DEVELOPMENT of HYDROLOGICAL LUMPED MODEL TO ESTIMATE RUNOFF HYDROGRAPH: CASE STUDY WADI SUDR IN SINAI PENINSULA, EGYPT

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ABSTRACT

*Hydrologic modeling is commonly used to estimate runoff from watersheds which is the most important parameter in any water resources design project. There are many hydrologic models that calculate runoff hydrograph and peak discharge with limited and specified equations. These equations may not be the representative equations of study area. Therefore this research aims to develop a new hydrologic lumped model contains most of the available runoff hydrograph and peak discharge equations to solve hydrologic problems in any watershed. The model was developed with Visual Basic programming language. The model is calibrated with results of the well-known **W**atershed **M**odeling **S**ystem (WMS) hydrologic model. The calibration/validation results indicate that the new developed model is accurate and is capable of simulating the runoff hydrograph. The model is then applied to study area (Wadi Sudr in Sinai Peninsula) and the hydrologic parameters of Wadi Sudr in Sinai, Egypt are identified and determined*.

Keywords: Visual basic, WMS, hydrographs, hydrologic Models, runoff, Wadi Sudr, Sinai Peninsula

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1. INTRODUCTION

Prediction of runoff for watersheds is a big concern for hydrologists and engineers. A range of different types of model is available to represent rainfall-runoff relationships. However, a limitation of most rainfall-runoff analysis models is that hydrologic parameters used to describe the rainfall-runoff process in wadi systems which must be calibrated and verified based on historical measured rainfall and flood events, Al-Smadi, (1998). There are a plethora of hydrologic/hydraulic models that are available for modeling watersheds and urban catchments. Singh and Woolhiser (2002) conducted an extensive review of how watershed hydrologic models have evolved over time. The earliest models include the Stanford Watershed Model (now HSPF) by (Crawford and Linsley, 1966) and HEC-1 (Hydrologic Engineering Center, 1968). Following the early development, emphasis was placed on more physically based models such as SWMM (Metcalf and Eddy et al., 1971), System HydrologiqueEuropeen (SHE) (Abbot et al., 1986) and TOPMODEL (Beven and Kirkby, 1979). Abdelaziz, (2000), developed a FORTRAN program for estimating runoff and sediment transport discharges for ungauged catchments in arid zones. Shaheen, (2005), used physically based rainfall-runoff estimation methods such as the Geomorphologic Instantaneous Unit Hydrograph (GIUH) approach., the developed GIUH model is applied to Al-Badan watershed of Faria catchment located in the northeastern part of the West Bank, Palestine. El-Sayed (2006), used the time-area curve concept implemented in a Geographic Information System (GIS) to calculate the hydrograph at the Wadi Sudr outlet. Sherief, (2008), used available data as well as GIS tools to assess flood hazard of El-Qaà pain area at southern Sinai. Abdelkhalek, (2011) implemented the Flash Flood Manager model called (FlaFloM) in Wadi Watier. The FlaFloM aims to protect the city of Nuweiba from the flash-flood hazards and contributes to the wise use of floodwaters. Khatami, et al., (2014), presented the larger scheme of the benefits for the applications of GIS in water resources and hydrological modeling in particular. Fathy, et al., (2014b) developed the Intensity Duration Frequency (IDF) curves of Wadi Sudr using the available field data. As a result, contour maps of Sherman coefficients are drawn based on the developed IDF curve. According to these maps the design rainfall intensity can be determined at any location of Sinai Peninsula. Fathy, et al., (2013,2014a) developed statistical equations to determine peak discharge and lag time at the outlet of Wadi Sudr. Theses equations are calibrated and verified using measured field data collected by National Water Research Center, Minister of Water Resources and Irrigation, El-Sayed (2006).

From reviewing the literature it was found that most of researchers depend on existing hydrologic models package to simulate the runoff process through their case study. Also they used only one method to calculate excess rainfall and runoff hydrograph ignoring the remaining equations during the simulation process. This means that the accuracy of their results may not good enough if they are compared to the corresponding ones depending on the remaining equations. In addtion the existing hydrologic models constrains the researcher to the hydrologic equations that existing in these models that may not the unique equations of the case study.

The objective of the present research is to develop a new lumped hydrological model to calculate runoff hydrograph and peak discharge using most of the available hydrologic equations in the literature. In addition the model is calibrated with the well-known hydrological model, Watershed Modeling System (WMS), and then applied to study area (Wadi Sudr Sinai Egypt) to identify and determine the values of its hydrologic parameters.

2. MODEL DEVELOPMENT

Creating the current hydrologic model will be achieved through the following systematic steps:

2.1 Filling “Pits” in the Raw Digital Elevation Model (DEM)

Pits are low elevation areas in DEMs that are surrounded by higher terrain that disrupts the flow path .To conduct watershed analyses with a DEM, its surface must be hydrologically connected. Fill process done along neighbor cells and its neighbor cells as shown in figure (1), Archuleta, C., et al., 2012.

2.2 Flow Direction

The flow direction is calculated by examining the eight neighbors of a cell and determining the neighbor with the steepest downhill slope as shown in figures (2, 3). This direction is then coded to facilitate the programming process, Archuleta, C., et al., 2012.

2.3 Flow Accumulation, Stream Grids, And Drainage Area

Through the flow-direction grid, it is possible to sum the number of uphill cells that “flow” to any other cell. This summing can be done for all cells within a grid to create a “flow-accumulation” as shown in figure (4), Chinnayakanahalli and Hill, 2006.

2.4 Watershed Delineation

By following a flow direction grid backward, we can determine all of the cells that drain through a given outlet. As represented in figure (5),Chinnayakanahalli and Hill, 2006.

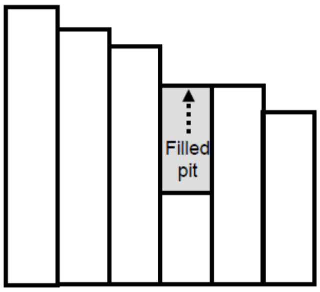

Fig. 1: Cross section of DEM surface.

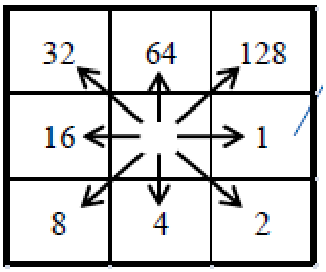

Fig. 2: Direction codes (integer numbers) assigned to cells in flow direction grids.

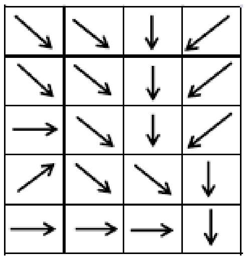

Fig. 3: Flow direction arrows created from the flow direction grid.

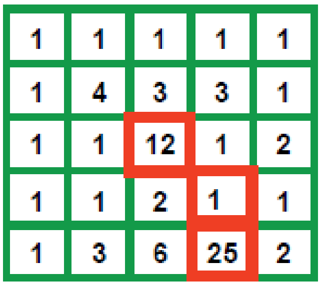

Fig. 4: flow accumulation grid values.

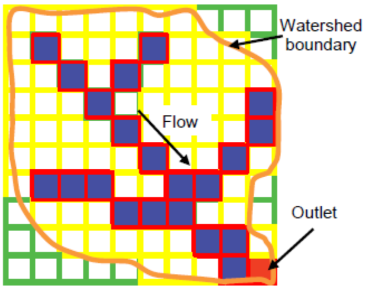

Fig. 5: A grid representation of a watershed boundary, stream network and outlet.

3. HYDROLOGIC EQUATIONS

The developed model uses the equations from the sources presented in table 1. Table 1 shows the main parameters of the equations involved in the model and their sources.

Table. 1 Description of hydrologic equations

Method name	Main parameters involved	Target of the equation	Date, author and Ref.
Soil Conservation Service (SCS)	(CN) curve number (P) accumulated precipitation	(S) storage losses (Q) accumulated runoff	SCS, 1972, [15] and Chow, et al., 1988.
Soil Conservation Service (SCS) , dimensionless unit hydrograph method	(T_L) lag time (Tr) storm duration (A) watershed area	(T_p) time to peak (q_p) peak discharge	SCS, 1972, [15] and Chow, et al., 1988.
Nash equation	(L) length of main stream (S) slope of the basin (A) watershed area	(n) shape parameter (k) scale parameter Runoff hydrograph	Nash, 1957
Clark equation	(Tc) time of concentration (A) watershed area	(K) Clark coefficient Runoff hydrograph	Clark, 1943
Geomorphologic instantaneous unit hydrograph	RA stream area ration, (RB) bifurcation ration, (RL) stream length ration, (LΩ) length of the high order stream (V) flow velocity at peak discharge (A) catchment area (αΩ) kinematics wave (SΩ) slope of high order stream,	Runoff hydrograph	Rodriguez-Iturbe, L, and Valdes J. B., 1979

4. RESEARCH TOOLS

The model is built by visual basic programming (VB.6) and free OLE Control Extension (ocx) codes such as (Mapwindow and Arcview Shape Files – A Read/Write). Available equations of lag time, time of concentration, excess rainfall, peak discharge and runoff hydrograph are adopted by model. The main windows interface of model can be seen in figures (6) through (9). Figure (6) represents the main window of the program. The delineation output and watershed properties can be seen through this window. Figure (7) explains the excess rainfall for each storm impulse according to the selected rainfall losses method. Figure (8) shows the methods for calculating the time of concentration, lag time, peak discharge and runoff hydrograph. Finally figure (9) the graphical interface of results

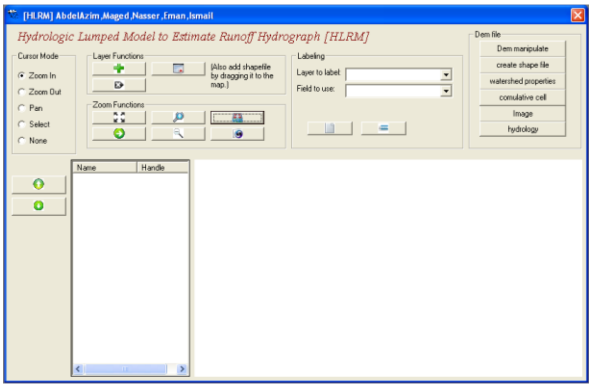

Fig. 6: Main window of developed model

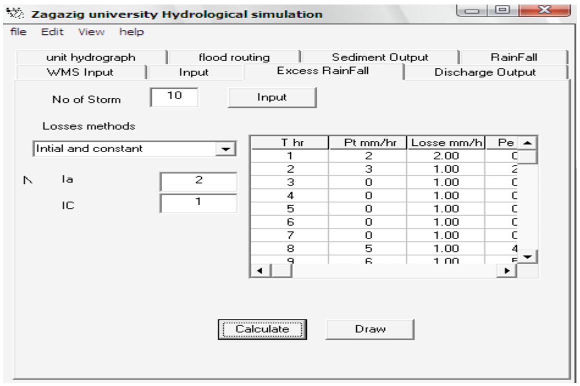

Fig. 7: Excess rainfall window

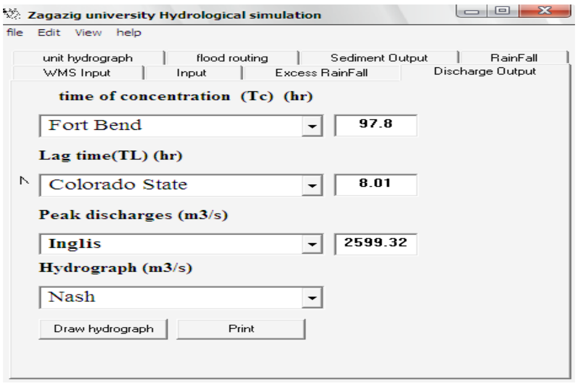

Fig. 8: Lag time, concentration time and runoff hydrograph methods window

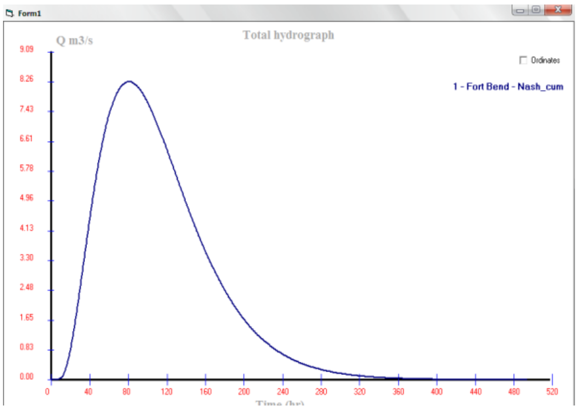

Fig. 9: Runoff graphic window

5. CALIBRATION of DEVELOPED MODEL

The calibration step is vital to check the model output for delineating watershed and calculating runoff hydrograph. Watershed modeling System (WMS) is a well-known hydrologic model was developed by Environmental Modeling Research Laboratory of Brigham Young University. WMS serves as a graphical user interface for several hydrologic and hydraulic models, (WMS, 2008). Hydrologic Engineering Center (HEC) is a lumped model is used during this research as calibrated tools of developed model. A two hypotheses DEMs, rainfall storm and CN losses are used for calibrating the developed model. The delineation of two hypotheses DEM is made by two models as shown in figures (10 to 13). Figure (10 and 12) show the WMS delineation on the other side figure (11 and 13) shows the developed model delineation. It is noticed from these figures that the models delineation is similar and the developed model is an effective tool for delineation process. After delineation process the runoff is computed from two watersheds using a hypotheses storm and curve number losses factor equal 90. The comparison between two hydrographs are shown in figures (16) and (15) for two watershed respectively. It can be clearly seen that, there are an acceptable agreement between developed model and WMS results as shown in figure (16) and figure (17). Figure (16) shows a comparison between the output hydrograph of models, and a good agreement can be noticed. Therefore it can be concluded that, developed model is an effective tool for the simulation watershed area and predicted its hydrograph depend on watershed properties and excess rainfall. The residual values are plotted versus the output of developed model as shown in figure (17). The residuals show a random distribution with a small range between (0.0 and 0.40) around the line of zero. It is very important to measure statistically the ability of developed model as a hydrologic model tool. In this study, statistical analysis has been done using, Microsoft excel (2007) the statistical parameters have been listed in table (2). It can be noticed that, there is an acceptable agreement between two models.

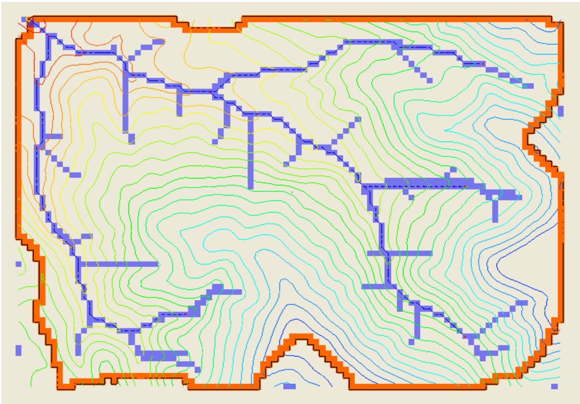

Fig. 10: WMS delineation (case1)

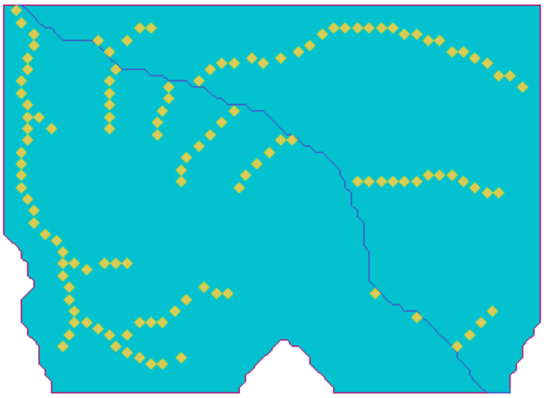

Fig. 11: Developed model delineation (case1)

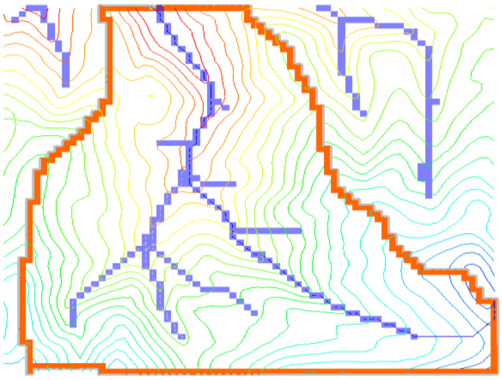

Fig. 12: WMS delineation (case2)

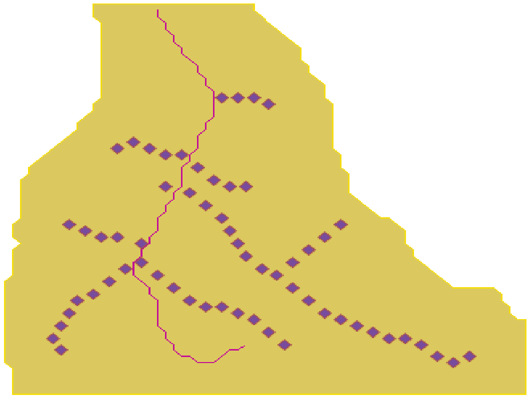

Fig. 13: Developed model delineation (case2)

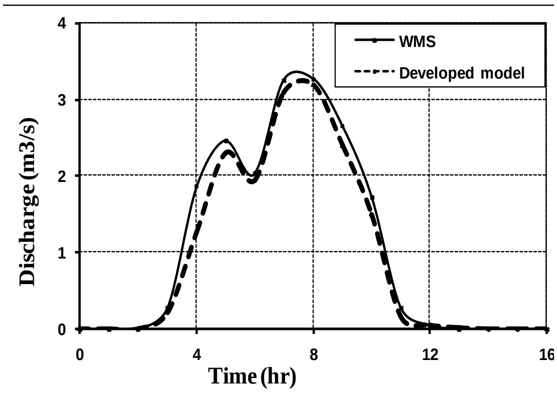

Fig. 14: Comparison between WMS and developed model hydrographs case (1)

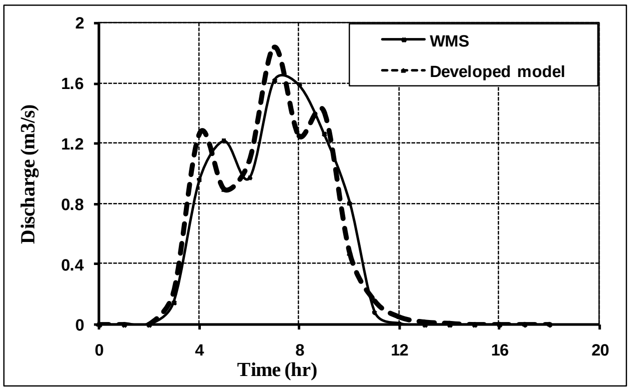

Fig. 15: Comparison between WMS and developed model hydrographs case (2)

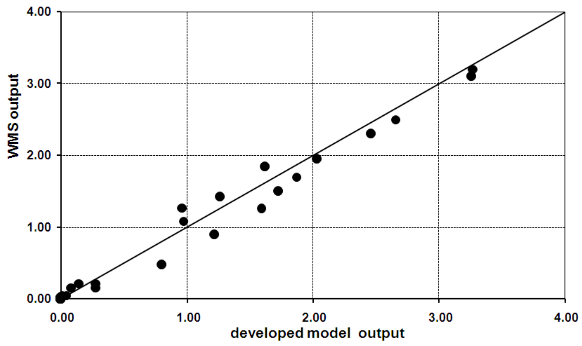

Fig. 16: Comparison between WMS and developed model output (hydrograph)

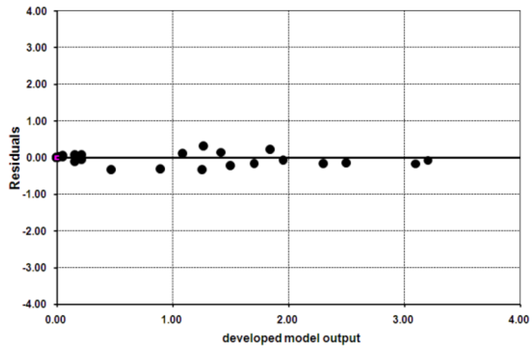

Fig. 17: Variation of residuals for different data sets with developed ones

Table 2 Values of statistical parameters for models comparison (calibration)

parameter	**Name**	**Calibration (velocity)**
Root Mean Square Error	RMSE	2 %
Coeff. of Determination	R^2	99 %

6. APPLICATION OF THE MODEL TO WADI SUDR

Wadi Sudr is the study area which is one of south-west Sinai wadis. It is located between latitudes 29o 35' and 29o 55', and longitudes 32o 40' and 33o 20'. It drains directly in the Gulf of Suez at Sudr town as shown in Figure (19). In the study area there are some stations to measure the rainfall and weather data as shown in Figure (18). This wadi is instrumented by Water Resources Research Institute (WRRI) for Rainfall and runoff measurements since 1989 till now, El-Sayed, (2006) [8]. Figures 24 and 21 show that the max impulse precipitation equals 5 mm and the max corresponding discharges equals 53 m3/s, the storm duration ranged between 7 to 14 hours and the lag time of the study area ranged between 6 -7 hours.

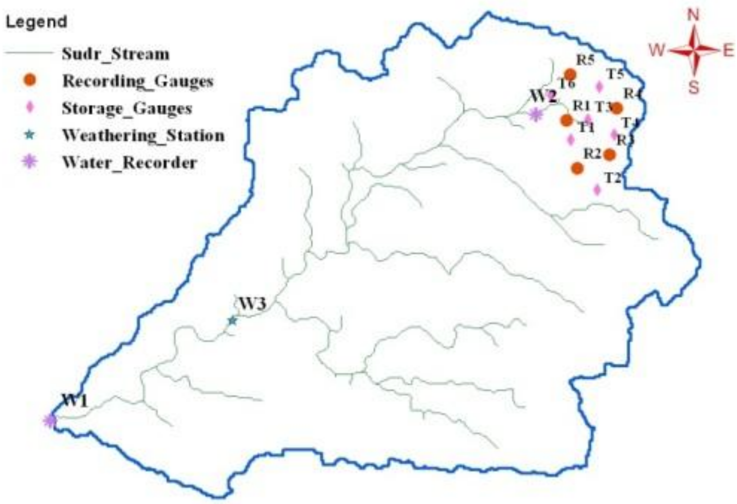

Fig. 18: Locations of rain gauges in WadiSudr watershed, (El-Sayed, 2006).

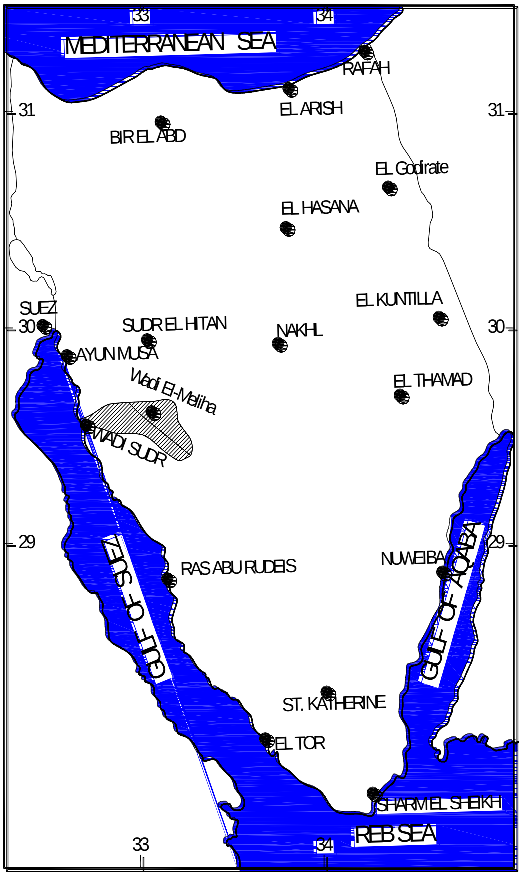

Fig. 19: General location map for Sinai, (Abdelaziz, 2000).

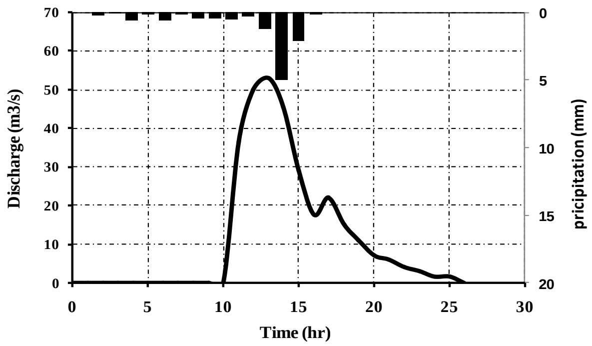

Fig. 20: Observed runoff hydrograph of wadi sudr corresponding to rain fall hyetograph (storm1), (El-Sayed, 2006).

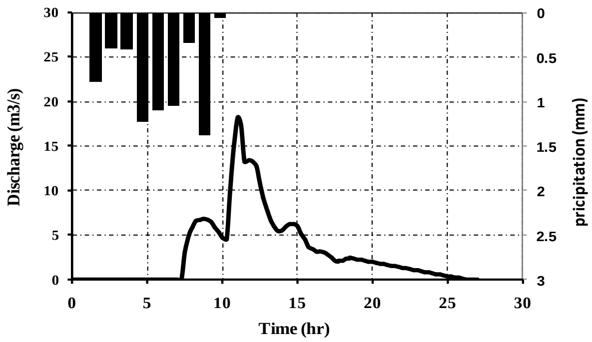

Fig. 21: Observed runoff hydrograph of wadi Sudr corresponding to rain fall hyetograph (storm2), (El-Sayed, 2006).

7. RESULTS AND DISCUSSION

The developed model is applied to one of the field problems. The case study (i.e., Wadi Sudr in Sinai peninsula) is modeled using the developed model. The main goals of the application process can be summarized in the following points:

- The application of the model for detecting the morphological properties of the case study;
- Comparison between the developed model outputs to that detected by WMS; and
- The hydrologic modeling of the case study including runoff hydrograph calculations.

For the present case, the file of topographic data was prepared in a suitable format to be modeled for the delineation process. The delineation of case study (i.e., Wadi Sudr) is done by WMS and developed models as shown in figure (22) and figure (23). The delineation outcomes indicate that the developed model is an accurate delineation tool. A comparison between the two models was done including the delineation outcomes. The comparison parameters were presented in figure (24). In addition, the geometric properties which are calculated using the two models are presented in table (4). It is clear that the maximum difference percentage between two models is (5%). It may be accepted value for this field of application. Two storms were adopted during the present application including storm one and two, see figures (20 to 21). The calculation of the rainfall losses were estimated, see table (3).

Table. 3 Adjusted CN Parameter

Storm	Total rainfall (mm)	Runoff volume (m3)	Excess rainfall (mm)	CN
(1)	11.9951	1089000	2.376847	92.873
(2)	6.756795	300724.9	0.656361	94.11
(3)	5.376731	292320	0.638016	95.62
average				94.201

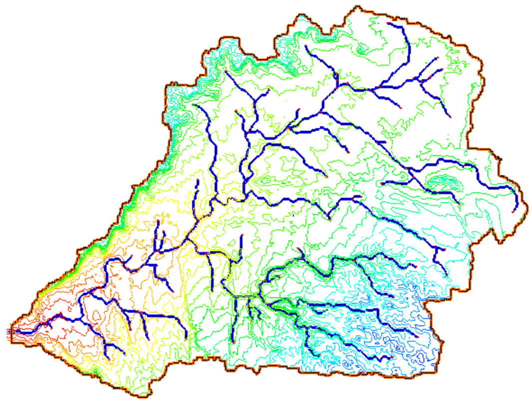

Fig. 22: WMS delineation (case study)

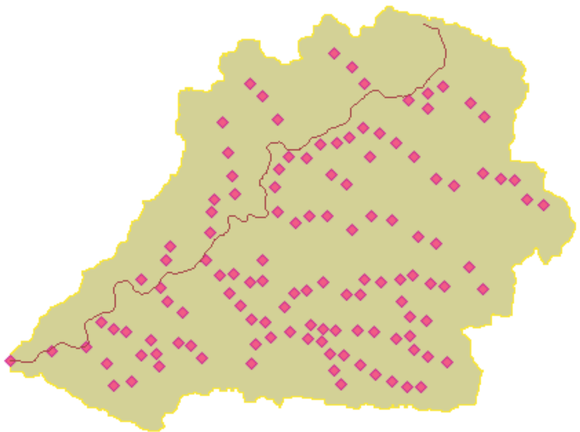

Fig. 23: Developed model delineation (case study)

Table .4 Geometric properties of Wadi sudr using two models

properties	WMS	Developed model
Area (km^2)	458.178	458
(S_0) Average slope of watershed	0.097	0.093
(L) length of main stream (m)	51602.02	51460
(S) Average slope of main stream	0.009	0.0086
(L) length from centroid to outlet (m)	26432.9	26220

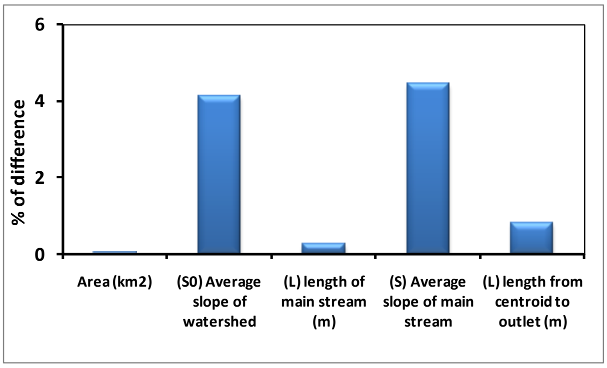

Fig. 24: Percentage of difference between delineation outputs of WMS and developed model (Wadi Sudr)

Depending on each of the calculated losses parameters and rainfall storms, WMS and the developed model are applied to estimate runoff hydrograph of Wadi Sudr using Clark method. The comparison between models results for storm one and two are presented, see figures (25 and 26). It can be seen that, there is an acceptable matching between the two developed hydrograph for the both storms. In fact, the developed model gives a slightly increase for the results more than WMS. The calculated values of peak discharges and time to peak for the two models are compared together as presented in figure (27) and figure (28) respectively. The difference between the two models can be neglected. The statistical analysis is done based on the results of the two models. The statistical results are presented in table (5). The results indicate that the developed model is an active hydrologic tool for predicting the runoff hydrograph for Wadi sudr.

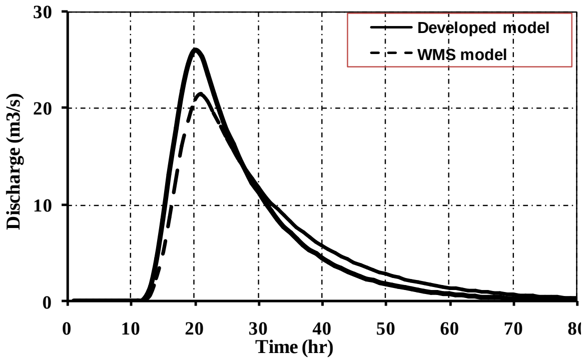

Fig. 25: Comparison between WMS and developed model using Clark equation (storm1)

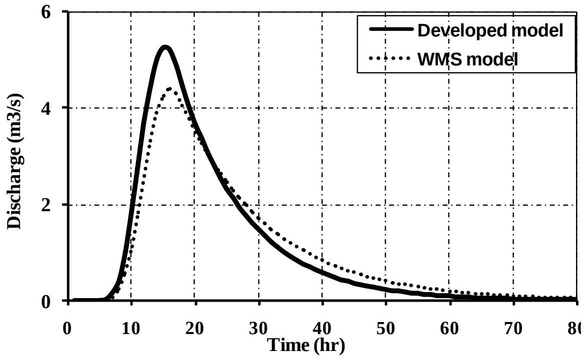

Fig. 26: Comparison between WMS and developed model using Clark equation (storm2)

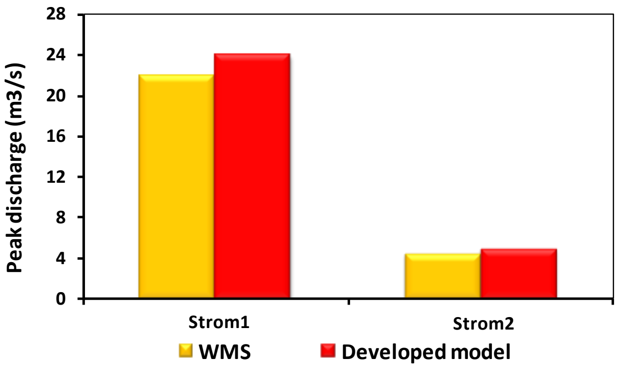

Fig. 27: Comparison between WMS and developed model output (peak discharges)

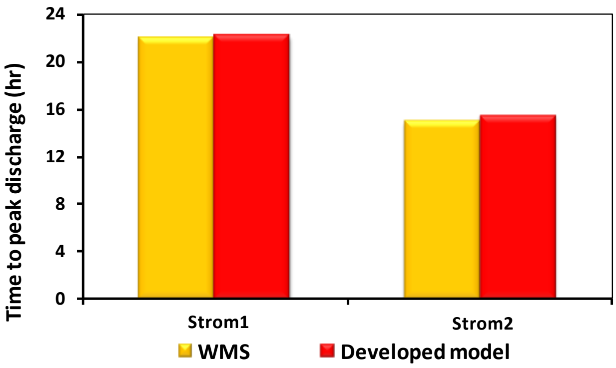

Fig. 28: Comparison between WMS and developed model output (time to peak discharge)

Table 5 Values of Statistical parameters for models comparison (calibration)

parameter	**Name**	**Calibration (velocity)**	**Ideal**
Root Mean Square Error	RMSE	2 %	0 %
Coeff. of Determination	R^2	98 %	100 %

Actually, the developed model is used depending on the default WMS values of Clark's parameter in the previous modeling process. It was necessary to compare between the results of both models. In fact, the main goal of the present study is to determine the hydrologic parameters of the case study for the different available hydrological equations.

There are several hydrologic equations to estimate runoff hydrograph. In the present study three equations are used including:

- Nash equation;
- Clark equation; and
- Geomorphologic instantaneous unit hydrograph (GIUH) equation.

Each of these equations has one or more parameters that must be adjusted before the application process. The procedure for the application process of the developed model to detect the values of the hydrologic parameters for the different equations includes the following steps:

- One of the available two runoff hydrograph was used to detect the optimum values for the different hydrologic parameters for the different equations using the developed models (**calibration process**); and
- The developed model with the detected values from the previous step was checked using the second runoff hydrograph (**validation process**).

For Nash equation the calibration step indicates that the optimum values of the parameters are as following:

- Shape parameter (n) = 2 and
- The scale parameter (k) = 1.27 hr.

The comparison between the developed hydrograph and filed data for the calibration and validation processes can be shown in figure (29) and (30), respectively. The percentages of errors for adjusted parameters of Nash equation are 5% and 6% for peak discharge and lag time, respectively.

For Clark equation the calibration step indicates that the optimum values of the parameters are as following:

- Clark coefficient (K) = 0.2

The comparison between the developed hydrograph and filed data for the calibration and validation processes can be shown in figure (31) and (32), respectively. The percentages of errors for adjusted parameters of Clark equation are 6% and8% for peak discharge and lag time, respectively.

Finally for geomorphologic instantaneous unit hydrograph (GIUH) equation the calibration step indicates that the optimum values of the parameters are as following:

- Stream area ration (RA) = 9 ;
- Bifurcation ration (RB) = 3 ; and
- Stream length ration (RL) =2.65

The comparison between the developed hydrograph and filed data for the calibration and validation processes can be shown in figure (33) and (34), respectively. The percentages of errors for adjusted parameters of GIUH equation are 12% and 6% for peak discharge and lag time, respectively.

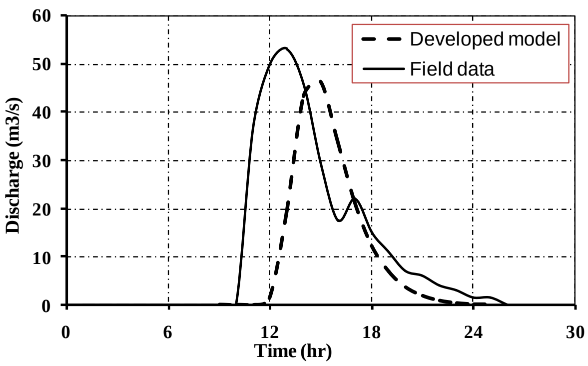

Fig. 29: Comparison between developed model and field data using Nash equation (storm1)

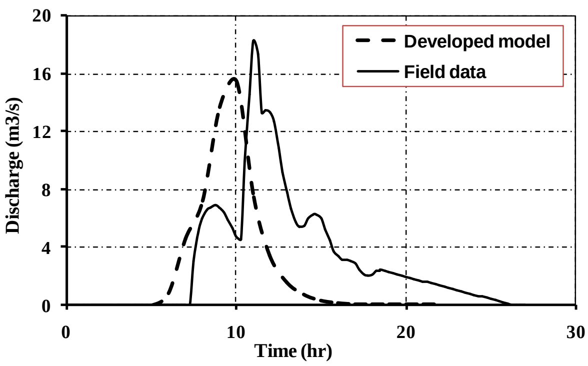

Fig. 30: Comparison between developed model and field data using Nash equation (storm2)

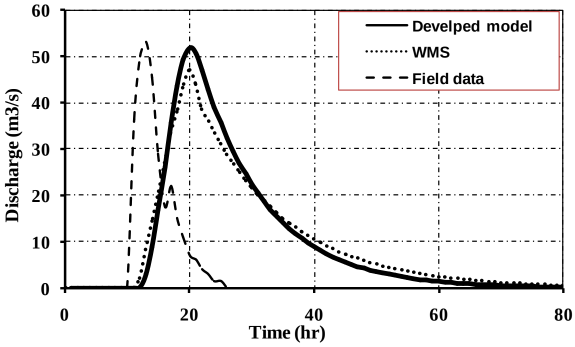

Fig. 31: Comparison between developed model and field data using Clark equation (storm1)

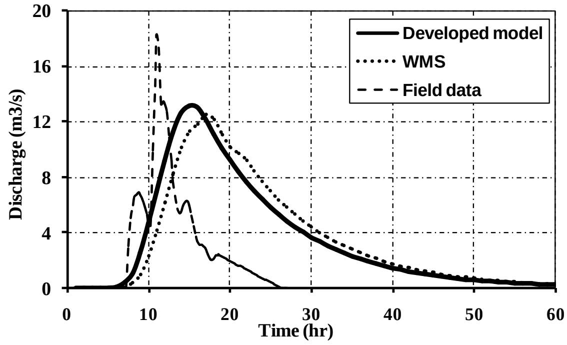

Fig. 32: Comparison between developed model and field data using Clark equation (storm2)

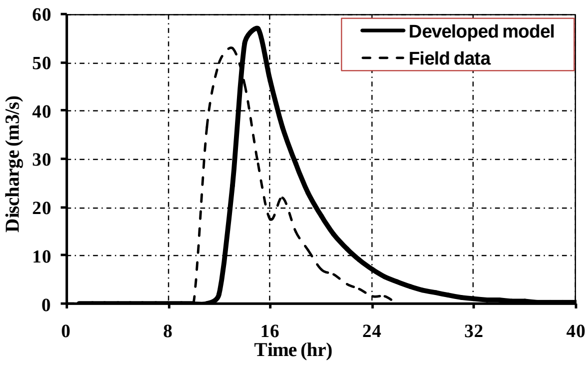

Fig. 33: Comparison between developed model and field data using GIUH equation (storm1)

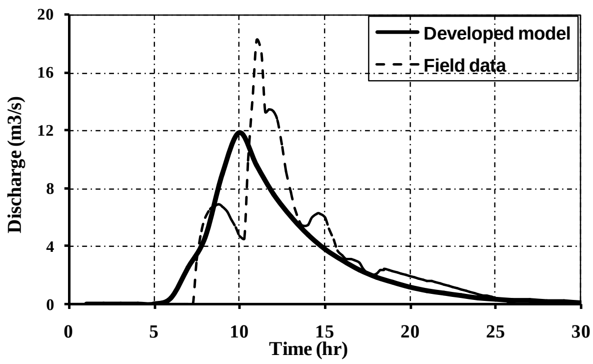

Fig. 34: Comparison between developed model and field data using GIUH equation (storm2)

8. CONCLUSIONS

The analysis and discussions of results presented in this paper using the developed model leaded to the following conclusions:

1- It is found that an acceptable agreements between developed mode results l and the resuts of watershed modeling system (WMS) with root mean square Error of 2 and and coefficient of determination of 99%.

2- The developed model predicts the runoff hydrograph of the study area (Wadi Sudr) accurately and can be used for other similar areas. For areas with different characteristics, the model needs a calibration/verification with localized data .

3- The hydrological parameters of the Wadi Sudr for the different available hydrologic equations are determined.

  a- For Nash equation the calibration step indicates that the optimum value of Shape parameter (n) = 2 and the scale parameter (k) = 1.27 hr.

  b- For Clark equation the optimum value of Clark coefficient (K) = 0.2.

  c- For geomorphologic instantaneous unit hydrograph (GIUH) equation the optimum value of stream area ratio (RA) = 9; bifurcation ratio (RB) = 3 and stream length ratio (RL) =2.65.

RECOMMENDATIONS

1- It is highly recommended to upate and test the performance of the developed model using recent observed data of flash flood whenever necessary data is available.

2- The developed updated model could be tested using different watersheds with different topography, land uses, and rainfall characteristics.

3- The performance and accuracy of the developed model can be improved if a high resolution DEM is used which was not available during this research.

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