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Flash Flood Management in Arid Areas

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Abstract: Flash floods are one of the major natural disasters that may hamper human activities and developments in arid areas. Desert area in Saudi Arabia as Egyptian desert is identified as a flood prone area where several flash floods were recorded and resulted in significant infrastructural damages and loss of life. In the present study, Wadi Arar basin, one of the major basins in the northern area of Saudi Arabia that is frequently subjected to severe flash flood damage, is selected for investigation. This wadi is similar to many Egyptian wades in their huge drainage basin area, variable geological units, heavy rain in short duration, sharp peak and runoff hydrograph shape. The flood management strategy in these basins is to control flood water by dams. Management and assessment of flash flood hazard in such basins is essential to assess the dam reservoir capacity according to the basin developments and the climate changes. This research has developed a systematic methodology for assessing flood hazard based on hydrologic and hydraulic analysis using geographic information system and remote sensing. This methodology can, with little effort, be applied to similar wades in Egypt and other arid areas in the Arab countries. The results presented in this paper can help the developers, planners and decision makers for flood management and land use planning in arid areas. It is recommended to follow the same procedure presented in this research in similar areas in Egypt to assess the flash flood hazards and to secure new communities.

Key words: Hydrologic analysis · Hydraulic analysis · Flood hazard assessment · Arid area · Flood management

INTRODUCTION

Flash floods are among the deadliest of weather phenomena. Floods cause about one third of all deaths, one third of all injuries and one third of all damage from natural disasters [1]. Flash flooding in arid regions is a double edged natural phenomenon being simultaneously a blessing and a curse [2]. Flash floods represent a natural phenomenon that results from large amount of heavy rainfall during a relatively short time, especially in mountainous areas [3]. Flash flooding occurs often along mountain streams where much of the ground is covered by impervious rocks. Drainage channels in such areas may be unable to accommodate the runoff that is generated by relatively small, but intense rainfall events. Many modeling approaches were developed to simulate floods [4]. The choice of the simulation approach depends on the purposes of the study [5]. Very little attention is paid for formulating rational land use planning to reduce flood induced disaster. Preparation of a comprehensive flood hazard map for an area would be one of the most crucial steps for implementing non-structural remedial measures. This paper aim is to develop flood hazard and intensity maps for Arar area located in the north of the Kingdom of Saudi Arabia. Wadi Arar is one of the largest wadis that exposed to heavy rainfall causing flooding in many parts of the drainage basin. Outlet areas have many infrastructure facilities such as roads, bridges, residential areas and industrial projects with a future plan for the expansion of these projects. This areal development is in danger due to Arar flood risk. Accordingly, Hydrologic and hydraulic analysis is performed to assess and quantify the degree of hazard and take the necessary preventive measures for the management and protection.

Description of the Study Area: Wadi Arar basin is located in the northern part of Saudi Arabian and it is one of the largest watershed in the Arabian Peninsula as shown in Fig. (1). The drainage basin area in Saudi Arabian only is about 9000 km^2 while the rest of the basin is located in Iraq country. Despite its aridity, it is occasionally subjected to heavy rainfall causing flash

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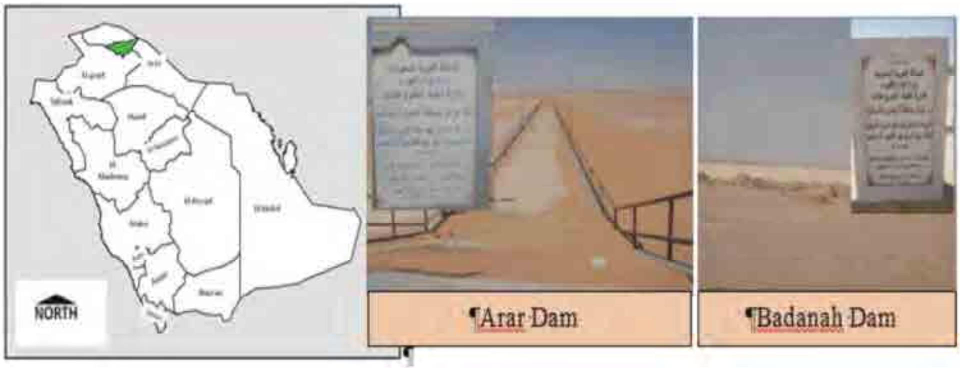


Fig. 1: Location map of the study area

Fig. 2: Rainfall storms and snow in the study area

floods (as in 2010 and 2011), which are commonly characterized by sharp peak discharges with short durations. Such floods pose a significant threat to the socio-economic development of local communities and to the prosperity of industry as shown in Fig. (2). To maximize the benefit of these floods, Arar dam (9 m height and 1828 m length) was built in 2006 to store about 10.366 million m^3 of water. Also, Badanah dam (9 m height and 783 m length) has been built in 2008 to store about 4.67875 million m^3 of water. This water is used for different purposes such as domestic and agricultural purposes.

The infrastructure in Arar area is represented by a group of buildings such as villages and cities, factories and other vital installations in addition to a network of primary and secondary roads and pistils, as shown in Fig. (3). The main roads in the region are; Arar / Hezam ElGlamid, Arar / AlGadedah and Arar / Aykulaih, where Arar is located at the crossroads of this road network. The most important characteristic of the region is the drainage network which is formed by heavy rains in ancient times to generate flash floods. Flood represents a major threat to these roads, cities, villages and industrial buildings. In spite of the seriousness of the flood, at the same time it represents an important source of surface water resources, especially in the dry season.

Topography: Data from the 90 m digital elevation model (DEM) of Wadi Arar shows that the ground elevation is about 900 meters above sea level at Showayhed ElHamad and Amoud mountain. Side slope is computed from DEM

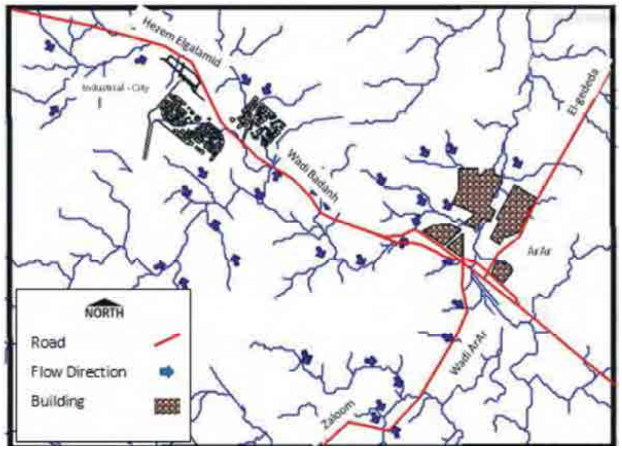


Fig. 3: Intersection of Arar drainage network with the infrastructures

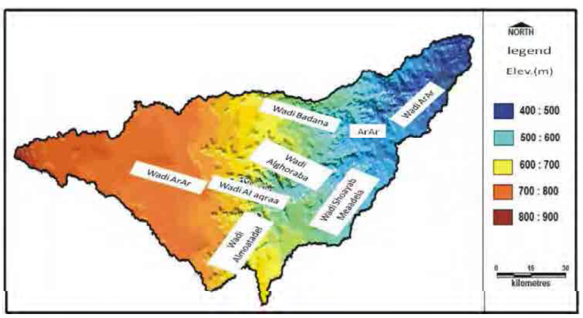


Fig. 4: Digital elevation model (Resolution of 90 m)

by using the surface analysis tool that is available in ArcMap software. The wadi morphology is characterized by steep slopes in the upper part of the basin, decreasing while approaching the basin outlet as shown in Fig. (4). All the topographic data are obtained from Kingdom of Saudi Arabia topographic map with scale 1:50000

Adjusting the Delineated Stream Network: The stream network and the basin boundary are delineated from the DEM using the Watershed Modeling System (WMS) software [6]. The resulted stream network is compared to topographic map. It is noticed that there is a difference at southern part of the basin. This difference is due to existence of a road that changes the flow direction at this location as shown in Fig.(5-a). However, the capability of WMS to change the flow direction is used to adjust the flow direction to simulate the actual stream network as shown in Fig.(5-b). According to this adjustment, an area of about 500 km^2 is added to the Arar basin area.

Arar drainage basin consists of a number of main wadis namely Badanah, Shoayeb Elhanzalya, Alghoraba, Shoayeb Meaadela, Alaqraa and Almoatadel. Using the Watershed Modeling System (WMS) software, the drainage basin is divided into 6 sub-drainage basins with areas ranging between 366 and 3047 km^2 as shown in Fig. (6). Table (1) shows the morphological characteristics of Wadi Arar sub-basins.

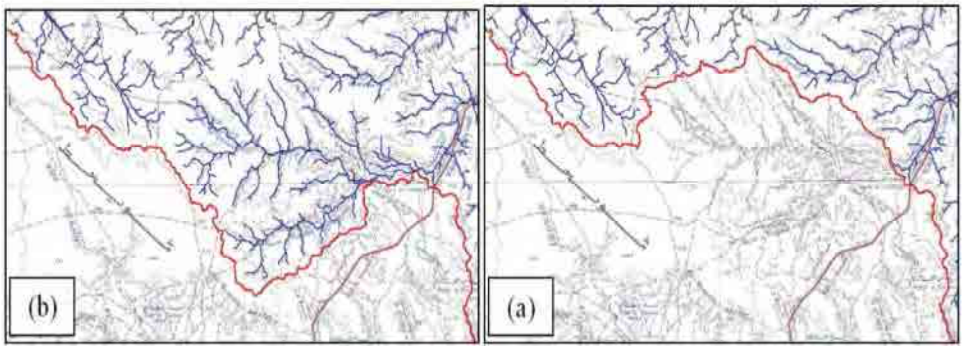


Fig. 5: Stream network before and after modification and adjustment

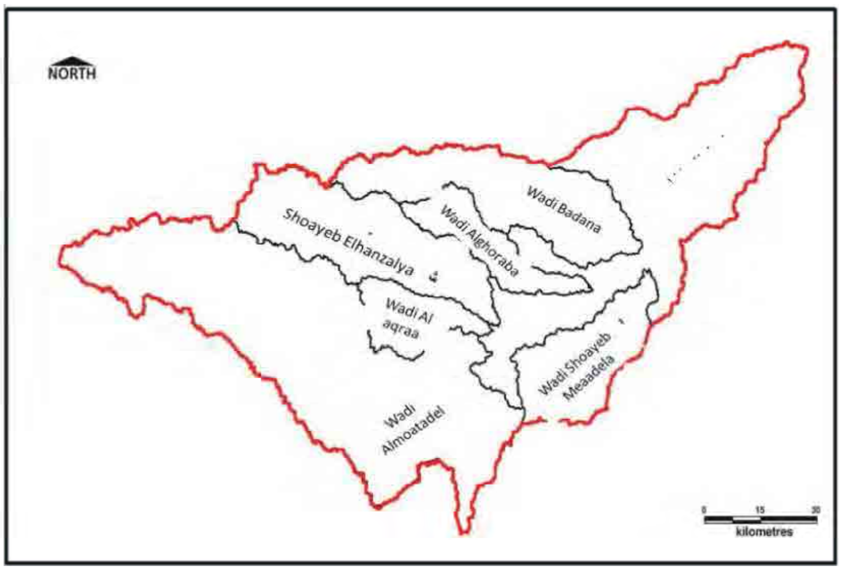


Fig. 6: Main Wadis in the study area

Table 1: Morphological characteristics for Main Wadis in the study area

Wadi name	Area (km^2)	Length (km)	Slope (m/m)	Mean elevation (m)
Almoatadel	3047	117	0.012	790
Shoayeb Meaadela	1146	75	0.014	774
Badanah	1108	84	0.023	683
Alaqraa	366	38	0.026	748
Alghoraba	398	55	0.025	701
Shoayeb Elhanzalya	690	49	0.018	632

Rainfall: The rainfall may be heavy, severe and sometimes thunderstorms causing flooding in steep areas especially from September to May. To identify the quantities of rainwater that fell on the study area during the previous years, recorded data of more than 15 stations to monitor the rain near the study area has been collected, as shown in Fig. (7). Thiessen polygon tool available in WMS is used in order to determine the stations affecting the drainage basins of the study area. According to Thiessen polygon, wadi Arar is affected by rainfall measured of only two stations; Arar and Hezam ElGlamid rainfall recording stations, as shown in Fig. (7).

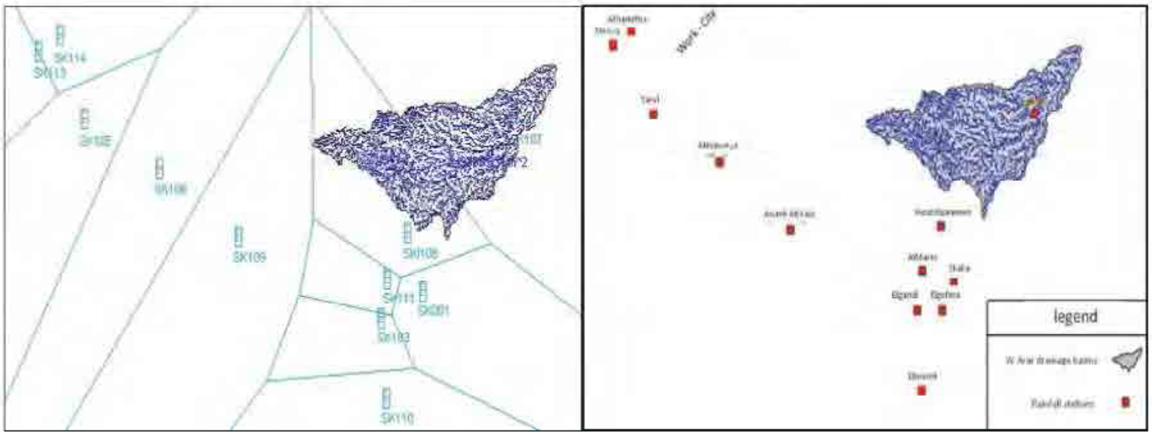


Fig. 7: Locations of Rainfall stations and Thiessen polygon in the study area

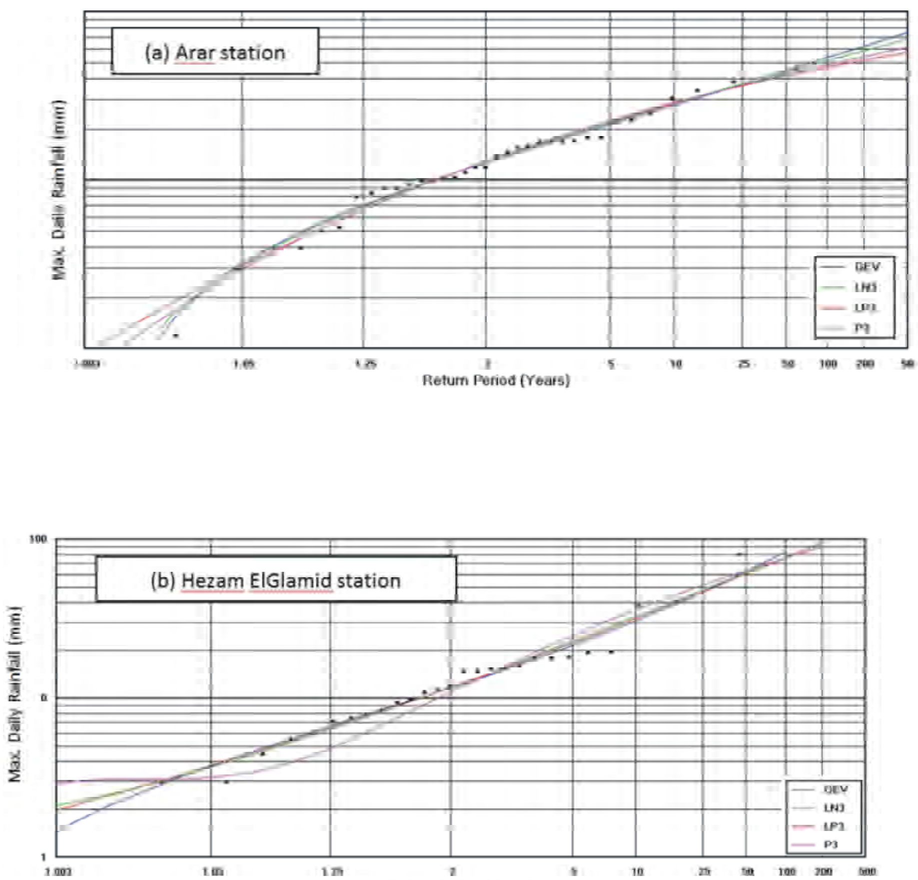


Fig. 8: Analysis of rainfall records for different stations

Statistical analysis is carried out for all the available rainfall data, to estimate the maximum daily rainfall at 2, 5, 10, 25, 50 and 100 years return periods using different distributions. The analysis showed that the maximum value of daily rainfall is 44.8 and 53.2 mm for 50 and 100 year return period at Arar station. The maximum value of daily rainfall is 63.6 and 82.9 mm for 50 and 100 year return period at Hezam El-Glamid station. The rainfall values for

Table 2: Rainfall depth at different return periods at Arar station (SK107)

Return Period (year)	General extreme value (GEV)	Log Normal type III	Log Pearson type III	Pearson type III
2	12.69	12.84	12.91	12.89
5	21.36	21.88	22.42	22.23
10	27.88	28.38	28.73	28.56
25	37.12	37.12	36.36	36.53
50	44.79	43.97	41.71	42.4
100	53.17	51.1	46.73	48.18

Table 3: Rainfall depth at different return periods at Hezam ElGlamid station (SK108)

Return Period (year)	General extreme value (GEV)	Log Normal type III	Log Pearson type III	Pearson type III
2	11.67	11.77	11.76	11
5	21.46	22.83	22.25	24.68
10	30.61	32.61	31.62	35.83
25	46.46	47.91	46.63	51.36
50	62.4	61.55	60.39	63.61
100	82.9	77.17	76.6	76.27

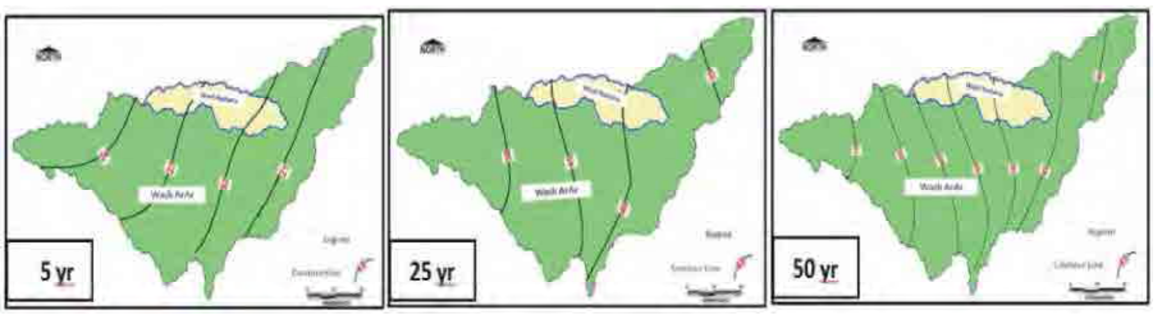


Fig. 9: Contour maps of the rainfall distribution at 5, 25 and 50 year return periods

50 and 100 year return period of effective stations are employed in the hydrological model (HEC-1) to estimate the runoff volumes and discharges for different sub-basins. Fig. (8) shows the results of the statistical analysis for Arar and Hezam ElGlamid rainfall recording stations. Table (2) & (3) summarize the results of the statistical analysis.

To identify the amount of rain expected to fall on different drainage basins in the study area, it requires linking topographic maps to the results of the statistical analysis of rainfall data for different stations. Contour maps of the rainfall distribution at different return periods are prepared. Fig. (9) shows contour maps of rainfall distribution at different return periods 5, 25 and 50 year respectively.

Intensity Duration Frequency Curves (IDF): Although the lack of detailed rainfall records with time (rainfall distribution with time, storm hyetograph) during the day, it is needed as one the hydrologic model inputs. So, the relationship between rainfall intensity, rainfall duration and return period is developed. The Intensity Duration Frequency Curves (IDF) is created using the daily rainfall data for the effective rainfall recording stations. Fig.s (10) & (11) shows the IDF curves for Arar and Hezam ElGlamid stations respectively.

Geology: Sedimentary rocks cover the entire drainage basin where limestone rocks occupy the greater part of the basin. These rocks are characterized by the presence of some cracks and joints that increase the percentage of rainfall loss. As shown in Fig. (12), wadi deposit covers the main stream of the main basin and sub-basins. Wadi deposit is characterized by its relatively high permeability and accordingly low runoff. The geological units can be identified in the study area as follows:

Wadi Deposit: Wadi deposit consists of sand and silt and gravel, therefore it absorbs large amounts of rainwater. These deposits located at the delta of Wadi Arar, Wadi Badanah and their sub-basins. The thickness of these deposits varies from one region to another within the drainage basin depending on the width of the wadi. It has formed by flood water that comes out of these wadis during ancient time.

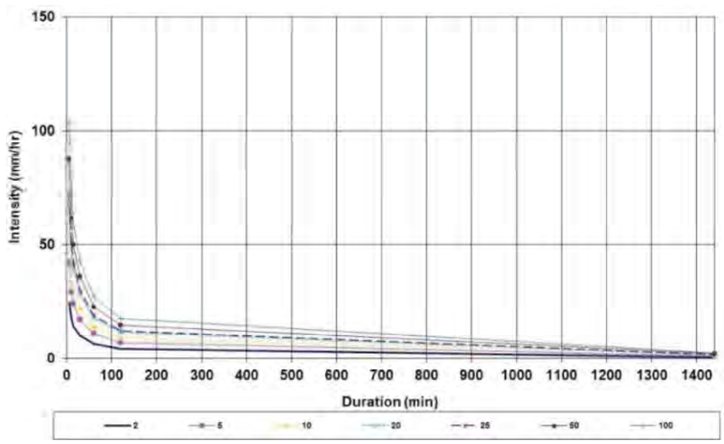


Fig. 10: IDF curves for Arar station

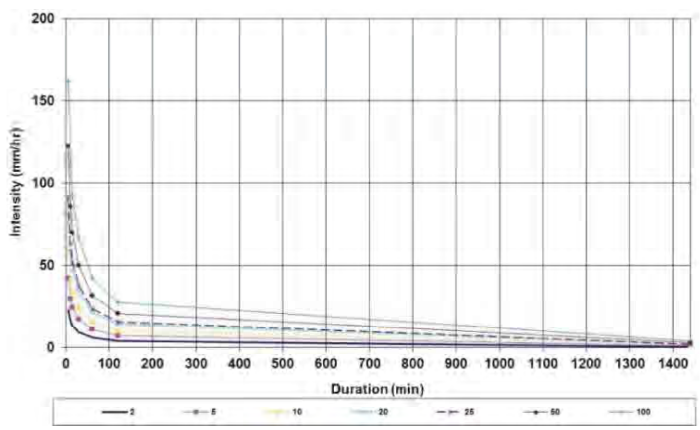


Fig. 11: IDF curves for Hezam ElGlamid station

Limestone: The upper Cretaceous in this area is consists mainly of limestone and the color of the stone varies between gray and light brown. There are several levels of limestone containing fossils of quartz and coral fossils at the top.

Structures and Faults: There are some faults in different directions, especially in the western part of the drainage basin. This indicates exposure of the region to some tectonic movement that has influenced the direction of water movement and stream network.

Hydrologic Analysis: Wadi Arar and wadi Badanah drainage basins are analyzed using WMS hydrologic model. Due to lack of runoff measurement, SCS unit hydrograph method is used to compute the runoff hydrographs [7]. As mentioned earlier, the drainage basins are divided into sub-basins. Rainfall data of all effective rainfall stations for 50 year design storm is input to the HEC-1 hydrologic module of the WMS software. Also, the land use and soil type map is used to estimate the water losses of each sub-basin and accordingly the rainfall excess that causes runoff.

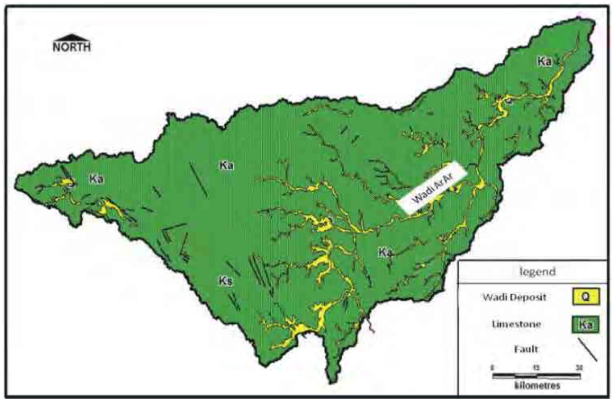


Fig. 12: Wadi Arar geological rock classification map

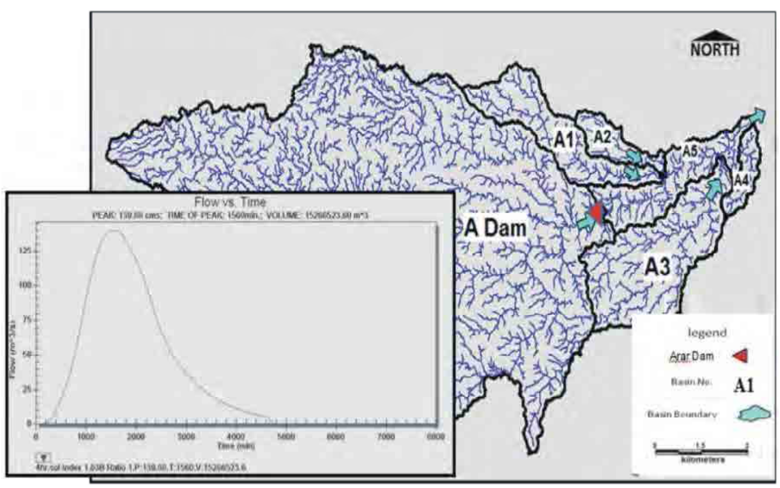


Fig. 13: Hydrological analysis of wadi Arar for 50 year design storm

As a result of the hydrological analysis, runoff volumes of the sub-basins were estimated for the design storm of 50 year return period, as shown in Figs. (13) & (14) for wadi Arar and wadi Badanah respectively. Tables (4) & (5) summarize the results of the hydrological analysis for all sub-basins according to 50 year return period design storm. The runoff volume at Arar dam is about 15.3 million cubic meters, while the peak discharge is estimated by 140 cubic meters per second. On the other hand, the runoff volume at Badanah dam is about 3.4 million cubic meters, while the peak discharge is estimated by 51.6 cubic meters per second.

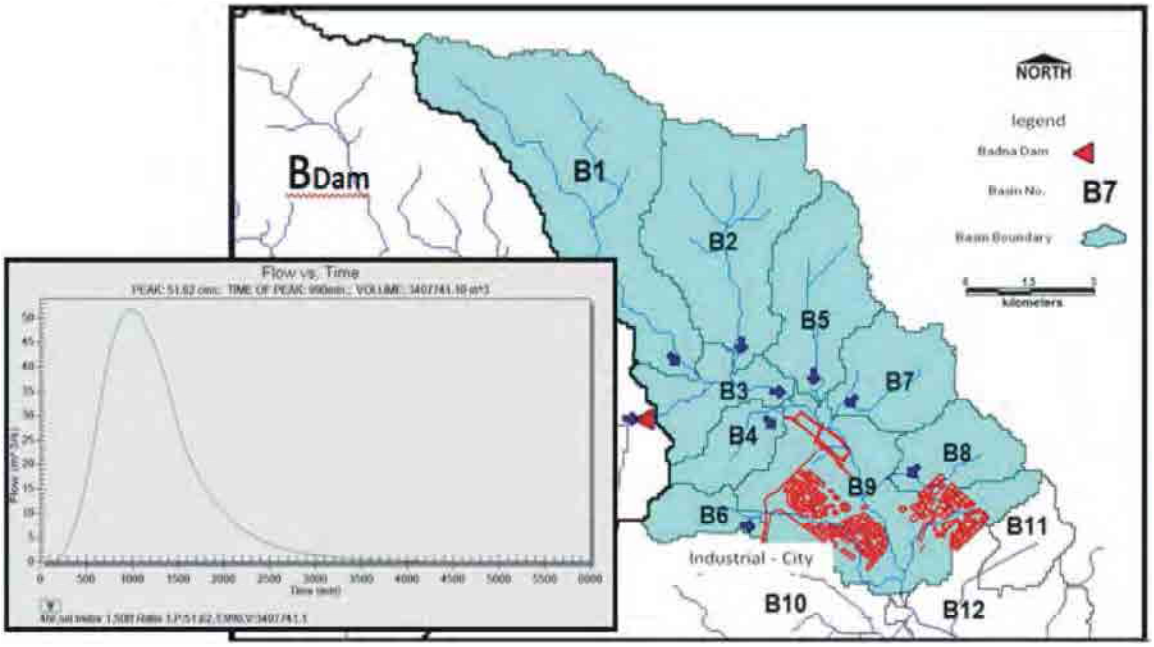


Fig. 14: Hydrological analysis of wadi Badanah for 50 year design storm

Table 4: Hydrological analysis of Wadi Arar for 50 year design storm

Arar Sub-basins	Area (km^2)	Length (km)	Slope (m/m)	Mean elevation (m)	Lag Time (hr)	Max. Discharge (m^3/s)	Volume (million m^3)	Time to Peak (hr)
A_{Dam}	5148.7	127.6	0.015	775.6	22.9	139.9	15.27	24.3
A_1	397.6	54.9	0.025	700.9	11.1	29.1	1.58	12.5
A_2	125.0	26.1	0.020	664.2	6.00	16.7	0.5	7.5
A_3	690.0	48.9	0.018	631.8	10.4	53.8	2.74	12
A_4	91.0	14.4	0.014	564.4	3.70	29.6	1.29	10.3
A_5	324.0	36.7	0.029	590.7	8.90	18.6	0.05	5.3

Table 5: Hydrological analysis of Wadi Badanah for 50 year design storm

Badanah Sub-basins	Area (km^2)	Length (km)	Slope (m/m)	Mean elevation (m)	Lag Time (hr)	Max. Discharge (m^3/s)	Volume (million m^3)	Time to Peak (hr)
B_{Dam}	858.2	70.6	0.022	706.8	13.6	51.6	3.41	15
B_1	25.2	10.8	0.030	628.7	2.2	18.2	0.49	3.8
B_2	16.5	6.5	0.034	613.0	1.5	26.8	0.07	3
B_3	5.2	3.9	0.024	583.4	1.0	11.4	0.34	2.5
B_4	3.7	3.3	0.034	588.9	0.8	9	0.04	2.3
B_5	9.3	5.7	0.037	600.4	1.2	18	0.23	2.8
B_6	2.8	2.8	0.042	604.4	0.7	7.9	0.22	2.3
B_7	6.6	3.5	0.037	591.2	0.9	15.3	0.12	2.5
B_8	5.1	3.3	0.033	592.1	0.9	11.7	0.09	2.5
B_9	17.6	6.0	0.023	573.2	1.4	29.4	0.05	3
B_{10}	122.3	17.6	0.028	608.1	4.0	23.6	1.06	5.5
B_{11}	3.70	3.30	0.035	579.6	0.8	9.5	0.27	2.3
B_{12}	31.3	7.10	0.029	599.7	2.1	23.3	0.07	3.8

Hydraulic Analysis: The result of survey work has been used to prepare the digital elevation model of Arar main discharge channel downstream Arar dam (48 km length), as shown in Fig. (15). HEC-RAS hydraulic model was applied to the number of 16 hydraulic cross sections along the flood channel, as shown in Fig. (15), for 50 year return period design storm. The hydraulic analysis assumed that the maximum discharge is 140 m^3/s in addition to sub-basins discharges downstream Arar dam (from A1 to A5).

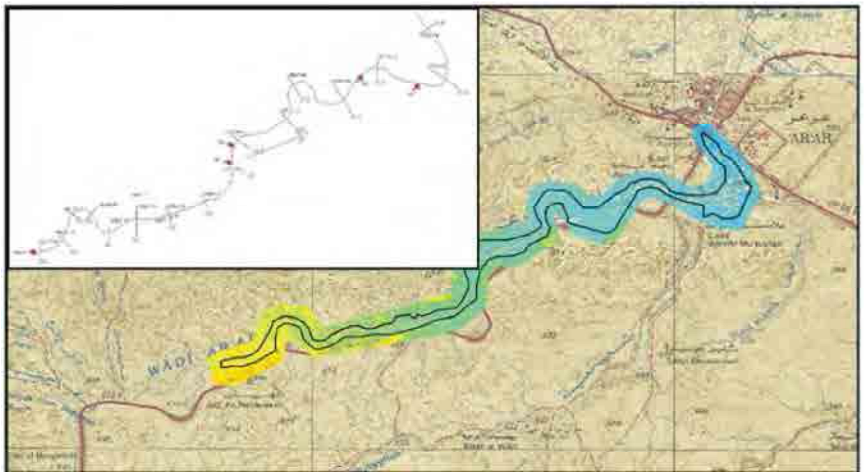


Fig. 15: DEM and cross sections along Arar main discharge channel downstream Arar dam

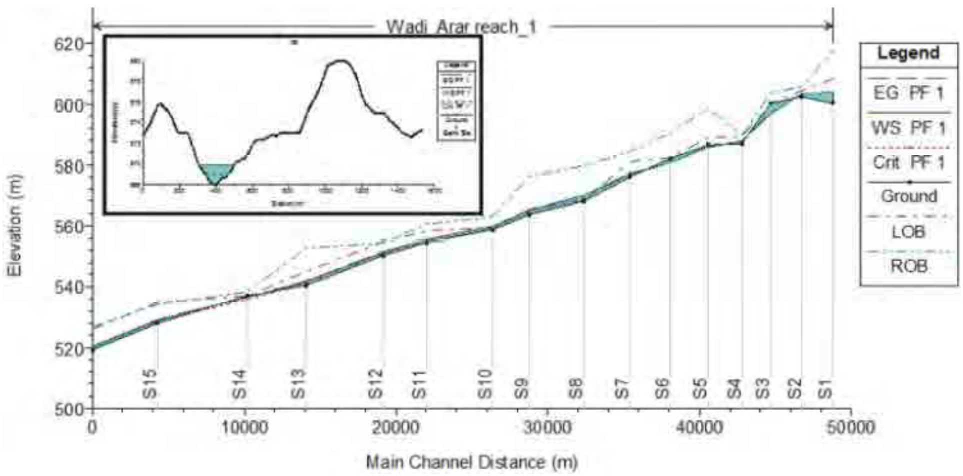
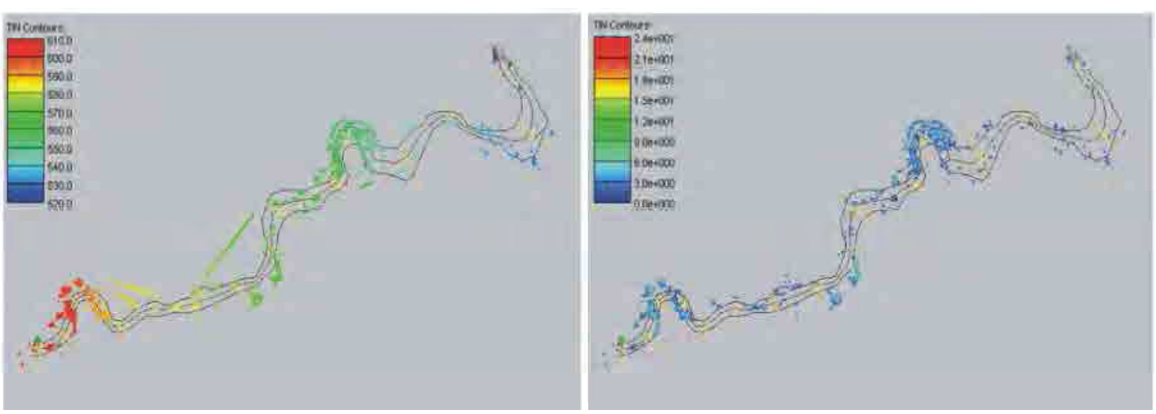


Fig. 16: Sample of hydraulic model results along Arar main channel



Surface water elevation Water depth

Fig. 17: Surface water elevation and water depth contours along Arar main channel

The hydraulic model simulated the water depth and velocity at each cross-section. Fig. (16) shows sample of the output of the hydraulic model of the longitudinal and cross section representing surface water level in each section. Fig. (17) shows the surface water elevation and water depth contours along Arar main channel.

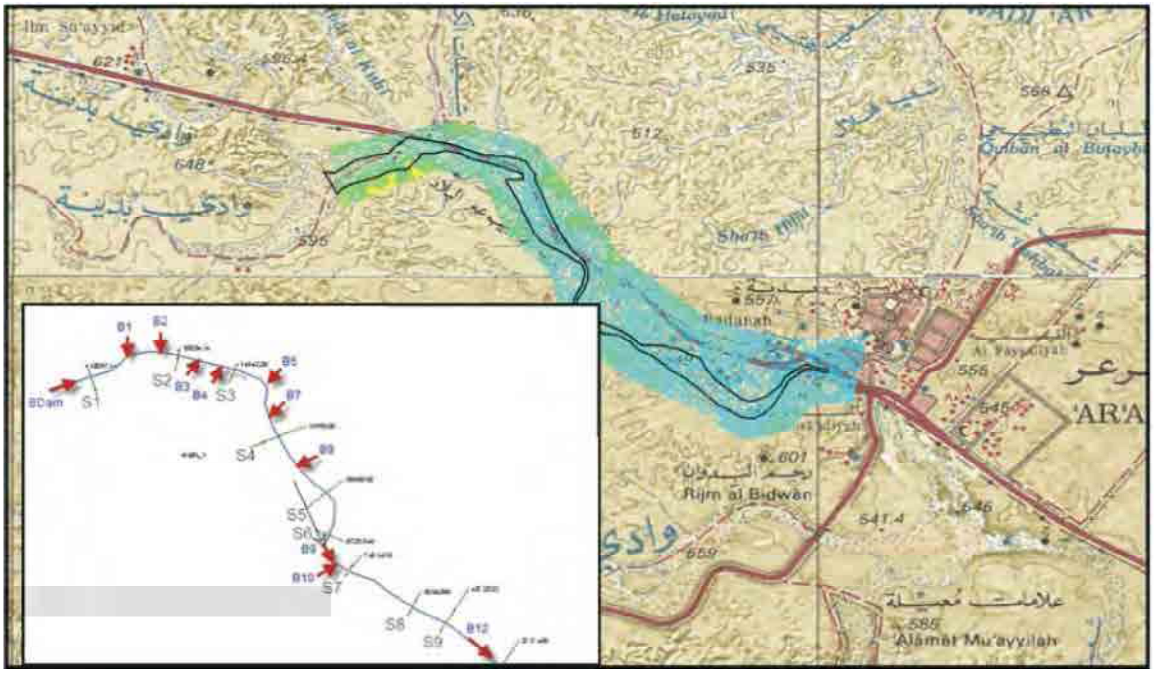


Fig. 18: DEM and cross sections along Badanah main discharge channel downstream Badanah dam

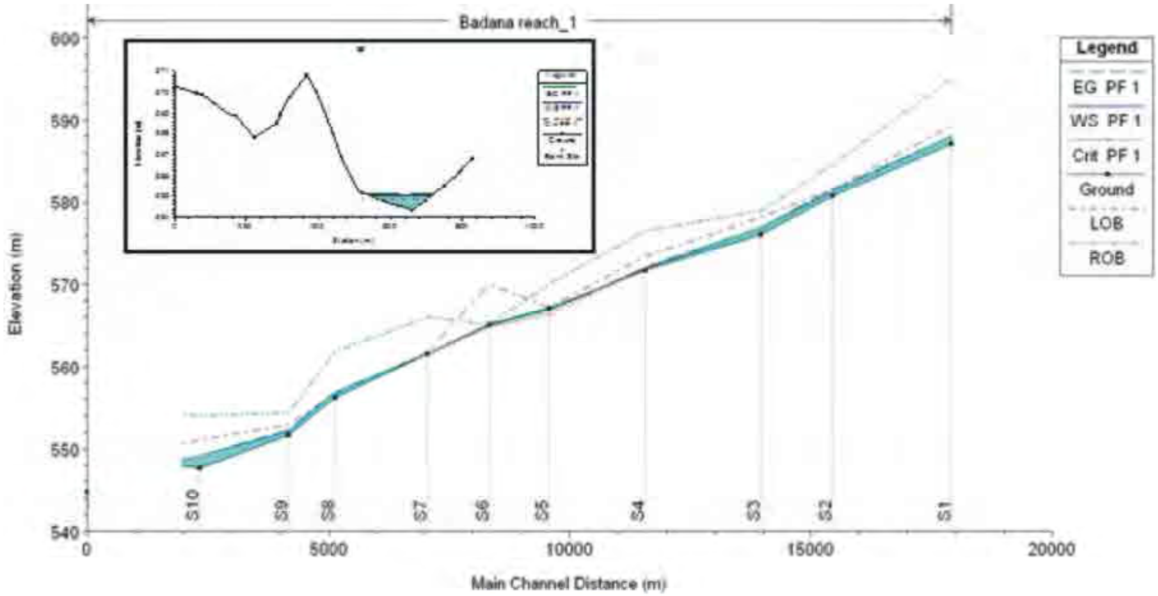
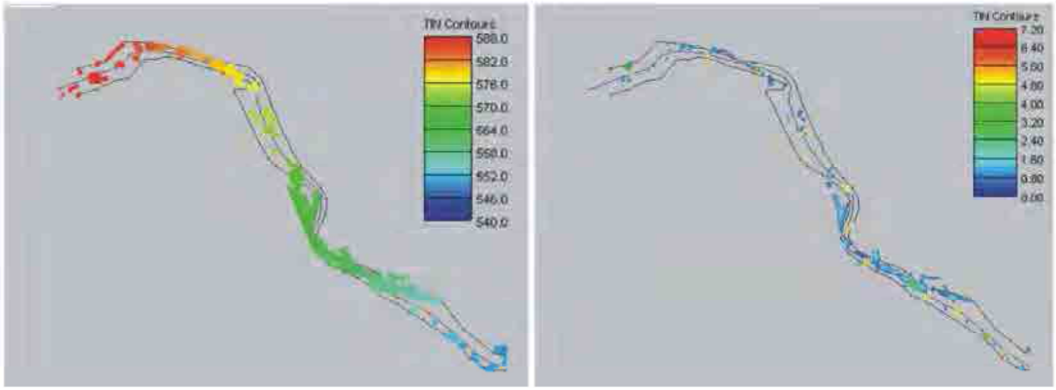


Fig. 19: Sample of hydraulic model results along Badanah main channel

Also, the result of survey work has been used to prepare the digital elevation model of Badanah main discharge channel downstream Badanah dam (16.5 km length), as shown in Fig. (18). HEC-RAS hydraulic model was applied to the number of 10 hydraulic cross sections along the flood channel, as shown in Fig. (18), for 50 year return period design storm. The hydraulic analysis assumed that the maximum discharge is 51.6 m^3/s in addition to sub-basins discharges downstream Badanah dam (from B1 to B12).

The hydraulic model simulated the water depth and velocity at each cross-section. Fig. (19) shows sample of the output of the hydraulic model of the longitudinal and cross section representing surface water level in each section. Fig. (20) shows the surface water elevation and water depth contours along Badanah main channel.



Surface water elevation　　　　Water depth

Fig. 20: Surface water elevation and water depth contours along Badanah main channel

Assessment of Flood Hazard: Flood Risk assessment requires an understanding of the causes of a potential disaster [8] which includes both the natural hazard of a flood and the vulnerability of the element at risk.

Risk = hazard * vulnerability (1)

The terms hazard means a potential event that causes damage to property. Vulnerability means the degree to which an agriculture area, people or structures are exposed to loss or damage caused by the impact of a hazard. Due to the lack of historical flood data, there is no information about the return period for certain flood events. This means that the common approach for hazard assessment (probability x consequence) is not possible. Therefore, two different techniques for flood hazard mapping are proposed based on hydrologic and hydraulic parameters:

- Mapping of hazard area based on hydrologic analysis
- Mapping of flood intensity based on hydraulic analysis

Mapping of Hazard Area based on Hydrologic Analysis: Flash floods occur when rainfall is too intense for the ground to absorb the volume of water. Therefore, attention is paid to two critical factors: intense rainfall rate and ground characteristics that enhance runoff. The ability of the ground to quickly absorb water, called the infiltration capacity, has a direct impact on how much water will flow to the nearest stream or underpass as runoff. The lower the infiltration capacity, the less rain water absorbed by the soil and the more water runs across the surface contributing to flooding. Infiltration capacity is related to soil moisture, soil type and soil surface conditions. In general, wet soil will have less infiltration than dry soil and more flood hazard. But in some areas the soil type and the soil surface conditions may be much more important to flood hazard than soil moisture. Soil composed of clay will not allow rapid infiltration of water and thus result in greater flood hazard than sandy soil, even if the clay soil is dry. Soils covered by impervious material, like parking lots, will have almost no infiltration capacity and result in much higher flood hazards than soils that are naturally vegetated. However, the combination of soil type and land use is contributed to infiltration capacity in particular and to water loss in general and accordingly to the runoff volume.

Steeply sloped watersheds are more prone to flash flooding because the water drains to the stream channel much more quickly than in flatter watersheds. That does not mean that flash floods cannot occur in gently sloped watersheds, but a greater slope increases the flood hazard by increasing the speed of the runoff. However, runoff calculation parameters; time of concentration and lag time are depending on the slope.

Probability rating of flooding in each hazard zone in every watershed was done by considering runoff volume for 100 year return period [9]. When compiling the final flood hazard map the runoff volume were considered for identifying the degree of the probability of occurrence of flooding in the flood hazard area. The flood hazard areas with different probability of occurrence were given values as follows:

- Area of runoff volume >10 million m^3 high
- Area of runoff volume 2 to 10 million m^3moderate
- Area of runoff volume< 2 million m^3 low

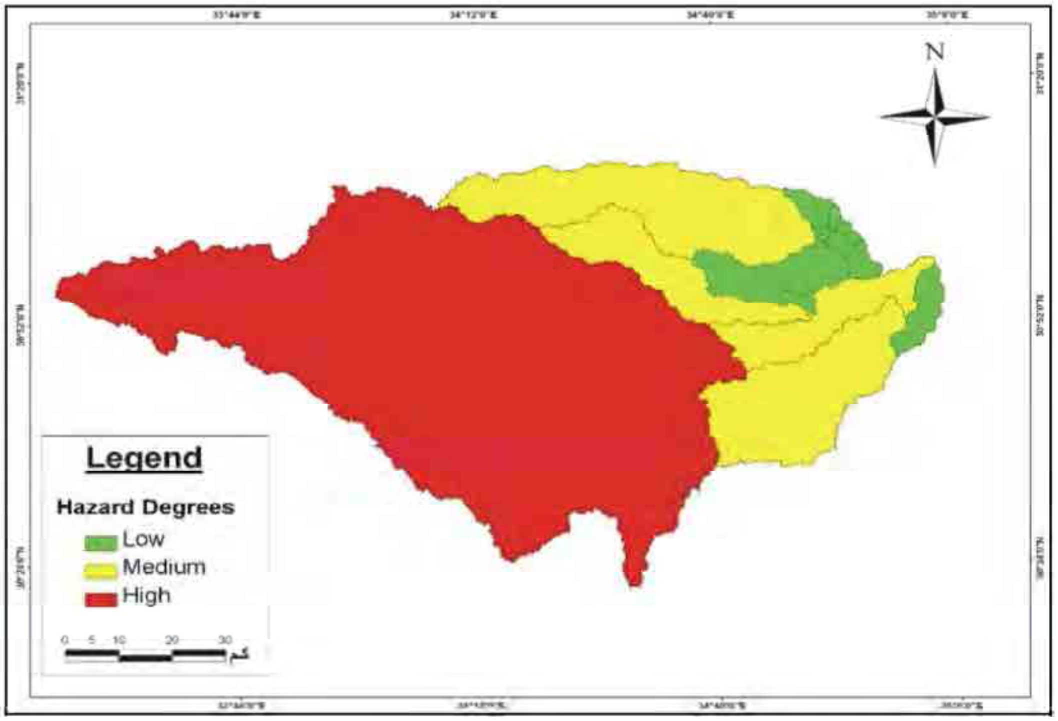


Fig. 21: Flood hazard map

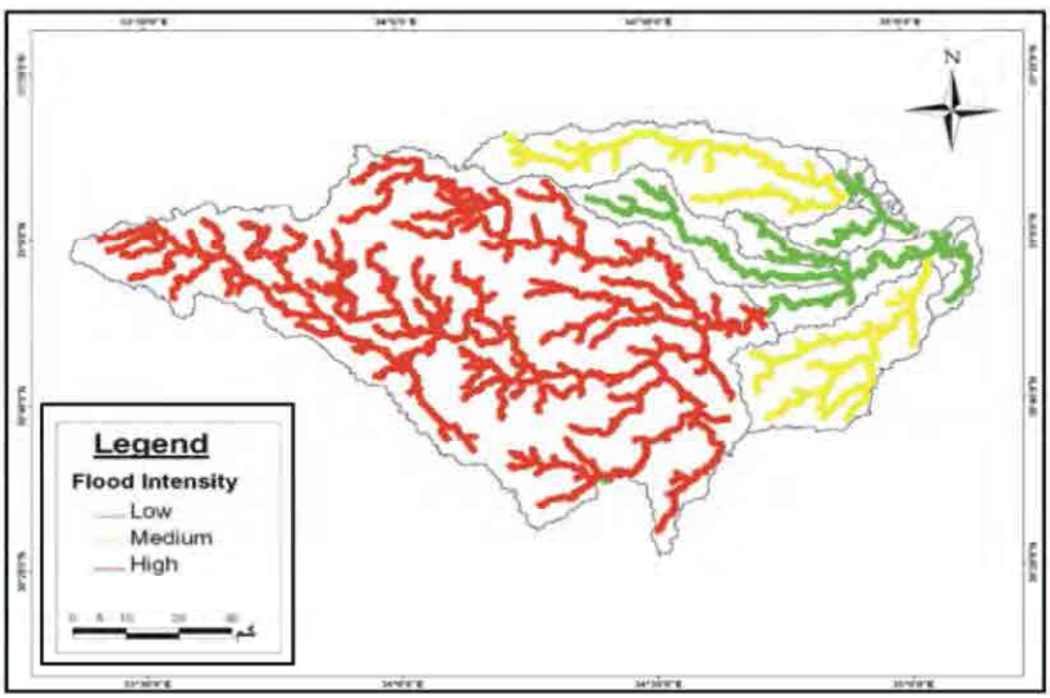


Fig. 22: Flood intensity map

Based on the final classes for rating the probability of the occurrence of flooding in the identifying flood hazard area, the final map was compiled as shown in Fig. (21). The map shows that the hazard level varies from high level to low level. It also shows that about 65% of the total area of the study area is under high hazardous whereas 28% and 7% are under moderate to low hazardous respectively.

Mapping of Hazard Area Based on Hydraulic Analysis: For the second approach, hazard level is estimated as a function of two readily available parameters from the hydraulic model; flood depth and flow velocity.

Hazard level = flood depth * flow velocity (2)

The flood hazard in this approach is expressed as a measure to differentiate between different stretches of the wadi based on the damaging power of the flash flood. The proposed methodology takes into account both depth and velocity, that are the two main parameters for the damage function. Furthermore, casualties are frequently estimated as a function of depth and velocity, among some other parameters [10].

The maximal hazard level corresponds to a flow intensity of 7 m^2/s [11]. Jonkman, [10] recommended this value as a threshold value. Higher flow intensities result in total destruction of buildings and other constructions. In this approach a flow intensity of 7 m^2/s corresponds to the expected maximal damage, both for economic damage and casualties.

After field checking of the validity and reliability of the map the flow intensity threshold values were adjusted [12]. When compiling the final flow intensity map the following figures were considered for identifying the degree of flow intensity hazard zone. The flow intensity thresholds values were given as follows:

- Area of flow intensities > 3 high
- Area of flow intensities 1 to 3 moderate
- Area of flow intensities < 1 low

Fig. (22) shows the calculated flow intensity map for Wadi Arar and Wadi Badanah. The map shows that the flow intensity varies from high value upstream wadi Arar to moderate and low values downstream the wadi till the outlet.

CONCLUSION AND RECOMMENDATION

The evaluation of flood hazard for wadi Arar and Wadi Badanah has been done through hydrologic and hydraulic analysis to study the impact of flood water on the infrastructure and industrial area at the drainage basins outlets. In the hydrological analysis, the runoff volume and discharges are estimated at different sub-basins for 50 year return period design storm.

The results of the hydrological analysis indicated that the actual storage capacity of Arar dam (10.366 million m^3) is not enough to occupy the runoff volume for 50 year return period design storm (15.3 million m^3). On the other hand, the actual storage capacity of badanah dam (4.7 million m^3) is higher than the estimated runoff volume for 50 year return period design storm (3.4 million m^3).

The results of the hydraulic analysis indicated that Arar and Badanah main channels are capable to accommodate the simulated peak discharge for 50 year return period design storm. All the channel cross-sections are safe and able to occupy the flood discharge and protect the surrounding areas.

This research has developed a systematic methodology for estimating flood hazard and intensity maps based on a geographic approach using GIS and RS. The flood hazard and intensity maps obtained from this study can be used as basic data for designing flood prevention assist flood mitigation and land use planning. The methodology can, with little effort, be extended to other similar areas in Egypt. Thus, the results obtained in the research will be of great practical value to planners, designers and decision makers.

According to this research it is recommended to add extra hydraulic structures at Wadi Arar to protect the infrastructure and industrial area at the drainage basin outlet. It requires constructing a dam or set of additional dams upstream wadi Arar drainage basin. It is depending on the field studies and the characteristics of the proposed sites for the establishment of each dam. Also, any further development expansion or extension should be based on the flood risk analysis and mapping. It is recommended to follow the same procedure presented in this research in similar arid areas in Egypt and other Arab countries.

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