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Hydrological Modelling of Flash Flood at Wadi Samail, Oman

Mohammed ABDEL-FATTAH(1), Sameh KANTOUSH, Mohamed SABER, and Tetsuya SUMI

(1) Graduate School of Engineering, Kyoto University

Synopsis

In the arid regions, flash floods are among the most devastating hazards in terms of human losses and economical damages. On the other hand, however, flash floodwater can be an important source of water in arid environments. Unfortunately, there is often a lack of data on key hydrological processes in arid areas. This limits the ability to understand the flash flood process and use this knowledge to minimize its threat. Oman is one of arid countries that mainly faces flash flood in the coastal drainage systems. Wadi Samail (W. Samail) in the north coast of Oman is selected as a case study for flash flood hydrological modelling. Computation is carried out using sophisticated techniques where remote sensing data used with Rainfall Runoff Inundation Model (RRI) to simulate several flash flood events at W. Samail and compare between different mitigation measures options. DEM data and satellite imagery have been used to propose suitable locations of dams based on available reservoirs total volumes and delineated watershed.

Keywords: Flash Flood, Wadi, Oman, RRI

1. Introduction

The Arab region affected by many disasters that are mainly flash floods and drought where flash floods became more frequent in the last decade. This phenomenon should be discussed deeply, to find interpretation for it. Climate change could be the driving force for this amendment; or it is just due to increasing media coverage and wide spreading of advanced monitoring tools. Oman is an arid country, where the average annual rainfall, throughout most of the country is less than 100mm varying from less than 20 mm in the internal desert regions to over 350 mm in the mountainous areas (MRMWR, 2008).

Recently, flash floods are frequently occurring in the arid region as Oman, which counter with various challenges to the management of wadi flash floods. Records shows that major flash floods occurred in Oman in 1989, 1997, 2002, 2003, 2007, 2010, 2015 and 2016.For instance, Gonu 2007 event caused 50 fatalities and 3.9 billion USD of economic losses in Oman (Al Khatry and Helmi, 2008). Flash flood is a flood, which is characterized by its quick occurrence resulting in a very limited opportunity for warnings to be prepared and issued (Collier, 2007). Flash floods causes could be excessive rainfall or an accident like a dam or levee break. W.Aday, W. Kabir and W. Samail are the main wadis that have experienced flash floods with major damage to people and property (Al-Rawas and Caterina, 2006).

Rapid increase of population, urbanization and economic developments have pushed people for construction in high disaster risk zones such as on wadi floods plain. The location of villages in arid Arabic areas (including Oman) has been determined by the water availability and therefore, many

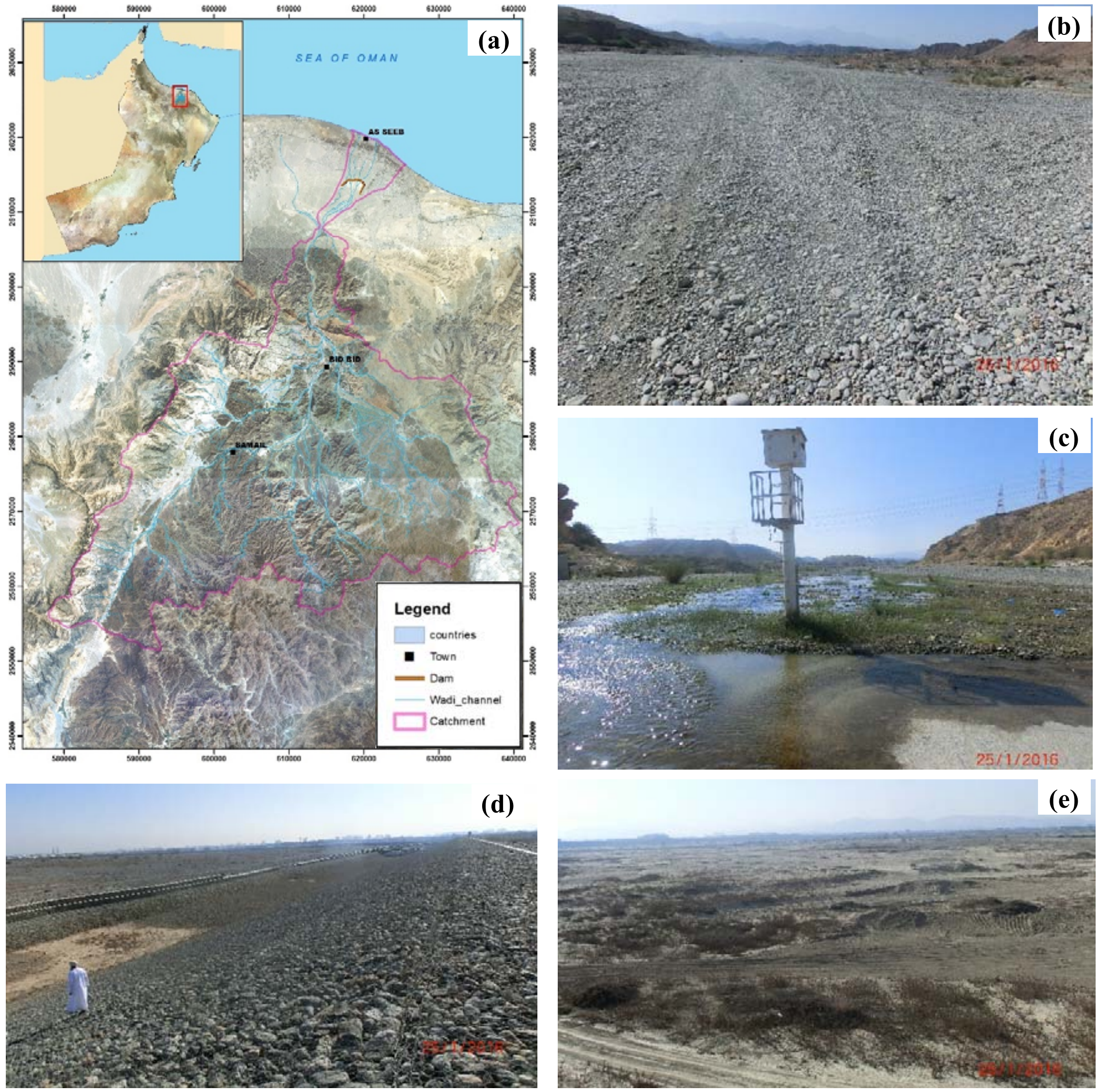

Fig. 1 W. Samail (a) location map (MRMWR, 2015), (b) main channel showing the wadi bed materials and its dry condition, (c) Al-Khoudh water flow measurement station and wadi week base flow at the downstream part, (d) Al-Khoudh Dam and (e) Al-Khoudh Dam reservoir showing its dry condition and siltation problem of it.

development activities exist mainly along the wadis.

Muscat (capital of Oman) is the fastest growing city in Oman. Due to its geographic location, which is surrounded by mountains, and the horizontal expansion of the urban areas, most of the wadis and the main channels have been occupied by urban development (Al-Rawas and Caterina, 2006). More hydrological studies are urgently needed to evaluate flash floods risk in Oman and propose innovative mitigation technologies.

Rainfall–runoff responses predictions in arid climate as wadi system always presents unique challenges (Abdel-Fattah, et al., 2015). One of the main challenges beside data limitation is the hydrological models themselves, where the majority of models developed for catchments that have different characteristic from wadi system features. 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 is selected in this study. Another aspect of this paper is to focus on both structural measures for flash flood retention as dry dams, and water harvesting. The location of such mitigation structures must be carefully designed to avoid transferring the problems to the developed downstream area of the wadi.

This paper objectives are to i) study wadi runoff features and factors that affecting on it; ii) adopt sophisticated methodology which face hydrological modeling limitation in the arid environments; iii) simulate and assess some flash floods events; iv) to propose and evaluate flash floods mitigation scenarios by a single concentrated and distributed dams.

2. Study Area

Oman's ephemeral rivers (wadis) may be classified into those that drain to the coast, and those that drain to the interior desert (Al-Qurashi, et al., 2008). Wadi Samail is one of the costal wadi, situated in the north of Oman (Fig. 1-a). The catchment can be subdivided into two areas; Samail South (upstream of the Al-Khoudh flow gauging station and 8 km north Al-Khoudh Dam, with elevation above sea level (a.s.l) ranging from 74 m to 2462 m, area 1669 km^2) and Samail North (from Al-Khoudh flow station to the coast, including Al-Khoudh Dam and Samail Alluvial fan, ranging from sea level to 109 m a.s.l., area 62 km^2). Wadi Samail total area is 1741 km^2.

The main geological units in the target catchment are: Ophiolite, Hajar Super group, Hawasinah, Aruma Huqf and Hadhramaut group interspersed with alluvial wadi deposits. The wadi channels bed materials are mainly gravel and sands (Fig. 1-b) with weak base flow mainly at the downstream part originated the subsurface water flow as depicted at Fig. 1-c. Land cover is mainly bare rock and desert with sparse vegetation cover. The terrain is mountainous, with slopes reached to 76% at the hill slope (estimated from a 30 m resolution DEM).

Comparing to much of the Arabian Gulf area (Nouh, 2006), (Al-Qurashi, et al., 2008), availability of rainfall and flow data for Wadi Samail is reasonable. There are nine recording rainfall gauges, three telemetric stations and two flow measurements stations. The annual average rainfall at these gauges ranges from 90 mm at Samail Station to 212 mm at Jabal Al-Hayl (MRMWR, 2015).

Al-Khoudh Dam is a recharge-flood protection dam which was constructed in 1988 at the downstream part of W. Samail (Fig. 1-d). The dam is an earthen type with 5,100 m crest length, up to 11 m high, a spillway section of 3,000 m long (Al-Ismaily, et al., 2015). The dam reservoir area is 3.2 km^2 with a design capacity of approximately 11.5 million m^3 (Fig. 1-d). The top soils of the dam reservoir bed are experiencing the formation of a relatively low-permeability cake or siltation—up to 3 m deep in some areas as shown in Fig. 1-e and stated by Al-Ismaily, et al. (2015). This siltation process decrease the dam reservoir capacity, decrease water infiltration to groundwater and increase the evaporation losses. Due to limitation of Al-Khoudh dam (in terms of its capacity and location) the Omani government start to construct more dams in such important wadi.

The target area studied by many authors as Al-Rawas and Caterina (2006) who explored the main challenges that are hindering progress on flash flood research and used a physically-based GIS supported modeling to assess and predict flash floods. Saber (2010) simulate different flash flood events at W. Samail using Hydro-BEAM model and apply the calibrated model to other wadi systems. Al-Housni, et al. (2014) use a lumped tank model to simulate flash floods in W. Samail. Al-Ismaily, et al. (2015) make a hydropedological study to investigate the impact of the of Al-Khoud dam construction on soil development in W. Samail.

As 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 asses this rising risk are highly recommended.

3. Methodology

Hydrological modelling was used to determine the most vulnerable areas in wadi Samail, leading to the development of a mitigation plan aiming to reduce flood damages. Remote sensing data as well as GIS technique have been utilized for data input, preprocessing and visualization of the results. Rainfall Runoff Inundation model (RRI) has been

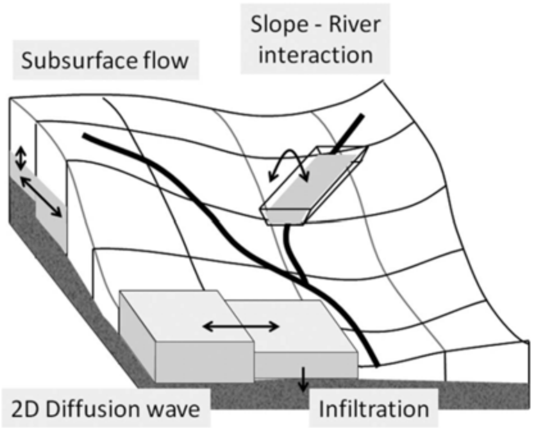

Fig. 2 Schematic diagram of RRI model (Sayama, et al., 2012)

utilized to simulate several flash floods events and evaluate different management scenarios of flash floods at the target basin. RRI model is a hydrological model (Sayama, et al., 2012), which developed for humid areas and it is first time to be used for flash floods evaluation at Oman.

This model has been calibrated using Al-Khoudh water measurement station ((Fig. 1-c). Due to data availability the measured and the simulated discharge are daily average so further calibration for more fine temporal resolution is required. A Sensitivity analysis is implemented to evaluate the weight of different parameters within the model. The parameter setting is based on the field investigation and literature review.

RRI simple dam operation rule has been used to compare between the different mitigation scenarios. Reservoir water evaporation and infiltration have been ignored in this version of RRI. The hydraulic design of dam bottom outlets to retard flood wave, cut the peak flow discharges and safely passing the floodwater only through the bottom outlet.

The criteria for the proposed dam locations and their characteristics are based on the following: 1) flow directions of each cell and watershed boundary have been estimated using GIS and DEM data; 2) rainfall-runoff hydrological modelling using Hydro-BEAM and synthetically design storm to make a geographical distribution of the surface runoff and allocate the potential prone area of flash floods; 3) estimation of cross sections capacity of the wadi drainage channels by using DEM and Google Earth images to detect the safe passing flow capacity of each channel; 4) propose several dams locations according to the surrounding topography; 5) establish height and volume curve (H-V) for each dam using in-house developed code, DEM and flow directions information of each mesh; 6) calculate the expected design flood volume and the required dam height to mitigate this flood; 7) outlet setting in each dam compatible with the downstream channel capacity and 8) comparing between the different dams locations and decide the best option that can retain the flood volume with the lowest dam height and don't affect the surrounding developed areas as agriculture land and houses.

3.1 RRI Model

The used model is 2D Rainfall-Runoff-Inundation (RRI) model, which is capable of simulating rainfall–runoff and flood inundation simultaneously (Sayama, et al., 2012). Fig. 2 shows a schematic diagram of the RRI model. The model deals with slopes and river channels separately. At a grid cell on which a river channel is located, the model assumes that both slope and river are positioned within the same grid cell.

A channel is discretized as a single vector along the centre line of the overlying slope grid cell. The channel represents an extra flow path between grid cells lying over the actual river course (Sayama, et al., 2012). Lateral flows are simulated on slope cells on a 2D basis. Slope grid cells on the river channel have two water depths: one for the channel and the other for the slope (or floodplain) itself. The inflow–outflow interaction between the slope and river is calculated based on different overflowing formulae depending on water-level and levee-height conditions (Sayama, et al., 2012).

3.2 Input Data

Watershed delineation

This study primarily used HydroSHEDS data because they include flow-direction and flow-accumulation data sets, that are useful for identifying the locations of rivers (Lehner, et al., 2008). They are also considered one of the best topographic data sets that are globally available for flood inundation simulation (Inomata, et al., 2010). The used HydroSHEDS data is 30-s resolution.

Topographic Data

Topographic data were obtained by the Shuttle Radar Topography Mission (SRTM) data (USGS, 2008). The used data set is void filled 1arc-second elevation data that are result of additional processing to address areas of missing data or voids. The study area is characterized by high range of relief with elevation ranges from 2462 a.s.l. at the upstream, to sea level at the downstream, and generally slopes towards the North discharge the flow into the Arabian Gulf as shown in Fig. 4.

Rainfall Data

As mentioned before we have nine rainfall stations at the study area and we use Thiessen method to interpolate this rainfall measurements all over the watershed as shown in Fig. 3 for Gonu 2007 event. For this flash flood which was generated from severe cyclone, only four stations form the nine stations have measured this event.

4. RRI Model Application for Flash Floods Estimation

RRI model has been applied for flash flood simulation in W. Samail after its calibration and validation as indicated in Fig. 5. The simulated hydrographs show good fitting with the measured one and indicating the wadi flash floods unique features as shown in Fig. 5-a. The wadi flow gauging station is 7 km upstream of Al-Khoudh dam (Fig. 1-c and Fig. 5-a).

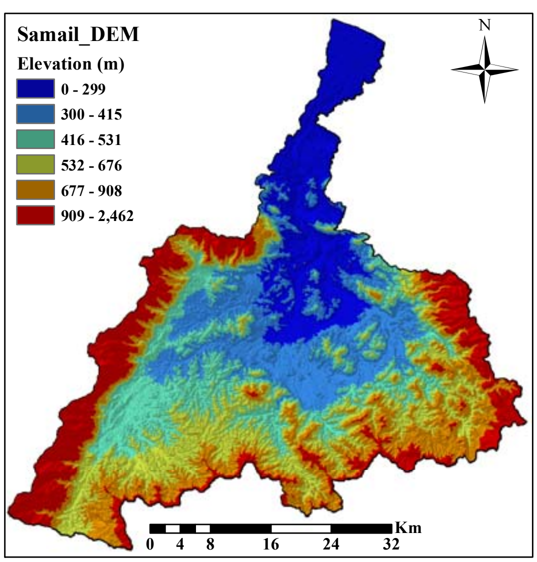

Fig. 4 W. Samail Digital Elevation Model (DEM)

Flash floods events between 2005 a 2010 have been simulated as shown in Fig. 5-a. The most severe event is June-2007 events, which generated from Gonu Cyclone which have high impact on many wadis at Oman. Using the merit of the distributed models discharge of each mesh all over the basin is computed. Variation of hydrograph peak can be noticed from one event to another. This is due to different rainfall intensity and pattern for each event. The simulated hydrographs show the flow features of flash floods at wadi system, where it takes a few hours to reach to the peak discharge and then gradually decreasing until end of the event.

Surface runoff geographic distribution maps (Fig. 5-b&c) confirm that for the same rainfall event, some parts of the watershed have flash floods and inundation and on the other hand, some locations have no flow. But more surface runoff rate existed at the downstream part. It is can be noticed that the inundation map is highly affected by the topographic and land use condition.

These discharge and inundation distribution maps can be helpful in flash floods, water resources, urban and land use management. It can be useful in detecting flash floods prone areas and consequently mitigate and mange flash floods at those areas. In addition, it can be valuable for wadi development and land use management to identify the best location for residential, touristic, industrial, agricultural activities. Surface runoff zones can give signs of the potential groundwater locations, where

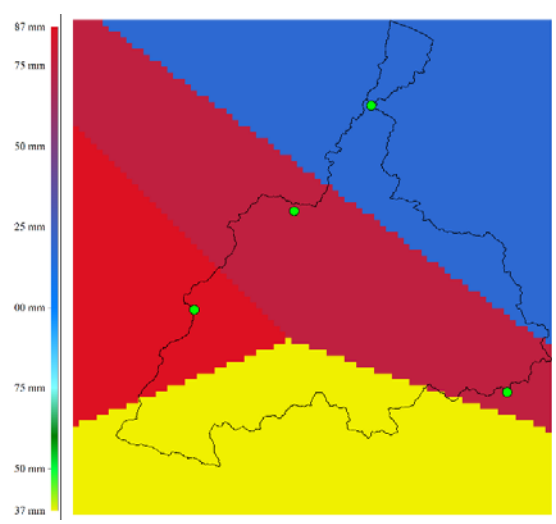

Fig. 3 Measured rainfall for Gonu 2007 event in W. Samail

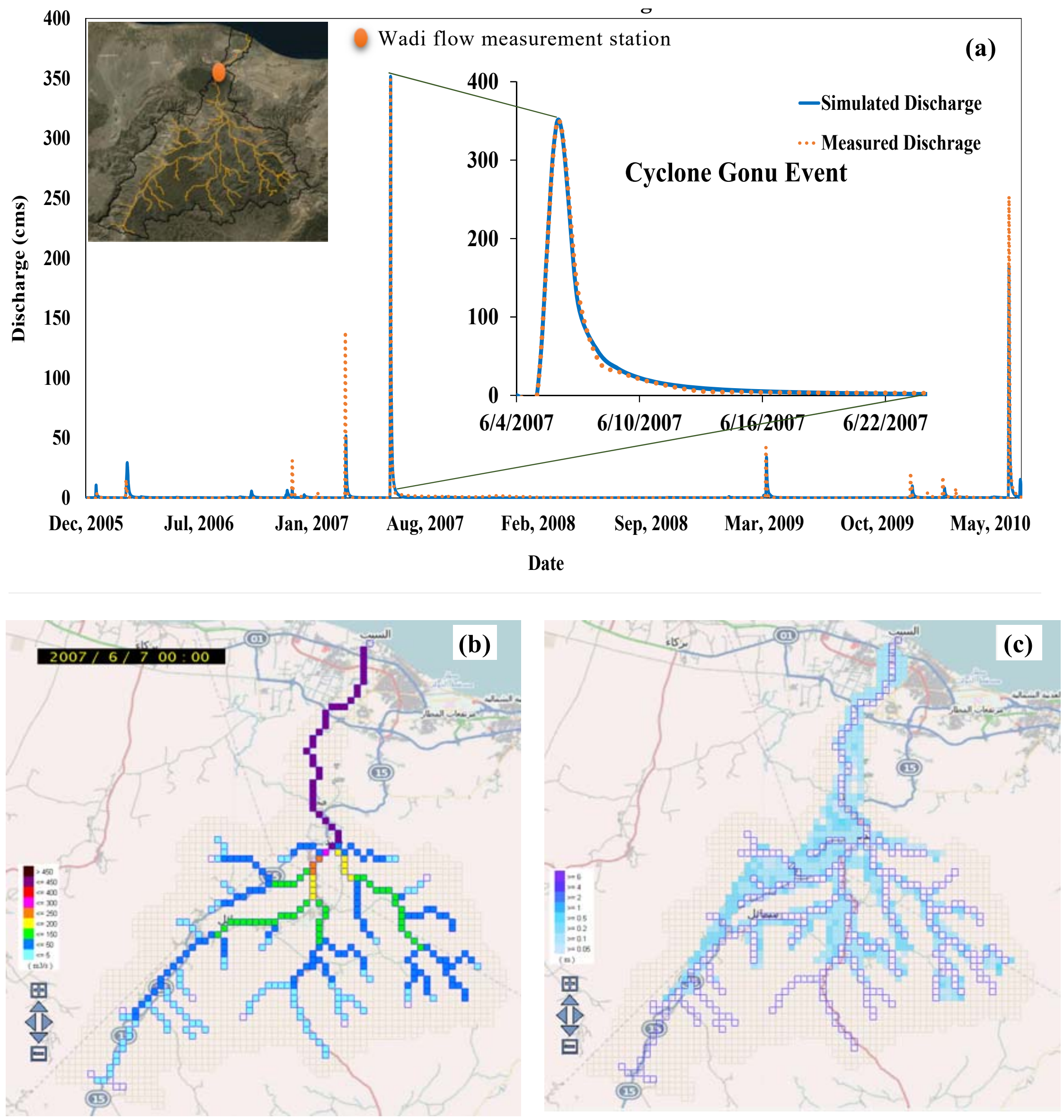

Fig. 5 Flash flood simulation at W. Samail using RRI model: a) long term measured and estimated hydrograph (average daily discharge m^3/s) from 2005 to 2010 highlighting Gonu 2007 flash flood event, b) peak estimated discharge distribution map, c) maximum estimated inundation distribution map

the transmission losses and groundwater recharge are linearly related to surface runoff (Saber, 2010). Once sustainable groundwater resource is detected, especially at arid environment like wadi system, other development activities as land reclamation for agriculture can be constructed.

5. Flash Floods Mitigation Scenarios Comparison

In the arid region, flash floods are in fact common, but their occurrence and processes are poorly understood. There is an urgent need to mitigate and utilize floods water as a new supply to sustain a minimum water resources base in rural desert areas. The management approach should involve developing a strategic methodology for evaluating wadi flash floods potential, mitigation, and floods water resource management as well as a rainfall-runoff simulation model (Kantoush, et al., 2011& Sumi, et al., 2013). This research flash floods management approach based on the hard structure

Table 1 Characteristics of the proposed dams

	Concentrated Dam	Distributed Dam 1	Distributed Dam 2	Distributed Dam 3
Location: Y : X	23.554344 58.103665	23.554344 58.103665	23.371503 58.090958	23.368906 58.157186
Reservoir Capacity (MCM)	75	40	9.6	25.8
Height (m)	50	40	22	22

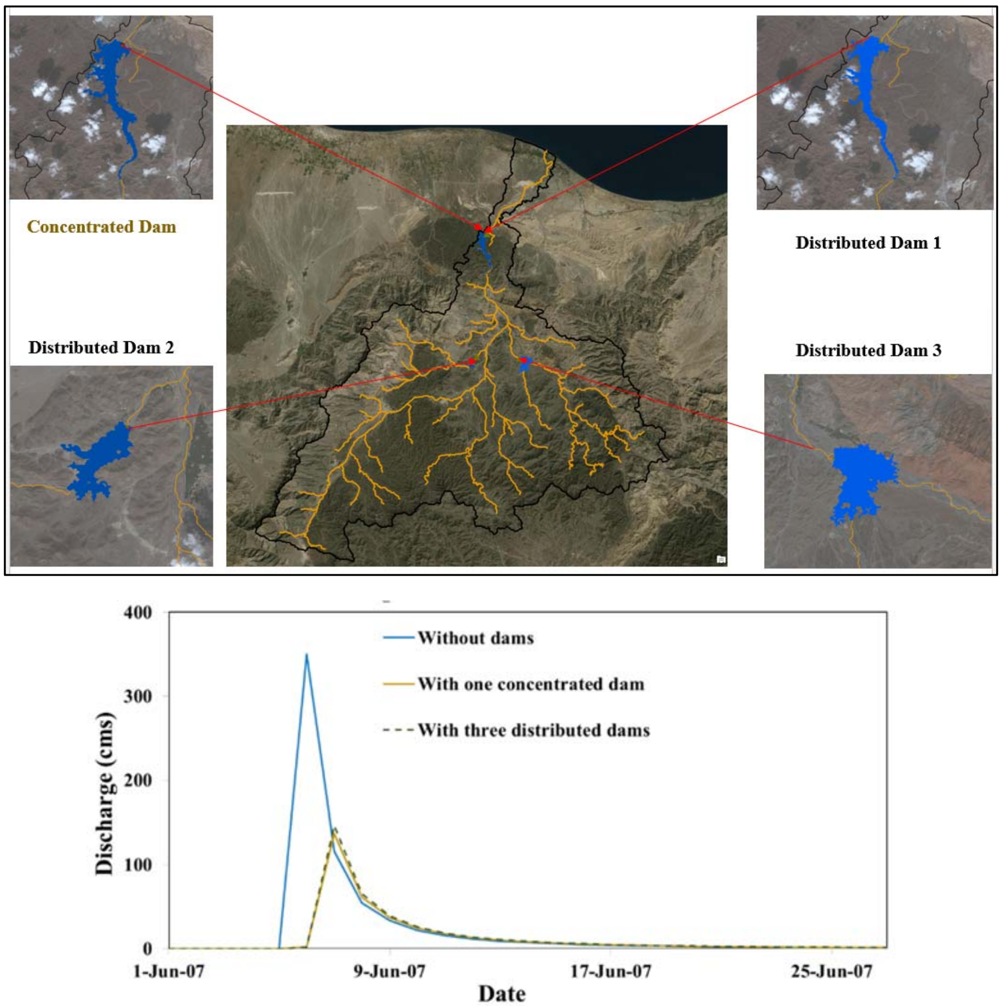

Fig. 6 The proposed flash floods mitigation structures and the simulated hydrographs before and after mitigation scenarios application

measures concept and comparison between applying single concentrated or several distributed dams.

Mitigation structures should be designed in a coordinated manner, to assess their overall effect (Abdel-Fattah, et al., 2016). This study analyzes the wadi flash flood mitigation for three cases: 1) no dams, 2) three distributed small dams allover over the catchment in the upstream, and 3) proposed large dam in the middle or downstream area of the wadi as shown in Table 1 and Fig. 6. The effect must be quantified through a comparison of the consequences with and without mitigation structures over the whole wadi. Various factors are considered to study and improve the assessment methodologies.

The design storm is selected as Gonu 2007 cyclone which was the most severe rainfall event in the recent history of Oman and it has a return period of 1000 year at that time. Table 1 shows the different characteristics of each dam. The dam height is based on the calculated reservoir volumes that estimated using the DEM data. Distributed dams application decrease the concentrated dam height and its reservoir volume.

From the simulated hydrographs (Fig. 6) and the geographical distribution maps of the surface runoff, it can be noticed that both strategies could be effective in floods mitigation at the downstream part of W. Samail. Where mitigation dams application decrease the daily average surface runoff rate from 350 cubic meter per second (cms) to 150 cms at the downstream reach. There are some difficulties for dam construction in the upstream areas, where usually these locations are remoted with no convenient accessibility. However, the distributed dams will have better mitigation for the upstream part. Other merits of the upstream dams that it could manage the water resources and sediment all over the watershed for water use and development for the upstream area beside the downstream area. The distributed dams could be used for local groundwater recharge.

6. Conclusion

With increasing stress due to flash floods disaster and water resources limitation in Oman, application of rainfall-runoff models can be a part of the solution to mitigate flash floods, and at the same time manage and sustain the water resource. The main problem at flash floods studying is obviously the lack of observations in most of the flash floods prone basins, so there is urgent necessity to adopt a new methodology to simulate and forecast flash floods in arid regions. This study aims to discuss flash floods simulation and management in wadi system and evaluate different concepts of flash floods mitigation. W. Samail at the Oman Coast is selected as a case study for this target.

A trail to simulate several flash floods events at our target study case was implemented, where remote sensing and measured data utilized beside RRI hydrological model as a main tool. This flash floods simulation methodology, which presented in this manuscript, should be further calibrated and validated for more fine temporal resolution and more wadis in Oman. The simulation results highlight the main feature of wadi flash floods as its hydrographs have extreme steep and rapid rising to peak flow after a few hours, which increase the degree of risk of flash floods comparing to normal floods.

The distributed map of simulated discharge for flash floods events, indicating high spatial variability of runoff. Not all flash floods have a homogenous geographic distribution, due to rainfall, geomorphologic and land use variation. The distributed dams have advantage of water resources management all over the watershed for water use and development for the upstream area beside the downstream area. Other comparison aspects should be taken into account in future as economical assessment, sediment management, and water evaporation for better evaluation of the different management scenarios.

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