Flash Floods Mitigation for Al Kharj City, KSA: Case Study

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Abstract: ***Al Kharj city is under the effect of wadis of 14166 km^2 catchment area. Due to its urban expansion, many rainfall events led to flash floods that inundated parts of the city and caused huge economic losses. A man - made water passage was constructed to convey flash floods to the city downstream. A hydrologic study is carried out for estimating 100 yr. design storm, delineating of wadis, determining their morphological characteristics using Watershed Modeling System (WMS) and estimating the maximum flood discharge using Hydrologic Engineering Center - Hydrologic Modelling System (HEC - HMS). The dimensions of this passage and the associated culverts are proved insufficient for rainy storms of 50 yr. return period or larger which led to water spillage. Two solutions are proposed. The first is to re - design the water passage and the culverts to convey the 100 yr. flood using Hydrologic Engineering Center - River Analysis System (HEC - RAS). The second solution is to construct series of dams on selected upstream wadis. A comparison between the two solutions is provided.***

Keywords: design; flood management; hydraulic; hydrology; surface runoff; mitigation; flash

1. Introduction

One of the dominant types of disasters occurring in a territory of a country are floods and flash floods, which cause a lot of material loss and casualties (Adi Maulana, et al, 2023). In recent decades, flash floods have become a major natural disaster and show a continuously increasing trend on a worldwide scale. The magnitude of the damages associated with flash floods requires forecasting and monitoring strategies to understand the vulnerability factors, analyse the mechanisms of flash floods, and mitigate disasters (Xiekang Wang, et al, 2023). Many regions in Saudi Arabia are witnessing urban development especially Riyadh Region. Al Kharj city located in Al Kharj Governorate in Kingdom of Saudi Arabia, which considered the second largest city in this region after the capital Riyadh city as shown in Figure 1. Al Kharj is a governorate in central Saudi Arabia. It is one of the important governorates in the Kingdom of Saudi Arabia (Wikipedia, 2024). Located in the southeast of the capital Riyadh, it covers an area of 19, 790 km^2 ~ 4, 890, 215.5 acres, and has a population of 376, 325 people, according to the statistics of the General Authority for Statistics for the year 2010 (Saudi General Authority for Statistics 2010).

During six years from 2004 to 2010, there was an increase in both the occupational housing and population by 35% and 17.5%, respectively. Al Kharj city is expanding at the expense of neighbouring flood plains. The city is under the effect of a group of wadis of total catchment area of about 14166 km^2. Daily rainfall depth at some locations in the catchment area was very high. For example, Air Base meteorological station recorded 70 mm on the 3rd of December 2003 and Hawtat Bani Tamim meteorological station recorded 73 mm in the 11th of April 2004 according to the Department of Hydrology, Ministry of Water and Electricity of Saudi Arabia, 2012. Moreover, rainy storms of daily depths less than the aforementioned values may result in huge flash floods. Such an example is the December 2003 flash flood that caused many damages. Recent flash floods also occurred in different locations near Al Kharj city.

Urbanization causes an increase in the severity of floods. Suriya and Mugdal (2012) studied an urban watershed in Chennai (Thirusoolam sub watershed). They found that urbanization reflected in the stream flow and concluded, urbanization increases flooded area and water depth for the same amount of rainfall. In addition, they recommended that for effective urban planning, hydrologic impacts of urbanization should be taken into consideration.

Mona A. Hagras, et al. (2013) studied flood plain mitigation in arid regions taking south of Al - Kharj city, Saudi Arabia as case study. The study aims at presenting the characteristics of the watersheds affecting the southern urban area of Al - Kharj, almost completely located inside the flood plain of wadi Al - kharj and evaluating the flood hazards associated with higher rainfall events. Detailed field studies were conducted for the study area to inspect the existing drainage works, the conditions of neighbouring areas, and the characteristics of the effective wadis.

Konrad (2016) found that changes in land use associated with urban development affect floods and increase runoff to streams. As a result, urbanization can limit stream channels capacity to convey floodwater. Roads and buildings constructed in flood - prone areas are exposed to increased flood hazards, including inundation and erosion. Detailed hydrologic studies can help communities reduce their vulnerability to floods.

Sharif et al. (2016) examined flood hazards in the urbanizing catchment of Al - Aysen in Riyadh, Saudi Arabia. Remote sensing and geographic information system were employed to obtain and prepare input data for hydrologic and hydraulic models, with the former based on curve number approach. Flood hazard zones and affected streets were identified

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through model simulation. They concluded that flooding events affect the road network and create driving hazards.

Youssef et al. (2016) studied flash floods occurred in Jeddah, Saudi Arabia in 2009 and 2011. The impact of these two flood events has been disastrous causing extensive flooding that killed 113 people in 2009 and damaged infrastructure and property (more than 10, 000 homes and 17, 000 vehicles). They concluded that among the many factors which play as a major contribution in worsening the flood disaster, the ones that are related to wadis tributaries such as narrow passes and high slopes. Besides, anthropogenic activities that include the proliferation of slums and construction in the valleys coupled with the lack of suitable water streams to accommodate the amount of water flows and the presence of obstacles have led to changing the flow direction.

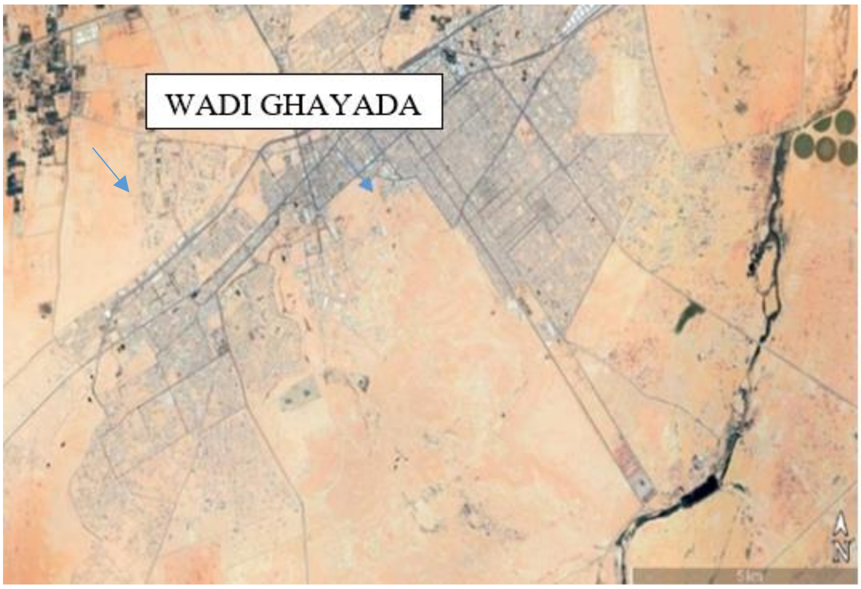

Figure 1: Al Kharj city and WADI GHAYADA.

El Shinawy et al. (2017) assessed flash flood potentials of Wadi Al Sail Al Kabir and their impacts on Miqat Qarn Al Manazel area, western Saudi Arabia, for sustainable development. They used WMS model to delineate the watershed, HEC - HMS program to simulate rainfall - runoff processes for 50 and 100 yr. floods and HEC - RAS program to delineate flood plains. The study revealed that the wadi has the capacity to carry the 50 yr. flood without any harmful effects on the study area, while as the 100 yr. flood may result in adverse consequences on the public welfare.

Amal AL Mushayt, et al. (2018), have chosen Wadi Nesah as a case study for estimation the peak discharge of flash flood and implementation of the advanced harvesting techniques of flood water and avoiding the damage on the infrastructures and urban community in the Wadi.

Yanjun Zhao, et al. (2023), developed the new urban hydrological model TVGM - USWM that considered the nonlinear rainfall - runoff relationship and the flow routing in an urban drainage system. They applied the modelin the Huangtaiqiao drainage basin of Jinan City, China. Results showed that urbanization has a significant amplifying effect on the design flood processes, especially for floods with small frequency, and the impact of urbanization on the time - to - peak of the design flood gradually decreased as the frequency of the design rainfall decreased.

The objectives of this study are to evaluate the sufficiency of the existing water passage and hydraulic structures (culverts at intersections with roads) in Al Kharj city to convey the 100 yr. flash flood and to propose solutions to protect the city from severe flash floods.

2. Materials and Methods

2.1 2015 Situation

Due to repeated inundation of many areas in Al Kharj city by flash floods, Al Kharj Municipality in 2012 constructed an artificial channel by excavation and backfilling the side slopes starting just upstream Al Kharj city. The channel is considered as a water passage through the city, and is known locally by “WADI GHAYADA” as shown in Figure 1. This water passage collects all the runoff water from the upstream watersheds. At the beginning (just downstream Al Akhawain Bridge, km 0.0), the water passage has 55 m width and 4 m depth. It continues with the same width passing from Al Maraie (km 6.16), Ibn Sina (km 9.23), El Gamaah (km 11.17) and Al Riyadh (km 12.96) culverts that have cross section areas of 78, 102.5, 93.6 and 92.25 m^2, respectively. After which the width decreases to 35 m due to existing roads and houses until Al Hedathi culvert (km 13.34) with a smaller cross sectional area of 67.2 m^2. Beyond this culvert the width increases again but the water passage ends without any formation. It then passes from the narrow El Yamama culvert (km 16.18) of cross section area 78 m^2. The total length between the beginning of the water passage (at Al Akhawain Bridge) and El Yamama culvert is 16.18 km. The longitudinal slopes of the reaches between the culverts range between $5.0811 x10^{-4}$ and $12.105 x10^{-4}$.

There are four dams in the upstream watersheds with a total capacity of nearly 21 million m^3. In addition, there are many small earth check dams and temporary earth embankments that are used to store water for short time period for traditional local system water distribution between farms. These earthen structures are removed after the water feeds farms.

2.2 Hydrologic and Hydraukic Studies

At Al Kharj city, there are no measurements for the surface runoff from wadis that can be used to calibrate or validate any hydrologic model. This is the usual situation for arid regions. As a result the methodology of the hydrologic study consists of three parts; meteorological study to analyze data of annual maximum daily rainfall to estimate the design rainfall storm, wadis delineation and morphological analysis of streams' networks, and rainfall - runoff study using suitable hydrologic model for the estimation of the maximum discharge corresponding to the design rainfall storm.

For the meteorological study, daily rainfall data were collected for six meteorological stations (Department of Hydrology, Ministry of Water and Electricity 2012). The basic data of the stations is provided in Table 1. Annual maximum daily rainfall was identified. Analysis of this data was performed to choose the probability distribution that best fits the data.

Table 1: Meteorological Analysis.

Meteorological Station	El - Qwaihia	Air Port	Air Base	Al Kharj	Al Hariq	Hawtat Bani Tamim
Longitude° (E)	45.23	46.72	46.74	47.4	46.52	46.83
Latitude° (N)	24.08	24.93	24.75	24.17	23.62	23.5
Altitude (m)	1010	614	620	430	540	525
Available Data (from - to)	1963 - 2004	1985 - 2010	1980 - 2010	1970 - 2011	1964 - 2011	1965 - 2011
Best Fit Probability Distribution	Log Pearson Type III	2 Parameter Log Normal	Pearson Type III	Gumbel External Type	Pearson Type III	Pearson Type III
Annual maximum daily rainfall for a						
200 yr. Return Period	65.91	52.16	86.00	50.30	62.60	86.00
100 yr. Return Period	61.81	48.06	75.46	44.80	57.30	74.20
50 yr. Return Period	56.71	43.94	65.08	39.20	51.70	62.40
10 yr. Return Period	39.95	34.09	41.67	26.00	36.70	36.10

Data source: Department of Hydrology, Ministry of Water and Electricity, 2012.

Digital Elevation Model (DEM) 90 m data was downloaded from NASA site (https: //csidotinfo. wordpress. com/data/srtm - 90m - digital - elevation - database - v4 - 1/). Watershed Modeling System (WMS) (AQUAVIEW 2015) was used to delineate the watersheds affecting Al Kharj city and to determine their streams' networks. Also WMS was used to obtain the main morphological characteristics of the watersheds i. e. area, length of the main stream and average relief of the main stream.

Based on the geological map of the study area (Saudi Geological Survey 2015), the watersheds surface geology mainly consists of sedimentary rocks (60 - 90%) and wadi deposits (10 - 40%). Many faults, cracks and joints are also existing. These prevailing types of rocks, deposits and geological structures recommend medium values of runoff coefficient and curve number.

HEC - HMS model (Hydrologic Engineering Center 2015) was used to estimate the runoff hydrographs and maximum discharges. Manning equation was used to determine the steady state maximum carrying capacity of the water passage considering its 2015 dimensions. HEC - RAS model (Hydrologic Engineering Center 2015) was used to check the carrying capacity of the water passage for the 100 yr. runoff hydrograph. One - dimensional unsteady module was used. Topographic field survey AutoCad maps was used to obtain the cross sections of the water passage as input to the model. Manning roughness coefficient was estimated based on the surface soil characteristics (D_{50}) using Strickler equation.

3. Results

There are no fixed culverts' dimensions and no fixed longitudinal slopes for the reaches between culverts. Using the field topographic survey of the water passage and the surface soil characteristics (D_{50}) to estimate Manning coefficient and applying Manning equation, it was found that the maximum discharge that can be conveyed in the reach between Al Riyadh culvert and Al Hedathi culvert equals 276 m^3/ sec. The critical reach is between Al Riyadh culvert and El Yamama culvert.

Table 1 provides the best fit probability distributions for the six meteorological stations. The different probability distributions are mainly due to the difference in the available data series lengths and the geographic settings of the stations. The annual maximum daily rainfall for the six meteorological stations for different return periods; 10, 50, 100 and 200 yr. are provided in Table 1. From the table it is seen that Air Base meteorological station gives the maximum values of the annual maximum daily rainfall for all the return periods followed by Hawtat Bani Tamim meteorological station. On the other hand, Al Kharj meteorological station gives the minimum values of the annual maximum daily rainfall for all return periods. Thiessen method was used for areal distribution of the annual maximum daily rainfall for the different considered catchments. Available rainfall data does not include temporal distribution of rainfall depths or intensities. Bell method for the distribution of rainfall intensities for short rainfall events (Zekai Sen 2008) was used to construct Intensity - Duration - Frequency (IDF) curves for the 100 yr. return period as shown in Figure 2.

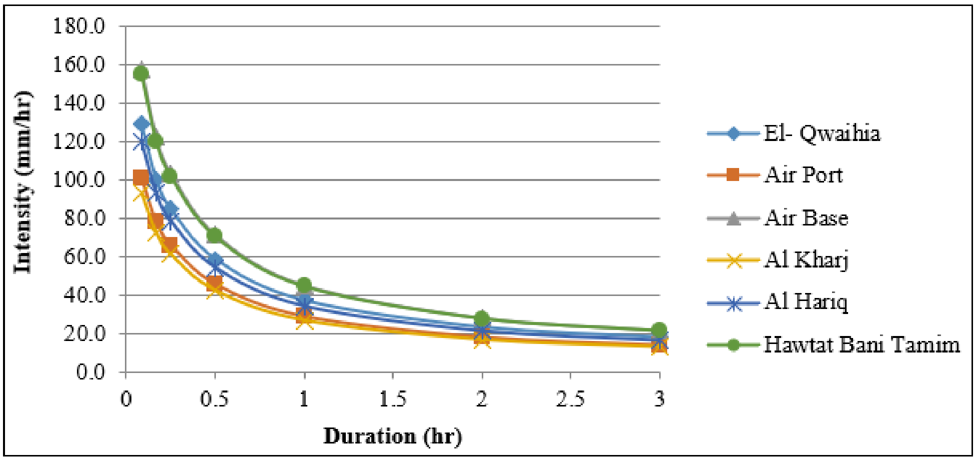

Figure 2: IDF curves for 100 yr. return period

These curves are used to estimate the intensity of rainfall corresponding to a duration period equals to the time of concentration for each considered catchment. The time of concentration was estimated using the Federal Aviation equation (Sharifi and Hosseini 2011).

Figure 3 presents the delineation of the watersheds affecting Al Kharj city, and the results of the morphological analysis are shown in Table 2. The total area of watersheds affecting Al Kharj city is 14166 km^2. Wadi Nesah is the nearest wadi to the bginning of the water passage. Its catchment area, main stream length and average relief of main stream are 1896 km^2, 164 km and 0.0029, respectively.

Prevailing types of rocks, deposits and geological structures recommend medium values of runoff coefficient and curve number. Based on that the corresponding average estimated curve number CN ranges from 65 to 70.

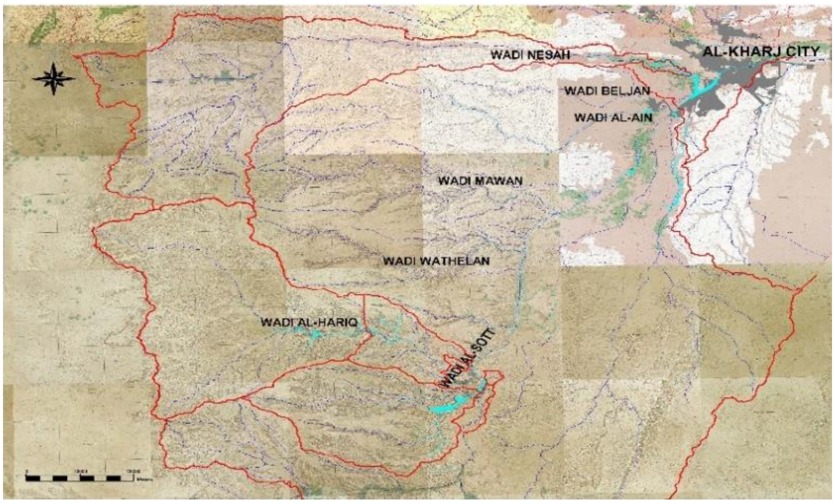

Figure 3: Delineation of wadis affecting Al Kharj city.

Table 2: Main morphological characteristics of watersheds affecting Al Kharj City

Watershed	Area (km^2)	Main Stream Length (km)	Main Stream Relief (m/ m)
Wadi Nesah	1896	164	0.0029
Wadi AlAin	489	70	0.0080
Cumulative of Beljan and AlKhabi wadis	884	185	0.0026
Wadi Wathelan	634	78	0.0081
Wadi Mawan	292	53	0.0108
Cumulative of AlSott and AlHariq wadis	9971	189	0.0019

Using HEC - HMS model, it was found that the maximum runoff discharge from the watersheds upstream the beginning of the water passage (excluding the areas that their runoff waters are stored in the existing dams) corresponding to 100 yr. rainfall storm equals 455 m^3/ sec. The contribution of the runoff discharge of Wadi Nesah, which is the nearest wadi to the water passage, is 175 m^3/ sec. The 100 yr. maximum runoff exceeds the carrying capacity of the water passage of 276 m^3/ sec which leads to spillage of water mainly in the reach between Al Riyadh and El Yamama culverts. Rainfall storm for 50 yr. return period gives 323 m^3/ sec maximum runoff discharge which also exceeds the water passage carrying capacity.

4. Discussion

Based on the above analysis it is obvious that rainfall events of 50 yr. return period or larger result in maximum runoff discharge greater than the carrying capacity of the water passage in Al Kharj city. The runoff water will spill out from the water passage and cause damage to neighbouring structures and infrastructure. Also, it may become a real threat to human lives. To tackle this problem, two solutions are proposed hereinafter.

4.1 The First Solution

The first proposed solution is to enlarge the dimensions of the water passage and the culverts based on 100 yr. maximum runoff discharge. The potential of this solution is investigated using HEC - RAS model. Several dimensions of water passage and culverts were simulated until no spillage occured. Table 3 provides a comparison for the culverts dimensions as 2015 situation and the proposed culverts' dimensions for no spillage. Moreover, the simulation considered increased water passage widths between 61.2 and 77.6 m with a constant design depth of 4 m. Running the model using these dimensions, no spillage occurred. Due to enlargement of water passage dimensions, land expropriation is necessary. The cost of this solution includes excavation, backfilling and pitching for the water passage ; plain and reinforced concrete for the culverts construction and compensation for the people for their land expropriation.

Table 3: Comparison between culverts dimensions as 2015 situation and proposed culverts dimensions for no spillage (first solution).

Culvert	dimensions as 2015 situation*	Culvert area (m^2)	culverts dimensions for no spillage*	New culvert area (m^2)
Al Maraie	12x3.25x2	78	19x3.25x2	123.5
Ibn Sina	12x3.35x2.55	102.5	12x3.35x2.55 + 6x3.5x2.55	156.06
El Gamaah	12x3x2.6	93.6	20x3x2.6	156
Al Riyadh	13x3.3x2.15	92.25	22x3.3x2.15	156.1
Al Hedathi	8x4.2x2	67.2	8x4.2x2 + 11x4x2	155.2
El Yamama	12x3.25x2	78	18x3.25x2	117

*number of vents x vent width (m) x vent height (m)

4.2 The Second Solution

The second proposed solution is to build series of dams at selected locations on the upstream watersheds to decrease the runoff water to the water passage in Al Kharj city. Although flash floods cause a lot of damage, the perception of local farmers of building dams is unfavorable as it may deprive the farms from the needed water and sediment, in addition to environmental cautions. However, if dams are operated in proper way they can provide a robust solution. At the selected appropriate site, the dam storage is estimated based on rainfall storm of relatively high return period i. e.100 or 200 yr.

The low flows (floods of 2 - 10 yr. return period) may be managed by completely opening of the dam lower gates to provide water and sediment to the downstream without any storage in the dam reservoir. Medium flows (10 - 25 yr. return period) may be managed by releasing water and sediment through dam gates associated with storing the water greater than 10 - 20% of the flood volume. High flows (higher than 25 yr. return period) may be managed by storing the total incoming flood. The stored water in the dam reservoir for the medium and high flows may be released after the end of the rainfall event from dam gates according to downstream demands. Dams designed according to this methodology are considered multi - purpose dams as they are used for protection from flash floods, storage of water for different uses and for groundwater recharge.

Nine dams were proposed; two in Al Hariq, three in Hawtat Bani Tamim and four in Al Kharj governorates. Locations of dams are provided in Figure 4.

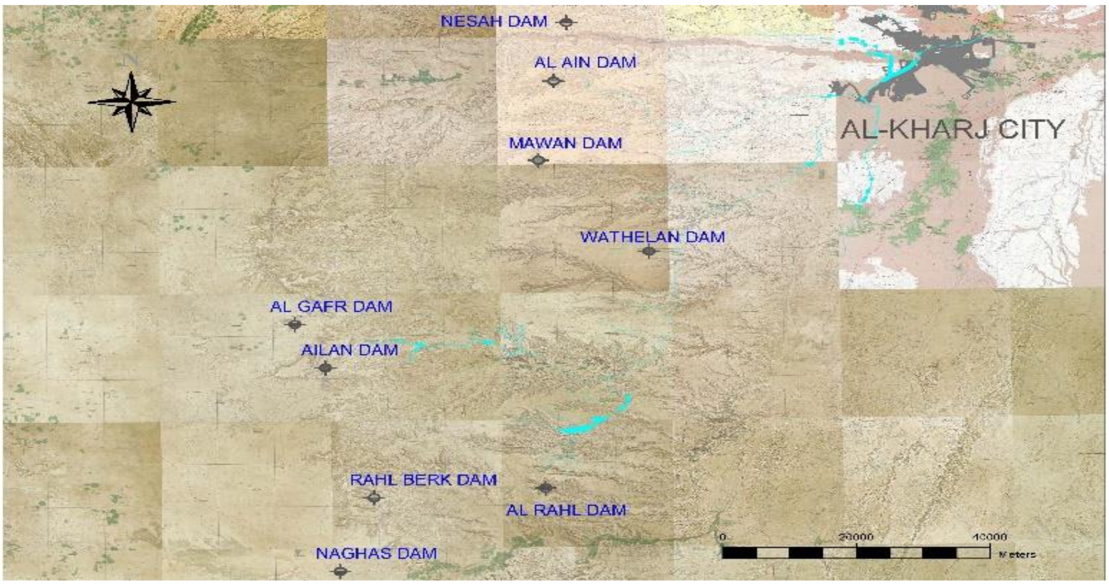

Figure 4: Dams locations, second solution

The proposed dams are hydraulically designed to store the runoff volume corresponding to the rainy storm of 200 yr. return period based on elevation - storage curves developed for the reservoirs upstream dams' locations and provision for spillways' heads and free boards. Their heights range between 8 and 18 m and their storages capacity range from 1.15 and 19 million m^3. The total storage of the dams is 49.35 million m^3. The most important dam is Wadi Nesah dam of 13 m height and 19 million m^3 storage because it is the nearest dam to the water passage, in addition this wadi usually causes many harms to both Al Hayathem and Al Kharj cities. The nine dams in addition to the existing four dams of 21 million m^3 storage, if operated properly as described above, may protect Al Kharj city without any need to change the 2015 water passage design. The cost of this solution is the cost of building the nine dams.

4.3 Comparing the two Solutions

The comparison between the two solutions is provided in this section to facilitate the decision making process. Technically the two solutions provide protection for Al Kharj city against flash floods. Dams provide protection not only for Al Kharj city but also for the other cities in Al Kharj Governorate. However, without proper management of dams, it will not provide the optimum solution. This needs professional hydrologists for rainfall - runoff real time simulation and technicians for dams operation with perfect fast communications. The water passage will convey water to downstream the city without use. Dams will lead to charging the groundwater due to long retention time and regulate the surface water according to farms water demands downstream the dams.

Regarding the cost, the first solution has higher cost than the second solution mainly due to land expropriation and the need for people compensation for their lands. Management of water by dams will add revenue for the groundwater and the regulated surface water.

Both solutions provide relief to the local community; however, the dams' solution may require an awareness campaign to change the local communities' negative perception regarding dams. Finally, concerning environmental issues, Environmental Impact Assessment (EIA) is needed to tackle various environmental issues and to prepare Social and Environmental Management Plan (SEMP) before construction of dams. Al Kharj Municipality can decide on the most suitable solution based on the above comparison.

5. Conclusions

Al Kharj Municipality constructed a water passage to convey the flash floods from upstream wadis to downstream Al kharj city to avoid the repeated economic losses in the city due to inundation by these flash floods. Using hydrologic and hydraulic models, it has been shown that the dimensions of the water passage and the culverts constructed at the intersections with roads are insufficient to convey the flash floods of 50 yr. return period or larger. Two solutions are presented and discussed. The first is to re - design the water passage and the culverts to convey the 100 yr. maximum discharge. For this solution, the floodwater will be conveyed to downstream the city without spillage. The new water passage and culverts dimensions are provided. The second solution is to construct nine dams on selected upstream wadis in addition to the existing four dams with storage capacities that can impound the 200 yr. floods. This solution requires proper operation of dams to ensure water releases required to satisfy farms irrigation needs without causing any spillage to the city. The proposed dams' operation has been briefly discussed. Comparison between the two solutions is presented. Choice of the suitable solution is contingent to Al Kharj Municipality based on cost, social and environmental considerations.

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