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Flood analysis using HEC-RAS model: a case study for Hafr Al-Batin, Saudi Arabia

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Abstract. Hafr Al-Batin is a Saudi Arabian city located in the northeastern part of the kingdom. The city lies in the dry valley of Wadi Al-Batin, part of Wadi Al-Rummah, which leads inland towards Medina and formerly emptied into the Arabian Gulf. Hafr Al-Batin is located in an area where three valleys meet, which makes the city under high risk of flooding, especially when intense rain occurs during short duration as in the case of arid and semi-arid regions. The yearly average rainfall intensity of Hafr Al-Baten is estimated to be 125 mm. Recently, extreme rainfall events occurred, generating flood water to flow from all valleys towards the city, causing serious damage to public and private properties. In this study, HEC-HMS and HEC-RAS models are used to simulate flood occurrence in the city. The results indicate that the average flow depths within the part of the main channel passing through Hafr Al-Batin city were 3.02 m, 3.26 m, 3.45 m, 3.76 m, 4.04 m and 4.34 m for the simulated 2, 5, 10, 25, 50 and 100-year design floods, respectively. Flood hazard maps are also generated to identify the areas within the city with high risk of flooding.

1 Introduction

In Saudi Arabia, floods are considered to be the major catastrophic natural hazard. According to Momani and Fadil [1], more than 121 fatalities, around 20,000 sheltered families and billions of dollars in losses were due to the natural disasters in Saudi Arabia in 2009 in addition to the effects on human health as a result of flooding. Moreover, the amount of three billion riyals was the monetary loss. Maghrabi [2] stated that several fatalities and massive destruction in structures, properties and highways occurred as a result of massive floods due to heavy rains, which affected Jeddah in 2009.

In recent years, there has been a considerable amount of attention to flooding in Saudi Arabia. Studies have been conducted to study floods in different regions of Saudi Arabia using different techniques. Nouh [3] used three methods (region curves, common peak flow models and duration reduction curves) to estimate the maximum flood in the southwest region of Saudi Arabia, and statistical measures were used to compare the accuracy of the three methods. The study concluded that the region curve method gives the best statistics. Al-Turbak [4] constructed a geomorphic-climatic model in three arid catchments in Saudi Arabia and found that the developed model is capable of predicting surface runoff hydrographs accurately when detailed and accurate data are available. Subyani [5] studied flood probability and the hydrological characteristics in western Saudi Arabia of some main wadis, including Fatimah and Usfan, and found that Gumbel's extreme value distribution is the best fitting model for identifying and predicting future rainfall occurrence. Al-Shareef et al. [6] performed a study on Wadi Marwani basin in Jeddah, Saudi Arabia to find the best method that can be used to estimate the peak discharge. Four methods were tested, namely the Modified Talbot Method (MTM), the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), the Regional Flood Frequency Analysis (RFFA) regression equations and the Probabilistic Rational Method (PRM). The Root Mean Square Error (RMSE) was used to measure the accuracy of the four methods. The results indicate that the PRM is a more accurate model to compute the peak discharge compared to the others. Dawod et al. [7] concluded that the most accurate national hydrological model for the Makkah area is the model developed based on actual precise field measurements in the southwest part of Saudi Arabia. However, they mentioned that the curve number method should be considered as the optimum flood modeling approach when the topography, land use, meteorological and geological datasets are available. Sharif et al. [8] produced a flood hazard map for the rapidly urbanizing catchment of Al-Aysen in Riyadh, Saudi Arabia, using hydrologic/hydraulic model simulation. They also studied the impact of urbanization on the peak discharge and runoff volume resulting from different storms with various urbanization scenarios.

Hafr Al-Batin city, which is located in the eastern part of the Kingdom of Saudi Arabia, is also suffering from

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the occurrence of floods. In the past few years, flash floods hit the city many times and caused losses in economic and human life. This paper focuses on the simulation of the occurrence of floods in Hafr Al-Batin city by constructing hydrologic and hydraulic models, and based on these models, a flood hazard map will be developed to help the decision makers to identify the areas within the city with high risk of flooding, which can help them in adopting appropriate plans to control and reduce the effect of floods.

2 Material and methods

2.1 Study area

Hafr Al-Batin is located in the northeast of Saudi Arabia, 430 km to the north of Riyadh, 74.3 km from the Iraq border and 94.2 km from the Kuwait border. The city lies in the dry valley of Wadi Al-Batin, which is the main source of the flash flood. In 2003, the population of Hafr Al-Batin was estimated to be around 190,000 and reached 600,000 in 2010 [9]. Figure 1 shows the location of Hafr Al-Batin city and boundary of Hafr Al-Batin watershed.

The partially urbanized Wadi Al-Batin catchment was selected for this study with a drainage area of approximately 1669 km^2. The catchment drains in the dry valley of Wadi Al-Batin, which is part of the larger valley of the long, now-dry river Wadi Al-Rummah. The city of Hafar Al-Batin occupies approximately 3.6% of the catchment area.

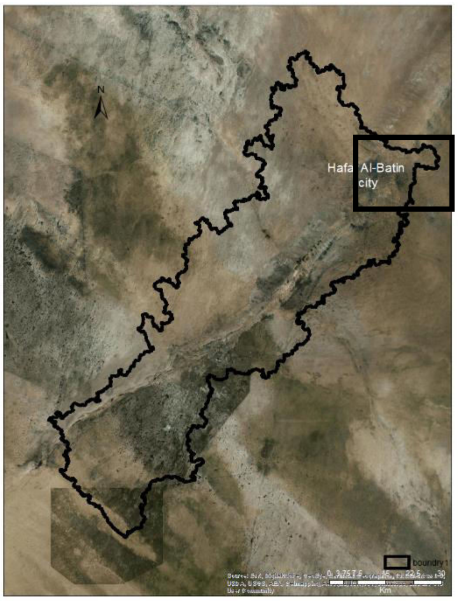
The watershed of Hafr Al-Batin is distinguished by three main streams. The first stream runs from southeast to northwest and is called Al-Batin valley, which is the largest one. The second stream is north Fleaj stream which runs from north to south, and the third stream is south Fleaj stream which runs from south to north. These three streams are considered as the main sources of runoff for Al-Batin valley.

2.2 Rainfall

Precipitation is considered as one of the major input parameters required for hydrologic studies. The precipitation at a specific return period must be determined. The return period is “the average interval, in years, between the occurrence of a flood of specified magnitude and an equal or larger flood” [10]. In arid and semi-arid regions, rainfall is characterized by temporal and extremely high spatial variability.

In general, the average annual rainfall over Saudi Arabia ranges between 5 and 230 mm with Hafr Al-Batin receiving an average of about 125 mm. Data collected from rain gauge operated by the Saudi Presidency of Meteorology and Environment (PME) was used to perform frequency analysis. Based on the available record, Log-Pearson Type III distribution (LPT III) [11] was used to estimate the frequency of the daily rainfall over the catchment. LPT III requires computing logarithms of the data, then estimating the mean, standard deviation and skewness coefficient of these logarithms. The skewness coefficient is used to estimate *K* coefficients for different return periods that are used together with the means and standard deviations to estimate frequency rainfall values. Figure 2 shows the frequency distribution of the rainfall data as it is fitted to the LPT III distribution. The LPT III estimated the maximum daily rainfall values for the return periods between 2 and 100 years as shown in Table 1.

(a)



(b)

Figure 1. Hafr Al-Batin catchment area: (a) location of Hafr Al-Batin catchment and (b) Hafar Al-Batin city and the watershed boundary.

2.3 Methodology

In this study, HEC-HMS and HEC-RAS were used to construct the hydrologic, hydraulic and floodplain models.

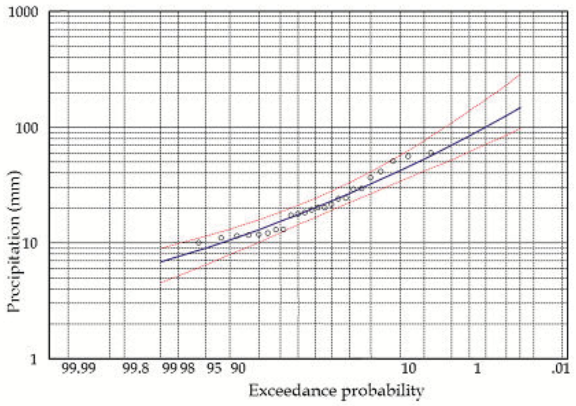


Figure 2. Fitted Log-Pearson III.

Return period	Rainfall (mm)
2	20
5	32
10	42
25	57
50	70
100	85

Table 1. Maximum daily rainfall (mm) for different return periods.

HEC-HMS is a comprehensive hydrologic modeling tool developed by the U.S. Army Corps of Engineers and the Hydrologic Engineering Center (HEC). The model is designed to simulate rainfall-runoff processes for a wide range of watershed types. HEC-HMS uses several sub-models to represent different components of the runoff process with the choice of numerous infiltration methods, unit hydrograph and flood routing methods [12]. The Soil Conservation Service (SCS) [currently the Natural Resources Conservation Service (NRCS)] curve number (CN) method [13] is the main approach used for estimating the infiltration capacity and runoff for various combinations of soil and land/use cover type. Newer versions of the models included major enhancements, such as Green and Ampt infiltration, grid-based runoff calculation and the use of radar-based gridded rainfall estimates.

HEC-RAS is a window-based hydraulic model also developed by the U.S. Army Corps of Engineers and the Hydrologic Engineering Center. The model uses output hydrograph from HEC-HMS as an input to calculate and analyse the floodplain hydraulics [14]. Generally, water elevation at a location in a floodplain is a more direct interest for flood analysis than magnitude of discharge. Water elevation is determined by a hydraulic analysis, which is oftentimes performed subsequent to a hydrologic analysis. The model is used to simulate steady, gradually varied, rapidly varied and unsteady one-dimensional flow and to delineate flood zones, which is the most common application of the model. Continuity, momentum, energy and Manning equations are used for these computations.

The major steps followed in this study include the following: construct an IDF curve for Hafr Al-Batin; generate a Digital Elevation Map (DEM) for the study area; delineate the watershed; use HEC-HMS to develop a hydrologic model for the watershed; and use HEC-RAS model to develop the hydraulic model and generate flood risk maps for Hafr Al-Batin city.

3 Results and discussion

Table 2 summarises the runoff volumes and peak flows at the outlet of Hafr Al-Batin watershed for different return periods. Figure 3 shows the outflow hydrographs for the watershed for different return periods. The figure indicates that for small return periods, one peak is observed resulting from the urban runoff. For larger return periods, the runoff generated from the barren portion of the catchment becomes very significant and results in a delayed peak, making the outflow hydrograph bimodal. As the return period increases, the delayed peak starts to dominate the hydrograph and completely masks the first peak for events larger than the 100-year events.

Return period	Runoff volume (x1000m^3)	Peak discharge (m^3/s)
2	176.9	12.5
5	422	23.8
10	882.9	42.1
25	3644.2	82.9
50	8428.6	132.3
100	16210.2	241.7

Table 2. Runoff volumes and peak discharges at the outlet for different return periods.

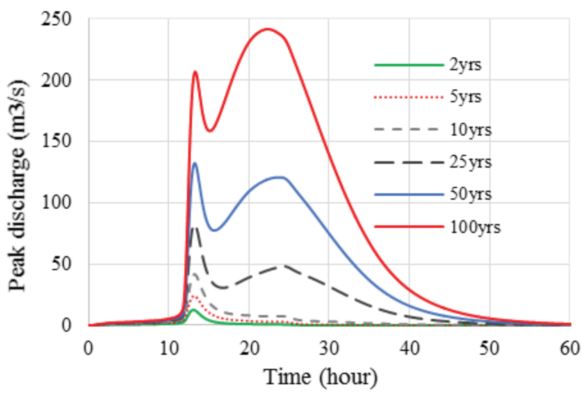


Figure 3. Outflow hydrographs for different return periods.

HEC-RAS model was run to compute the depths corresponding to the maximum discharge computed by HEC-HMS at the defined cross sections and performs interpolations along the reaches. Figure 4 shows the maximum water surface elevation profile along the main channel for a return period of 100 years. The average flow depths of flood within the city were found to be 3.02 m, 3.26 m, 3.45 m, 3.76 m, 4.04 m and 4.34 m for the simulated 2, 5, 10, 25, 50 and 100-year design floods, respectively. Table 3 summarises the statistics of the flow depth of flood for that part of the main channel passing through the city. The table indicates the high values of depths that might reach to approximately 7 m at some locations within the city, which shows the critical condition that the city might undergo during storm events. The high flow depth within the city is mainly due to the topography and location of the city of Hafr Al-Batin, which is located at low elevation and where three main streams are merged.

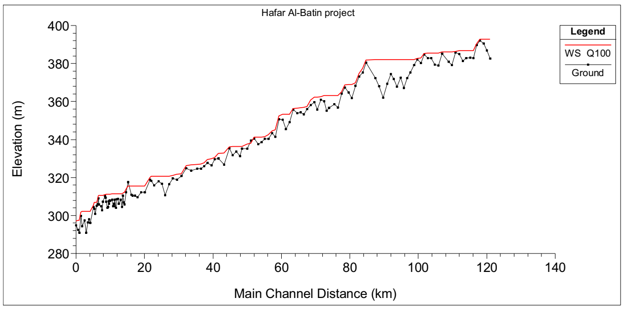


Figure 4. Water surface profile along the main channel for a return period of 100 years.

Return period	Maximum flow depth (m)		
	Minimum	Maximum	Average
2	0.26	5.74	3.02
5	0.35	6.02	3.26
10	0.47	6.21	3.45
25	0.76	6.55	3.76
50	0.84	6.91	4.04
100	0.94	7.27	4.34

Table 3. Statistical summary of maximum flow depths along the main channel passing through the city for different return periods.

To develop the flood hazard map, the peak flows for each sub-catchment simulated by HEC-HMS were inputted into HEC-RAS and the solution generated by HEC-RAS model was imported and read by Geographic Information System (GIS). The process was repeated for all return periods. Each time, a new scatter point file containing the water depths resulting from the HEC-RAS simulation was read into GIS as two-dimensional scatter points that are connected to delineate the flood inundation as shown in Figure 5 for the 100-year storm. These scatter points, which contain the water surface elevations, were interpolated at a 60-m spacing along the main channel centreline where cross sections were extracted in the urban area to achieve more accurate floodplain delineation. The inundated areas were represented as flood polygons in the developed flood hazard map, as shown in Figure 6, for the 100-year design storm. The inundated area intersects with several major and minor roads in the city, indicating the risk of driving through these roads during flood events.

4 Conclusion

This paper constructed hydrologic and hydraulic models to quantify flood hazards in the city of Hafr Al-Batin. The catchment was divided into sub-catchments to improve runoff estimation with smaller sub-catchment in the urban portion of the catchment. The hydrologic/hydraulic model simulations quantified the runoff hydrograph corresponding to different design storms and helped delineate the resulting flood inundation maps.

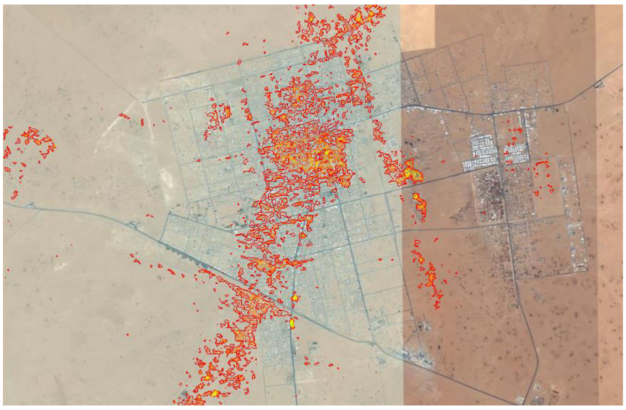


Figure 5. The 100-year floodplain depths.

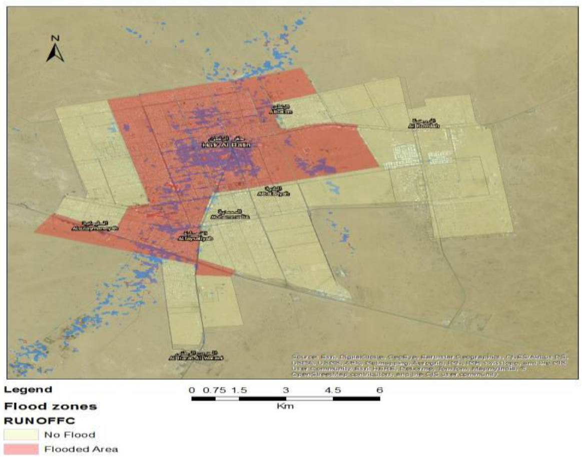


Figure 6. Flood hazard map for Hafr Al-Batin city.

The results of this study can be utilized for planning purposes and in the design of flood control project as it has quantified the runoff corresponding to different design storms and used hydraulics and geospatial data in delineating the flood zones.

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