HYDROLOGICAL MODELING OF DISTRIBUTED RUNOFF THROUGHOUT COMPARATIVE STUDY BETWEEN SOME ARABIAN WADI BASINS

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The surface flow discharge in the arid regions is characterized by behaviors which are different from the humid areas. A physically-based, distributed hydrological model to estimate wadi runoff and to evaluate initial and transmission losses as well as flood control in the arid regions is proposed. A comparative study has been done between W. Al-Khoud (Oman), W. Ghat (Saudi Arabia) and W. Assiut (Egypt) concerning runoff behaviors to understand the effect of watershed characteristics and climatic conditions on wadi runoff. From the results, the runoff features are affected by the catchments area, slope, as well as rainfall events frequency and duration. The results of numerical simulation exhibit reasonable fit with the observed ones, however, a paucity of high quality data. This approach can satisfactorily evaluate the wadi runoff behaviors such as discontinuously surface flow and estimating transmission losses.

Key Words: *Transmission losses, runoff, wadi system, kinematic wave model, discontinuously surface flow*

1. INTRODUCTION

Infrequent surface water flow in wadi system may cause natural flood hazards but it can be managed to be valuable water resources throughout an appropriate decision support based on effective methodologies. A wadi is an Arabic word which was used to describe ephemeral streams in arid and semi-arid regions[1)]. The ephemeral streams in arid and semi-arid regions are characterized by; the paucity of data on rainfall, flow, soil properties and initial conditions[2),3)]; the lack of high quality observations[4),5)]; the influence of seasonal and inter-annual vegetation variability, and the difficulty of estimating potential evaporation[6)]; complexity of channel morphology[7)]; much higher flow variability, extended periods of zero surface flow and the general absence of low flows except during the recession periods[8)]; and the behavior of flow discharge takes short time to reach the maximum peak[3)]. Problems, implications and features of rainfall-runoff modeling in arid areas are given in many reviews[5),9),10),11),12),13)]. Transmission loss in the arid regions has been discussed in different literatures[14),15),16),17)18)], where the rate of loss is linearly related to the volume of surface discharge.

Effective water management and utilization of wadi surface flow based on availability of the data are urgently needed. So, in this study, a trial is made to develop an effective methodology for estimation spatiotemporal surface runoff in wadi system through comparative study between some different Arabian wadi basins as well as to evaluate initial and transmission losses and their effect on both surface and subsurface water.

2. THE TARGET WADI BASINS

The selected wadi basins are W. Al-khoud, Oman, W. Ghat in Saudi Arabia, and W. Assiut, Egypt. W. Al-khoud is located between long: 57° 58′ W & 58° 02 E ′ and lat: 24° 00′ N & 23° 00 S ′. W. Ghat is located between long: 41° 46′ W & 42° 10 E ′ and lat: 19° 20′ N & 19° 00 S ′. W. Assiut is located between long: 32°30′ E & 31°12 W ′ and lat: 27°48′ N & 27°00 S ′ as shown in Fig 1. Their catchment areas are 1874.84 km2, 649.55 km2 and 7109 km2, respectively. They are characterized with topographic features varying from mountains to plain areas. Elevations range from 20 m to 2000 m in W. Al-Khoud and W. Ghat but W. Assiut varies from 20 to 900m.

3. METHODOLOGY

A physical-based distributed hydrological model to evaluate wadi runoff features in addition to estimate initial and transmission loss in wadi system is introduced. It is based on modification of Hydro-BEAM (Hydrological River Basin Environmental Assessment Model) which was first developed by Kojiri et al.[19]. It consists mainly of: the watershed modeling using GIS technique, surface runoff and stream routing modeling based on using the kinematic wave model, the initial and transmission loss modeling is estimated by using SCS method[20] and Walter's equation[14], and groundwater modeling based on the linear storage model as depicted in Fig. 2.

The original Hydro-BEAM was adopted for simulation in the arid areas in wadi system as described in the following sections. The watershed to be investigated is modeled as a uniform array of multi-layered mesh cells.

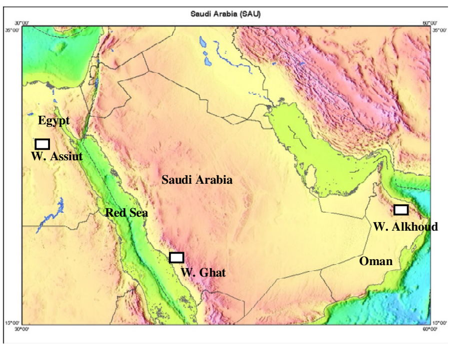

Fig.1 Location map of W. Al-Khoud, Oman, W. Ghat, Saudi Arabia, W. Assiut, Egypt[21].

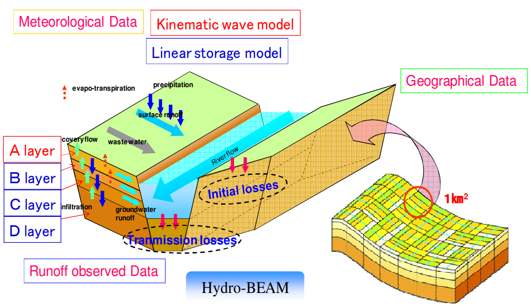

Fig. 2 Conceptual model of Hydro-BEAM

They are four layers, labeled A, B, C and D. A-layer and overland flow is calibrated using the integrated kinematic wave model. B-D layers are the subsurface layers, which are evaluated using linear storage model. Initial and transmission losses are evaluated as the subroutine model in Hydro-BEAM.

(1) Watershed modeling

The data of digital elevation model (DEM) was processed using Arcview GIS to delineate and determine the watershed and stream networks of the target wadi basins. The land use data of the world, GLCC (Global Land Cover Characterization) and ECOCLIMAP Data (a global database of land and surface parameters) were used for identify the land use types. The global data are reclassified into 5 types as follow; Forests, field, desert, city, water.

(2) Climatic data

The global climatic data of National Climatic Data Center (NCDC) have been used. Thornthwaite method is used to calculate daily mean potential evapotranspiration as given in Eqs. (1), (2), and (3).

$$E_p = 0.553 D_0 \left(\frac{10 T_i}{J} \right)^a , \quad J = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.514} \qquad (1)$$

$$a = 0.000000675 J^3 - 0.0000771 J^2 + 0.01792 J + 0.049293 \qquad (2)$$

$$E_a = M \times E_p \qquad (3)$$

Where, E_a, and E_p (mm/d) are the actual and the potential evapotranspiration; T_i (0^C) is the monthly average temperature, J: is the heat index, D_0 (h/12h) is the potential day duration and M is the reduction coefficient.

(3) The kinematic wave model

The kinematic wave runoff model is applied for surface runoff and stream routing modeling under the assumption of the river channel triangle cross section. In Hydro-BEAM, the integrated model of kinematic wave is used for overland flow and A-layer flow as expressed in Eqs. (4), (5), and (6).

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r(x,t) \qquad (4)$$

$$q = \begin{pmatrix} \alpha (h - d)^m + ah \\ ah \end{pmatrix}, \quad when \begin{pmatrix} h \ge d \\ h < d \end{pmatrix}, d = \lambda D \qquad (5)$$

$$\alpha = \frac{\sqrt{\sin\theta}}{n} (Manning\ Eq.), a = \frac{k \sin\theta}{\lambda} (Darcy\ Eq.) \quad (6)$$

Where, h is the water depth (m), q is the discharge per unit length of flow [m^3/m.s], r is the effective rainfall intensity [m/s], t is the time [s], x is the distance from the upstream edge, and α, m is constant concerning frictions, λ is the porosity, D is the thickness (m), and d is the saturation pondage (m),

(4) Linear storage model

Linear storage model as given in Eq. 7 is used for modeling of groundwater in layers B, C, and D layers in each mesh of the studied wadis.

$$\frac{dS}{dt} = I - O, \text{ where, } O = (k_1 + k_2) \cdot S \tag{7}$$

Where S is storage amount [m], I is inflow [ms^{-1}], O is outflow [ms^{-1}], k_1, k_2 are outlet coefficients.

(5) Initial and transmission losses model

Due to the importance of the loss in the arid areas, the initial and transmission losses models were incorporated to Hydro-BEAM.

a) Initial losses

The SCS method[20] is adopted to calculate initial losses in the target catchments. Runoff in sub-basins occurs after rainfall exceeds an initial abstraction (I_a) value. Rainfall excess, P_e, is related to the effective potential retention value (S) as given in Eq. (10). The optimum values of λ were obtained in the least squares fitting procedure were around 0.05 for most experimental plots which were observed by Hawkins et al.[22]. Therefore, it was decided to set it as 0.05 in this study. The initial abstraction λ is a function of potential maximum retention S. S is a function in curve number (CN) which can be evaluated based on the land use or soil types as given in Eqs. (11) and (12).

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{8}$$

$$CN = \frac{25400}{254 + S} \tag{9}$$

$$I_a = \lambda S \tag{10}$$

Where P is the depth of rainfall (mm), P_e is the depth of runoff or excess rainfall (mm), I_a is the initial abstraction (mm), S is the maximum potential retention after runoff begins (mm), λ is a dimensionless parameter varying from 0 to 1, and CN is the curve number.

b) Transmission losses

A regression model form was developed to assess transmission losses[14] as given in Eq. (13). Unit of the equation was converted from (acre-ft) into metric unit (cubic meter). The equation was adopted in this study to estimate transmission loss in each mesh based on the flow direction from the upstream to the downstream point.

$$V_1 = 0.026 V_A^{0.872} \tag{10}$$

Where V_1 is the transmission loss for first kilometer (m^3), V_A is the upstream flow volume (m^3).

4. NUMERICAL SIMULATION

The simulation have been done using the modified Hydro-BEAM and based on the availability of observed and climatic data in the target wadi basins. The simulation periods have been chosen throughout the first half of 2007 in W. Al-Khoud. The watershed modeling of the selected wadis are processed based on DEM using GIS. The land use types was reclassified from the global data into five categories; forests, field, desert, city and water. In arid regions, desert is the dominant but the others are the scarce in occurrence. The simulated results of surface flow discharge in the studied wadi basins exhibit that discharge behaviors are different from the humid areas. It is characterized by the shorten time in the start and the end of the flood event. In other words, it is showing extremely steep rising and rapid recessing during the same event.

The simulated discharges coincide in their characteristics with the observed ones in W. Al-Khoud as depicted in Fig.3. One of the important merits of this work is evaluating multiple consequent storm events in spite of their including long dry periods between the events. The first event was in March 18, 2007, where the maximum peaks of the observed and simulated runoff are 950m^3/s and 838m^3/s, respectively, as in Fig. 4. The second event was in June 6, 2007. The maximum peaks of the observed and simulated hydrographs are 1185 m3/s and 1200 m3/s respectively as in Fig. 5. Both events are strong storms and they are showing satisfied fitting in their behaviors.

A sensitivity analysis of the model parameters have been done to get the optimal solution by trial-error calibration method. The optimal calibrated results show that RMSE= 14.580 and R^2 =0.8897 which imply the reasonable model performance in terms of matching surface runoff volume, peak flow and time to peak for the selected period of simulation.

These results declared that the difference between performance of the original hydro-BEAM comparing with the modified one in arid regions as shown in Fig.6 where the results of simulation is entirely disagree with the observed runoff and simulated hydrograph limbs are not steep as in the observed one. It is obvious that the importance of incorporating a new scheme of initial and transmission loss into Hydro-BEAM as well as the identified parameters for Wadi system.

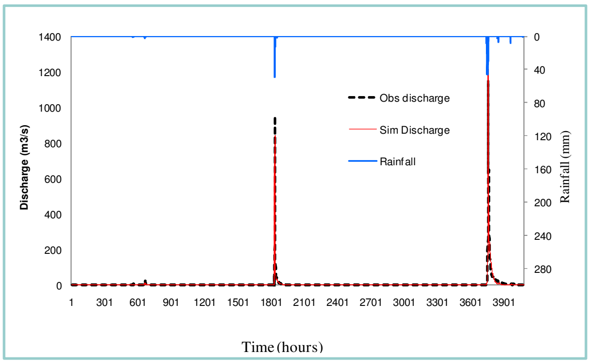

Fig.3 Hourly hydrographs of simulated and observed discharges of the simulated periods in wadi Al-Khoud.

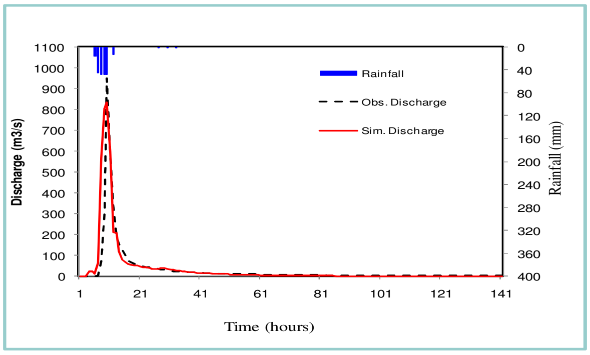

Fig.4 Hourly hydrographs of simulated and observed discharges in wadi Al-Khoud during (Mar. 18- 2007)

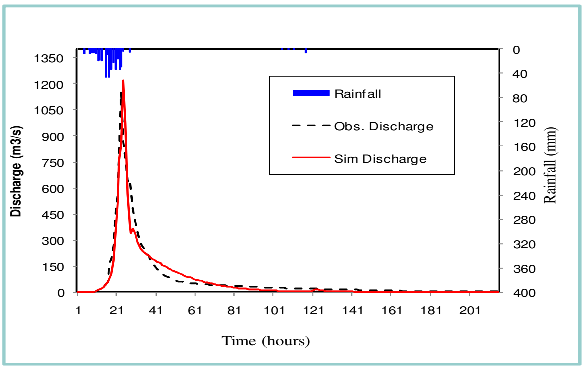

Fig.5 Hourly hydrographs of simulated and observed discharges in wadi Al-Khoud during (Jun. 6- 2007)

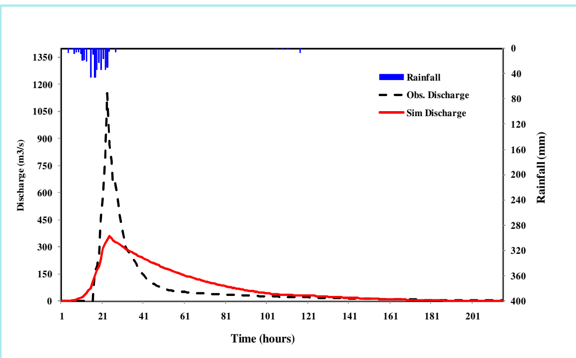

Fig.6 Hourly hydrographs of simulated and observed discharges by using the original Hydro-BEAM (Jun. 6- 2007)

The distribution maps of surface runoff in wadi Al-Khoud reveal spatiotemporal behaviors of wadi flow during the different stages of the hydrographs. For instance, at the early stage of flow or rising of the hydrograph limb toward the maximum peak, discontinuously surface flow appeared and with increasing the flow rate, the discontinuously surface flow will be connected until reaching to the maximum flow and then in the stage of ascending of hydrograph, it will disappear again until the flow will be zero flow as represented in Fig.7.

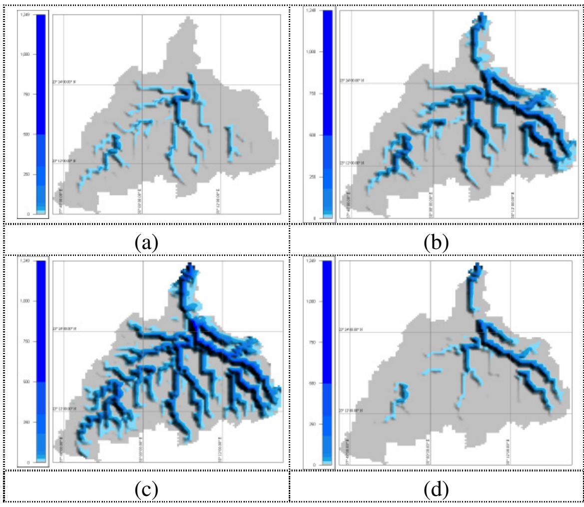

Fig.7 Distribution maps of surface runoff of (Mar. 18, 2007) event, (a) Early stage of surface flow, (b) hydrograph is rising toward the maximum peak of discharge, (c) reaching to the maximum of distribution, (d) starting the recession of surface flow to zero flow.

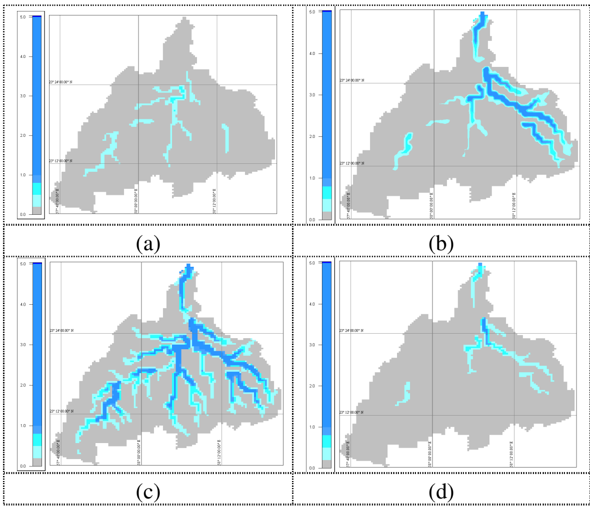

Fig.8 Distribution maps of transmission losses of event of (Mar. 18, 2007), (a) Early stage of transmission losses, (b) hydrograph is rising toward the maximum peak of transmission losses, (c) reaching to the maximum of distribution; (d) starting the recession of transmission losses to zero value.

Transmission losses were evaluated simultaneously with runoff simulation by using Walter's equation. The results of simulation reveal that transmission losses are affected by the volume of surface runoff as evidence that the rate of losses is linearly related to the volume of surface discharge which is similar to the conclusion of Walters and Jordan[14), 7)]. The distribution maps of transmission losses show the same behaviors as runoff due to the relationship between both of them which reflects the discontinuously occurrence as shown in Fig. 8.

The proposed approach is also applied by the way of comparative study between both of W. Ghat in Saudi Arabia, and in W. Assiut in Egypt as well as W. Al-Khoud, however, the lack of observed data. W. Ghat and W. Assiut simulation results exhibit the same characteristics of runoff at W. Al-Khoud. Surface runoff hydrographs show steep rising and rapid ascending where the maximum peaks of discharge are 36m^3/s and 12.52m^3/s respectively. But, time to peak of discharge and duration of flow are much longer in wadi Assiut than those of W. Al-Khoud and W. Ghat because the catchment area is larger and the catchment slope is gentler as shown in Fig. 9 and Fig. 10. It is deduced that from the available climatic data, the average of rainfall events in W. Al-Khoud is the multiple events every year which are more frequent than those of W. Ghat and W. Assiut which is one event every two years and one event every five years, respectively.

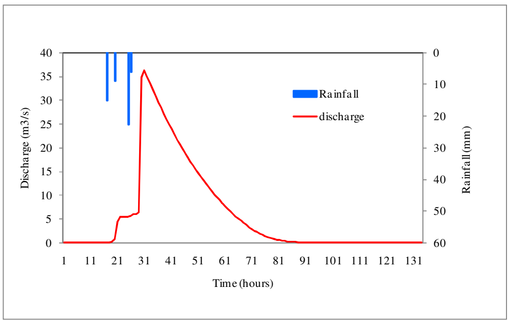

Fig.9 Hourly hydrograph of simulated discharge in W. Ghat during (May 11, 1982).

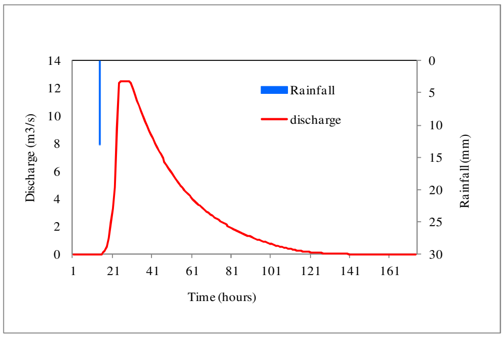

Fig.10 Hourly hydrograph of simulated discharge in W. Assiut during (Nov. 2-5, 1994).

Table 1 Results of simulation of the three basins

	W. Khoud	W. Ghat	W. Assiut
Area (km^2)	1874.84	649.55	7109
Slope	Steep	Steep	Gentle
Peak of disch.	838 m^3/s	36 m^3/s	12. 5m^3/s
Time to peak	4-7 hrs	14 hrs	10 hrs
Flow duration	44 hrs	60 hrs	106 hrs
Runoff	88.98%	86.22%	92.47%
Init. & T.losses	11.02%	13.78%	7.53%

Throughout the comparative studies between them, it is deduced that they are exhibiting similar behaviors concerning surface runoff characteristics where surface runoff hydrographs show steep rising and rapid ascending. Moreover, they are depicting discontinuously surface flow at the early and lately stages of rising and ascending of hydrographs. The runoff behaviors are extremely affected by some factors such as the catchment area and slope which have a significant effect on the peak of discharge, time to the peak, and duration of flow. For instances, in W. Al-Khoud and W. Ghat, the area is smaller than W. Assiut but the discharge is higher at the downstream points of both of them because they are more steeper than W. Assiut which have a significant effect on the travel time to reach the outlet point and consequently the peak discharge time to peak will be earlier than wadi Assiut.

Also, the catchment area of W. Assiut is larger than the other two catchments which imply that the travel time of flow will be longer in W.Assiut than the others. Duration of flow is also variable as reported in table 1 where in W. Assiut, it is longer than the other two wadis, however the flow is low comparing with the others due to the catchment conditions as prescribed.

5. SUMMARY AND CONCLUSION

A Physically-based, distributed hydrological model for wadi system has been developed to simulate the surface runoff and transmission loss in the ephemeral streams throughout comparative studies between the selected wadi basins. It is concluded that the simulated runoff are completely coincide in their behaviors with the monitored one that prove an appropriate performance of the proposed model to predict the future flood events. From the distribution maps of surface runoff in the wadi system, the discontinuously surface flow is perfectly depicted as one of the most import characteristics of ephemeral streams. Transmission loss is affected by the volume of surface runoff as evidence that the rate of losses is linearly related to the volume of surface discharge.

A comparative study between some Arabian wadis has been done. Results of simulation declared that the runoff features are affected by the catchments area, slope, and rainfall events frequency and duration as listed in Table 1. Runoff features in the ephemeral streams are characterized by different behaviors from the runoff in the humid area based on the results as follow: i)-There is a time lag between hyetograph and hydrograph peaks. ii)-Flood event time including starting and cessation is short. iii)-Initial and transmission losses are considered the main source of subsurface water recharge. iv)-discontinuously surface flow in space and time occurrence.

It is concluded that the proposed approach is considered an applicable methodology in the arid areas and consequently a vital contribution to estimate distributed surface runoff and transmission losses in the other arid regions. Regional application for the proposed model in other arid regions for flash flood prediction purpose is our future research.

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