J. Egypt. Acad. Soc. Environ. Develop., 22 (1):17-32 (2021) **(D-Environmental Studies)**
E.mail: easedjournal_egypt@yahoo.com **ISSN 1110-8770**
www.jades.journals.ekb.eg **eISSN 2314-5471 (online)**

Flash Flood Modeling Using HEC-RAS (2D) model on Wadi Reem in the western region, Kingdom of Saudi Arabia

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Received March 26, 2021
Accepted: May 20, 2021

ABSTRACT

Various infrastructures in Saudi Arabia are affecting by floods and rainfall that may damage constructions at urban areas due to water flows in the main valleys and streams. Asser Region in western Saudi Arabia is characterized by its high rainfall intensity that leads to flash floods. The present study aims to evaluate and identify potential floods in coastal areas of Wadi Reem basin and to show the urban areas exposed to flooding with flood water in the coastal city. Runoff calculation is an important part of regional runoff forecast and water resources evaluation model. The Soil Conservation Service (SCS) curve number (CN) model developed by the U.S. Department of Agriculture National Resources Conversion Service (NRCS) is the most popular and widely applied model for direct runoff estimation. The current work used HEC-RAS (2D) in order to simulate Flood map depth and velocity in Wadi Reem coastal areas. Watershed and its stream was delineated using digital elevation model (DEM) and morphological parameters calculated using Watershed Modeling System (WMS). Rainfall frequency analysis was performed for selected three rainfall gages using annual maximums of 24-h rainfall. This study deals with geographic information systems (GIS), hydrologic modeling (water modeling system, WMS), and hydraulic modeling (Hydrologic Engineering Center River Analysis System, HEC-RAS) to evaluate the impact of flash flood hazards on Wadi Reem coastal area.

Keywords: Flash flood, Wadi Reem, Morphological parameters, HEC-HMS Modeling and HEC-RAS 2D Model.

INTRODUCTION

Flooding is common natural disaster with a devastating and widespread effect responsible for economic losses and mortality (Teng *et al.*, 2017). Flood causes about third of all natural disasters in the world. Geographic Information Systems (GIS) and digital elevation models (DEM) are now commonly used for flood analysis and flood risk prediction. Floods are considered as one of the most common disasters and probably the most devastating (Baoyin and Hailin, 2009). Between 1998 and 2017, floods affected more than two billion people worldwide and flood together with storms and droughts contributed to 80–90% of the worldwide natural disasters in the last ten years (WHO, 2020).

The western region of Saudi Arabia is characterized by low altitude-flat coastal plain bounded from the east with a chain of high rugged mountains of the Arabian Shield oriented North-Northwest to South-Southeast. Many of the major cities and villages along the coastal plain are situated along or at the mouth of these wadis. Due to the aridity of the area and lack of long-term strategic planning, most of the population tends to settle along wadi courses and sides. Flash floods along these wadis caused severe damages to lives and properties in the past (Subyani *et al*., 2009).

Most parts of Saudi Arabia are classified as hot and dry (Köppen, 1936), where rainfall is irregular and the climate is characterized by high temperatures (Al-Jerash, 1985; Al-Taher, 1994). However, the south-western region of the country is classified as semi-arid (Köppen, 1936).This region is characterized by having rainfall throughout the year, where the topography enhances local convective rain (Al-Mazroui, 1998; Abdullah and Al-Mazroui, 1998).

The main objective of this study is to estimate the direct runoff of wadi Reem watershed and to generate Flood map depth and velocity using HEC-RAS 2D Model.

METHODOLOGY AND DATA

Methodology and Data used in this work as shown in Figure (1).

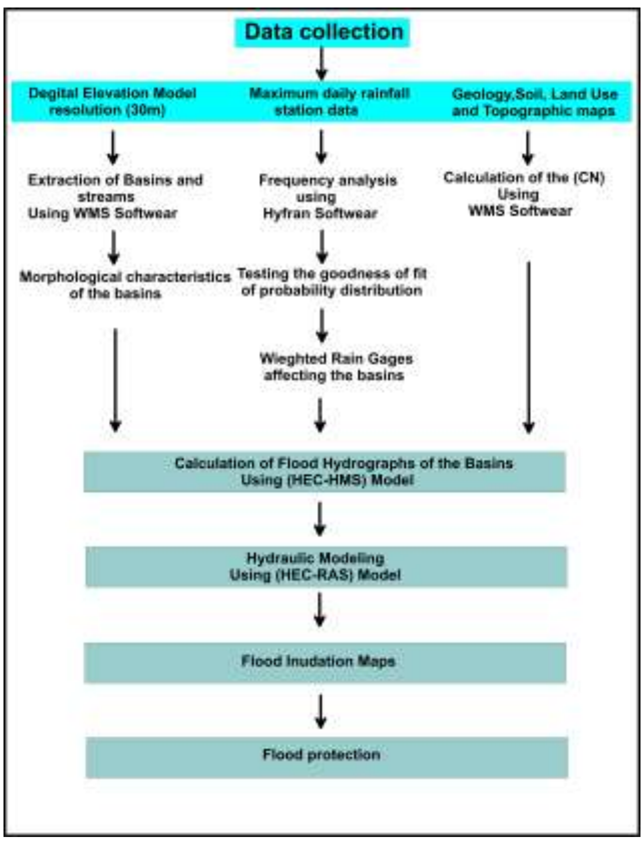

Fig. 1: Flowchart showing the methodology adopted in the current work.

1. WMS model

The study of morphometric basin characteristics in western Saudi Arabia is based on the DEM data. All the drainage basins and networks as well as their morphometric characteristics were extracted using the watershed modeling system (WMS, V.10.1) through the drainage module by selecting “Compute Basins Data”, where the morphological properties of the basins were calculated automatically. These properties can be shown in the “Display option”. This system provided most of the morphometric parameters of the studied basins and their stream attributes with the assumption that the flow accumulation threshold is 0.2 (Strahler 1952; Ally *et al*., 1980).

2. Hydrologic Modeling

In this study HEC-HMS Model was selected for the run off forecasting which play a key role in early flood warning. Program was developed by the US Army Corps of Engineers Hydrologic Engineering Center (HEC) and is the replacement for HEC-1 (Feldman, 1995).

3. Hydraulic Modeling

The hydraulic modeling software, Hydraulic Engineering Center-River Analysis System (HEC-RAS 5.0.4) is widely used open source hydraulic flow analysis programmer developed by the United States Army Corps of Engineers-Hydrologic Engineering Center (Hydrologic Engineering Centre, 2008, 2016). The model is available for 1D and 2D modeling. In this study a 2D HEC-RAS model was used.

RESULTS AND DISCUSSION

Study area and Location

The Wadi Reem catchment area is located in Asseer Region, Saudi Arabia, between latitudes 17°42'15.51''N to 18°16'20.05''N (North) and longitudes 41°59'35.68''E to 42°22'35.04''E (East) (Fig. 2).

Fig. 2: Location Map of Wadi Reem basin.

The study area basin is surrounded by high mountains from east and the north. Reem basin can be divided into three main topographic features; The Red Sea coastal plain (Tihamah), the Hills, and the Scarp of Hijaz Mountains. Tihamah area is a flatted land located in the East and North East of wadi Reem basin, and its width is about 33 km and its elevation varies from 0 level to 300 m above sea level. The hills are area which sloping slightly at west of the Scarp Mountains and the elevation of the hills varies from 400 m to 1,139 m above sea level (Fig. 3).

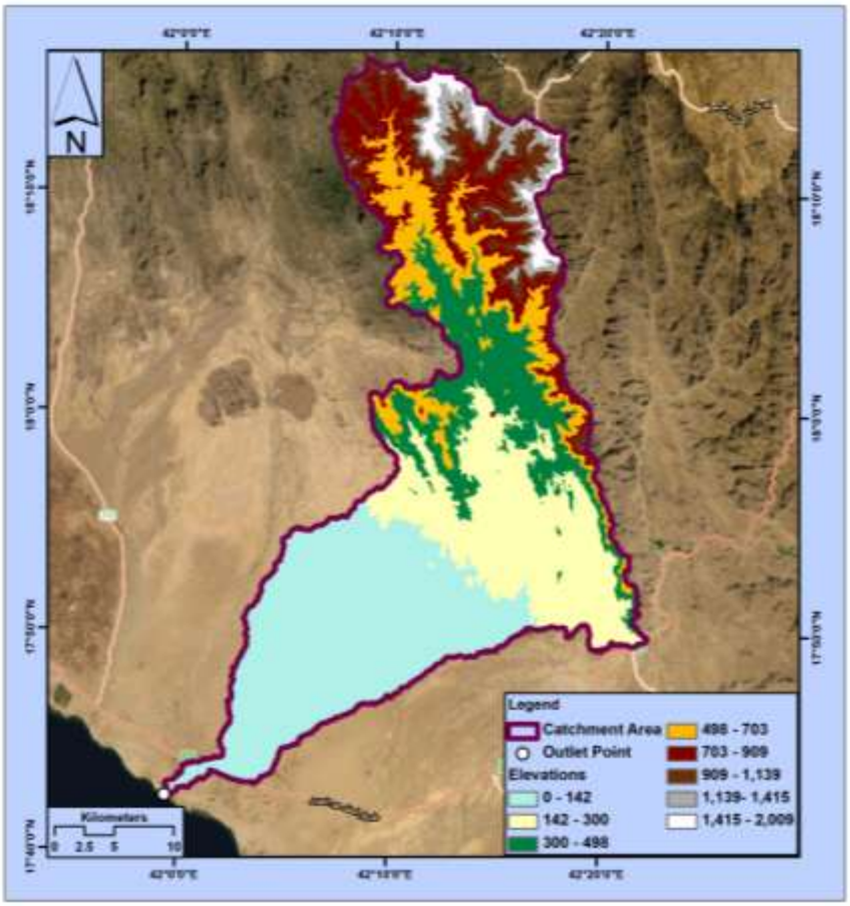

Fig. 3: Digital elevation map (DEM) of Wadi Reem basin.

Morphological characteristics

Basic parameters such as area, perimeter, elevation, slope, width, length of watershed and stream length could be extracted directly from the DEM using WMS Softwear. The Wadi Reem drainage basin has an area 205.42 km^2 and the main morphological parameters of Wadi Reem basin are shown in Figure (4) and Table (1).

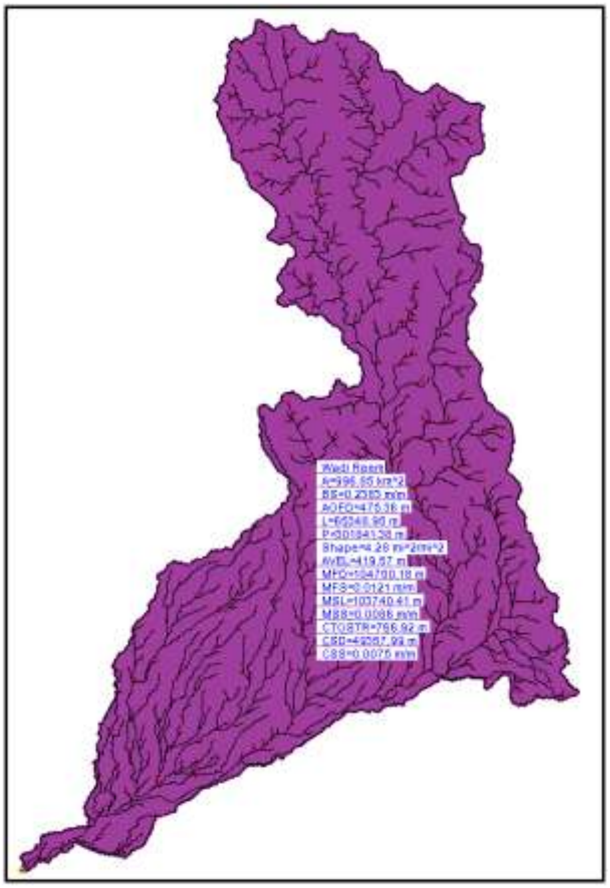

Fig. 4: Wadi Reem basin delineation extracted directly from DEM Using WMS Softwear.

Table 1: The morphological characteristics of Wadi Reem basin.

Parameter	Units	Wadi Reem
Basin Area (A)	km^2	996.85
Basin overland Slope (BS)	m/m	0.238
Mean basin elevation (AVEL)	m	419.57
Basin length (L)	m	65348.95
Basin Perimeter (P)	m	301841.38
Maximum Stream Lengh (MSL)	m	103740.41
Maximum Stream Slope (MSS) (watercourse) average slope	m/m	0.0086
Basin length along main channel from outlet to upstream boundary (MFD)	m	104750.18
Average overland flow distance (AOFD)	m	475.36
Basin slope along main channel from outlet to upstream boundary (MFS)	m/m	0.012
Length along main channel from outlet to point opposite centroid (CSD)	m	49357.99
Slope along main channel from outlet to point opposite centroid (CSS)	m/m	0.0075
Distance from Centroid to stream (CTOSTR)		766.92
Shape Factor	m^2/	4.28

Geology and Land use

Interpretation of the geological maps (GM-70C and GM-75C) (1:250,000-scale) acquired from the Saudi Geological Survey database for the study area revealed the rock types in The Wadi Reem Basin area and is shown in Figure (5).

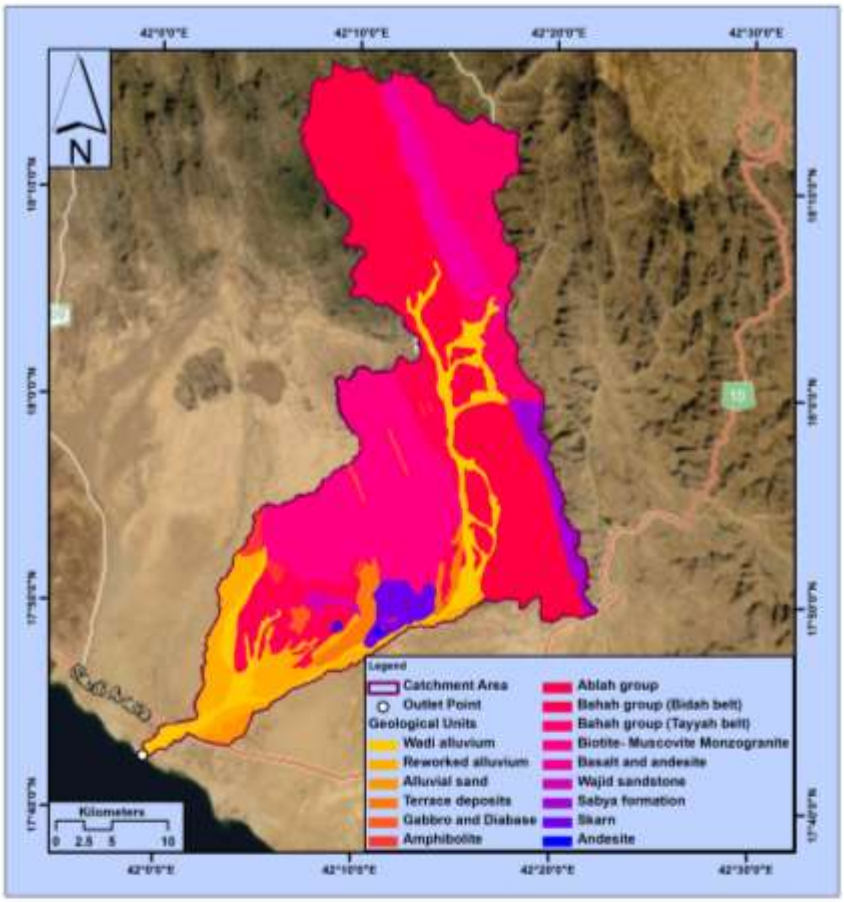

Fig. 5: Geological map of the Wadi Reem basin.

Based on field observation and the supervised classification of Setinal-2 satellite image results showed that there are seven types of land use/land cover in the studied basins, namely: Mixed forest or shrupland, Mixed cropland vegetation and shrups, Cropland and Pasture, Farmlands, Mixed Urban or Built-up Land, Rocky areas and Desert areas as shown in Figure (6). The land use classification of Wadi Reem basin is given in (Table 2) shows that 23.08% of land is used as Mixed forest or shrupland, 16.96% land is used as Mixed cropland vegetation and shrups, 3.06% land is used as Cropland and Pasture, 8.08% of land is used as Farmlands, 3.55% land is used as Mixed Urban or Built-up Land, 5.08% land is used as Rocky areas and 40.1% land is used as Desert areas.

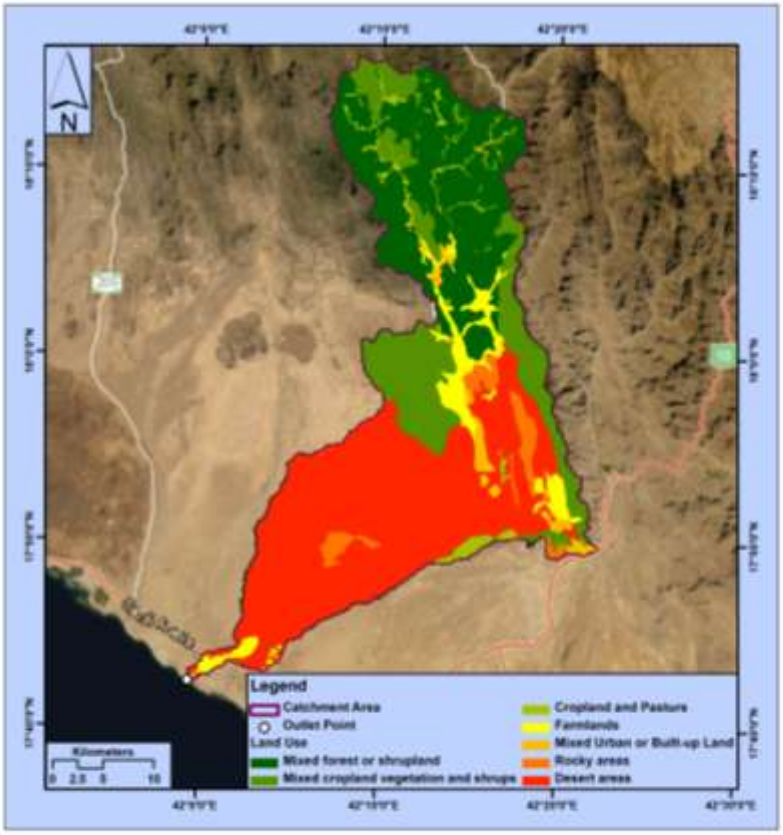

Fig. 6 : Land use map of the Wadi Reem basin.

Table (2): Classification of Land Use types and their spatial coverage in Wadi Reem basin.

Land Use classification	Area (km^2)	Percentage of Area %
Mixed forest or shrupland	230.13	23.08
Mixed cropland vegetation and shrups	169.14	16.96
Cropland and Pasture	30.54	3.06
Farmlands	80.56	8.08
Mixed Urban or Built-up Land	35.43	3.55
Rocky areas	50.67	5.08
Desert areas	400.12	40.1
SUM	996.85	100

Hydrologic soil maps and Curve Number

The SCS model categorizes soil types into four groups which are A, B, C and D, in accordance with their infiltration rate (Sindhu *et al*., 2013). CN is the curve number, a dimensionless number that range from 0-100, which is drawn from a table provided by the SCS handbook of Hydrology depending on the HSG, land use /land cover, and Antecedent moisture condition (AMC) (Songara *et al*., 2015; Satheeshkumar *et al*., 2017; Amutha and Porchelvan, 2009). The hydrologic soil groups (HSG) in the study basins included four types of Hydrologic soil Group four groups which are A, B, C and D, in accordance with their infiltration rate

(Sindhu *et al*., 2013) **(Fig. 7)**.The The calculated curve numbers for Wadi Reem basin was 72.72 as shown in **Figure (8)**.

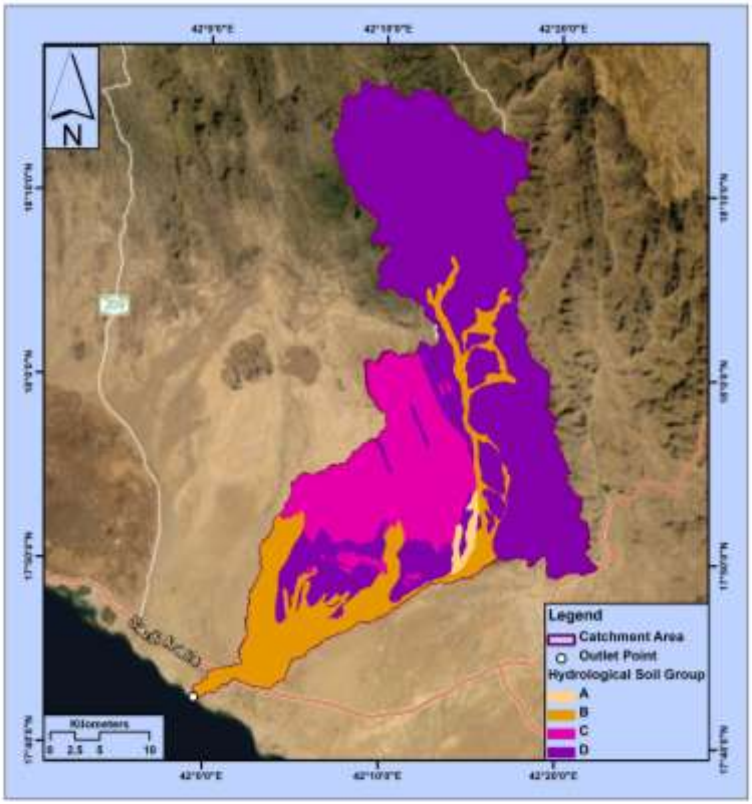

Fig . 7: hydrologic soil group's map for Wadi Reem Basin.

Fig. 8 : Curve Number map for Wadi Reem Basin.

Rainfall station data

It was found that Wadi Reem is affected by three meteorological stations and these stations are operated by the Ministry of Water and Electricity (MOWE), according to the Thiessen polygons as shown in Figure (9). Theses rainfall station data as the following; Rajal Almaa (SA116), Alhabil (SA144) and Aldarb (SA102), The records also revealed that these stations cover a period of 44 years, 46 years and 39 years, respectively (Figs.10-12).

The depth of the rain was determined in various return periods (5, 10, 25, 50, and 100 years) using the Hyfran-Plus (Hyfran, 1998) and various statistical distributions, such as normal, log-normal, Gamma, Gumbel, and log-Pearson type III, used to verify the results. It was concluded that the method (Normal) is the most suitable for Rajal Almaa (SA116), the method (Gamma) is the most suitable for Alhabil (SA144) and method (Log-Pearson type 3) is the most suitable for Aldarb (SA102) (Fig. 13) and (Table 3).

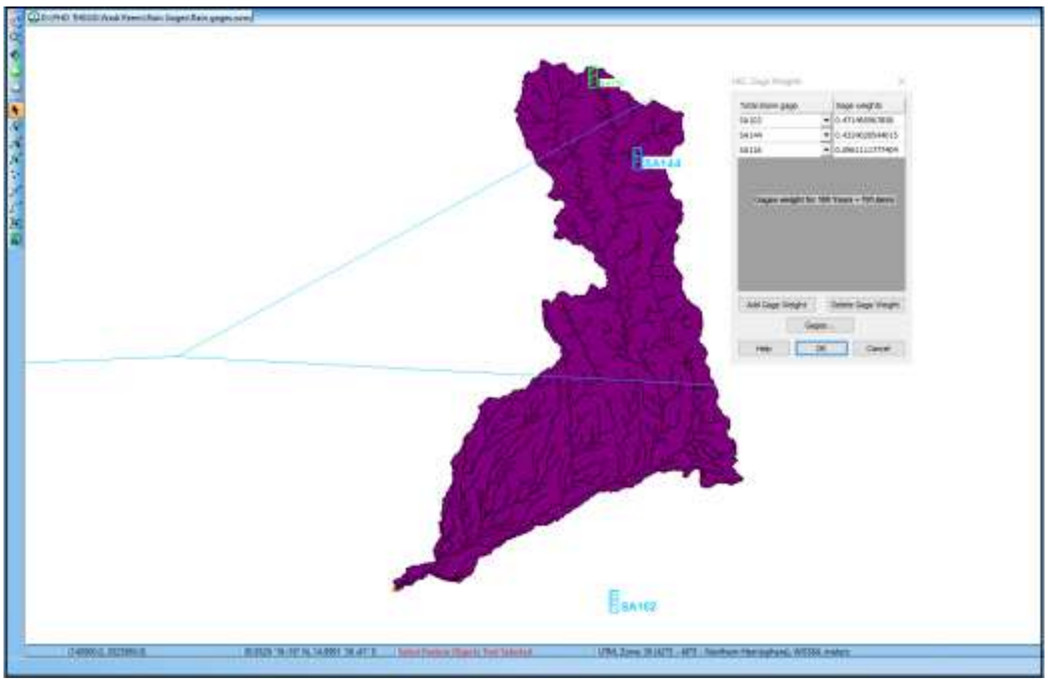

Fig. 9: Rain gages weight from all station affecing on wadi Reem basin.

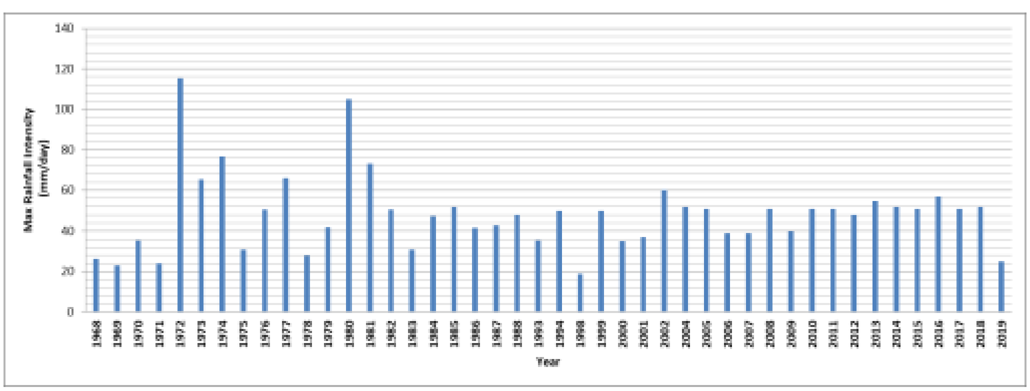

Fig. 10: Maximum annual daily rainfall of Rajal Almaa (SA116) station from 1968 to 2019.

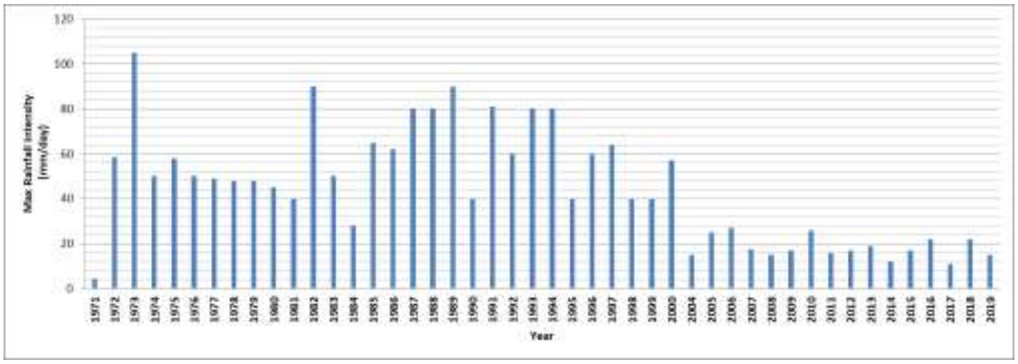

Fig. 11: Maximum annual daily rainfall of Alhabil (SA144) station from 1971 to 2019.

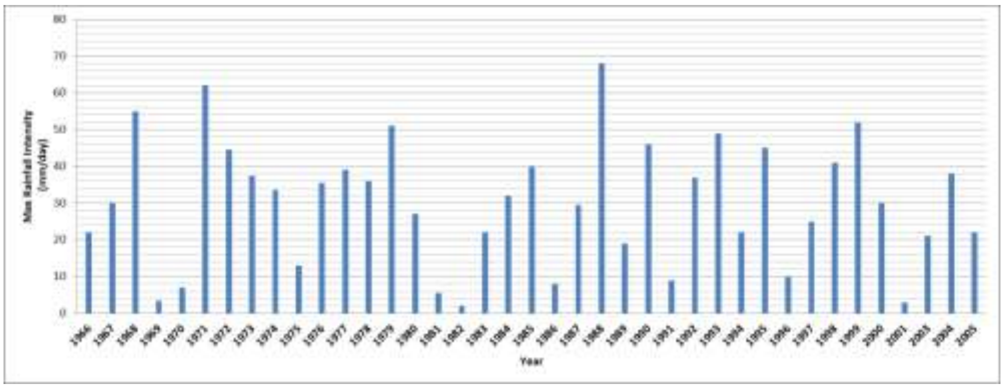

Fig. 12: Maximum annual daily rainfall of Aldarb (SA102) station from 1966 to 2005.

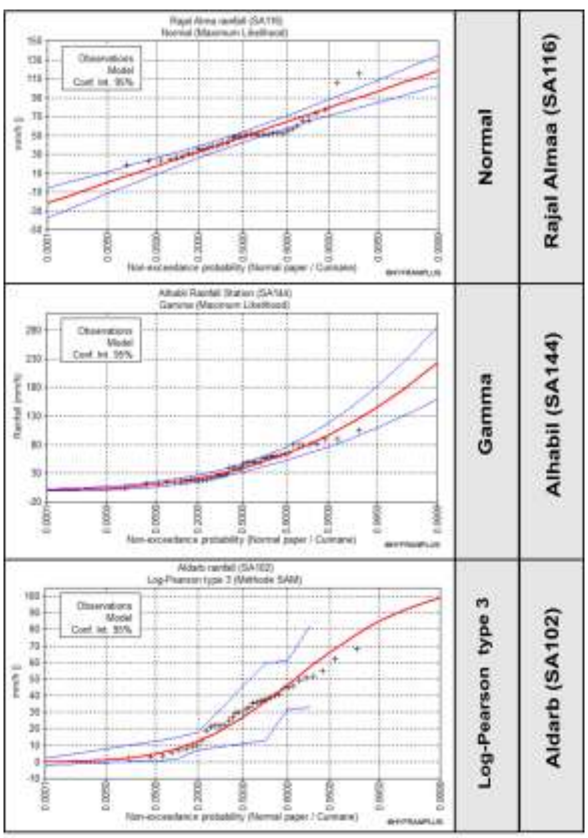

Fig. (13): Probability distribution curve of Rajal Almaa (SA116), Alhabil (SA144) and Aldarb (SA102) using Normal, Gamma and Log-Pearson type 3 distributions.

Table (3): The results at different return periods of extreme rainfall events.

The series of daily rainfall	Statistical distribution	5 years	10 years	25 years	50 years	100 years
Rajal Almaa (SA116)	Normal	64.2	72.5	81.3	87	92.2
Alhabil (SA144)	Gamma	64.3	81.2	102	117	132
Aldarb (SA102)	Log-Pearson type 3	46.5	57.5	68.6	75.2	80.6

Hydrologic Modeling

HEC-HMS is widely used as a rainfall runoff modeling tool, and it uses separate sub models to represent each component of the runoff process, including models that compute rainfall losses, runoff generation, base flow, and channel routing (Du *et al*., 2012).

After the completion of the basin model with WMS, the model was exported into HEC-HMS project file as shown in Figure (14); this figure shows the schematic representation of the basin model in HEC-HMS contains the hydrologic elements. After steps of the calibration and validation, we can have the runoff generated by the model after creating simulation run and view the results as 740.1 m^3/s for 100 Year return period as shown in Figure (15).

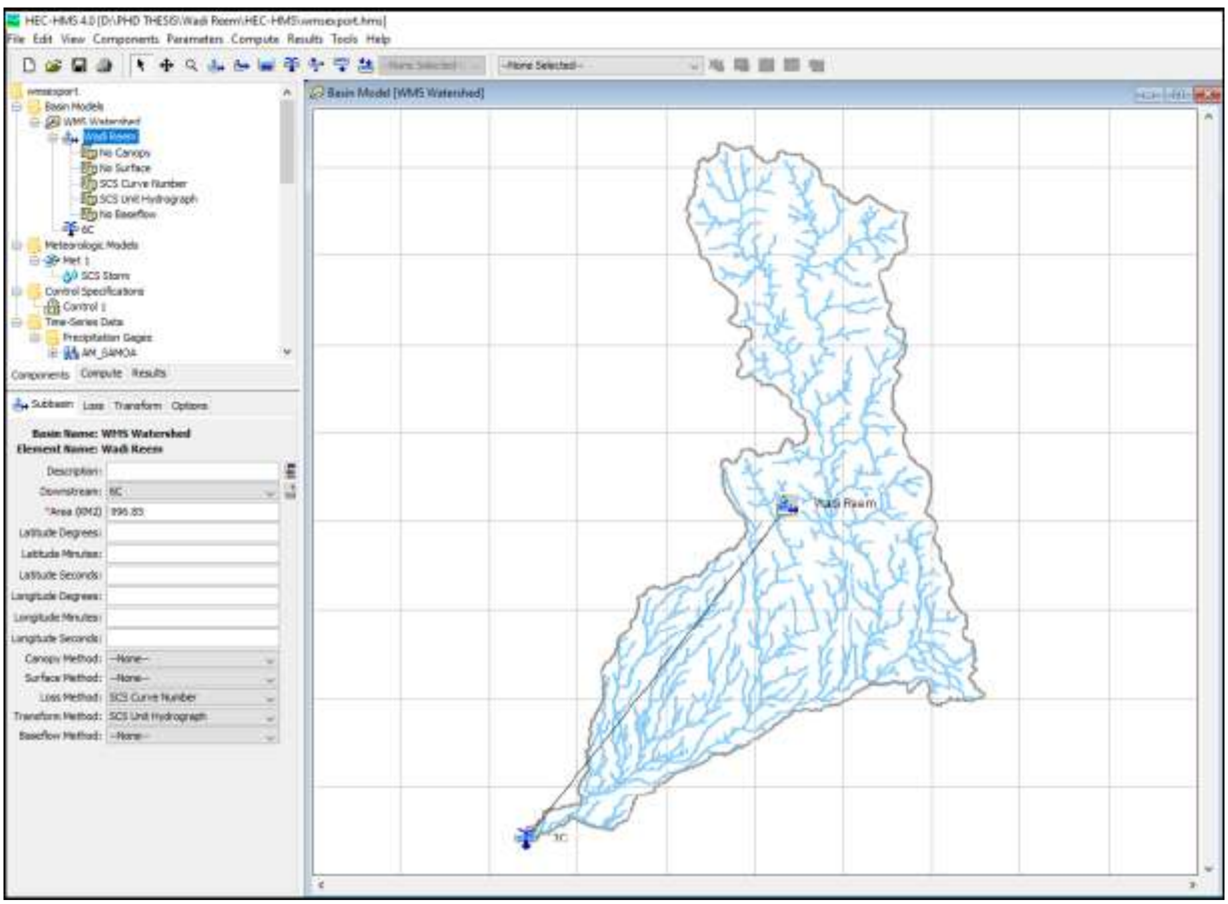

Fig. 14:schematic representation of the basin model of Reem in HEC-HMS.

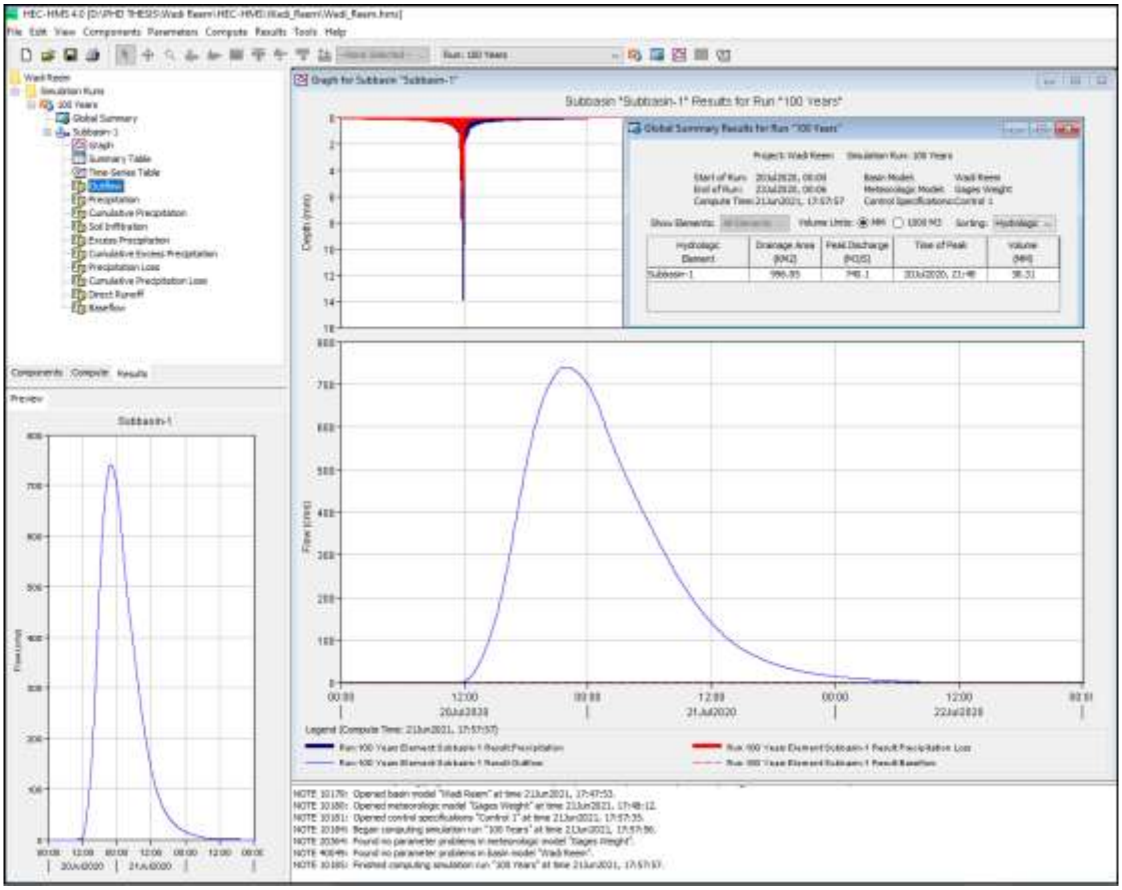

Fig. 15: Outlet Hydrograph created by HEC-HMS for 100-year Return period

Hydraulic Modeling using 2D HEC-RAS Model

The most important parameters for the HEC-RAS hydraulic model are geometric and flow data. The geometric data have been developed by drawing the stream of Wadi Reem system schematically with flow direction. This was done by using the button of river reach of the HEC-RAS, the methods explain in details in software manual (U.S. Army Corp of Engineers, 2010).

Flood Depth

The maximum flood depth maps were generated by the 2D model by taking into consideration the maximum depth for each mesh cell**.** It is concluded that water levels inside the existing natural channel inundated and flooded over this channel and the existing natural channel did not drainage all the water out site the built up and residential area from the north and these area may be affected by flood as shown in Figure (16).

Fig. 16: Flood waters depth and flooded areas simulated by HEC-RAS2D model for 100-year of Reem.

Flood Velocity

Another important result of the 2D modeling process is flood velocity. This is computed by recording the maximum velocity for each cell in the computational mesh **Figure (17)**. From this map the buildings are potentially affected by the 0.5– 1 m/s flood velocity which covers most of the flood area.

Fig. 17: Flood velocityderived from HEC-RAS 2D model for 100-year of Wadi Reem.

Flood Hazard Assessment

The flood velocity was not taken in this basin because it is below the limit. To generate the flood hazard categories, the water depth for each flood extent was classified according to the Japanese criteria of the Ministry of Land Infrastructure and Transport and the flood hazard map is shown in Figure (18).it in noticed that the high risk areas are shown in orange color and dark Blue, these regions are closer to the wadi bed. They are dangerous during floods as the water level can reach up to 4 m. They mainly occupy the congested areas near the roads.

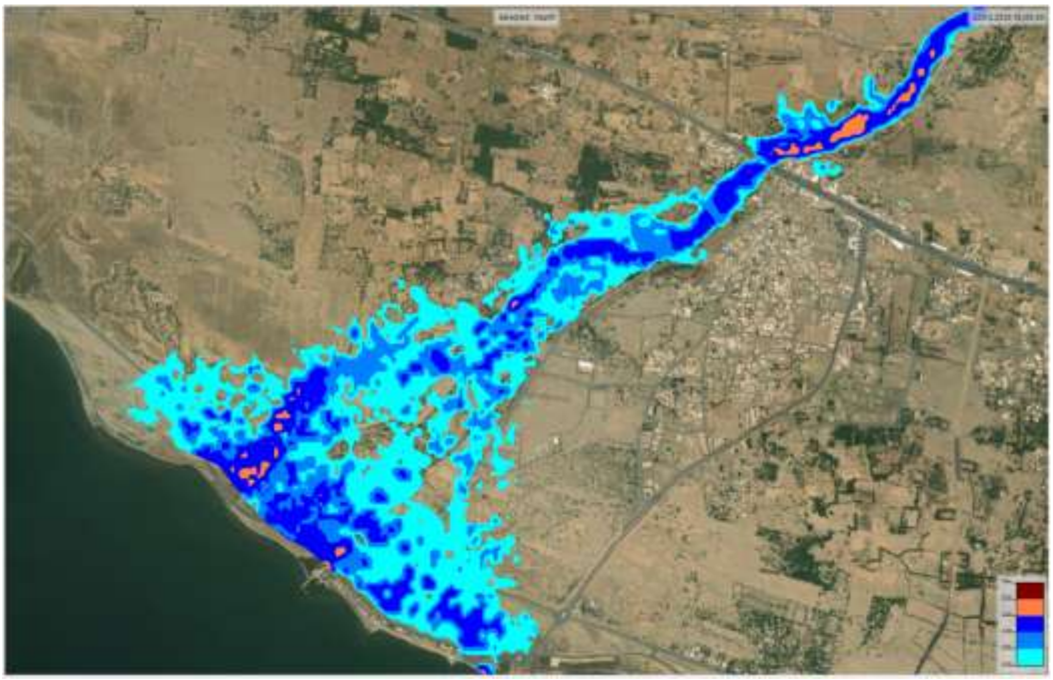

Fig . (18): Flood Hazard map of Wadi Reem based on flood depth classification according to the MLIT derived from HEC-RAS 2D modelling.

Conclusion

The study concludes the following; the watershed of Wadi Reem and its stream delineation process were carried out with the aid of Watershed Modeling System (WMS) software. In the present study, the CN values found to be 72.72; Hydrologic modeling was carried out by HEC-HMS program that simulated rainfall-runoff process using curve number model. The HEC-HMS model was selected because it can investigate the applicability of hydrologic modeling in arid and semi-arid regions, in order to simulate rainfall-runoff through the employing of HEC-HMS model using Soil Conservation Services, Curve Number and SCS Unit Hydrograph. For 100-year return period, hydrograph results indicate that; the hydrograph volume is about 38193654 cubic meters with a peak discharge of about 740.1 m3/s for Wadi Reem Basin.

This study discusses the implementation of 2D model that shows the flood water depth, spread, and velocity based on the hydraulic modeling of the HEC-RAS program for urban developing areas. The study also provides 2D model of the flood water inflow spread, velocity, and depth, as these characteristics are not available in the one-dimensional flood water inflow model.

The results of HE-RAS 2D Model indicated that; the main channel of Wadi Reem basin has not the capacity to carry the 100-year return period peak flood Hydrograph and the flood inundated in these wadis with different depths and velocities.

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نمذجه مياه السيول باستخدام نموذج (HEC-RAS (2D على وادى ريم بالمنطقة الغربية ، المملكة العربية السعودية

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2- قسم الجيولوجيا بكلية العلوم جاهعة الازهر (فرع أسيوط)

المستخلص

تم دراسة الحوض المائى لوادى ريم ومسارات الاودية باستخدام برنامج نظام نمذجة المياه (WMS). أمكن تحديد قيمة رقم المنحنى (CN) لتكون 72.72؛ كا تم تنفيذ النمذجة الهيدرولوجية بواسطة برنامج HEC-HMS الذي يحاكي عملية جريان هطول الأمطار في المناطق القاحلة وشبه القاحلة باستخدام رقم المنحنى ووحدة SCS Hydrograph. بالنسبة لفترة العودة التي تبلغ 100 عام ، تشير نتائج الهيدروغراف إلى أن ؛ حجم الهيدروغراف حوالي 38193654 متر مكعب مع ذروة تصريف حوالي 740.1 متر مكعب / ثانية لحوض وادي الريم. تم فى هذه الدراسة مناقشة تنفيذ نموذج ثنائي الأبعاد يوضح عمق مياه الفيضان وانتشارها وسرعتها بناءً على النمذجة الهيدروليكية لبرنامج HEC-RAS لمناطق التطوير الحضري. توفر الدراسة أيضًا نموذجًا ثنائي الأبعاد لانتشار تدفق مياه الفيضان وسرعتها وعمقها ، حيث إن هذه الخصائص غير متوفرة في نموذج تدفق مياه الفيضان أحادي البعد.أشارت نتائج نموذج HE-RAS 2D إلى أن القناة الرئيسية لحوض وادي الريم ليس لديها القدرة على حمل هيدروغراف ذروة الفيضان لفترة 100 عام والفيضان يغمر مساحة من الاراضى عند نهاية الوادى بأعماق وسرعات مختلفة.