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Assessment and Management of the Flash Floods in Al Qaseem Area, Kingdom of Saudi Arabia

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Abstract: The available water resources in Saudi Arabia are under increasing stress and the hydrological problem is being complicated by the adoption of inadequate management strategies. The hydrological parameters (drainage networks, flow direction and flow length) have been extracted from the DEM of the SRTM using the automatic procedures embedded into the ArcGIS algorithms. The multi-temporal satellite images of the TM and ETM+ were obtained and processed to delineate the landcover and also to detect the extent of wadi alluvium, active channels and the accumulated water ponds. Cross sectional areas of the active channels and the extracted hydrological parameters of the DEM were integrated into the open channel flow equation of Manning's to determine the spatially distributed time area zones of Wadi Al Rimah. The measuring of changes in cross-sectional areas of an active channel reach free of any tributary inflow and the estimated flow travel time gave a transmission loss rate of 12 mm per hour. The TRMM data of the 7th of January 1999, the time area zones and the estimated transmission loss were used to compute the runoff hydrograph. GIS analysis of the extent of resulting water ponds and bottom topography of the playas dotting the Mesozoic carbonate rocks at outlet, showed that the excess runoff is approximately 19% and the flash flood event of January 1998 has delivered about 252 million cubic meters to the main playas. Outcropping of the Paleozoic sandstone (i.e. Al Saq aquifer) at the lower part of the catchment provides a good opportunity to harvest these occasional flows otherwise representing a hazard and being wasted. The construction of a dam downstream is quite feasible, but a detailed geotechnical and environmental impact assessments are required.

Key words: Remote sensing · GIS · Flash floods · Management · Transmission loss · Wadi · Groundwater

INTRODUCTION

The drylands are suffering from scarcity of water resources, with the exception of small particular areas endowed by fossil groundwater or the collection of runoff discharge. Currently, much of the non-renewable deep aquifers are being depleted by the aggressive pumping of fossil groundwater for irrigation as well as other different uses. Therefore, the fragile resources of the inhabited dryland areas are under increasing pressure of population growth and urban expansion, which in turn resulted in severe environmental degradation [1]. Consequently, the rapid deterioration and depletions of water resources of the dryland can threaten the local environment and inadequate water supplies which may create crises in the near future. On the other hand, urban areas and of course the agricultural areas are favorably developed on the expense of alluvial plains and dry channel beds, which are prone to flash floods [2]. Flash flooding and associated sediment transport in drylands are often overlooked as an environmental problem, due to the relative infrequent occurrence of runoff events and lack of observations [3, 4]. The absence of good quality data of rainfall, discharge and sediment erosion may present a particular problem for hydrological modeling in the dryland catchments [5].

This poor understanding of the hydrological processes has further been complicated by the interaction of urban development and resulting runoff. Urbanization process itself through the construction of impervious surfaces; building, roads, storm sewers and paving has decreased the infiltration capacities of the underlying soils and it significantly increase runoff-discharge downstream [6, 7]. Therefore, the runoff could be contaminated by different types of pollutants depending on activities and waste products from urban areas.

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Moreover, site selection of the adopted management strategies for flash floods (e.g. dams) could only fulfill the required protection, but the collected runoff itself is wasted. Therefore, it is so necessary to understand the interplay of geo-environmental setting and development variables to determine the required measures, which have to be adopted to achieve efficient management of fragile water resources.

The management strategies of flash floods are controlled by the hydrogeological and climatological characteristics of the catchments, land use pattern and distribution and the local water use and need. Indeed, the rainfall pattern in drylands presents the main difficulty for a useful runoff harvesting. In total, the precipitation is erratic and rainfall events can be spaced over years; thus the recharge to groundwater usually is very low when compared with the mean annual precipitation [8]. However, the exceptional great storms occasionally overpass the total annual precipitation; can thus provide a good opportunity for considerable groundwater recharge as the accumulated runoff is abundant [9].

The impoundments and runoff harvesting are key elements in the management of the dryland drainage basins ranging from micro catchments covering small areas (i.e. few hectares) to mega catchments draining several hundred square kilometers [10]. Several techniques and structures are being implemented in different Saharan areas including, but not limited to; excavated and rock-cut cisterns, contour trenching and terracing, retention dykes for water ponding and farming, earth-core structures and dams constructions. Despite the fluctuations in runoff; the sedimentation problem (particularly for reservoirs of dams) is not only reducing the storage capacities, but also affects the conditions of groundwater recharge and the stability of these structures. The management of flash floods and runoff harvesting can only be improved if the hydrological data are sufficient and the processes of the catchments are well-understood and fully considered [11]. This is because the imperfect knowledge of the characteristics of such flows, compounded by the scarcity of relevant data and observations, makes it extremely difficult to evaluate the potential magnitude and frequencies of flows.

The lack of data problem has considerably been overcome as megascopic observations and various quantitative data can be obtained and extracted from the widely available satellite images and Digital Elevation Models (DEM) of different sources and resolutions [5]. Straightforward, remote sensing images are widely used to identify and map multi-temporal land use-land cover features [12], which in turn can be linked with dominant processes, activities and microscopic observations to identify the hydrological problems. The analysis of multi-temporal satellite images particularly those acquired shortly before and after flash flood events are useful to identify the active channels and to infer important runoff parameters such as maximum channels -wetted perimeters (i.e. peak flows), water ponds and estimates of transmission losses [5]. On the other hand, the mapping of drainage channels and catchment divides can be derived with reasonable accuracy using the available DEM for most of the globe such as, the Shuttle Radar Topography Mission (SRTM) DEM of 90 m resolution [5] and also from the Advanced Spaceborn Thermal Emission and Reflection Radiometer (ASTER) DEM of 30 m resolution [13]. Whatever the source of drainage networks and utilized processing algorithms, the comparison of these derivatives against their counterparts on satellite images or detailed field surveyed topographic maps remains a necessary measure to assess the quality of drainage portraying and the accuracy of consequent hydrological analysis [14].

The aim of this paper is to investigate the hydrology of Wadi Al Rimah draining Al Qaseem area in Saudi Arabia. The flash floods will be quantitively assessed in order to determine the current negative impacts and also to determine the potential to the development of limited water resources. The available multi-temporal satellite images and DEM and geological data will be analyzed to select the optimum locations suitable for harvesting runoff and replenishing the main aquifer of Al Saq supporting the agricultural activates in the area.

Study Area: The agricultural areas are being distributed throughout the Kingdom of Saudi Arabia, particularly in the desert belts underlain by groundwater aquifers. It is estimated that 1.5 million hectares of land are being cultivated, mainly on the low laying soils of playa and alluvial plains in different drainage basins within the Kingdom [15]. Although concerns are growing for the aggressive pumping of the groundwater aquifers, which are believed to depleted, additional groundwater-fed cultivations are being developed. Al Qaseem area, which is located approximately in the centre of Saudi Arabia, gains its importance as it contains more than 50% of the total cultivated areas in the Kingdom and drained by large drainage basins, which have their headwaters carved in the Asir mountain series to the west (Fig. 1). Generally, rainfall in the Kingdom takes place primarily during winter

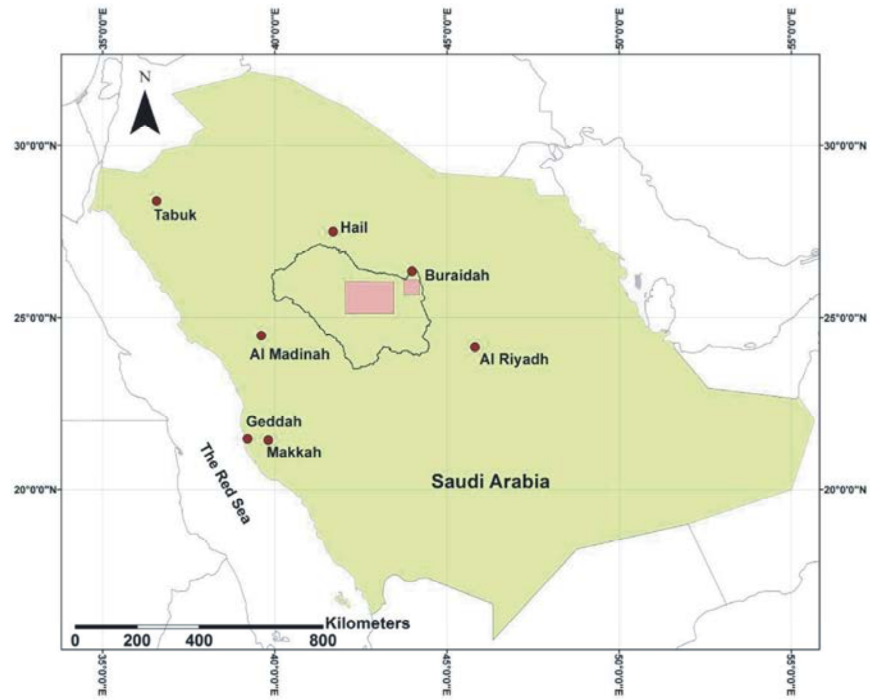

Fig. 1: Location map of the study area, the solid rose areas refer to locations of Figure 3

and spring, which are caused by combination of disturbances from the Mediterranean and the Sudan trough [16]. Annual rainfall of 100 to 200 mm occurs in the central area extending from north of Riyadh and Al Qaseem to the vicinity of Hail [17]. The distribution of rainfall in the area is extremely variable; rainfall is sporadic and erratic. The prevailing arid conditions are occasionally interrupted by some heavy storms that generate channel-runoff, which could confluence and attenuate downstream into destructive flash floods. The city of Buraidah (i.e. the main city in Al Qaseem region) and its neighboring rural and cultivated areas are being affected by these severe flash floods mainly produced by Wadi Al Rimah. The catchment of Wadi Al Rimah equates an area of 107,000 sq km and it is considered one of the biggest wadis that are draining the Asir-Najd plateau eastward.

The upper reaches of the wadi system are carved in the resistant Precambrian igneous and metamorphic rocks belonging to the Arabian Shield and they are mainly outcropping in the western part of the catchment (Fig. 2). The eastern edge of these basement rocks are flanked by some lava fields (i.e. Harrat) developed during the Mid-Tertiary and Quaternary periods [18]. Generally, the basaltic flows of Harrat are being dotted by salt flats occupying the lava cones and the abandoned paleochannels. The Paleozoic sedimentary rocks form a great curved belt along the eastern edge of the older crystalline rocks. The basal sequence of these sedimentary rocks (i.e. Al Saq Formation) are mainly composed of sandstone strata and represent the principal aquifer in the central part of the Kingdom. The age of Al Saq sandstone and its equivalent units (i.e. Wajid sandstone in southwestern Saudi Arabia) ranges from Cambrian to Ordovician, based on fossil contents as well as elemental chemistry [19]. Al Saq sandstone follows closely the regional eastward dip of the Pre-Cambrian basement; the depth to the sandstone below the ground surface could reach 2000 m at a distance of 130 km east of the outcrop. Boreholes show that the regional dip is exceptionally steep in Tabuk area in the northwest of Saudi Arabia. The thickness of Al Saq sandstone also varies from 400 in the southern part of Al Qaseem to 800 m in the northern part of the study area [20].

The uncontrolled withdrawal from the main aquifers with little attention paid to the volume of water actually required for irrigation, considerable water have been wasted from the agricultural drainage system. By 1984, some artesian wells had been in use for nearly 20 years have ceased and the water table in certain areas is considerably being reduced [21]. The rapid decline of water table indicates that the recharge is almost negligible and is occurring only during heavy flash flood events affecting these outcrops. The annual recharge is

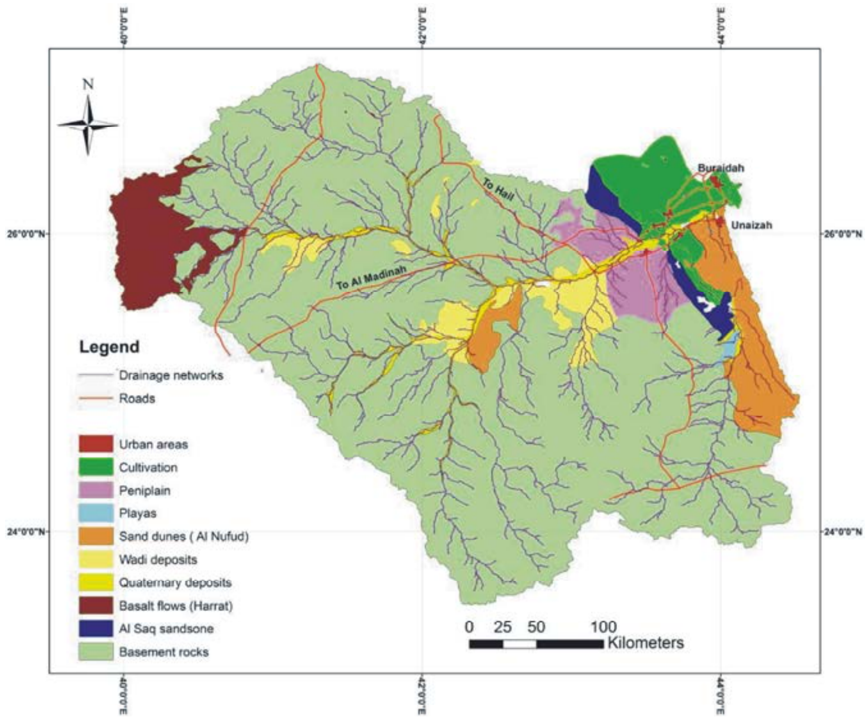

Fig. 2: The landcover map of Wadi Al Rimah, based on the geological maps, DEM and Landsat TM image of 1999

estimated in Al Qaseem area to 80 million cubic meters of water, while in Hail to the north the annual recharge is estimated to 20 million cubic meters of water [21]. The samples collected from wells drilled in Al Saq aquifer showed a radiocarbon age of 28,000 years, which imply the significance of the Quaternary wet climatic periods on the hydrology of Saharan deserts in Saudi Arabia [22].

Therefore, it is necessary to investigate distribution of the aquifer-outcrops in the catchment and the hydrology of flash floods to determine the potential harvesting of hazardous runoff otherwise being wasted. Several severe flash floods were recorded during the past few decades and were capable to reach Buraidah at the catchment; and the negative impact of these flows was considerable. This clearly indicates that these flows can be controlled particularly at the outcrop area of Al Saq and thus increasing recharge to the declining groundwater.

MATERIALS AND METHODS

The management of flash floods in the dryland environment is confronted by the availability of limited datasets on rainfall, transmission losses, runoff, land cover and hydrological structures in the area. This limitation is partially being overcome by the increasing availability of remotely sensed data including orbital measurements of rainfall such as the Tropical Rainfall Monitoring Mission (TRMM) and the monitoring of landuse and landcover changes through different operating satellites such as Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+). The quantitative assessment of a flash flood (e.g. duration, peak discharge rate and total flow volumes) resulting from given storm required the integration of several datasets including TRMM data, SRTM DEM and multiple Landsat images particularly those acquired shortly before and after the flash floods. The open channel flow equation of Manning's was used to estimate the runoff velocities at certain cross sectional areas of the active channels in order to determine the time-consumed by flows to reach the outlet. Therefore, several processing procedures were executed to firstly determine the flash flood hazard on the developed areas of Wadi Al Rimah and secondly to estimate the potential harvesting of flash floods at certain areas of the catchment to increase the recharge of groundwater.

The Landsat satellite images of March 1987, February 1998, April 1998, July, 1998 and January 1999 were processed and interpreted to delineate the active channels and water ponds accumulated in the playas dotting the lower part of the catchment (Fig. 3). The TRMM image for

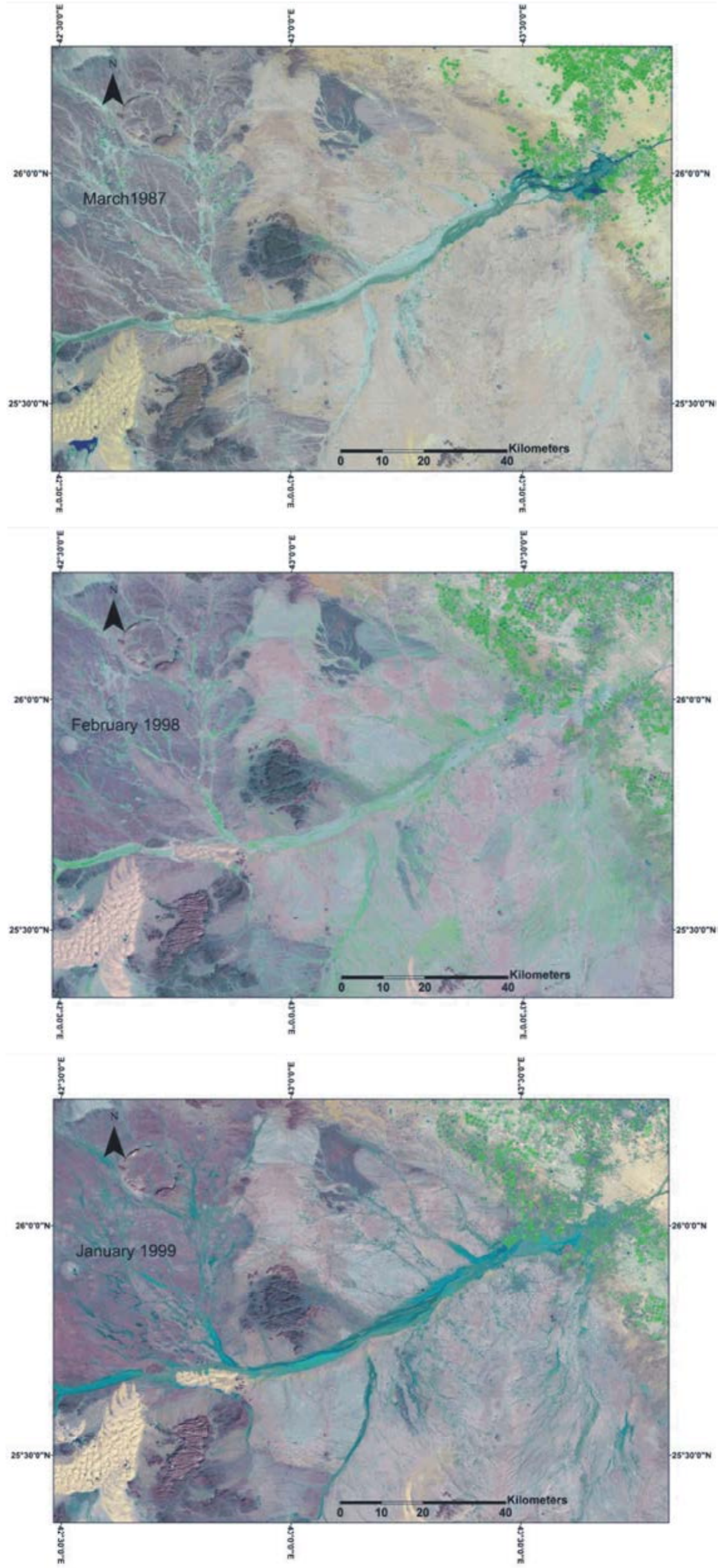

Fig. 3: Distribution and extent of active channels and flash floods based on the Landsat images, March 1987 (top), February 1998 (middle) and January 1999 (bottom)

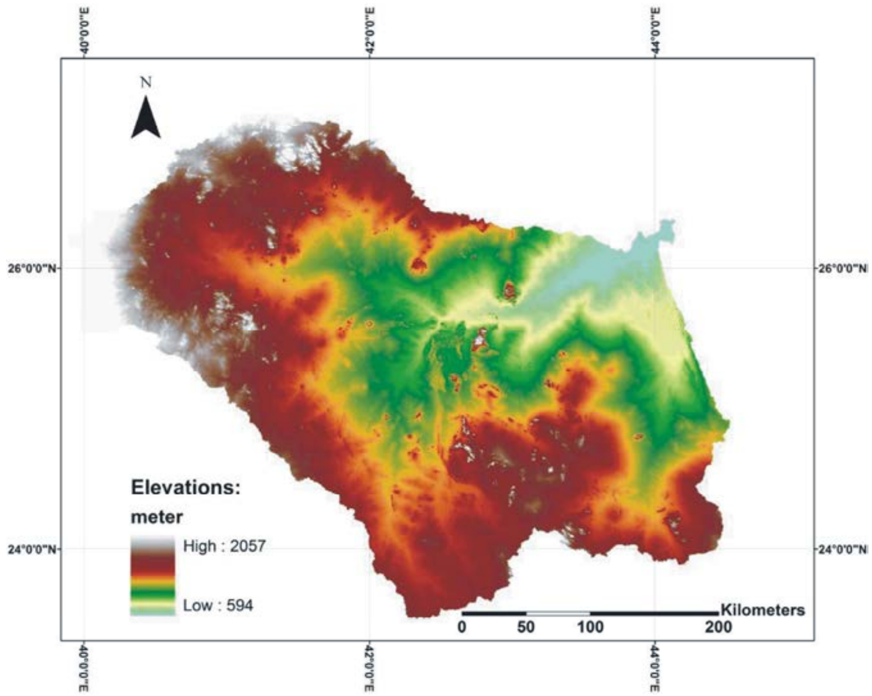

Fig. 4: DEM of Wadi Al Rimah catchment

the flash flood events of January 1998 and January 1999 were obtained and processed into GIS to determine the distribution of rainfall depths over the entire catchment. The DEM (Fig. 4) has been used to extract the drainage networks and to calculate the different time-area zones applying the open channel flow equation of Manning's. Theses analyses are useful to investigate the spatial relationship of agricultural fields and the land cover units with the drainage networks and also to estimate the runoff hydrographs using the input rainfall data, time area zones and estimates of transmission losses.

The hydrological analyses of DEM were carried out using the widely used D-8 algorithm embedded in ArcInfo software with some modifications in the filling of DEM step [23]. This method requires, first, that all the sinks (i.e. local depressions) of the DEM to be filled and raised in elevation to their neighbouring cells in order to ensure the flow continuity within the catchment to an outlet [24]. Then the flow direction of each cell into the lowest elevation cell of the surrounding eight cells was determined for the entire DEM. Once the route of flow is determined for each cell, it is possible to accumulate the number of upslope flow contributing cells (i.e. areas) and the flow pathways. Finally a threshold of the minimum flow accumulation number was set to extract the fingertips of delineated channels and different catchments within the area.

Once the channel networks were extracted, the spatially distributed time area zones were calculated in order to calculate the hydrograph at certain outlets and to determine the different flow parameters for the cross sectional areas indicated by recent active channels on the satellite images. However the resolution of SRTM is not high enough to represent an accurate cross section (i.e. it does not capture the small scale terraces or leaves within the channels). But most open channel methods require that channel cross sections are generalised prior to estimating flow characteristics [25], so SRTM data should provide a reasonable approximation for the relatively large channels considered here.

The overland and channel flow velocity was estimated empirically using the Manning Equation:

$$V = \left(\frac{R^{0.67} S^{0.5}}{n} \right) \tag{1}$$

where:

V : Is the cross-sectional average velocity (m/s)

n : Is the Manning coeffecent of roughness

R : Is the hydraulic radius (m)

S : Is the slope of the water surface which is assumed to be parallel to the slope of the channel bed.

The widths of the channels at selected cross sections were measured from the active channels mapped from the satellite images. These selected cross sections were overlaid on the DEM for the estimation of mean depth. Slope was estimated from the DEM for reaches centred on the selected cross sections. Hydraulic Radius (which is nearly equal to the depth of flow in shallow braided channel systems in dryland areas [3] was calculated from the measured cross section areas and perimeter. Manning's n was set to 0.02 for channels and 0.06 for hillslopes; these values are typical of reported values from similar catchments [26]. Once the flow velocity and flow length within each cell are calculated, it is possible to estimate the travel time for every cell in the catchment. Therefore, the catchment can be subdivided into different time-area zones (in hours) separated by isochrones.

This time-area diagram for the catchment can represent a spatially distributed unit hydrograph without the need for empirical functions for the time of concentration. The resulting rainfall/runoff of each time zone can be routed downstream in a cascading manner that considers abstractions due to storage or loss over the segments of flow pathway.

RESULTS

Significant runoff events in the past two decades in the catchment of Wadi Al Rimah were monitored using several sets of available satellite data. Some of these events were coincidently captured while flows were in the channels and the other events were implied by marked increase in brightness of channel bed materials within the active channels and the accumulation of water ponds in low lying playas. The different parts of the catchment did not equally contribute runoff to outlet as indicated by the reflectance of channels beds. This could be related to the spatial pattern of rainfall events over the area. For example, GIS analysis of TRMM data of the 5th of January 1998 showed that the storm has covered the lower half of the catchment having its centre over the outlet, whereas the storm of 7th of January 1999 has nearly affected the entire catchment and the highest intensities were recorded over the western and southern parts of the catchment (Fig. 5).

However, the local geology and land cover may be of importance here; the low undulating topography of eastern tributaries are covered by Quaternary sand sheets and alluvium. The runoff initiation threshold for these areas is likely to be high, as infiltration rates are much higher due to the porous nature of the substrate. Therefore, the runoff contributing areas, even under the same rainfall amounts, will be different. The catchment of Wadi Al Rimah is ideal to examine the capabilities of remotely sensed data, GIS and DEM derivatives to quantitatively estimate the accumulating flow volumes; as the catchment is closed and the playas are occupying the outlet. There was also a good correlation between the TRMM rainfall data and the extent of active channels as

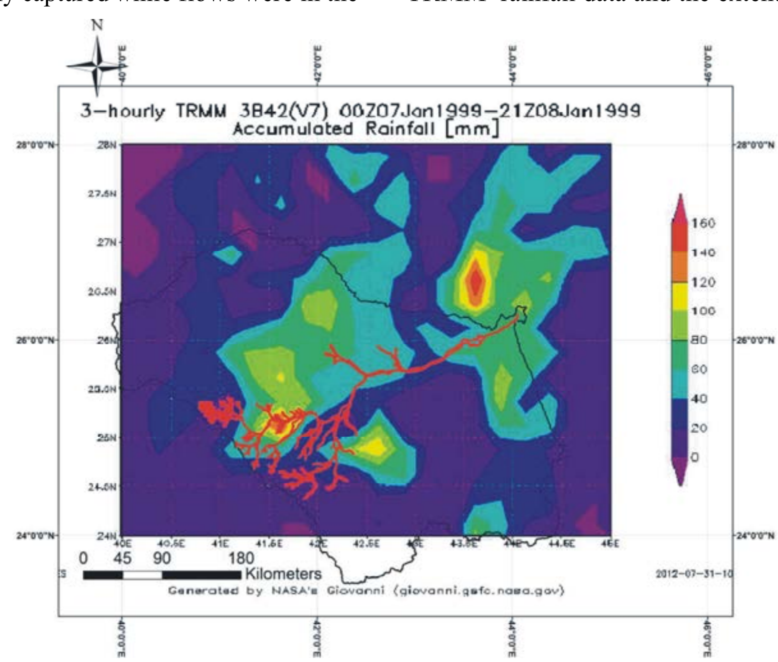

Fig. 5 A: TRMM estimated total rainfall (mm) and distribution over Wadi Al Rimah catchment on the 7th of January 1999 Note: the correspondence between the rainfall pattern and the resulting active channels (red lines), which are digitized from the Landsat image acquired shortly after this rainfall event (Fig. 3)

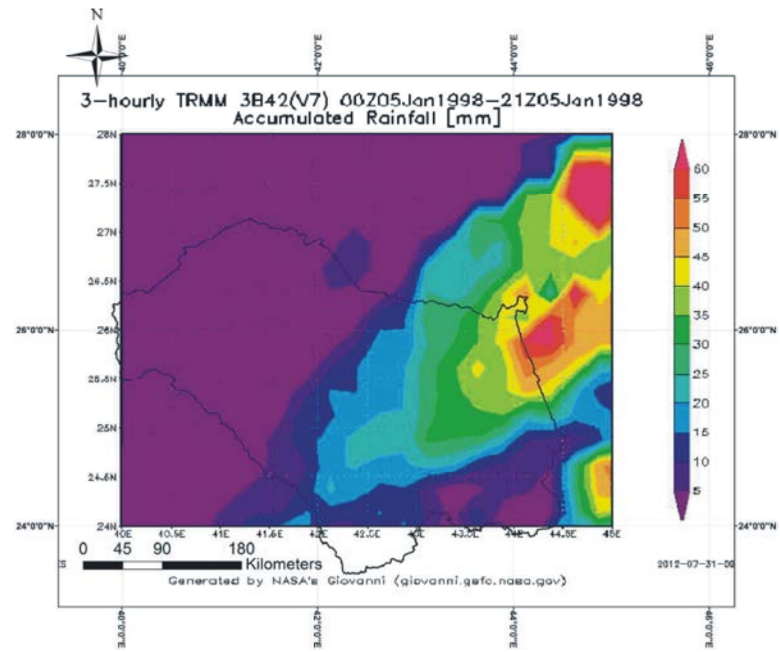

Fig. 5 B: TRMM data of the 5th of January 1998 rainfall event
Note the considerable differences in rainfall patterns each event

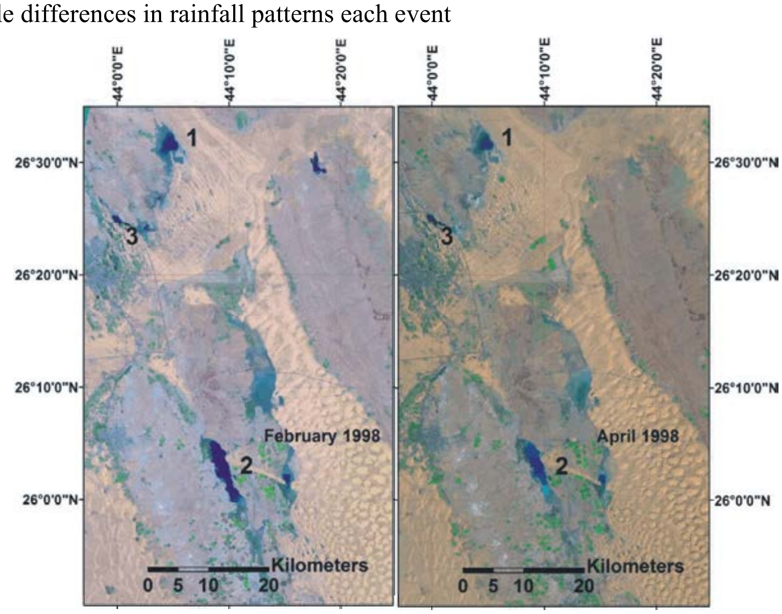

Fig. 6: The resultant water ponds of the flash flood of January 1998
Note: the changes of surface extent between February and April 1998. The stored water volumes in ponds 1, 2 and 3 were computed using these delineated surface areas and the dry-bottom topography derived from the SRTM

well as the resulting water ponds on the satellite images. Therefore, the significant rainfall and runoff accumulation can be detected by different remote sensing platforms and computed in GIS environment.

The spatial distribution and rainfall depths were used to estimate the total rainfall volumes over the entire catchment. Thereafter, the aerial extent of water ponds were digitized from the satellite images of these events and the bottom topography of the inundated playas (i.e. depth) was extracted from the SRTM to compute the stored water volumes. The estimated total volume of the rainfall of 5th of January 1998 is approximately 1274 million cubic meters of water and the resulting runoff water delivered to three main playas; namely 1, 2 and 3 (Fig. 6)

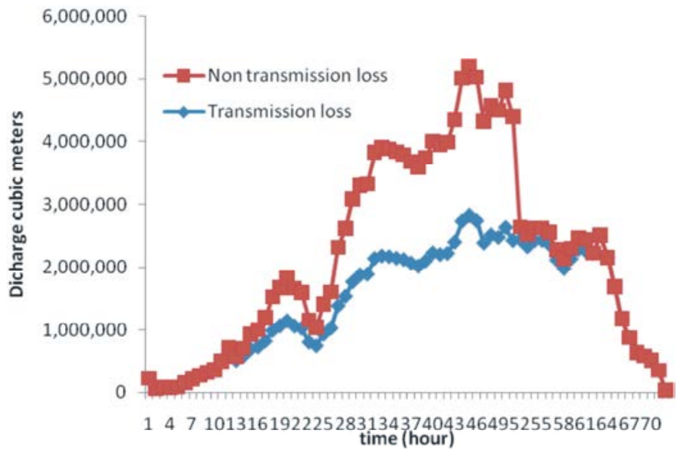

Fig. 7: The simulated runoff hydrograph for Wadi Al Rimah using the entire flow contributing areas (i.e. time zones) and the distributed rainfall of Fig. 5 A

Note: the impact of transmission loss on the hydrograph peaks and attenuations

has covered surface areas of 26, 19 and 15 km^2 and measured 93, 57 and 92 million cubic meters of water respectively. On average, the resulting runoff that could be harvested may reach 19% of the significant rainfall events, which affects large portion of the catchment and attains a considerable depth and intensity.

The spatially distributed time-area data suggest that the flow generated at the most western upstream hillslopes requires a maximum of 71 hours to reach the outlet (Fig. 7). The most significant finding is that most of the runoff infiltrates into the alluvium beneath the channel bed and bank during its transmission through the channel. During the January 1999 event, the estimated flow travel time from a certain channel reach, free from any tributary flow until it get totally infiltrated was approximately 6 hours. Most of runoff within this tributary channel has completely been lost before reaching the outlet of the catchment. The peak discharges were implied by the estimating wetted perimeter of the active channel at spaced apart- points. This estimation gave a transmission loss rate of 12 mm\hour for the flow to get totally infiltrated by reaching the most distant location downstream. This obtained estimate of transmission loss rate was considered to calculate the hydrograph of the flash flood event of 7th of January 1999, which could not be calibrated simply because the gauging of runoff is not available. The outcropping of Al Saq aquifer in the eastern part of the catchment provide a good opportunity to control the flash floods upstream of Buraidah and to collected these flows to be recharged into the main aquifer, which is suffering from aggressive pumping. The topography of Al Saq peniplain in the downstream part of the catchment makes the construction of proposed dam quite feasible, as the main channel reaches 1.6 km in average and the surrounding rock shoulders are 19 m higher than the channel bed.

DISCUSSION

Magnitudes of flash floods are controlled by a combination of rainfall characteristics (amount, intensity, duration and distribution over the catchment). Additionally, local lithological and geomorphological conditions also influence the runoff production within the catchment, even under the same meteorological conditions. In general, the whole catchment is unlikely to be uniformly affected by an individual storm. Therefore, the flow-producting hillslope areas will be different from one storm to another. This temporal and spatial variation in runoff processes makes it extremely difficult to generalise a standard conceptual model for dryland catchments. This has given rise to a plethora of hydrological models which incorporate different elements. It is entirely possible that more than one rainfall event has occurred between acquisition of the successive images used for this research. This could result in errors in discriminating the contributing hillslopes and estimating the potential runoff to be harvested and recharged into Al Saq aquifer. The location of outcrops of Al Saq aquifer at the lower part of the catchment makes the potential harvesting of runoff only significant during major flash floods of long return periods. This is because transmission loss significantly reduces the volumes of runoff. The majority of runoff events produced upstream, particularly in dryland catchments of thousands km^2 surface area, will not reach the outlet. Many flash flood models ignore this critical process and overestimate runoff because they model the hydrograph as simply the gross runoff production from the different land cover units within the catchments [2, 4, 27]. The overland flow production is lumped from the whole catchment and the role of channel networks, underlying rock units, geometry and pattern is too often overlooked. Realistically, dryland hydrological modelling approach should be semi-distributed, not just for overland flow production, but also for the subsequent channel routing and transmission loss. Such models can be implemented using existing GIS techniques, as outlined in this paper. Although, the simulated hydrographs whether produced for the whole or part of the catchment (Fig. 7) can not be tested, because there are no flow observations. This is why the method has been developed and this research has the potential of investigating the multi-temporal satellite images to define the occurrence of floods in arid and hyper-arid areas where installing and maintaining instrumentation is difficult.

The active channel cross sectional areas were estimated from these images and used as input to a simple open-channel flow equation (Manning) which has been widely used for both overland and channel flow estimation for both dryland and humid catchments [28-30]. The isochron zones of the catchment [31] were delineated and used to model flow propagation through the catchment. The accuracy and resolution of the DEM [32, 33] and other hydrological parameters (e.g. Manning's n) have a significant effect on the catchment hydrograph, but the sensitivity of model output to these parameters is addressed elsewhere [26]. As part of the next phase of research, the method developed in this study to estimate transmission losses can be applied to instrumented dryland-catchment for validation. Where the satellite images acquired shortly before and after the occurrence of key flash flood events along with the DEM can be used to simulate the runoff hydrographs.

It is of utmost importance to understand the response of dryland catchments to rainfall events is essential in order to assess the impact of flash floods on the increasing anthropogenic activities within these catchments. Furthermore, the groundwater resources are being withdrawn at rates much larger than the recharge occurring during these flash floods. Therefore, the management of flash floods should consider both protection and maximizing the benefits of produced runoff. Dams have been constructed throughout Saudi Arabia from antiquity for water storage, flood control and irrigation [34]. Until 1983 the Kingdom of Saudi Arabia had constructed upto 100 dams of various types and sizes in different drainage basins. Two of the largest structures constructed upto that time were the Wadi Jizan Dam and the Mudhiq Dam in Najran, which have storage capacities of 71 and 86 million cubic meters, respectively [21]. Most of these modern storage dams are located in the upstream of mountainous area of southwestern Saudi Arabia, whereas most of the small recharge dams are build in the Najd region. Additionally, the operation of these dams depends on releasing the floodwater thorough gated outlets, which are provided at different levels to regulate the rate of outflow for irrigation and domestic use and also to recharge the alluvial aquifer downstream. However, the groundwater resources have been depleted from some alluvial aquifers, where dams were constructed upstream on the fingertips channels incised in rugged mountainous area and the annual recharge rate is very low and varies between 3 and 21 % of the total annual participation [8]. Consequently, the collection of floodwater into reservoirs upstream has deprived the thin alluvial aquifers in most downstream areas from replenishment by the occasional flows. Furthermore, the non-regulated pumping of groundwater upstream is also affecting the groundwater flow into downstream area of the aquifer used to sustain the rural areas. The degradation of groundwater in Wadi Fatmah in Makkah area is a clear example; the agricultural production from the fields in Wadi Fatmah has mostly sustained Makkah since early historical periods until few decades ago. The groundwater-fed cultivations of Wadi Fatmah have almost disappeared following the aggressive pumping of its fragile groundwater resources, which started in 1947 to support the municipal water supplies to Makkah as well as Geddah (80 km west of Makkah on the Red Sea coast) [35]. Therefore, the aquifer is almost depleted and most of the fields are abandoned, as the sporadic and erratic rainfalls are barely sufficient to replenish the underlying aquifer systems of rural areas upstream.

CONCLUSION

The lack of hydrological data for the dryland catchments affects the management strategies being implemented for controlling flash floods and harvesting runoff. This data limitation can be significantly overcome by the analysis of active channels affected by recent flash floods. These channels are marked by distinctive reflectance on the satellite imageries such as Landsat TM and ETM+. These data are used, along with DEM derivatives, in a GIS for the determination of synthetic spatially distributed time area–zones of Wadi Al Rimah catchment; thus estimating the flash flood pathways and discharge and also to estimate potential runoff to be harvested. It is highly recommended to construct a large storage dam at the lower part of Wadi Al Rimah, where Al Saq sandstone is outcropping by the main channel. It is important to recognise that produced runoff within larger catchments can be completely lost into the underlying channel alluvium before reaching the outlet. Therefore, this proposed dam will significantly contribute to recharging Al Saq aquifer from the severe flash flood of long return periods otherwise capable to reach Buraidah. Finally it is recommend that dryland hydrological modelling should take advantage of the increasing availability of high spatial and temporal resolution satellite images, so that flash flood protection measures can be properly managed and allocated. This will also maximise the benefits of the limited water resources available in the dryland.

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