall-runoff modelling in semi-arid regions, with limited data. Therefore, the developed model using HEC-HMS, in this paper offers a suitable alternative of rainfall-runoff modelling in data scarce semi-arid regions.

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