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Application of Geographic Information Systems in Reducing the Risk of Flash Floods. Case Study Wadi Ghareb, Gulf of Suez, Egypt

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ABSTRACT
Egypt has deficit in water resources, so the optimal use from rainfall water is necessary. Egypt is exposed sometimes to accidentally flash flood hazards. In spite of flash floods led to damage to infrastructures, properties and loss of life but it can be used to harvest runoff flood. This study is based on integrated geologic, topographic and geophorphologic studies to prepare the required input data for different GIS layers such as: Digital Elevations Model (DEM), land forms, geologic setting, watershed characteristics, drainage lines, morphometric parameters, slope, flow direction and flow accumulation. Ras Ghareb city is one of the places which is subjected recently to heavy rainfall storms such as those occurred on December 2010, October 2016, February 2018, April 2019, March 2020, January 2022 with rainfall depth of 38.9 mm, 25.1mm, 17.01mm, 28.5mm, 39.8 mm and 60.48mm, respectively. Storm of December 2010, which caused a great damage in the study area, is selected to be analyzed. The HEC-HMS software is applied to estimate the peak discharge and runoff volume. The results show that the runoff volume of Wadi Ghareb is about 7.0357 million m^3 year. Return period is expected to occur each 72 years with a probability of 1.35%, while a rain of 1.0 mm can occur every year with a probability of 94.59%. So, suggested tools of harvesting techniques for mitigation of flash flood hazard is recommended such as culverts under the asphaltic roads to protect it, detention dams to reduce velocity of flash flood and giving chance for replenishment of shallow aquifers. Also, earth dams can be used to allow the water to flow. Rain station is recommended to measure collected rainfalls.

Keywords: Watershed, Morphometric parameters, Flash Flood, Surface water runoff, Digital Elevations Model.

1. Introduction

Ras Ghareb city has experienced several flash floods in recent years, notably in 2010 and 2016. The flood that occurred on December 29-30, 2010, resulted in significant damage to various government buildings, including schools, a youth center, and the city council building. According to Moawad (2021), Ras Ghareb and its surrounding areas have exposed to frequent flash floods, which have led to the Closing of the coastal road and disrupted transportation to and from the Red Sea Governorate. The flash flood on October 26-27, 2016, tragically resulted in the loss of numerous lives and caused extensive damage to infrastructure and property.

The present work focus on mitigating flash flood risks in Ghareb area through applying Geographic Information Systems (GIS) to identify the data layers that influence runoff. The study also aims to optimize water harvesting strategies and determine the most effective locations for constructing detention and earth dams to manage flash floods. Additionally, the research seeks to harness the benefits of flash floods while minimizing their risks through various harvesting initiatives, thereby assisting decision-makers in implementing timely and informed regulations before and after such critical events. GIS plays a crucial role in decision-making and can be applied across a variety of sectors, including government, business, and urban planning. Numerous studies have cited GIS applications in analyzing flash flood hazards, especially concerning Ras Ghareb region.

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2. Materials and Methods

2.1. Site description

Wadi Ghareb is located east of the Gulf of Suez, between latitudes 28˚00' and 28˚12' N and longitudes 32˚45' and 33˚12' E. It is bordered to the west by the water divide, including Gebel Abu Khashaba (1460 m) and Gebel Ghuwayrib (1359 m), which separates the wadis that drain into the Nile River from those that flow into the Gulf of Suez Fig. 1. Covering an area of 288 km², Wadi Ghareb has experienced multiple recurring flash floods, causing significant damage to infrastructure as the floodwaters move toward the Gulf of Suez. Figure 2 presents a flowchart illustrating the applied methodology in present study.

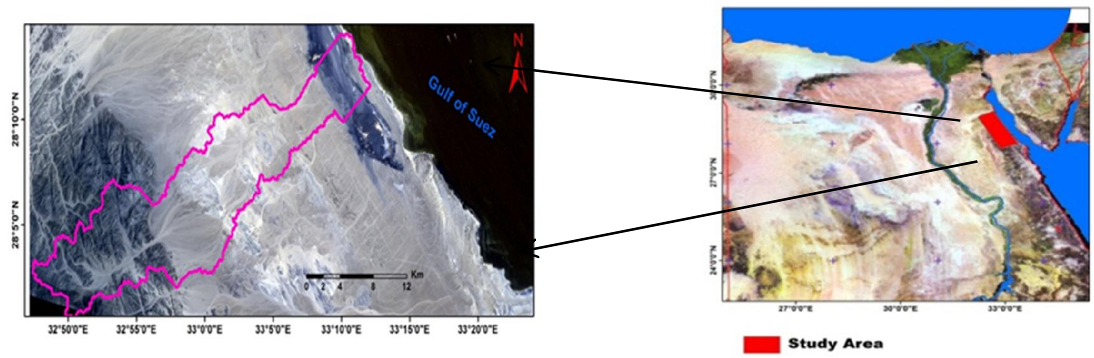

Fig. 1: Image Satellite (ETM) of Wadi Ghareb showing the Location of the Wad

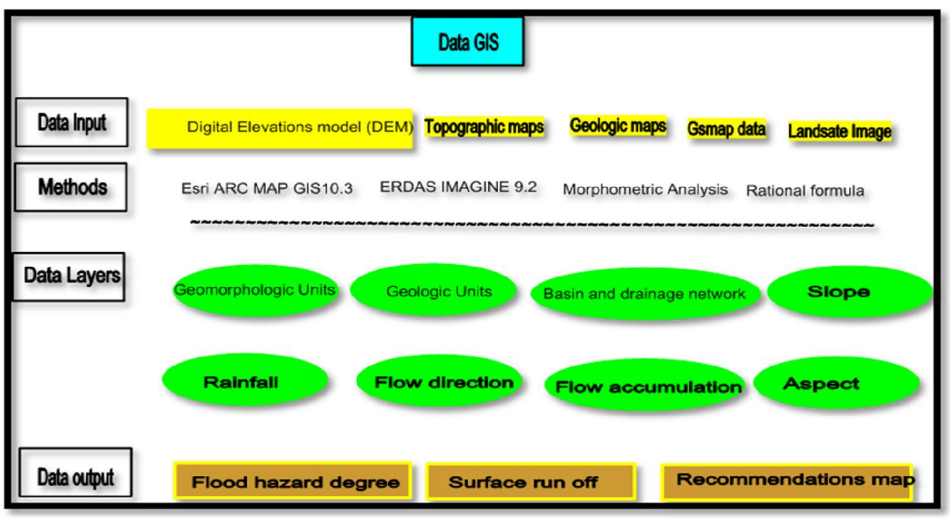

Fig. 2: Flow Chart of the study including the data sources and methodology

2.2 Geomorphologic and geologic setting

According to the Digital Elevation Model (DEM) of the study area (Fig. 3) as well as topographic maps at scales of 1:50,000 and 1:100,000, geologic maps at a scale of 1:500,000, and Landsat 8 satellite imagery, Wadi Ghareb is predominantly covered by the Precambrian basement rocks of the Gulf of Suez mountains. The geomorphologic characteristics of Wadi.

2.2.1. The Geomorphologic units

Geomorphologic units are shaped by both endogenic and exogenic processes. In the study area, three distinct Geomorphologic units have been identified (Fig. 4) : the basement mountainous terrain, the piedmont plain, and the coastal plain.

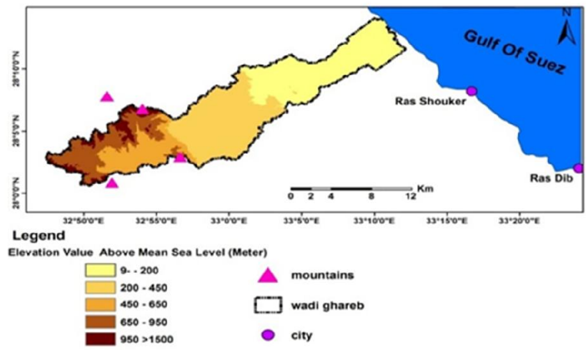

Fig. 3: Digital elevations model of Wadi Ghareb

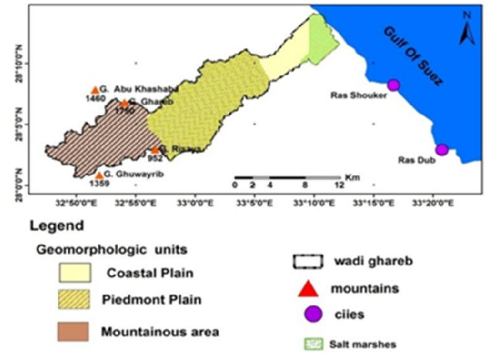

Fig. 4: Geomorphological units of Wadi Ghareb

a) Basement mountainous terrain:

This unit primarily consists of igneous rocks and is extensively dissected by numerous faults. It is located in the western part of Wadi Ghareb, with elevations exceeding 500 meters above mean sea level, indicating high relief. It covers an area of about 98.76 km² representing 34% of the area the Wadi and has a steep west to east slope. It is considered as the main watershed area of Wadi Ghareb.

Several prominent mountains are part of this unit, including Gebel Ghareb (1705m), Gebel Risays (948 m), Gebel Abu Khashaba (1469 m), and Gebel Ghuwayrib (1359 m). The terrain is significantly influenced by faults trending SW, NW-SE, and NNE-SSW, in addition to NW-SE fault systems. Rainfall in this area flows eastward toward the Gulf of Suez. Due to the intersection of faults and fractures, the prevailing drainage patterns are dendritic and trellis types.

b) Piedmont plain

It lies between the coastal plain and the mountainous region, this unit covers an area of approximately 138.79 km², accounting for about 48% of the total area of Wadi Ghareb. Its elevation ranges from 100 to 500 meters above mean sea level. The terrain is primarily covered by alluvial deposits and alluvial fans, dating back to the Miocene age. It has a gentle slope extending toward the Gulf of Suez.

c) Coastal plain

The coastal plain lies between the Gulf of Suez and the piedmont plain covering the eastern part of Wadi Ghareb.

It is bordered to the east by the Gulf of Suez, which generally trends in a NW-SE direction. This unit represents the lowlands forming the delta of the Wadi and covers an area of approximately 50.8 km², accounting for about 18% of the total Wadi area. Its elevation ranges from 0 to 100 meters above mean sea level. The coastal plain consists of Pleistocene terraces composed of gravel, coral, loamy shell deposits, and various types of coastal and inland Sabkhas (Youssef, 1992). It also features several NW-SE trending headlands, such as Ras Ghareb (Milad, 2006).

2.2.2. Hydrographic basins

Wadi Ghareb is one of the largest drainage basins in the Gulf of Suez region, covering an area of approximately 288 km² with a perimeter of 137.1 km. It features an alluvial fan spanning about 28 km² and drains eastward from the highly elevated basement rocks toward the Gulf of Suez, forming an alluvial plain. The Wadi originates from the northern slopes of Gebel Abu Khashaba (1460 m) and the western slopes of Gebel Ghuwayrib (1359 m).

The main channel of Wadi Ghareb has a slope of 1.973 m/km and extends over a length of 54.2 km. At the upstream,, the drainage system develops steep-sided, narrow canyons that gradually widen and form flat valley floors near their outlets. The main channel generally follows the orientation of major faults and fractures. The region exhibits well-developed angular to sub-angular dendritic and trellis drainage patterns, particularly around the major fault zones. Wadi Ghareb is divided into five main sub-basins. Sub-basin 1 and Sub-basin 2 are classified as fifth-order basins, while Sub-basin 3, Sub-basin 4, and Sub-basin 5 are fourth-order basins.

2.2.3. Geology

The geology of the study area has been extensively examined by several researchers, including (Strahler, 2002), (Said, 1962), (Gorab and Marzouk, 1967), Youssef (1992) and Milad (2006). The area is primarily composed of Precambrian basement rocks, which are overlain by sedimentary formations ranging from the Lower Cretaceous to the Quaternary Geological maps of Beni Suef and South Sinai, at a scale of 1:500, 000 (CONOCO, 1987) Ghorb & Marzouk, 1967 11(Fig. 5), were used as a reference to identify the (Fig. 5).

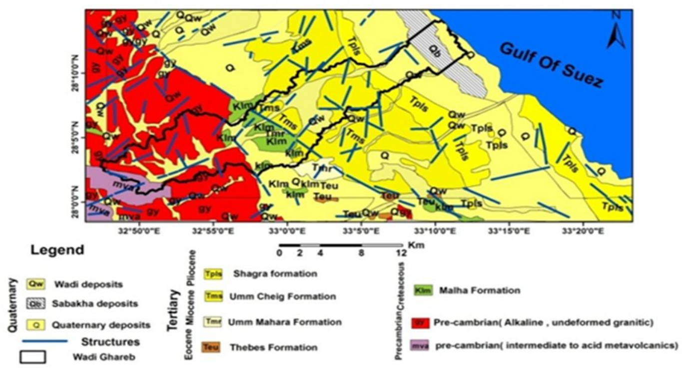

Fig. 5: Modified geologic map of the study area (CONOCO, 1987)

The stratigraphic successions in the study area are as the followings:

I. Basement rocks

The basement rocks in the study area date back to the Precambrian to early Paleozoic era and are considered the backbone of the Eastern Desert (Youssef, 1992).

These rocks form the core of the mountain range and primarily consist of granite, intermediate to acidic metavolcanics, and metapyroclastic rocks. Located on the western side of the study area, the basement complex serves as the main watershed region of Wadi Ghareb, covering approximately 16.5% of its total area. This region includes key basement ridges such as Gebel Ghareb (1750 m) and Gebel Risays (952 m), both situated west of Wadi Ghareb. The basement rocks in the study area are highly fractured due to faults and joints (Milad, 2006) and are intersected by numerous massive dikes composed of trachyte, rhyolite, and basalt. Due to its fractured and weathered nature, the basement complex is considered one of the significant water-bearing units in the region.

II. Lower Cretaceous

The Nubian Sandstone unconformably overlies the Precambrian basement complex and is considered the oldest sedimentary rock unit in the study area. In Wadi Ghareb, it is represented by the Malha Formation (Klm), which is the oldest Cretaceous rock unit. This formation consists of alluvial nearshore "Nubian-type" sandstones that rest unconformably on older strata (Said, 1962)

The Malha Formation is composed of kaolinitic, cross-bedded fluvial sandstone interbedded with mudstone. The Lower Cretaceous rocks cover approximately 8% of the total study area, primarily occupying the southwestern corner of Wadi Ghareb.

III. Tertiary

The Tertiary is represented by Lower Eocene, Lower to Middle Miocene and Pliocene.

Lower eocene

The lower Eocene is represented by Thebes formation which consists of thiny bedded outer shelf chalk and chalky limestone (Milad, 2006). It covers 0.3% of the study area and makes scarps of the southern part of the study area.

Lower to middle miocene

It is represented by Umm Mahara Formation which is made up of coarse to very coarse calcareous conglomerate boulder beds alternating with gritty coralline limestone beds.

Middle to upper miocene (Umm Gheig) (Tms)

It is identified as Gharamul by Ghorab and Marzouk, (1967). This formation consists of algal limestone that is occasionally dolomitic and is not bedded. Its thickness measures 126 meters (Said, 1962). In the study area, Miocene outcrops cover approximately 26.4% of the exposed sediments.

Pliocene (shagra formation)

The Shagra Formation primarily consists of sandstone, with some clay and biolistic sediments present (Conoco, 1987) It accounts for 8.3% of the study area. Its thickness varies between 146 meters and 237 meters in In Ras Ghareb area (Souaya, 1954).

4) Quaternary deposits

Quaternary deposits the Pleistocene and recent deposits, which consists of alluvial fans, Wadi deposits, as well as sand, gravel, and sabkha deposits (Conoco, 1987). It also includes elevated terraces featuring coral and Oyster banks (Youssef, 1992). This formation covers 60.4% of the total area and is regarded as a water-bearing formation within the study area.

2.3. Structural setting

The Gulf of Suez represent one of the most intensively – faulted areas on the face of the earth (Said, 1962) bordering the depression on both sides are two major marginal faults usually marked by lines of high vertical escarpments on the up thrown sides. The tectonism in the area is complicated and the tectonic events of different ages are manifested by numerous faults, some folding and fractures (Youssef, 1992). The rose diagram (Fig. 6) revealed the presence of three main sets of lineaments oriented NE-SW, NW-SE and NNE-SSW are delineated in the study area. The main trend of lineaments NE-SW is parallel to the main trends of the Gulf of Aqaba, while the lineaments NW-SE is parallel to the Gulf of Suez.

2.3.1. Lineaments

The Lineaments of Wadi Ghareb have been traced for each sub-basin, with their directions and lengths measured and represented in a rose diagram. Based on this data, the following conclusions have been reached:

1. The rose diagram depicting the number of lineaments (N%) (Fig. 7) indicates that the most prominent direction is NE-SW, which represents the major lineaments, while those parallel to the NW-SE trend of the Gulf of Suez are relatively less frequent across all sub-basins.
2. Additional trends observed include NNE-SSW and N-S.

The density of lineaments is high at the southern part of Wadi Ghareb, which attributed to the predominance of basement rocks, while it low at the northern part due to the presence of sandstone and sandy plains.

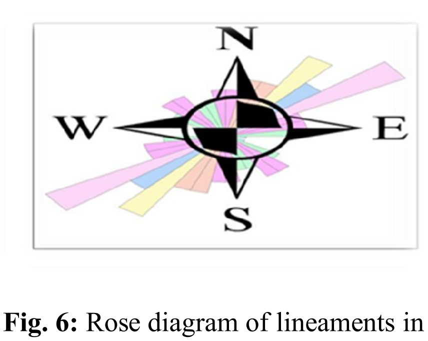

Fig. 6: Rose diagram of lineaments in Ghareb

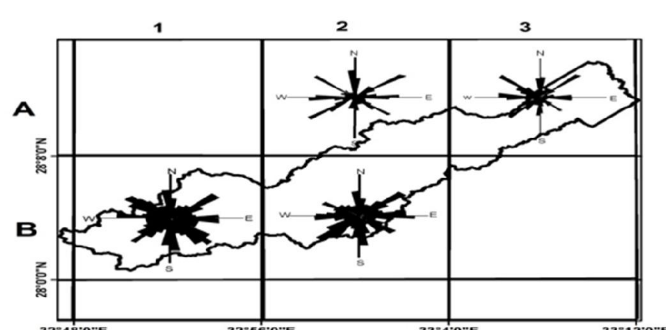

Fig. 7: Azimuth frequency diagram of structural lineaments

2.4. Data and applied methods

To achieve the objectives of this study, the following data and methods have been employed:

Climatic data from the Egyptian Meteorological Authority (EMA 1949-2018) for Suez and Hurghada Stations, covering the period from 1945 to 2000, with coordinates (29° 52' N & 32° 28' E) and (27° 17' N & 33° 46' E), respectively.

Topographic maps at scales of 1:100,000 (Military Survey, 1971) and 1: 50, 000 Egyptian General Survey Authority, (1988).

Geological maps at a scale of 1:50,000 (CONOCO, 1987) 6 to identify the geology and geological structures of Wadi Ghareb.

Digital Elevation Model (DEM) (SRTM-C) with a resolution of 30 meters was utilized to quantify the structure and shape of the topography, facilitating the creation of slope and aspect maps. The extracted data from the DEM was used to generate the drainage network, flow direction, flow accumulation, watershed delineation, and stream networks. Morphometric parameters were calculated to assess the flood hazard probability of the sub-basins.

Landsat 7 satellite imagery (ETM) was used to determine the location of Wadi Ghareb.

ARC/Map1 Software version 10.3 Copyright 1999-2014 and Erdas/Imagine 9.2 (2014) were employed for map analysis, including rectification, sub-setting, and mosaicking.

HEC-HMS14 Software version 4 (2010) was utilized for storm analysis and rainfall-runoff calculations.

Historical climate data collected from the Egyptian Meteorological Authority (EMA) during the period from 1951 to 1999.

Global Satellite Mapping of Precipitation GSMaP, 2000-2023, was used to gather rainfall data for the upstream areas of Wadi Ghareb (32° 45' E & 28° 15' N).

2.5. Climatic conditions

The study area experiences hot summers and mild winters. The highest temperatures were recorded in August, reaching 35.60°C in Suez and 33.40°C in Hurghada, while the lowest temperatures occurred in January, measuring 10.30°C and 10.40°C, respectively.

The peak average daily evaporation rates were recorded during the summer months, particularly in June, with values of 12.78 mm/day in Suez and 17.26 mm/day in Hurghada. Relative humidity levels typically exhibit an inverse relationship with air temperature, peaking in the winter and dropping during the summer. In Suez, the highest relative humidity was recorded in December at 61.87%, while the lowest was in May at 46.16%. In Hurghada, the maximum relative humidity occurred in February at 54.88%, and the minimum was in June at 41.51% Table 1.

Table 1: Average monthly air temperature (T˚C) relative humidity (RH%) and evaporation at the meteorological stations of the study area for 56years period (1945- 2000).

	Suez station					**Hurghada station**				
Month	**Max. Temp.**	**Min. Temp.**	**Average Temp.**	**Relative Humidity %**	**Evapo-ration**	**Max. Temp.**	**Min. Temp.**	**Average Temp.**	**Relative Humidity %**	**Evaporation**
Jan.	19.5	10.3	14.9	57.55	6.02	20.8	10.4	15.6	48.42	**8.48**
Feb.	21	11	16	56.34	6.78	21.8	10.8	16.3	54.88	**9.52**
Mar.	23.8	13.1	18.45	53.44	8.45	21.1	13.8	17.45	46.15	**10.47**
Apr.	28.8	16.5	22.65	47.58	10.89	27.5	17.8	22.65	44.23	**12.59**
May.	31.9	19.5	25.7	46.86	11.93	30.5	21.6	26.05	42.35	**14.87**
Jun.	34.8	22.4	28.6	49.16	12.78	32.6	24.6	28.6	41.51	**17.26**
Jul.	35.6	23.8	29.7	34.14	11.99	33.3	25.9	29.6	43.95	**16.67**
Aug.	35.6	21.4	28.5	55.53	10.98	33.4	26.1	29.75	46.53	**15.89**
Sep.	33.1	22.6	27.85	57.12	10.31	31.5	24.1	27.8	48.96	**14.68**
Oct.	30.3	20	25.15	59.33	9.17	29.6	20.9	25.25	54.32	**11.36**
Nov.	25.4	15.9	20.65	60.43	7.09	26.1	16.3	21.2	51.06	**9.46**
Dec.	21	11.9	16.45	61.87	5.89	22.5	12.5	17.5	51.87	**8.25**

Evaporation rates are influenced by different factors such as air temperature, relative humidity, and wind speed. The maximum average daily evaporation for all stations occurs during the summer, while the lowest rates are observed in winter.

Precipitation is a crucial factor in this study. The rainy season begins in October with sporadic showers, increasing in frequency through November, December, and January extending until May. Occasional summer showers may also occur. Variations in rainfall along the coast are primarily attributed to the distance from the Mediterranean Sea, the orientation of the coastal zone relative to prevailing winds, and the distance from the coast inland (MPGAP, 1987). Based on available precipitation data (1951–2023) for the upstream area of Wadi Ghareb, daily maximum rainfall ranges from 0.01 mm to 60.48 mm, with an average of approximately 21.04 mm. Annual rainfall ranges from 1.00 mm to 107.74 mm, with a mean value of about 26.21 mm (GSMap, 2023).

2.6. Morphometric characteristics of Wadi Ghareb

The protection of Ras Ghareb area from flood disasters can be achieved through a morphometric analysis of the five sub-basins of Wadi Ghareb. This study relies on geomorphological features and morphometric parameters, which were analyzed by tracing the drainage network using a Digital Elevation Model (DEM) (SRTM-C) with a 30m resolution and topographic maps at a scale of 1:50,000. Using Strahler's method (Strahler, 1957), the streams were ordered, and various parameters were measured and calculated based on Horton's method (1932), and (1945). The morphometric parameters were calculated using ARC/GIS 10.3 (Table 2 & 3). The specifications of the stream networks are crucial for studying basin characteristics (Strahler, 1957; Strahler, 2002). Basin size influences the number and total length of each stream order.

Table 2: Morphometric data of the Wadi Ghareb and Sub basins

Name		**Wadi Ghareb**	**Sub basin1**	**Sub basin2**	**Sub basin3**	**Sub basin4**	**sub basin5**
Area (A) (Km^2)		288	159.53	57.9	11.9	10.6	3.9
Perimeter (P) (Km)		137.1	97.4	55.2	34.3	17.2	10.1
Basin Width (w) (km)		6.5	4.1	1.97	0.96	1.6	1.4
Order of trunk channel		6^{rd}	5^{rd}	5^{rd}	4^{rd}	4^{rd}	4^{rd}
Direction of main trunk		**West east**	**West east**	**West east**	**North east South west**	**South east North west**	**North west South east**
First order	**Stream No.**	824	465	161	40	40	15
	Length (km)	568.3	219.8	83.2	15.8	14.9	4.5
Second order	**Stream No.**	167	91	40	7	*8*	*4*
	Length (km)	210.8	103.5	52.6	9.4	6.1	3.4
Third order	**Stream No.**	45	*25*	9	2	3	2
	Length (km)	113.4	64.4	25.8	6.3	3.7	0.5
Fourth order	**Stream No.**	12	5	2	1	1	1
	Length (km)	49.4	24.5	9.5	7.9	4.5	1.4
Fifth order	**Stream No.**	2	1	1	-	-	-
	Length (km)	42.7	27.01	14.5	-	-	-
Sixth order	**Stream No.**	1	-	-	-	-	-
	Length (km)	15.1	-	-	-	-	-

The parameters analyzed include

The parameters analyzed include: Watershed Area (A), Stream Order (U), Stream Length (Lu), Basin Perimeter (Pr), Basin Length (Lb) and Valley Length (Lv), Texture Ratio, Sinuosity Ratio, Form Factor Ratio, Compactness Ratio, Shape Index, Circularity Ratio, Elongation Ratio, Bifurcation Ratio and Weighted Mean Bifurcation Ratio, Drainage Density, Stream Frequency, Relief and Relief Ratio, Ruggedness Number, and Length of Overland Flow. Arc/Map software and the DEM were used to perform the slope analysis for the studied basin. The slope map of Wadi Ghareb (Fig. 8) indicates that slopes range from 0° to 67.4°. High slopes are observed in the southern, western, and southwestern parts of the basin, where the basement rocks are located. In contrast, gentler slopes are found in the delta and central areas of Wadi Ghareb, which are characterized by Quaternary sediments. These gentler slopes provide favorable conditions for groundwater replenishment. The aspect of a slope is defined as its orientation in relation to cardinal points or compass directions. The direction a slope faces, particularly concerning sunlight exposure (aspect), significantly impacts vegetation, snowpack, and construction practices. Additionally, research is being conducted on the effects of wind exposure as a two-aspect application. In the study area, the aspect map (Fig. 9), has been classified into ten categories: Flat, North, Northeast, East, Southeast, South, Southwest, West, Northwest, and North.

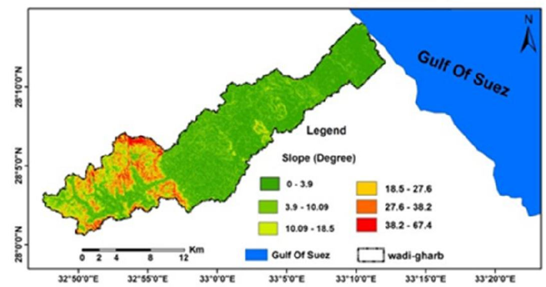

Fig.8: Slope of Wadi Ghareb

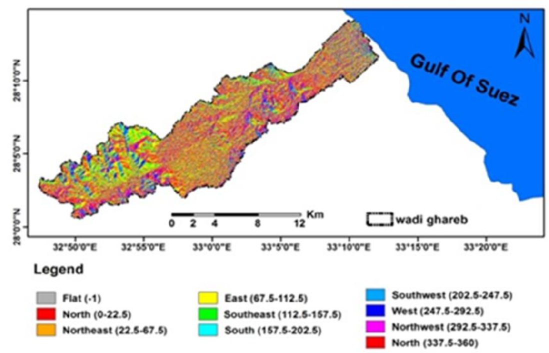

Fig. 9: Aspect of Wadi Ghareb

Table 3: Morphometric Parameters of the studied Wadis

Name Parameters	Unit	Wadi Ghareb	Sub basin1	Sub basin2	Sub basin3	Sub basin4	Sub basin5
Sum of stream numbers (∑Nu)		1051	587	213	50	52	22
Sum of stream lengths (∑Lu)	km	999.7	440.21	185.6	39.4	29.2	9.8
Valley length (LV)	km	55.3	38.72	23.1	10.6	7.2	4.3
Basin Length (Lb)	km	42.1	29.03	17.4	9.2	5.9	2.5
Texture Ratio (Tr= Nu/P)	km^{-1}	7.66	6.03	3.86	1.46	3.03	0.057
SinuosityRatio (Si= Lv/Lb)		1.31	1.33	1.43	1.15	1.15	1.72
Form Factor Ratio (FFR = (A/ Lb2)	-	0.162	0.189	0.191	0.141	0.305	0.624
Compactness Ratio (SH=P/2(√πA)		2.28	2.18	2.05	2.8	1.49	1.44
Shape Index (Ish= 1.27A/Lb2)	-	0.206	0.24	0.243	0.178	0.387	0.792
Circularity Ratio(Rc= 4∏A/P2)		0.193	0.212	0.24	0.128	0.452	0.483
Elongation Ratio(Re= (2√A/π)/ Lb		0.455	0.491	0.493	0.423	0.623	0.891
Bifurcation Ratio Rb= (∑Nu /∑Nu+1)		4.1	3.62	4.66	3.7	3.6	2.58
Weighted Mean Bifurcation Ratio WMRb= (∑Rbu/Rbu+1) (Nu + Nu+1) /(∑Nu+1)		4.65	4.01	4.79	5.2	4.5	3.2
Drainage Density (D= (∑Lu/A)	km^{-1}	3.47	2.76	3.21	3.311	2,755	2.513
Stream Frequency (F= (∑Nu /A)	km^{-2}	3.64	3.68	3.679	4.2	4.9	5.64
Upstream Elevation	m	1064	1641	869	189	204	178
Downstream Elevation	m	1	127	121	2	86	110
Relief (R)	m	1063	1514	748	187	118	68
Relief Ratio (Rf= R/Lb)	m/m	0.036	0.052	0.042	0.020	0.02	0.027
Ruggedness No. (Rn=R*D)		5.564	4.178	2.397	0.619	0.325	0.171
Length of overland Flow (Lo = 1/2D)	km	0.144	0.181	0.156	0.151	0.181	0.198
Slope index(SI=E85-E10 /0.75LV)	m/m	0.0200	0.0101	0.0086	0.0195	0.0087	0.0049

2.7. Flow direction and flow accumulation

Flow direction and flow accumulation maps play a crucial role in hydrology by modeling how surface runoff contributes to flooding. Flow direction is measured based on the steepest descent from each cell. Using Arc Map and ArcGIS tools were applied to determine the flow direction. The calculated primary flow direction of Wadi Ghareb corresponds with the orientation of its main channel, which drains into the Gulf of Suez, as shown in (Fig. 10). Flow accumulation is the process of simulating surface runoff by determining flow direction. It identifies the primary stream channels that serve as collectors for surface runoff. (Fig. 11).

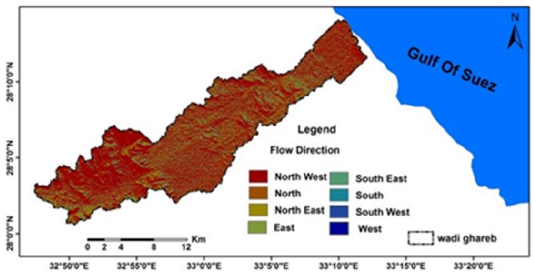

Fig .10: Flow direction of Wadi Ghareb

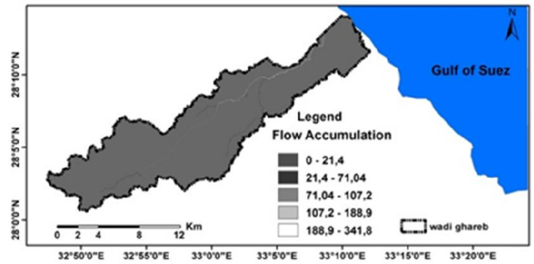

Fig.11: Flow accumulation of Wadi Ghareb

2.8. Evaluation of flash flood hazard

Based on the analyzed morphometric parameters, seven parameters exhibit a direct proportional relationship with hazard. These parameters are drainage density (D), stream frequency (F), area (A), relief ratio (Rr), ruggedness number (Rn), circulation ratio (Rc), and slope index (Si). Conversely, three parameters show an inverse relationship: weighted mean bifurcation ratio (WMRb), length of overland flow (Lo), and sinuosity (Si).

2.9. Probability and return period analysis

The return period is a statistical measure that is usually derived from historical data collected over a significant timeframe. Generally, a return period represents the average time interval between events, such as floods. It is determined as the inverse of the exceedance probability. According to (Ponce, 1989), the relationship between the exceedance probability G(x) and the return period (T) can be expressed as follows:

$$G(x) = 1/T \quad (1)$$

The return period (T) can be calculated using the Weibull formula (Brook, 1986).

$$T = (N+1)/m \quad (2)$$

Where:
N: is the total number of events in the dataset, representing the highest event of each year.
m: is the rank of each event in the dataset, arranged from largest to smallest.

2.10. Rainfall -runoff modeling

The rainfall-runoff relationship during any rainstorm is influenced by the dynamic interaction of rainfall intensity, soil infiltration, and surface storage. Runoff occurs when rainfall intensity surpasses the soil's infiltration capacity, assuming there are no physical barriers hindering surface flow. For Wadi Ghareb, the Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS version 4 (2010) is employed to simulate the precipitation-runoff processes within the watershed. The primary components of the model include:

Basin model: This encompasses the physical characteristics of the watershed.
Rainfall storm data: This pertains to the precipitation event, including its duration, and consists of details such as starting and ending dates and times, as well as the time step.
Loss calculation: The Soil Conservation Service Curve Number (SCS-CN) method SCS, is utilized to calculate losses and estimate the rainfall/runoff relationship.

Desert floods are typically characterized by sharp peak discharges that occur over short durations. The most severe storm occurred in 2010, producing a total rainfall of 60.48 mm. On December 29 and 30, 2010, the Wadi Ghareb area was hit by intense flash floods, resulting in extensive damage to infrastructure and loss of life. Rainfall data was obtained from the satellite data website (GSMAP, 2023). This storm continued for 18 hours, beginning at 10:00 AM on December 29 and ending at 3:00 AM on December 30. This severe storm has been selected for creating a hydrograph and calculating the runoff volume and runoff depth.

3. Results and Discussion

3.1. Morphometric characteristics of drainage basins

According to abovementioned analysis of the different parameters of Wadi Ghareb basin, the area is divided into five sub-basins, as shown in (Fig 12). The morphometric characteristics of the main basin and its sub-basins have been analyzed and calculated, as presented in Tables 2, 3 and illustrated in (Fig 13).

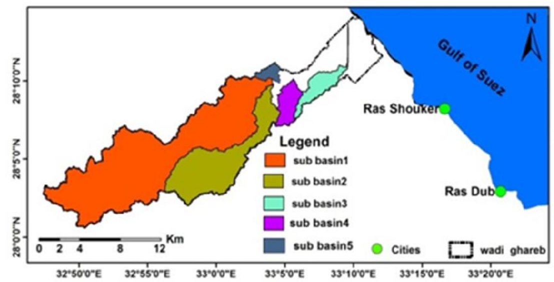

Fig.12: Sub basins of Wadi Ghareb

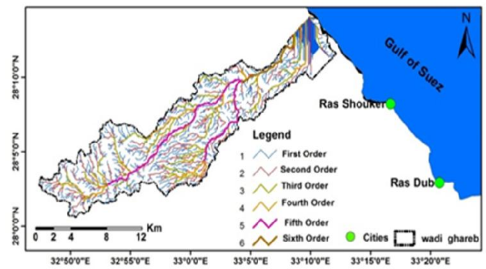

Fig.13: Stream orders of Wadi Ghareb

Watershed area (A)

The total area of Wadi Ghareb is approximately 288 km². Sub-basin 1 is the largest sub-basin , covering about 159.53 km², while Sub-basin 5 is the smallest one, with an area of around 3.9 km². The areas of Sub-basins 2, 3, and 4 are approximately 57.8 km², 11.9 km², and 10.6 km², respectively.

Basin perimeter (Pr)

The perimeter of Wadi Ghareb is approximately 137.10 km. The perimeters of the sub-basins vary, with Sub-basin 1 having the longest at 97.40 km, and Sub-basin 5 having the shortest at 10.10 km.

Basin width (W)

The width of Wadi Ghareb is approximately 6.5 km. The width of the sub-basins range from 4.1 km for sub-basin 1 to 1.97 km for sub-basin 2.

Steam order (U)

The main trunk of Wadi Ghareb is classified as a sixth-order stream. The sub-basins are ranked as fifth order for sub-basins 1 and 2, while sub-basins 3, 4, and 5 are classified as fourth-order streams.

Stream length(Lu)

The total stream length in Wadi Ghareb reaches approximately 999.70 km. Among the sub-basins, stream lengths range from 440.21 km at sub-basin 1 to 9.80 km at sub-basin 5. The stream lengths show a direct correlation with the number of streams, as well as with the area, perimeter, and overall length of each basin.

Basin length (LB) and valley length (Lv)

The basin length refers to the shortest distance between the source and the mouth of the stream. For Wadi Ghareb, the calculated basin length is approximately 55.30 km, ranging from 29.03 km in sub-basin 1 to 2.50 km in sub-basin 5. The valley length represents the total length of the main trunk stream. In Wadi Ghareb, the valley length is 55.30 km, varying from 38.7 km in sub-basin 1 to 4.3 km in Sub-basin5.

Texture ratio (Rt)

According to Smith (1958), basin texture is classified into three categories: coarse (< 6.4 km^{-1}), intermediate (6.4–16 km^{-1}), and fine (> 16 km^{-1}). The texture ratio of Wadi Ghareb is 7.66 km^{-1}. Among the sub-basins, texture ratios range from 6.03 km^{-1} in sub-basin 1 to 0.057 km^{-1} in sub-basin 5. The values for Sub-basins 2, 3, and 4 are 3.86 km^{-1}, 1.46 km^{-1}, and 3.03 km^{-1}, respectively. These values indicate that all sub-basins fall within the coarse texture category, which is favorable for groundwater recharge.

Sinuosity ratio (Si)

The sinuosity ratio, defined as the ratio of valley length to basin length, indicates the degree of stream meandering. Wadi Ghareb has a sinuosity ratio (Si) of 1.31. Among its sub-basins, the sinuosity values range from 1.15 in sub-basins 3 and 4 to 1.72 in sub-basin 5. sub-basins 1 and 2 have sinuosity ratios of 1.33 and 1.43, respectively. These values suggest that sub-basin 5 has the shortest water flow travel time to the outlet, whereas Sub-basins 3 and 4 exhibit longer flow paths, providing greater potential for groundwater recharge.

Form factor ratio (FFR)

It is defined as a numerical index that reflects the shape of the basin, with values typically ranging from 0.1 to 0.8 (Horton, 1932). The analyzed sub-basins exhibit generally elongated shapes, with values ranging from 0.624 in Sub-basin 5 to 0.141 in Sub-basin 3. This indicates that surface water in these basins requires a longer time to travel to the outlet.

Compactness ratio (SH)

The compactness ratio (SH) is the ratio between the perimeter of a basin and the circumference of a circle with an equal area to the basin (Horton, 1945). For Wadi Ghareb, the compactness ratio is 2.28, while for the sub-basins, it ranges from 2.8 (sub-basin 3) to 1.44 (sub-basin 5). This indicates that all the sub-basins have an elongated shape.

Circularity ratio (Rc)

The circularity ratio approaches 1 when the basin shape is circular, and it tends to zero when the basin is rectangular (Miller, 1953). The time of concentration of flow is shorter in circular basins than in elongated ones. The calculated circularity ratio for Wadi Ghareb is 0.19, while the values for the sub-basins range between 0.12 (sub-basin 3) and 0.48 (sub-basin 5). These values confirm the elongation of the basin.

Elongation ratio (Re)

The elongation ratios, which are generally less than one, is 0.45 for Wadi Ghareb, with values for the sub-basins ranging between 0.42 (sub-basin 3) and 0.89 (sub-basin 5). The variations in the elongated shapes of the sub-basins are due to the effects of faulting in the study area. Thus, Wadi Ghareb and its sub-basins exhibit moderate to high elongation. The elongation ratio is crucial for understanding the basin's hydrology and estimating flood hazards. For a given rainfall event, less elongated sub-basins will produce higher peak runoff and faster travel velocities to the outlet.

Bifurcation ratio (Rb) and weighted mean bifurcation ratio

The bifurcation ratio of Wadi Ghareb is 4.1, while the bifurcation ratios of the studied drainage sub-basins range from 2.58 for sub-basin 5 to 4.66 for sub-basin 2. This indicates that these basins are nearly pear-shaped to elongated. The values of the weighted mean bifurcation ratios are very close to each other, with 5.2 for sub-basin 3 and 4.01 for sub-basin 1, while the weighted mean bifurcation ratio for Wadi Ghareb is 4.65.

Drainage density (Dd)

The drainage density of Wadi Ghareb is 3.47 km^{-1}, while the values for the sub-basins range from 3.31 km^{-1} for sub-basin 3 to 2.51 km^{-1} for sub-basin 5. This indicates that the basin has a highly branching drainage network and is composed of more resistant rocks with a low infiltration capacity.

Stream frequency (Fs)

The stream frequency value of Wadi Ghareb is 3.64 km^{-2}, while the values for the sub-basins range from 5.64 km^{-2} for sub-basin 5. This indicates a high potential for runoff water collection.

Relief ratio

In the studied area, the relief ratio of Wadi Ghareb, which represents the relief divided by the basin length, is 0.038. For the sub-basins, the relief ratio values range from 0.052 for sub-basin 1 to 0.02 for sub-basin 4.

Ruggedness number (Rn)

The ruggedness number (Rn) is the product of relief and drainage density (Melton, 1986) A higher ruggedness number indicates greater runoff. The ruggedness number (Rn) for Wadi Ghareb is 5.564, and it ranges from 0.17 for sub-basin 5 to 4.18 for sub-basin 1.

Length of overland flow (Lo)

It represents the distance that water flows over the ground surface before it becomes concentrated in a drainage channel. It is calculated as the reciprocal of twice the drainage density. The overland flow for Wadi Ghareb is 0.14. For the sub-basins, it ranges from 0.151 for sub-basin 3 to 0.198 for sub-basin 5. These low values of overland flow indicate that the runoff water is highly concentrated in these sub-basins.

Slope index

The slope index for Wadi Ghareb is 0.020 m/m, while for the sub-basins, it ranges from 0.019 for sub-basin 3 to 0.005 for sub-basin 5. These low values of the slope index indicate a high potential for flash floods.

3.2) Evaluation of relative flash flood hazard

From the selected morphometric parameters, the method of equal spacing or simple linear interpolation between data points was chosen to derive the empirical relationship between the relative hazard degree of a basin. Assuming that a straight linear relationship exists between sample points, intermediate values can be calculated from the geometric relationship as shown in Equation 3 (Davis, 1975):

$$Y = \frac{(Y\max - Y\min)(X - X\min)}{(X\max - X\min)} + Y\min \quad ....(3)$$

Where:
Y is the relative hazard degree.
Ymax and Ymin are the upper and lower limits of the proposed scale (class five and first class).
Xmax and Xmin are the higher and lower estimated values of any parameter.

Table 4 presents the results for the calculation of the hazard degree. Based on these results, the investigated sub-basins can be classified according to the estimated degrees of hazard, as shown in (Fig. 14.)

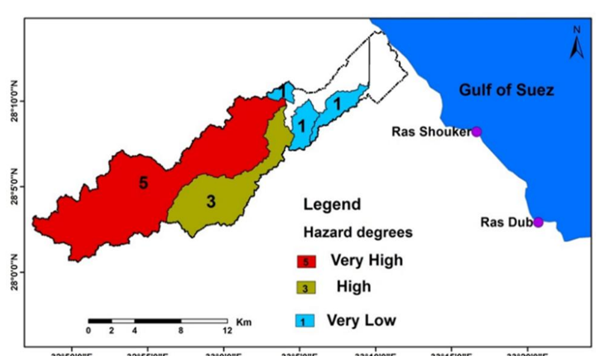

Fig.14: Hazard degrees of Wadi Ghareb

Table 4: Flash flood hazard degree sub basin Wadi Ghareb

Sub Basin	Hazard Degree of the chosen parameters											Sum	Basin Hazard Degree
	A	D	F	Ish	SI	R	Rn	C	Lo	WMRb	Si		
Sub 1	5.00	2.23	1.00	5.00	2.41	5.00	5.00	1.95	2.45	3.38	3.73	37.15	**5**
Sub 2	2.38	4.50	1.00	2.36	1.99	3.75	3.22	2.26	4.57	1.82	3.04	30.89	**3**
Sub 3	1.21	5.00	2.06	1.00	5.0	1.00	1.45	1.00	5.00	1.0	2	25.72	**1**
Sub4	1.17	2.22	3.49	1.82	2.02	1.00	1.15	4.65	2.45	2.40	2	24.37	**1**
Sub 5	**1.00**	**1.09**	**5.00**	**1.40**	**1.0**	**1.88**	**1.00**	**5.00**	**1.00**	**5.00**	**1**	**24.37**	**1**

1. Extremely highly hazardous: with a flood hazard degree of 5 (Sub-basin 1).
2. Moderately hazardous: with a hazard degree of 3 (Sub-basin 2).
3. Weakly hazardous: with a hazard degree of 1 (Sub-basins 3, 4, and 5). 3.3) Rainfall characteristics and Return Period:-

According to rainfall data collected from the Global Satellite Mapping of Precipitation (GSMap, 2000–2023), Wadi Ghareb has experienced several severe storms over the past two decades. Table 5 and (Fig. 15) present the total rainfall depth, duration, and intensity of the selected storms.

Table 5: Data storms of Wadi Ghareb

Storm(mm)	Rainfall Depth (mm)	Duration (hrs)	Intensity (mm/hr)
29-30 Dec. 2010	60.48	18	3.34
26 -27 October 2016	25.2	17	1.48
5-6 February 2019	37.7	15	2.51
11-12 March 2020	28.5	15	1.9
1-2 January 2022	39.8	9	4.42

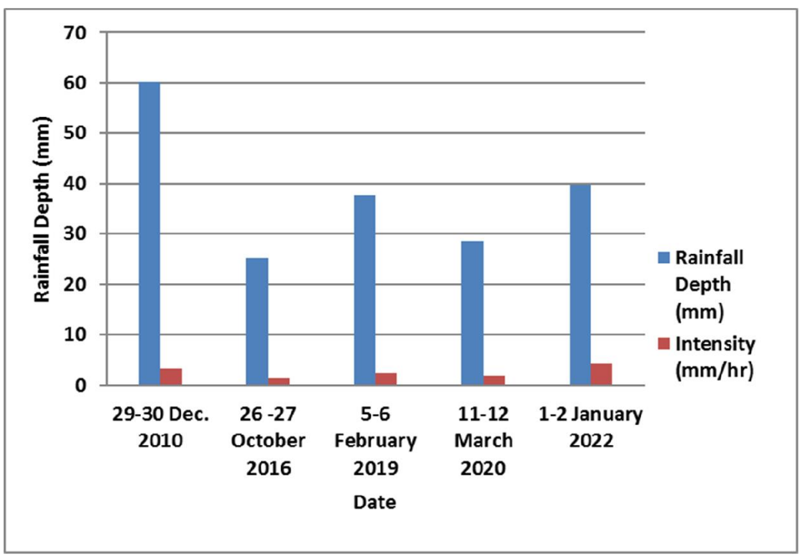

Fig. 15: Storms and its intensity of Wadi Ghareb

The number of occurrences of maximum monthly rainfall depths within different ranges is shown in Table 6, from which the following observations can be made:

A maximum rainfall depth of less than 5 mm occurred in 36 years, representing approximately 50% of the data.
Rainfall depths between 5 mm and 20 mm occurred in 22 years, accounting for about 30.6% of the collected data.

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Rainfall depths ranging from 20 mm to 30 mm were recorded in 10 years, representing around 13.8% of the data.
Maximum monthly rainfall depths exceeding 30 mm occurred in only 4 years, making up about 5.6% of the dataset.
Based on seventy-two years of rainfall records from 1951 to 2023 for Ras Ghareb, the return period and probability of exceedance have been calculated, as shown in Table 7. On semi-logarithmic paper, the relationship between the return period and the maximum monthly rainfall is plotted in (Fig. 16).
By applying curve fitting to the data points on this graph, the following equation was derived:

$$Y = 13.10 \ln(x) - 2.416 \quad (4)$$

Where:
Y = Maximum daily rainfall (mm)
x = T = Return period (years)

From the curve shown in Figure 16, the return period has been calculated. It is observed that as rainfall increases, the return period becomes longer, and vice versa. For example, a storm with a rainfall depth of 60.48 mm is expected to occur once every 72 years, with a probability of 1.35%, whereas a rainfall event of 1.0 mm may occur approximately every 1.06 years, with a probability of 94.59%.

In conclusion, the storm that occurred in January 2010 is estimated to be a rare event, likely to occur only once every 72 years. Based on the available data from 1951 to 2023, it is evident that the effects of climate change have become more pronounced over the last two decades (2003–2023), as reflected by the increase in maximum monthly rainfall during this period.

Table 6: Occurrences of maximum monthly rainfall depth for different ranges over72 years

Max. monthly rainfall (mm)	<5mm	5-20 mm	20-30 mm	>30 mm
No. of occurrence in 72 years	36	22	11	4

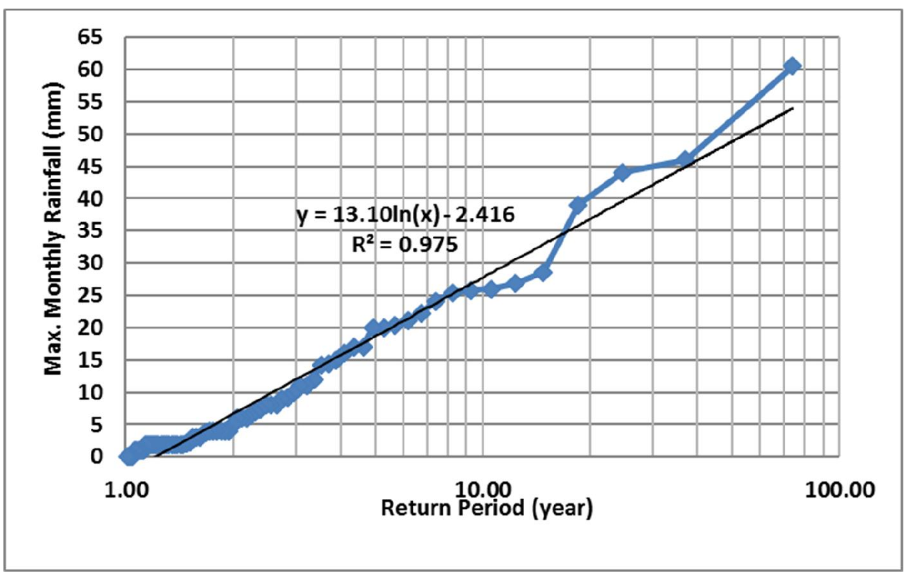

Fig. 16: Relationship between return period (years) and maximum monthly rainfall (mm)

Table 7: Return period and probability of exceedance for maximum monthly rainfall During the period (1951–2023).

Monthly Rainfall (mm)		Rainfall descending (mm)			Return period	Probability of exceedance %
Year	**Monthly rainfall**	**Year**	**Monthly rainfall**	**Rank**	**T**	**G**
1951	9	2010	60.48	1	74.00	1.35%
1952	4	2006	45.98	2	37.00	2.70%
1953	4	2013	44.08	3	24.67	4.05%
1954	8	2016	38.99	4	18.50	5.41%
1955	6.01	2014	28.6	5	14.80	6.76%
1956	2	2019	26.82	6	12.33	8.11%
1957	2	1990	26	7	10.57	9.46%
1958	2	2001	25.83	8	9.25	10.81%
1959	6	2018	25.43	9	8.22	12.16%
1960	0	2012	24.13	10	7.40	13.51%
1961	7.34	2005	22.3	11	6.73	14.86%
1962	0	1987	21	12	6.17	16.22%
1963	2	2004	20.3	13	5.69	17.57%
1964	3	1975	20	14	5.29	18.92%
1965	2	1978	20	15	4.93	20.27%
1966	2	2023	17.05	16	4.63	21.62%
1967	3	1988	17	17	4.35	22.97%
1968	2	1994	16	18	4.11	24.32%
1969	2	1985	15	19	3.89	25.68%
1970	1	2003	14.3	20	3.70	27.03%
1971	9.19	2015	14.21	21	3.52	28.38%
1972	2	1996	12	22	3.36	29.73%
1973	2	1980	11	23	3.22	31.08%
1974	4	1992	11	24	3.08	32.43%
1975	20	2017	10	25	2.96	33.78%
1976	0	1971	9.19	26	2.85	35.14%
1977	2	1951	9	27	2.74	36.49%
1978	20	1954	8	28	2.64	37.84%
1979	2	1997	8	29	2.55	39.19%
1980	11	2007	8	30	2.47	40.54%
1981	1	1961	7.34	31	2.39	41.89%
1982	2	2021	7	32	2.31	43.24%
1983	2	2020	6.34	33	2.24	44.59%
1984	4	1955	6.01	34	2.18	45.95%
1985	15	1959	6	35	2.11	47.30%
1986	1	2000	6	36	2.06	48.65%
1987	21	1991	5	37	2.00	50.00%
1988	17	1952	4	38	1.95	51.35%
1989	3	1953	4	39	1.90	52.70%
1990	26	1974	4	40	1.85	54.05%
1991	5	1984	4	41	1.80	55.41%
1992	11	1993	4	42	1.76	56.76%
1993	4	2008	3.99	43	1.72	58.11%
1994	16	2009	3.7	44	1.68	59.46%
1995	2	2011	3.4	45	1.64	60.81%
1996	12	1964	3	46	1.61	62.16%
1997	8	1967	3	47	1.57	63.51%
1998	1	1989	3	48	1.54	64.86%
1999	1	2002	2.24	49	1.51	66.22%
2000	6	2022	2.19	50	1.48	67.57%
2001	25.83	1956	2	51	1.45	68.92%
2002	2.24	1957	2	52	1.42	70.27%
2003	14.3	1958	2	53	1.40	71.62%
2004	20.3	1963	2	54	1.37	72.97%

2005	22.3	1965	2	55	1.35	74.32%
2006	45.98	1966	2	56	1.32	75.68%
2007	8	1968	2	57	1.30	77.03%
2008	3.99	1969	2	58	1.28	78.38%
2009	3.7	1972	2	59	1.25	79.73%
2010	60.48	1973	2	60	1.23	81.08%
2011	3.4	1977	2	61	1.21	82.43%
2012	24.13	1979	2	62	1.19	83.78%
2013	44.08	1982	2	63	1.17	85.14%
2014	28.6	1983	2	64	1.16	86.49%
2015	14.21	1995	2	65	1.14	87.84%
2016	38.99	1999	1	66	1.12	89.19%
2017	10	1970	1	67	1.10	90.54%
2018	25.43	1981	1	68	1.09	91.89%
2019	26.82	1986	1	69	1.07	93.24%
2020	6.34	1998	1	70	1.06	94.59%
2021	7	1960	0	71	1.04	95.95%
2022	2.19	1962	0	72	1.03	97.30%
2023	17.05	1976	0	73	1.01	98.65%

3.4. Rainfall runoff modeling

3.4.1. Model input data

I) Basin model component

Based on the morphometric characteristics, Wadi Ghareb is treated as a single basin with a total area of 288 km². Table 8 presents the basin data used in the model, including catchment area (km²), basin length (km), valley length (km), maximum and minimum elevation (m), and average slope (m/m).

Table 8: Wadi Ghareb Characteristics

Wadi Ghareb	Area (km^2)	Basin Length (Km)	Valley Length (km)	Max. Elev (m)	Min. Elev. (m)	Average Slope (m/m)
	288	42.1	55.3	1064	1	**0.036**

II) Rainfall data

For Wadi Ghareb basin, the data from the storm that occurred on December 29–30, 2010, was used in the model (Table 9). This dataset includes the start date and time, end date and time, and the selected time step, which was set at one hour. (Fig. 17) illustrates the hyetograph of December 2010 storm.

Table 9: Storm data (December, 2010)

Total storm	Storm duration	Intensity (mm/hour)	Maximum rainfall in hour (mm)
60.48	18	3.34	20.8

III) Losses calculations

Initial abstraction (Ia) refers to the portion of rainfall that occurs before surface runoff begins. It is influenced by various factors such as vegetation cover, soil infiltration capacity, and the antecedent moisture condition of the soil.

The initial Abstraction (Ia) is calculated based on the maximum soil retention (S), using the following equations:

$$S = 25400 / CN - 254 \quad (5)$$

$$Ia = 0.2 \times S \quad (6)$$

The Curve Number (CN) is a coefficient that represents the runoff potential of a given area. It is influenced by factors such as soil moisture conditions, land use, hydrologic conditions, and soil type. Depending on the hydrologic soil group and overall hydrologic conditions, CN values range from 0 to

100. Higher CN values (greater than 90) indicate minimal infiltration and higher runoff potential, while lower CN values (less than 50) represent more pervious surfaces with greater infiltration capacity.

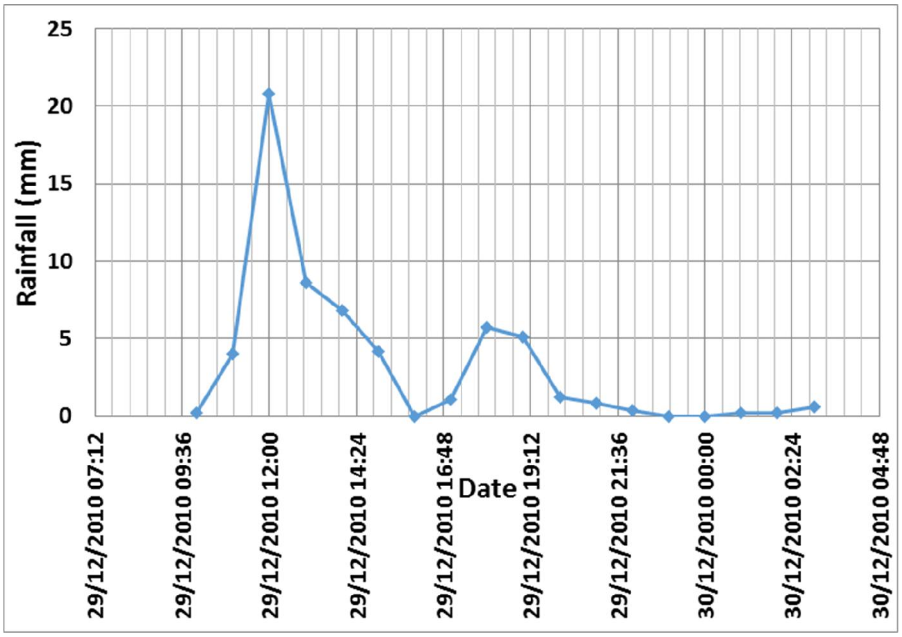

Fig.17: Hyetograph data of rainfall storm (2010) of Wadi Ghareb

A weighted CN is calculated based on the percentage of each land cover type within the total sub-catchment area and its corresponding CN value.

$$\mathrm{CN} = \frac{\sum_{i=1}^{k} A_i CN_i}{\sum_{i=1}^{k} A_i} \quad (7)$$

Where:
CNi represents the appropriate Curve Number for the portion of the watershed with an area Ai The calculated weighted average CN values are summarized in Table 10.

Table 10: Calculation of CN for different geological units at Wadi Gharib basin

Geology	Area	Total area	% Area	CN	Weighted CN
Basement	74.43	287.96	25.85%	92	
lower Cretaceous	24.14		8.38%	77	72.996
Pliocene	8.15		2.83%	79	
Miocene	15.74		5.47%	79	
Quaternary	165.5		57.47%	63	
			100.00%		

IV) Time of Concentration and Lag Time.

Lag time is an indicator of how quickly a watershed responds to a rainfall event that generates runoff. Specifically, it refers to the time delay between the peak rainfall and the peak discharge. It is defined as the time interval between the center of mass of the excess rainfall and the peak of the runoff hydrograph (Granato, 2010).

Time of concentration (Tc) is the longest time it takes for water to travel from the most distant point in the watershed (the drainage divide) to the outlet. It is commonly calculated using the Kirpich equation (Subramanya, 2018), as shown below:

$$\mathbf{Tc} = 0.0195\frac{L^{0.77}}{S^{0.385}} \quad (8)$$

Where:
Tc = Time of concentration (minutes)
L = Basin length (meters)
S = Basin slope (m/m)

The lag time (TL) is estimated as 0.6 × Tc, according to Mockus, 1957. The calculated values of time of concentration (Tc) and lag time (TL) are presented in Table 11.

Table 11: Calculation of Tc and TL of Wadi Ghareb

S (m/m)	Lb (Km)	Tc (mim)	TL (min)
0.0252	42.10	292.32	175.39

3.5. Hydrograph generation

The data above was used to predict the rainfall-runoff relationship and produce a runoff hydrograph for Wadi Ghareb for the storm of December 2010 using the HEC-HMS version 4.0 (2010) model, (Table 12). The resulting hydrograph indicates that Wadi Ghareb experiences a substantial amount of runoff during the storm of December 2010 (7035.7*1000 m³), with a peak discharge of 212.7 m³/sec, (Fig18). From this hydrograph, the runoff depth and runoff coefficient are calculated using the following equations (Ponce, 1989).

$$\text{Runoff depth} = \frac{\text{Runoff volume}}{\text{Drainage area}} \quad \ldots\ldots(9)$$

$$\text{Runoff coefficient} = \frac{\text{Runoff depth}}{\text{Runfall depth}} \quad \ldots\ldots(10)$$

The results are presented in Table 12, from which the following observations can be made:

- The volume of surface runoff calculated for the 2010 storm (with a rainfall depth of 60.48 mm and a return period of 72 years) is 7035.7*1000 m³, with a maximum flow rate (peak discharge) of 212.7 m³/sec.
- This significant volume of runoff results in a runoff depth of 24.43 mm.
- The runoff coefficient, which represents the ratio between the runoff depth and the rainfall depth, is 40.4%. This means that 40.4% of the rainfall is converted into runoff.

Table 12: Results for hydrograph generation

Area (km^2)	Rainfall depth (mm)	Peak discharge (m^3/sec)	Runoff volume (103 m^3)	Runoff depth (mm)	Runoff coeff. (%)
288	60.48	212.7	7035.7	24.43	40.4

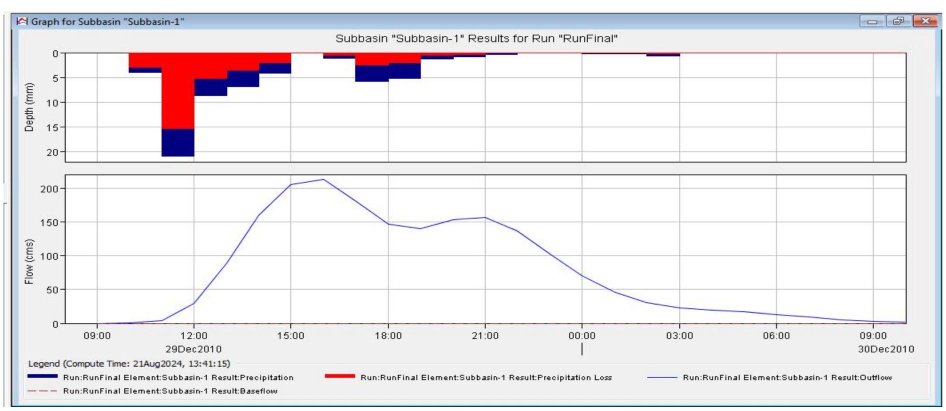

Fig. 18: Computed runoff hydrograph for Wadi Ghareb

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3.6. Conclusions and Recommendations

From this comprehensive study of Wadi Ghareb, the following conclusions can be drawn:

- The geologic succession of Wadi Ghareb consists of two units: basement rocks in the upstream area and sedimentary rocks in the downstream area. The main structural trends are NE-SW and NW-SE.
- The lineaments of Wadi Ghareb align with the drainage network, following the same directional patterns.
- The geomorphological units of Wadi Ghareb include mountainous areas, piedmont plains, and coastal plains.
- Morphometric analysis reveals that Wadi Ghareb and its sub-basins are elongated in shape and have low runoff volumes.
- The relative hazard degree calculation indicates that sub-basin 1 has an extremely high hazard degree.
- Historical data over the last 72 years show that the maximum monthly rainfall (60.48 mm) recorded in December 2010 is expected to occur once every 72 years.
- The results demonstrate that the runoff volume of Wadi Ghareb reaches approximately 7035.7*1000 m^3, with a peak flow rate of 212.7 m^3/sec.
- It is crucial to establish early warning systems to alert residents of potential flood risks, especially in urban areas located in flood-prone paths, hours before floods occur, to allow for precautions and safety measures.
- It is essential to propose technical tools for harvesting water from flash floods, such as earth dams, detention dams, cisterns, and culverts, to mitigate the hazards associated with flash floods.

Additionally, establishing several outlet channels directly in front of the dam, designed to divert water into reservoirs with a capacity proportional to the flood volume in the study area, is recommended. This approach would enable the utilization of stored water for agricultural and industrial development, contributing to the achievement of sustainable development in the region.Based on this comprehensive study, the following suggested water harvesting techniques for flash flood hazard mitigation are recommended, as shown in (Fig 19):

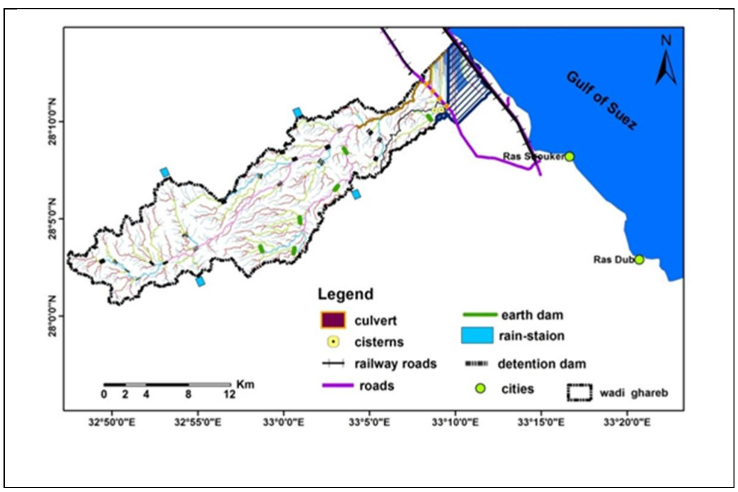

Fig. 19: The proposed systems for flash flood control at Wad Ghareb

- The construction of detention dams made from cobbles and boulders without cementation is recommended at sites covered by impermeable surface soils. These dams help reduce floodwater velocity, protect vulnerable sites, and store excess floodwater in surface reservoirs.
- The construction of earth dams should prioritize minimizing risks to infrastructure while also providing opportunities for replenishing shallow aquifers.
- To protect infrastructure in threatened sites, particularly major highways, it is recommended to build culverts beneath the roads at stream crossing locations.
- Construct storage cisterns in low-hazard, low-infiltration areas to store floodwater in local surface reservoirs.

- The establishment of meteorological stations is recommended for more accurate data collection and determination of flood risks.

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