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RAINFALL-RUNOFF MODELING FOR EXTREME FLASH FLOODS IN WADI SAMAIL, OMAN

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Flash flood forecasting is indispensable to construct efficient warning and mitigation of the increasing threat of flash floods in wadi systems. Flash floods modeling in arid region is hindered by the lack of appropriate hydrological models and data availability. Rainfall-Runoff-Inundation (RRI) model is applied in Wadi Samail as a case study for the most extreme flash flood events in Oman (1,000 year return period). Detailed sensitivity analysis were conducted for RRI model parameters indicating that the channel and hillslope roughness coefficients are the most significant parameters followed by the soil characteristics parameters such as soil depth, porosity and hydraulic conductivity. The most severe tropical cyclone in the recent history in Oman, Gonu-2007 and Phet-2010 were used to calibrate and validate the hydrological model. The results and the statistical analysis indicating that RRI model could efficiently simulate the extreme flash flood events in the arid wadi system. Where for model calibration, Nash-Sutcliffe efficiency (*NSE*) and Percent bias (*PBIAS*) indices equal to 0.93 and -14.3, respectively, and for model validation *NSE* and *PBIAS* equal to 0.86 and -12.0, respectively. Further improvements in RRI model is recommended to include the transmission losses and groundwater processes for better representation of the wadi system.

Key Words : *Flash floods, wadi, RRI, arid environments, hydrological modelling, extreme events*

1. INTRODUCTION

In wadi system, flash floods are among the most devastating natural hazards in terms of human losses and economical damages[1)]. However, the flood is an important source of water for such arid environments as wadi system. Wadi is an Arabic term, which refers to a valley and usually its channel is dry except during heavy rain events[2)]. It can be used to describe the ephemeral streams in arid regions. Flash flood is characterized by its quick occurrence resulting in a very limited opportunity for warnings to be prepared and issued[3)].

Recently in the arid region, Wadi Flash Floods (WFFs) are frequently occurring. Oman is one example where various challenges to manage this devastating natural hazard existed. It is an arid country with an average annual rainfall, throughout most of the country, less than 100 mm[3)]. Severe damages occurred in Oman in 1989, 1997, 2002, 2003, 2007, 2010, 2015 and 2016[3)] due to WFFs. The most extreme rainfall events occurred in Oman are due to Gonu-2007 and Phet-2010 tropical cyclones[4)], where both cyclones caused 56 fatalities with 6 billion USD of economic losses in Oman. Wadi Samail (W. Samail) is one of the main wadis in Oman which has experienced flash floods with major damages[1)] and selected as a case study for this research. Detailed hydrological studies are urgently needed to the WFFs risk and propose efficient countermeasures.

There are several hydrological models developed over the years to predict rainfall-runoff processes considering the interaction with the subsurface layers and simulate flood routing through the river networks. Rainfall-runoff modeling in wadi system is a complicated and challenging problem since we have to consider various interconnected variables and processes. The unique hydrological characteristics of the arid wadis include high spatial and temporal storm variability, high evaporation rate, lack of vegetation cover, low infiltration capacity of the poorly vegetated soils and exposed rocks, absence of base flow, intermittent channel flow and significant transmission losses through the wadi channels. Most of WFFs related studies are usually hindered by unsuitable models for arid regions and ungauged wadi (limited data). Surface runoff pattern is inimitable in the arid wadi basin, where an extensive overland flow can be generated from high intensity and short duration rainfall event. This surface flow is intensified by the topography and converges on the wadi channel network, usually resulted in flood flow over a bed that was initially dry. Consequently, hydrographs are typically characterized by extremely rapid rise.

None of the indirect regional methods provide accurate predictions of flood peaks in arid catchments, whereas the synthetic hydrograph methods are incompatible with the morphological and meteorological characteristics of wadi systems, which limits the use of the unit hydrograph model[1]. The distributed hydrologic models can possibly have the same performance or outperform the calibrated lumped models and can be consisted with the regional analysis methods in the arid or ungauged basins[1]. However, some of the distributed models' representation of the physical condition of the basin are not compatible with the wadi condition. Hence, the need to evaluate the suitability of alternative modelling approaches for wadi system and its scarce dataset arises.

In that regard, Rainfall-Runoff-Inundation (RRI) Model[5] is selected in this study to evaluate its applicability and performance in WFFs prediction. RRI model can represent several physical conditions of the flow, such as infiltration excess flow, saturation excess flow and the interaction between the inundation in the floodplain and the wadi channel. As far as we know, and after a detailed literature review, this is the first time for the RRI model to be applied in wadi system, so this study is very important to test the applicability of the RRI model in wadi system and arid or semi-arid environments. Furthermore, a sensitivity analysis was conducted to the parameters of RRI model that can help the wadi hydrologists. Where highlighted sensitive parameters and the established parameters range can be used as a guide for an efficient and reliable application of RRI model and other hydrological models in the wadi system.

2. TARGET STUDY AREA

W. Samail is located in the north coast of Oman (**Fig.1**) where Oman WFFs mainly occur in the coastal basins. Its outlet is 40 km of Muscat, which is the fastest growing city in Oman where most of the main channels have been occupied by urban and development. W. Samail total area is 1741 km^2 and characterized by a high range of relief with elevation ranges from 2462 m above sea level (with slopes reached to 76% at the hill slope), to sea level at the downstream. The general slope direction is toward

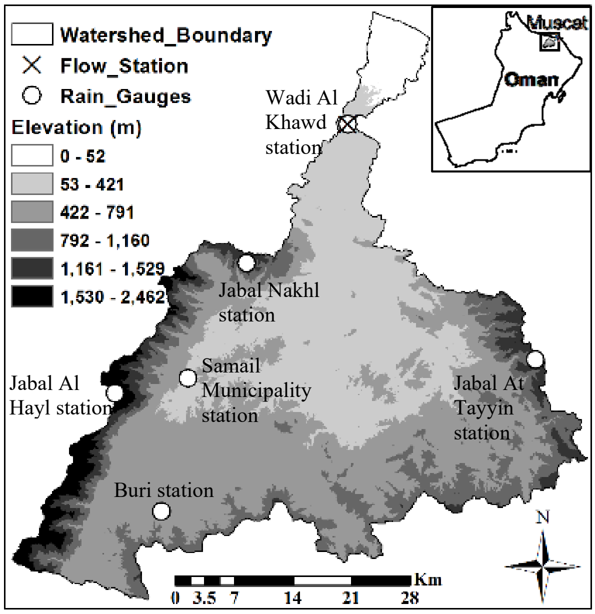

Fig.1 W. Samail location map in Oman, its digital elevation model and the measurements stations.

the north discharging the flow into the Arabian Gulf. The wadi channel bed materials are mainly gravel and sands with weak base flow mainly at the downstream originated from groundwater seepage. Land cover is mainly bare rock with sparse vegetation.

Comparing to much of the Arabian Gulf area, availability of rainfall and flow data for W. Samail is reasonable[6]. There are 6 rainfall gauges with annual average rainfall ranges from 100 mm at Al Khawd station to 212 mm at Jabal Al Hayl station[4]. The target area studied by many authors[1)7)]. As a result of increasing pressure of population, and unmanaged development, people started cultivation of new lands, even building their houses at more prone areas for flash floods in W. Samail. Therefore, there are increasing risk of flash floods in W. Samail and more hydrological studies to assess this rising risk are highly needed.

3. DATA AND METHODS

Remote sensing data (e.g., Digital Elevation Model (DEM) data) as well as Geographic Information Systems (GIS) techniques (e.g., spatial analysis, interpolation and watershed delineation tools) have been used for input data preprocessing and visualization of the results. RRI has been utilized to simulate several WFFs events. RRI model is a hydrological model[5], which was usually used for humid areas and it is the first time to be applied in wadi system. The model deals with slopes and river channels separately. The flow on the slope grid cells is calculated with the 2D diffusive wave model, while the channel flow is calculated with the 1D diffusive wave model.

Table 1 RRI model's major parameter description and setting for the different flow governing cases.

Parameter (case)	Definition	Units	Default	Range	Process	Calibration		
						Alluvium	Igneous	Sedimentary
n_{river} (a,b,c)	Channel roughness coefficient	$m^{-1/3}s$	0.03	0.015 - 0.04	Channel	0.022	0.022	0.022
n_{slope} (a,b,c)	Hillslope roughness coefficient	$m^{-1/3}s$	0.3	0.15 - 1.0	Runoff	0.3	0.35	0.3
d (b,c)	Soil depth	m	1.0	0.1 - 2.0	Soil	2.0	0.7	1.0
φ (b,c)	Soil porosity	-	0.475	0.05 - 0.6	Soil	0.475	0.2	0.3
k_v (b)	Vertical saturated hydraulic conductivity	ms^{-1}	5.56×10^{-7}	6.54×10^{-5}-1.67×10^{-7}	Soil	4×10^{-6}	-	-
S_f (b)	Suction at the vertical wetting front	m	0.3163	0.0495 - 0.3163	Soil	0.15	-	-
k (c)	Lateral saturated hydraulic conductivity	ms^{-1}	0.1	0.01 - 0.3	Soil	-	0.05	0.05
φ_u (c)	Unsaturation effective porosity	-	0	0.02 - 0.4	Soil	-	0.1	0.1

(case) RRI model governing case, to show in which flow case each parameter is contributing: (a) surface runoff only, (b) infiltration excess surface runoff and (c) saturation excess surface runoff and unsaturated subsurface runoff

RRI model has three flow cases or assumptions for each basin mesh and based on the soil/land use properties as follows: a) surface runoff only, b) infiltration excess surface runoff and Green-Ampt model for vertical infiltration and c) saturation excess surface runoff and unsaturated subsurface runoff.

A sensitivity analysis is implemented to evaluate the weight of the several controlling parameters using the above mentioned three model configurations. The parameter setting range is based on literature review and field investigation. This model was calibrated using Wadi Al Khawd flow gauge station **(Fig.1)**.

(1) Input Data

a) Rainfall data

As mentioned before, we have 6 rainfall gauges (**Fig.1**) at W. Samail that cover the target flood events and interpolated all over the watershed using Thiessen method to be utilized for RRI model calibration. As for the sensitivity analysis, only one rainfall gauge (Jabal Nakhl) for Gonu-2007 applied homogeneously through the basin. This station has the median Gonu-2007 total rainfall between the available gauges.

b) Topographic data& Watershed delineation

Topographic data were obtained by the Shuttle Radar Topography Mission (SRTM) data[8]. This study used HydroSHEDS[9] data, including its flow-direction and flow-accumulation products. These data sets are utilized for identifying the streams location and watershed boundary. They are considered as one of the best topographic data sets that are globally available for flood inundation simulation[10]. The used topographic data are 30-s resolution.

c) Land use

Based on the study area geology[4], the land use can be classified into three land uses. Two classes are igneous rock (mainly ophiolite) and sedimentary rock (mainly limestone) that have high relief and slope with very shallow soil depth. The third land use class is alluvium that is mainly located in the downstream part with low slope and higher soil depth.

4. RRI MODEL APPLICATION

RRI model has been applied for extreme flash floods simulation in W. Samail after its calibration and validation. Flood estimation was performed on an hourly basis to be able to reproduce the rapid WFFs events. For the channel cross-sections settings, we used surveyed data at two locations; one is at the upstream and the other is in the downstream in addition to Google Earth images and SRTM-1s DEM to estimate the channel width (W) and depth (D) parameters using the upstream area (A) information, where $W=C_W\ A^{SW}$ and $D=C_D\ A^{SD}$ (C_W=1.0, S_W=0.68, C_D=0.525 and S_D=0.24). The model calibration was suggested after making sensitivity analysis to detect the weight of each parameter on the calculated results and the most sensitive parameters. More than 1000 manual runs were implemented. Later Gonu-2007 and Phet-2010 tropical cyclones are used for RRI model calibration and validation, respectively.

Major sensitive RRI model parameters setting is indicated in **Table 1**, while the mountainous land use, including the igneous and sedimentary rocks, are governed by subsurface and the surface flow assumption (case-c), the alluvium land use is governed by the Green-Ampt model (case-b). To evaluate their effects on the predicted river discharges, we used the following five indices: Relative hydrograph peak error (PE)[11], Coefficient of determination or squared correlation coefficient (r^2, describe the degree of collinearity between simulated and measured data)[11], Percent bias ($PBIAS$, measures the average tendency of the simulated data to be larger or smaller than their observed counterparts)[11], Nash-Sutcliffe efficiency (NSE, indicates how well the plot of observed versus simulated data fits the 1:1 line)[12], Kling-Gupta efficiency (KGE, equally weight the three components bias, variability and correlation to improve the estimation of the performance error)[11].

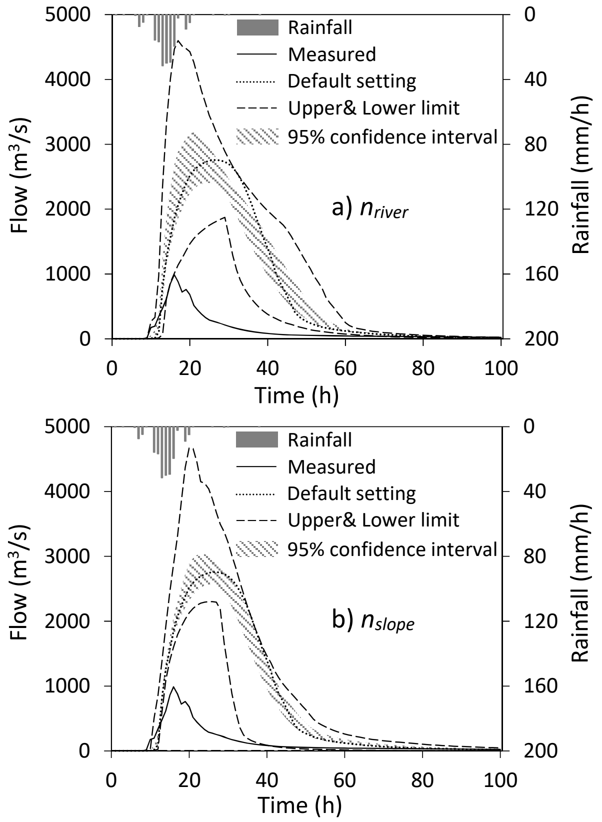

Fig.2 Variations of simulated hydrographs in W. Samail during Gonu-2007 event (Jabal Nakhl rainfall station) under different RRI parameters setting: a) channel roughness coefficient (n_{river}) and b) hillslope roughness coefficient (n_{slope}) at the first flow case assumption, which is surface runoff only.

5. RESULTS AND DISCUSSION

(1) RRI model parameters sensitivity analysis

Sensitivity analysis for RRI model was conducted in W. Samail to measure the relative significance of each model parameter in determining the output hydrograph peak and shape, as indicated in **Fig.2**, **Fig.3** and **Fig.4** the different flow cases. The measured flow is overestimated by the simulated hydrographs because the sensitivity analysis was performed using the simple one-factor-at-a-time method that change only one parameter during each simulation and maintain the other parameters to the default setting, where the simulated hydrograph using RRI default setting originally overestimate the observed flow as shown in in **Fig.2**, **Fig.3** and **Fig.4**.

According to results from sensitivity analysis, the most significant parameters in all flow cases are channel roughness coefficient (n_{river}) and hillslope roughness coefficient (n_{slope}). As for RRI case-b and case-c, the soil depth (d), and soil porosity (φ) are the second most significant parameters after the roughness coefficients. While vertical saturated hydraulic conductivity (k_v), lateral saturated hydraulic conductivity (k) and unsaturation effective porosity (φ_u) have a medium impact on the generated hydrographs. The suction at the vertical wetting front (S_f) and the lateral unsaturated hydraulic conductivity have minor impact on the model results, therefore they did not included in the presented figures.

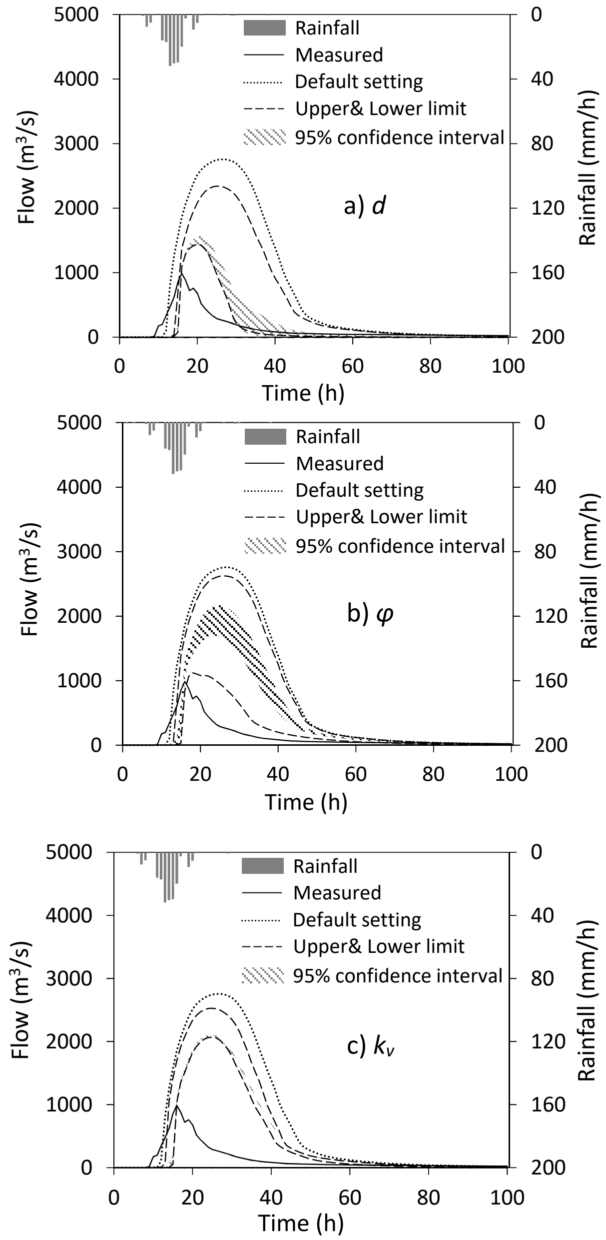

Fig.3 Variations of simulated hydrographs during Gonu-2007 event (Jabal Nakhl rainfall station) under different RRI parameters setting: a) soil depth (d), b) soil porosity (φ) and c) vertical saturated hydraulic conductivity (k_v) at the second flow case assumption which is infiltration excess surface runoff and vertical infiltration calculated using Green-Ampt model.

(2) Extreme wadi flash floods simulation

The RRI model was applied to W. Samail and using the merit of the distributed models discharge of each mesh all over the basin is computed. **Fig.5** and **Fig.6** show the hydrographs and spatial distribution maps of the surface runoff for Gonu-2007 and

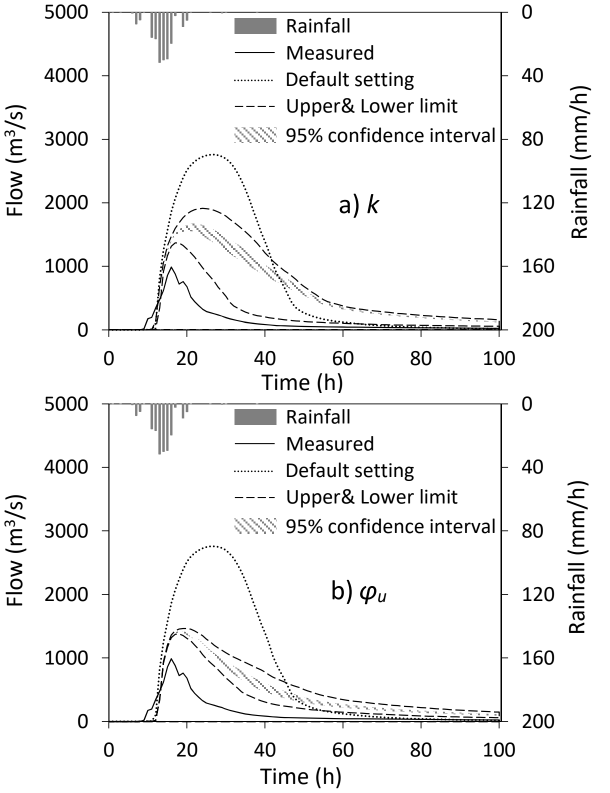

Fig.4 Variations of simulated hydrographs during Gonu-2007 event (Jabal Nakhl rainfall station) under different RRI parameters setting: a) lateral saturated hydraulic conductivity (*k*) and b) unsaturation effective porosity (φ_u) at the third flow assumption (saturation excess surface runoff and unsaturated subsurface flow).

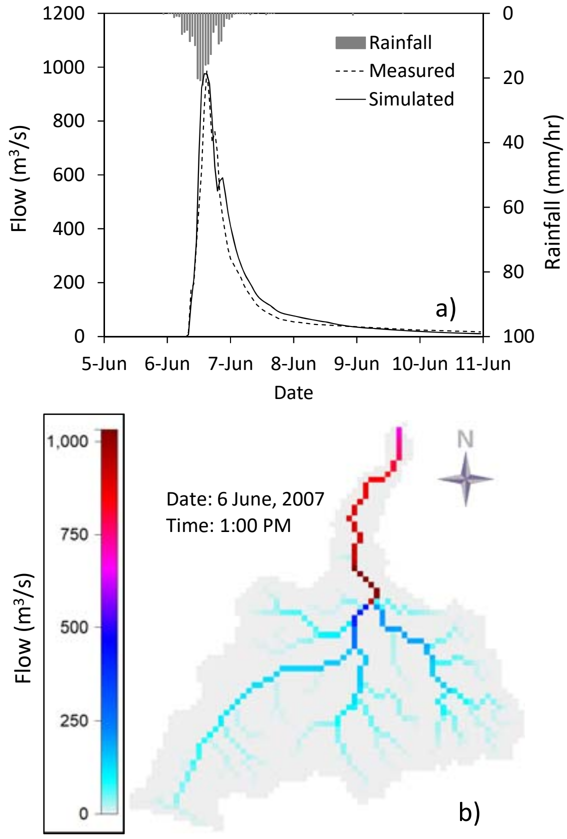

Fig.5 a) RRI model calibration results (Gonu-2007); b) peak flow's spatial distribution.

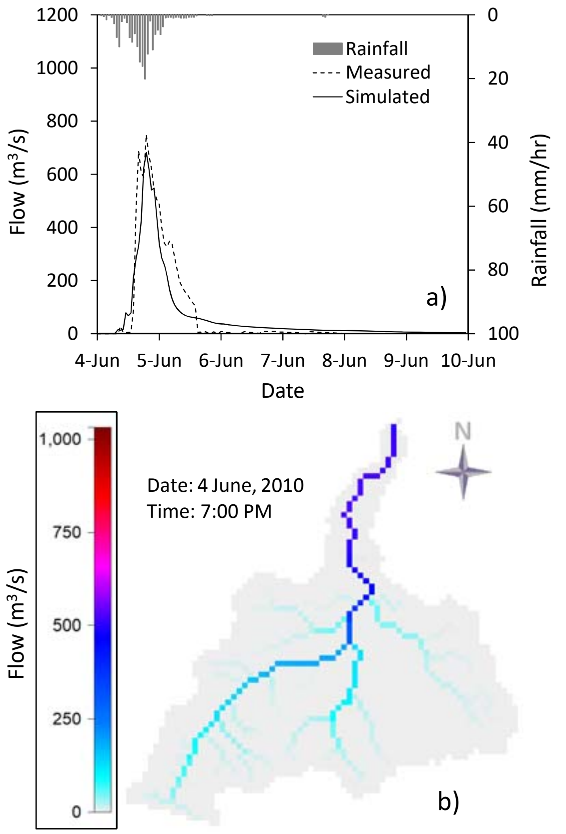

Fig.6 a) RRI model validation results (Phet-2010); b) peak flow's spatial distribution.

Phet-2010 extreme events. WFFs special characteristics can be figured out from the results where it takes a few hours to reach to the peak discharge and then gradually decreasing until the end of the event. Variation of hydrograph peak and spatial distribution can be noticed from one event to another. This is due to different rainfall intensity and pattern for e ach event. The results confirm that Gonu-2007 is more severe than Phet-2010 in terms of both discharge peak and geographical distribution.

The simulated hydrographs using the calibrated parameter setting (indicated in **Table 1**) show good agreements with the measured data as shown in **Fig.5-a**, **Fig.6-a** and **Table 2**. RRI model has better performance with Gonu-2007 event, where it was used as the calibration event. The model has been tested in the next extreme event (Phet-2010) and still has good performance and even better *PBIAS*, where for model calibration, *PBIAS* and *NSE* indices equal to -14.3 and 0.93, respectively, and for model validation *PBIAS* and *NSE* equal to -12.0 and 0.86, respectively. The peak generation is good for both events where the relative error in hydrograph peak (*PE*) is less than 2 % and 10 % of the measured peak flow in Gonu-2007 and Phet-2010, respectively.

Hydrograph recession has reasonable behavior, but it

Table 2 RRI model performance metrics for Gonu-2007 and Phet-2010 extreme flash floods. Ideal value means perfect model performance.

Index (Ideal value)	Gonu-2007	Phet-2010
PE (0 %)	-1.18	-9.05
r^2 (1)	0.96	0.89
PBIAS (0%)	-14.3	-12.04
NSE (1)	0.93	0.86
KGE (1)	0.81	0.74

is the main source of the results bias. The main source of this error is the absence of stable groundwater module in the RRI model (under development), to represent the active groundwater processes in W. Samail such as groundwater recharge and seepage to the channel. Even the hydrological model has good generation for the hydrograph main peak in terms of value and time to peak, still the model cannot generate some small and minor peaks in the measured data. That may be normal in any model due to variant simplifications of the real complex hydrological system in terms of scale and rainfall. Due to data limitation and relatively small area of W. Samail comparing to input data scale, RRI model inundation outputs were not calibrated and should be considered in the future.

The distribution maps (**Fig.5-b** and **Fig.6-b**) can be helpful in flash floods, water resources, urban and land use management. Surface runoff zones can give signs of the potential groundwater locations, where the transmission losses and groundwater recharge are linearly related to surface runoff[7)].

6. CONCLUSION

In the arid region, WFFs are common, but their occurrence and processes are poorly understood. There is an urgent need to mitigate and utilize floodwater as a new supply to sustain a minimum water resources' base in rural desert areas. The current study adopts a suitable methodology, which is applied for the first time in the wadi system to simulate flash floods in arid regions. The main research target was to evaluate RRI hydrological model applicability in wadi system for extreme flash floods events' simulation using W. Samail in Oman as a case study. Remote sensing and measured data were utilized beside the RRI model. The simulation results highlight the main features of WFFs. Detailed sensitivity analyses were conducted for the model parameters.

The calibration results showed an acceptable agreement between the simulated results and measured data and were approved by different statistical indices, indicating that RRI model could simulate efficiently the extreme flash flood events in the arid wadi system. Groundwater and wadi channel transmission losses should be considered in future, where these processes are essential in wadi system. Due to data limitation, the RRI inundation calculation was not covered by this research and should be further analysed and validated for more comprehensive evaluation of RRI model in the wadi system.

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