The Hydrology of Wadi Ibrahim Catchment in Makkah City, the Kingdom of Saudi Arabia: The Interplay of Urban Development and Flash Flood Hazards

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Abstract: This paper investigates the development of a hydrological model for the dryland catchment of Wadi Ibrahim, which hosts the Holy Mosque of Makkah, in order to assess the interaction of urbanizing the alluvial channels and the flow discharges of occasional flash floods. The original landscape and landcover of the catchment have witnessed significant changes during the past few decades, where most of the alluvial channels and the mountain footslopes have been covered by urban. The infrequent threat of flash floods has prompted the development of a mitigation measure including; installation of rainfall-sewage system and subsurface culverts, in addition to the conveyance of flows from the upper sub-catchment into another drainage basin. However, the latest flash flood event of 30th of December 2010 has resulted in fatalities and demonstrated the insufficiency of the current mitigation system to control flash floods. The runoff coefficient was estimated from the opportunistic observations and measurements of the flow discharge parameters for the latest event, in addition to the recorded rainfall parameters. The digital elevation model (DEM) was analyzed using Geographic Information System (GIS) to determine the spatially distributed time-areas zones of the catchment, which were used to simulate the runoff hydrographs under certain runoff coefficients and designed storms of long return periods. The development of urban areas on expense of the alluvial channels resulted in a significant surge of runoff discharge, and therefore increasing the threat of flash floods on urban areas downstream. As a result the transmission loss is diminishing; thus raising the alarm on the potential recharge to the underlying alluvial aquifer of the sacred well of Zamzam. Therefore, it is suggested that several small dams to be constructed at the fingertip drainage channels; to retain considerable amount of water and sediment within the catchment and to act as point-source recharge to the alluvial aquifer.

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1. Introduction:

The drylands are characterized by droughts and the scarcity of water resources, occasional heavy storms often develop severe flash floods that devastate the inhabited areas (Cooke et al., 1982; Tooth, 2000; Foody et al., 2004). The records of destructive flash floods and the notable regional frequencies have largely raised the public awareness and motivated more scientific research on the hydrological processes within the fluvial system (e.g. Walling and Gregory, 1970; Chin and Gregory, 2001). Originally, flash flood frequencies and magnitudes are controlled by the interplay of different natural variables, including precipitation, antecedent conditions of the catchment, distribution of alluvium and water storage areas, etc. However, the growth of urbanization within the catchments can be added as an additional significant controlling factor for the development of flash flood. Urbanization, through the construction of impervious surfaces; building, roads, storm sewers and paving usually decreases the infiltration capacities of the underlying soils, and it significantly increase runoff-discharge downstream. The estimated increase of runoff coefficients; higher flow peaks and the decrease of time to peak in urban catchment Depends on the extent of urbanization and the anthropogenic managements of runoff of these catchments (Suriya and Mudgal, in press (2011). In completely impervious and fully sewered areas, peak discharge increases 6 times more than in non-urbanized areas (leveson, 1980), and 90 % of the total rainfall may be converted into urban runoff (Shang and Wilson, 2009). However, the assessment of urbanization impact on the hydrological response of the developed catchments is complex and hampered by the lack of hydrological parameters and measurements, and the non-systematic temporal changes of the landuse and landcover due to urbanization (Smith and Bedient, 1981).

Generally, the hydrological data collected in drylands remain insufficient and limited due to technical, political and economical factors, and therefore, the hydrological processes are not fully understood and the hydrological models are uncalibrated (El Bastawesy et al., 2009). Nonetheless, most of these data are also limited and gathered by individuals or entities during pilot projects and various independent case studies, which cannot represent the diversity within dryland setting and processes. It is also difficult to monitor flash floods that occur suddenly, and the potential to capture during classical-field experiments is very rare. Therefore, the investigation of most flash flood-events was mainly based on post-event survey, which plays a critical role in gathering essential observations and data (Borga et al., 2008). The spatial and temporal variability of flash flood events even within a single catchment clearly demonstrate the need for the development of distributed model; to assess vulnerability and to mitigate against future damage.

Remote sensing data and Geographic Information System (GIS) techniques are widely used to estimate various distributed hydrological parameters for the investigation of catchment hydrology following given techniques and interpretations (Schultz, 1987; Scipal et al., 2005; Milzow et al., 2008). The most straightforward use of remote sensing images is to identify geologic, geomorphologic and landuse-land cover features, which in turn have a strong influence on overland flow generation. Several remote sensing- products such as the Tropical Rainfall Monitoring Mission (TRMM) and the Global Precipitation Climatology Project (GPCP) are increasingly available to measure the precipitation at semi-global coverage with a grid spatial resolution of 0.25^0 X 0.25^0 (Huffman et al., 2007; Hossain et al., 2011). The remote sensing-rainfall estimates are widely utilized in the hydrological models, particularly over the areas with poor or no rain-gauges data (e.g. Milewiski et al., 2009; Abu El Magd et al., 2010). However, the uncertainty of remote sensing- rainfall estimates on flood prediction has to be considered; the calibration with in situ data in different gauged areas showed non-systematic overestimation and underestimation (Almazroui, 2011). Although, the remote sensing-based rainfall estimates may represents the sole source of precipitation input to any hydrological model for the dryland catchments.

The digital elevation models (DEM) are mainly obtained from different sources and at different spatial resolution, and therefore are widely being used in the various hydrological models. The automatic delineation of catchment-hydrographic parameters from the DEM has gradually replaced the traditional manual delineation of these parameters from the conventional topographic maps (Band, 1986; Chorowicz et al., 1992). The manual method is a tedious and error-prone technique in dryland alluvial areas, where the thalweg or active longitudinal channel courses are not marked on topographic maps and significant changes in these courses can take place over relatively short periods of time. The major issues associated with the derivation of surface drainage networks from DEM are related to the quality, source and resolution of the DEM and to the processing techniques and algorithms employed (Zhang and Montgomery, 1994; Wolock and Price, 1994). However, the delineation of various morphometric parameters (for a typical dryland catchment) was not very sensitive to the change of DEM resolution (from 20 m to 90 m) (El bastawesy, 2007).

The aim of this paper is to develop a hydrological model for a typical dryland catchment, which has undergone dramatic urban expansion, in order to assess the impact of flash flood hazard on urban areas, and also to determine the effect of constructed mitigation measures on the fragile surface and groundwater resources of the area. Herein the Wadi Ibrahim catchment of Makkah city in the Kingdom of Saudi Arabia is selected for this study, due to its importance as it hosts the Holy Mosque of Makkah and considerable in situ data are available.

The study area:

Makkah city is located in the southwestern part of Al Hijaz province of the Kingdom of Saudi Arabia, between the low-lying coastal plain (Tihamat Al Hijaz) and the escarpment of the rugged Sarawat mountains that has resulted from the uplift associated with the Red Sea rifting. The mountains ranges of Makkah are structurally controlled; they are aligned in northwest-southeast (e.g. Mena Mountains) or east-west directions (e.g. El Tarqi Mountains). However, few mountains are isolated and conform semi-circular shape such as Thour Mountain (755 m) and El Nour Mountain (642 m). The chronology of underlying rocks units in Makkah area is complex; the isolated outcrops of amphibolites, gneiss and schist are of uncertain stratigraphic relationship to other layered rock units of the mountain ranges, and thus they are left unassigned on the geological map of the area (Fig 1). The predominant rock mass underlying the catchment area of Wadi Ibrahim belongs to the Precambrian, and mainly composed of quartz diorite and tonalite (Kamil Suite). These outcrops are of moderate to steep relief, and also range from massive to well deformed and foliated plutons. The Wadis of Makkah dissecting the mountain ranges are characterized by complex and interlocking patterns. This complex pattern of intersecting alluvial areas are very common in the dryland setting and reflect the morphotectonic evolution of these drainage basins, where the paleo-channels were used to flow through different directions than the contemporaneous flow pathways (e.g. El Bastawesy et al., 2010). The Quaternary wadi alluvium consists of unconsolidated, moderately to poorly sorted sand and gravel. The alluvium of the upper reaches of wadi courses is relatively thin and very poorly sorted, but it becomes well sorted and reaches considerable thickness in the lower reaches.

Fig 1: location map of the study area.

The urban pattern of Makkah metropolitan city is unique and controlled by the geomorphological setting; the city has sprawled in radial direction on the limited surface areas of the complex alluvial channels separated by the steep mountain ranges. It is estimated that approximately 9000 hectares of alluvial channels and footslopes of the mountain were converted into urban areas from 1978 to 2000 (Al-Ghamdi and Al-Najjar, 2002). The development also encroached the alluvial corridors, which dissect the barrier mountain ranges, and thus the urban areas in different subcatchments are locally connected. Moreover, tunnels or rock-cut corridors are commonly constructed in mountain ranges that obstacle the connectivity of neighborhood. The Holy Mosque of Makkah (i.e. Al Al Masjed Al Haram) is located within the lower reaches of Wadi Ibrahim catchment; it embraces the Kaaba, and the sacred well of Zamzam (located in a basement room 20 m east of the Kaaba). The Zamzam well is about 30 m deep and it taps the groundwater from the wadi alluviam (i.e. the upper half) and the underlying fractured and weathered basement rocks (i.e. the lower half). The well is heavily pumped to provide millions of visitors with sacred water which is available throughout the Holy Mosque via water fountains and dispensing containers.

The earliest available record of rainfall for Makkah area is dated back to 1966, when the Saudi Meteorological Authority installed a gauging station at Umm Al-Gud of Makkah. However another rainfall gauging station was installed by the University of Umm Al-Qura at the main campus in 1989, the rainfall data remains limited. Therefore, The Custodian of the Two Holy Mosques has installed 2 additional automatic network weather stations around Makkah since 2000 to deliver deliver accurate, and reliable meteorological measurements that can be used in hydrological applications. Overall, the available rainfall data of Makkah area shows a very high spatial and temporal variability. For example the total annual rainfall in 1980 was less than 5 mm, while the total rainfall of 1969 was 318 mm of which more 269 mm was precipitated in one single storm (Fig 2). Although surge in local rainfall magnitudes over the catchments of Makkah city is vital to the recharge of the underlying aquifer, but it usually develops severe and unfavorable flash floods. For example, a destructive flash flood has occurred in 1969 following the precipitation of more than 269 mm of rainfall over Makkah; the water partially filled the holy mosque and stood 2.5 m higher above the floor in vicinity of the Kaaba (Yousef, 1992).

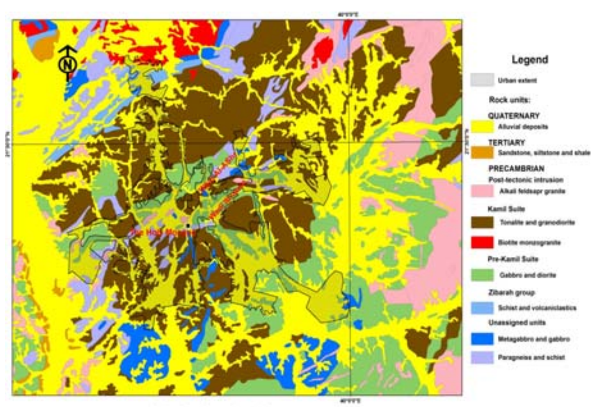

Fig 2: A simplified geological map shows the main rock units and the complex alluvial patterns, note the extent of developed urban areas

As a result of the repeatability of flash floods several mitigation measures and different engineering structures are constructed to collect and discharge the runoff from the urban and mountaneous areas in Wadi Ibrahim. An open channel with a maximum cross-sectional area of 2 m^2 constructed in the upstream zone of the catchment, in addition to several other interconnected lines of box culverts (cross sections vary from 4.5 to 18 m^2) constructed in the middle and lower parts of the catchment. A new culvert of 2.5 m depth and 3.5m width is being constructed to convey the runoff water from the urban areas within the upper sub-catchment northward into neighboring Wadi Al-Ashr via an alluvial channel, which breaches the barrier mountain range (Saudi Geological Survey, 2011). However, hazardous flash floods are developed and the most recent event of 30th of December 2010 has produced fatalities as large urban areas were flooded. Therefore, it is necessary to assess the impact of recent development in Wadi Ibrahim on the hydrological balance and the adequacy of the installed flash flood mitigation measures. Visual interpretation of recent satellite images shows that most of the alluvial bed of Wadi Ibrahim has been converted into urban areas, except few small and scattered parcels of bare alluvial soil in the supper sub-catchment. There is also a growing concern of the impact of these landcover changes on the recharge and quality of the groundwater water within Zamzam well surface catchment (Saudi Geological Survey, 2011).

2. Data and methods:

The morphometrical parameters of Wadi Ibrahim catchment was delineated from the available SRTM DEM following the ArcInfo multi-steps procedure of the D-8 method (Fig 3). The processing of a DEM to produce hydrologically correct and connected drainage networks requires that sinks be first removed (Jenson and Dominique, 1988; Mark, 1984; Wise, 2000). The naturally occurring sinks are not common within the study area. Only few cells were missing elevation data (i.e. voids) resulting from the generation technique of the SRTM DEM, and thus they have been assigned elevation values from the neighbouring cells via the 'filling' step. A given sink is filled to reach the nearest lowest elevation, the boundaries of the filled area may then be part of new sinks, which then need to be filled, and this iteration process is repeated until all the pits are removed. Once a hydrologically connected DEM is produced by sink removal, flow direction is calculated for each cell in the DEM into the most downslope of the neighbouring cells. The 'flow direction' grid is then used to calculate a grid of 'flow accumulation', and finally thresholding is applied to extract up-slope contributing areas for all the drainage channels in the DEM (Jenson and Domingue, 1988). The resulting drainage networks were overlaid on the satellite images to check that they correspond to visible wadis and to identify the urban areas constructed in the pathways of these thalweg drainage lines.

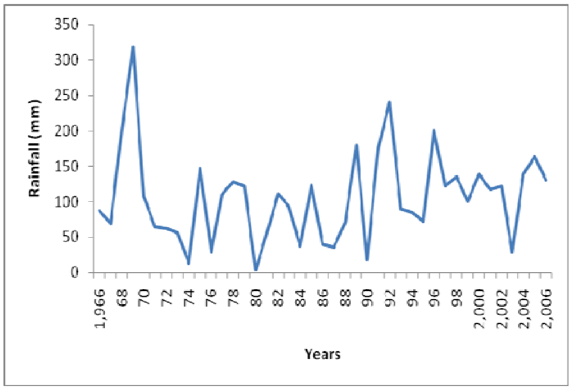

Fig 3: The total annual rainfall of Makkah area modified after Yousef (1992).

The DEM was also used to determine the spatially distributed time-area zones of the catchment, which conforms the runoff hydrograph when rainfall pattern and abstraction losses are uniform across the catchment (Maidment, 1993). It is interesting to note that the application of pure flow routing that neglects the volume of losses as the flow is transmitted from one zone into another, was not appropriate to the modeling of dryland hydrographs, as it omits one dominant hydrological processes (i.e. transmission loss into alluvium channels) (El Bastawesy et al., 2009). Here in the alluvium channels are no longer recognized and have been converted into urban. Therefore the Maidment technique of pure flow routing is acceptable; it will be used to estimate the runoff hydrograph resulting from the extreme rainfall events. Therefore, 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 flow routing is simulated as a purely translation process that neglects abstractions due to storage or loss over the flow pathway, and the runoff produced from any time-area zone will reach outlet of the catchment in a given time. Runoff will follow the same routes with the same velocity regardless of excess rainfall depth. The runoff velocities were estimated using the Manning Equation (equation 1), which is widely been used in modeling the flows of natural open-channels as well as storm-drainage from urban areas (e.g. Ramier et al., 2011).

V=(R^0.67*S^0.5)/n equation (1)

Where V is the cross-sectional average velocity (m s-1); n is the Manning coeffiecent 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. Municipal streets, whether planned or not, conveys large portion of runoff, and the flow- parameters of cross sectional areas (i.e. width * height of the platform) and wetted perimeter were measured. The Manning's n was averaged and set to 0.06 for hillslopes and 0.025 for urban areas; these values are typical of reported values in literature (e.g. Mignot et al., 2006). Slopes were estimated from the available DEM. Once these time-area zones was determined, the climatic data obtained for Makkah area were then analyzed to estimate the designed storm that will be used in computing the hydrograph for the catchment. A statistical probability technique was adopted; first the climatic data was ranked (i.e. from highest to lowest), then the return periods of the extreme storm was calculated using the following probability function (FAO, 1991):

$$P(\%)=(M-0.375*100)/(N+0.25) \qquad \text{equation (2)}$$

Where; P = probability in (%) of the observation, M = the rank of observation, and N = the total number of observation used.

A satellite image of SPOT 5 acquired at 2010 was also investigated to determine the landcover and hydrological parameters within the catchment (Fig 4).

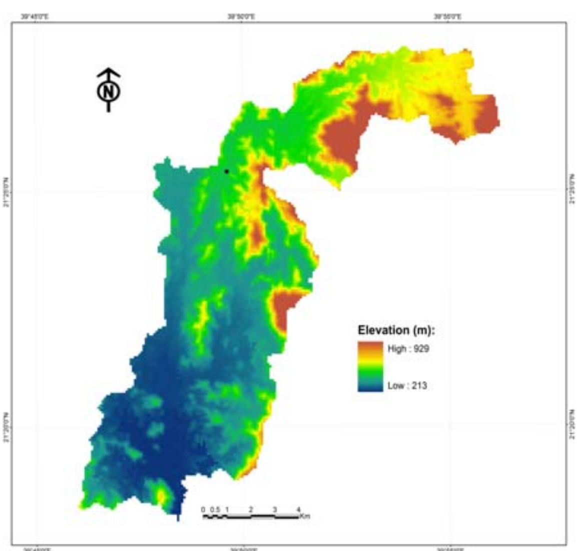

Fig 4: The SRTM DEM for Wadi Ibrahim catchment, location of The Holy Mosque is indicated by the black square.

3. Results:

Hydrology of the dry land catchment of Wadi Ibrahim is modeled to assess the impact of the occasional flash floods hazard, and to address the negative impact of the adopted mitigation measures. It is so important to note, therefore the drastic changes of the landscape on the recharge to groundwater aquifer feeding the sacred well of Zamzam. The analysis of recent satellite images and field observations showed that urban development has sprawled on the limited alluvium soils and adjacent foot slopes of the mountains. Because the estimated infiltration rates at the point-scale by the 'double ring ' are highly variable and associated with much uncertainly with up-scaling to the catchment level; the simulated hydrograph considered a uniformly distributed runoff coefficients estimated from the opportunistic observations and measurements of the 30^{th} of December 2010 hydroclimatical parameters. The discharge was measured at a well-defined cross sectional area of the trapezoidal concrete channel in the upper part of Wadi Ibrahim (Fig 5). The upstream flow contributing area at this channel cross section is approximately 6.7 km^2, the rainfall total depth was approximately 51 mm as measured at the nearest meteorological station of The Costudian of the Two Holy Mosques institute for Hajj Research , and the estimated runoff coefficient of this specific sub catchment is 60%. The catchment-simulated runoff hydrographs for the 30^{th} of December flash flood event is shown in Fig (6). It is important to consider that the urban development on the bare-soil parcels in the catchment will increase the runoff coefficient, as the alluvial surfaces will be obscured and mostly covered by urban features. Thus, the sensitivity of runoff hydrographs simulated at different runoff coefficients (i.e. for bare soil, hill slopes and urban areas) was investigated , and also the scenario of developing urban areas on these bare soil was tested for the impact on hydrograph magnitudes. These results show that the subtle changes in runoff coefficient was of significant impact on the magnitudes and attenuations of hydrographs (Fig 7). However, the changes of runoff coefficient for bare soil parcel were of the least impact on the developed hydrographs; it may be because these alluvium soils cover small surface areas of the whole catchment. In contrary, in large-area catchments the hydrograph (i.e. attenuation and duration) is mostly determined by the runoff coefficient and transmission loss into this alluvium (El Bastawesy et al., 2009). Frankly speaking, the flows developed within the upper reaches of large and undeveloped catchments may not reach the outlet as they totally seep into the underlying alluvium while moving downstream along these channels. In the catchment of Wadi Ibrahim urban areas are developed on almost all of the alluvial channel beds and these changes of the land cover has minimized the transmission loss. But on the other hand, it has amplified the peaks of hydrographs of the flash floods, and it thus increased the threat of flash floods to urban areas in the downstream. Tens of vehicles were drifted during the 30th of December 2010 flash flood event; and as a result several people lost their lives. The torrential flows were accompanied with loads of sediments gullied from the remnant alluvial terraces hanging upon some hill slopes as well as some rock boulders of different sizes, which were dragged by flows from the surrounding hill slopes and the artificially-cut foot slopes areas. The sediment loads can reduce the competent of the installed rainfall-sewage system, which could be partially blocked by the trapped sediments. However, the captured photos on 30th of December 2010 clearly show that the capacity of the culverts-discharge was exceeded and the flow depth reached more than 50 cm on the main roads located in the downstream of Wadi Ibrahim. Furthermore, the flood water has gushed into air from a manhole cover of one of the sewage- culverts, which may have contributed to increasing the surface runoff on downstream urban areas (Fig 8). These undesired outflows may have developed by the intense pressure caused by excessive water than the designed-discharge capacity of the culverts, or due to the clogging of this culvert by washed debris at some point downstream. Therefore, the likely development of a flash flood from more intense rainstorm (i.e. similar to those of 1969 and 1998), may be of serious consequences, unless extra-mitigation measures are considered. The current installed culverts and rainfall-sewage system were not sufficient to control the flows of flash floods during the latest event.

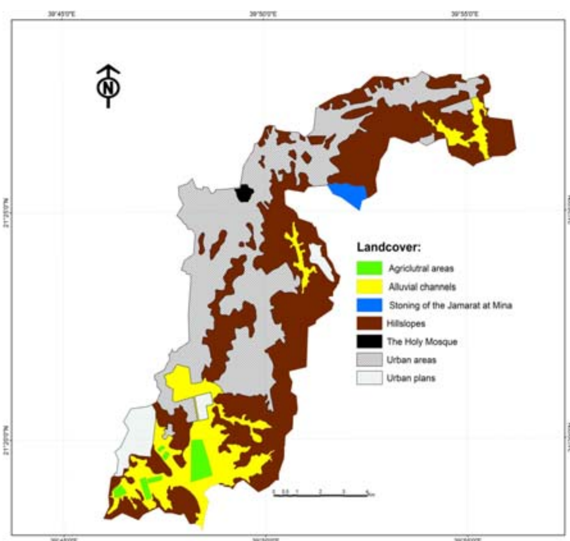

Fig 5: The determined landcover units for Wadi Ibrahim using a SPOT 5 satellite images of 2010.

Fig 6: A field photo of the channeled flash flood of the 30th of the 30th of December 2010 event.

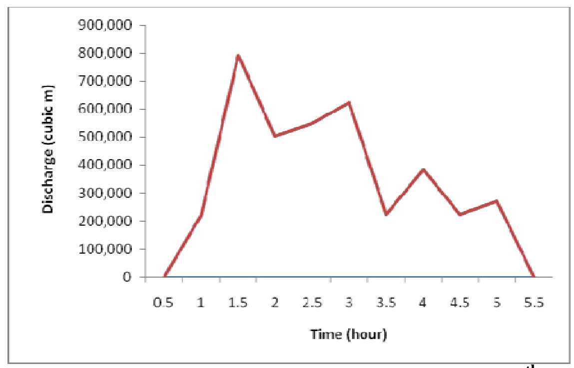

Fig 7: The simulated hydrograph for the 30th of December flash flood event in Wadi Ibrahim.

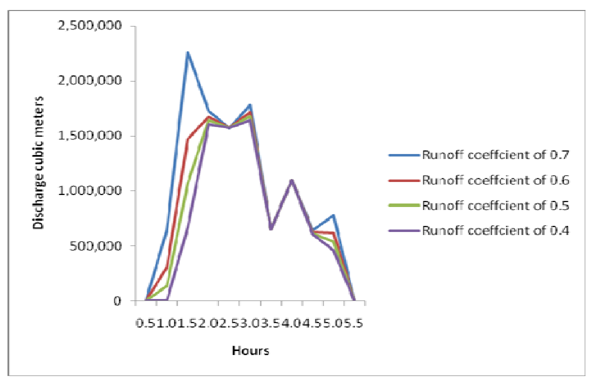

Fig 8: The sensitivity of simulated hydrographs for changes in the landuse and associate runoff coefficients, note the increase of peak discharge and the decrease of time to peak when runoff coefficient is increasing.

Fig 9: The outflows from sewers (top) and the runoff hazards on municipal streets of Makkah during the 30th of December 2010 flash flood (bottom).

4. Discussion:

The hydrology of flash floods developed within the dryland catchment is usually not fully understood. The observations and in situ data measurements are sparse; also the gauging of flash floods is very rare when compared with the seasonal or perennial flows of more humid areas. As such the modeling of flash floods can be grossly inadequate, particularly when it is based on calculated empirical parameters or data obtained from very few rainfall and runoff gauging stations. This data limitation may leads to erroneous conclusion, as the intricate meso-scale atmospheric patterns and complex terrain processes that control desert flash floods are neglected (Pilgrim et al., 1998; Greenbaum et al., 1998). The alternative approach to indirectly estimate flow discharge from the analyses of paleostage indicator (i.e. slack water deposits and drift shrubs and wood lines) (e.g. Baker, 1987) is also insufficient to represent the complex spatial and temporal variability of flows and associated sediment erosion pattern. Therefore, the developed hydrographs of dryland catchments always contains considerable uncertainty. Lots of research has investigated the subtle sensitivity of the hydrological model results to the minor changes in values of used parameters, such as the empirical roughness coefficient of Manning's widely used to estimate channel-flow velocities (El Bastawesy et al., 2009).

Thus, the modeling of flash floods needs to be further improved to minimize uncertainty in order to better manage these torrential flows. Particularly for urban areas and facilities that are being rapidly developed within certain dryland catchments due to, but not limited to the availability of local valuable socioeconomic resources. In Wadi Ibrahim catchment various mitigation measures are currently adopted to control the impact of flash floods on the Holy Mosque as well as other urban areas. The efficiency of these installed measures was recently tested as a severe flash flood has occurred on the 30th of December 2010 following the precipitation of 51 mm on average. Unfortunately, the modeling approach behind these implemented projects are not available, and it is not known if these engineering structures had considered the scenarios of landuse and landcover change within the catchment for their impact on altering the hydrograph as well as recharge to the ground water aquifer of the area. It is clear that the problems created by converting alluvial areas into urban are complex, and the concept of 'complete' flood control yet does not exist. In Wadi Ibrahim two main methods are being adopted to control flash floods, 1); Rainfall waters are collected through a sewage networks and confined subsurface culverts 2); Conveying flash floods from the upper part of Wadi Ibrahim into Wadi Al Ashr via a subsurface culvert, which is being fed from a rainfall sewage system and an open-lined channel. It was noticed that a considerable amount of flows during the latest event were moving along the main municipal streets; thus adequacy of the current rainfall-sewage system can be questioned. Obviously flash floods will continue to be a threat for urban areas in Wadi Ibrahim unless a more competent management is addressed. Herein it is suggested that several small-size dams have to be constructed at the bottom of the fingertip drainage to retain flows and sediments. Consequently high-velocity runoff will be reduced and values of peak discharge will be lessened. Moreover, these small dams can act as a point-source recharge to the alluvial aquifer, where most of the harvested water will seep into the underlying alluvium.

Of course further investigation is required for this particular suggestion to assess the cost-benefit analysis, feasibility of construction and the hydrological connectivity of the first-order drainage segments to the main alluvial aquifer. In the mean time, the entire hydrological management of Wadi Ibrahim catchment needs a further assessment of the effluent pattern of rainfall-sewage downstream. Indeed, the prevailing arid conditions and the severe shortage of underground water resources in the area require a careful management of the fragile water resources. The drainage pattern of Red Sea region (i.e. including Makkah area) is complex, structurally controlled and underwent different phases of morphotectonic evolution related to the Tertiary-Quaternary motions in connection with Red Sea Rifting (Alwash and Zakir, 1992). As such the alluvium thickness is highly variable along the downstream profile of these wadis; several contact-springs used to discharge water along the transect fault Plaines. The alluvial aquifers in Makkah area are mostly depleted by excessive pumping of the groundwater for local irrigation and potable water supplies (Alwash et al., 1986). The current outlets of the rainfall-sewage for Wadi Ibrahim as well as for the neighboring urbanized catchments, which are embracing the metropolitan city of Makkah, can be extended to a specific alluvial channel. This proposed collection of the harvested runoff would maximize the benefit from severe rainfall storms for groundwater recharge. Ideally, the selected alluvial reach has to be underlain by 'a trough' that attains considerable thickness, and also it should be hydrologically separate from contamination by other waste dump-sites and sanitary sewage outlets.

Conclusion:

The problem of flash floods in Wadi Ibrahim catchment is prominent, and it has been further complicated by the sprawl of urban development on the alluvial channels. Consequently, the significant reduction of transmission losses into the underlying alluvium has increased the runoff coefficient and discharge from this catchment. The adopted management strategies for the flash flood included the construction of a rainfall-sewage system in addition to conveyance culverts in the upper part of the catchment to transfer the flows into Wadi Al Ashr (i.e. a hydrologically separate drainage basin). The latest flash flood event of the 30th of December 2010 clearly showed the insufficiency of the current mitigation measures to deal with flash floods; the main municipal streets were flooded and fatalities occurred as several vehicles were drifted. It is evident that the urban areas of Wadi Ibrahim are prone to more serious threat of flash floods, particularly if more severe rainfall events (e.g. The 1969 and 1998 storms) are re-occurred. Indeed the flows of these severe storms will far exceed the maximum discharge capacities of installed culverts, and will develop considerable hazards. Furthermore, gullying of sediments from the abandoned fluvial terraces on hillslopes can cause clogging problems to the rainfall-sewage and delimit their designed capacity. It is highly recommended to consider the construction of several small dams at the fingertip channels, in order to retain considerable amount of water and sediments. These dams could be acting as a point-source recharge to the underlying alluvium aquifer, as the original replenishment of this aquifer from channeled runoff was greatly reduced by urban development.

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