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An integrated approach for evaluating the flash flood risk and potential erosion using the hydrologic indices and morpho-tectonic parameters

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Abstract

An arid climate and lacking adequate flood management systems are the main reasons for flash flood events in arid and semi-arid areas. The study area is a part of the Sinai Peninsula in Egypt, Wadi Gharandal subjected to several flooded events during the past decades. The present study incorporated hydrologic indices and morpho-tectonic parameters to identify the potential sediment accumulation and erosion. Integration of hydrologic indices, stream power index, sediment transport, and topographic wetness indices with morpho-tectonic parameters to produce and detect erosion and sedimentation associated with flash floods is the main objective. Consequently, the geographic information system (GIS) and the fuzzy k-means clustering algorithm were implemented for spatial data classification and management. The applied method revealed that the hydrologic and morphometric parameters play major roles in flash flood contributing factors. The low slope areas are associated with low run-off connected with a high sediment accumulation. Conversely, a high level of erosion is encountered in the steeper slope areas. Furthermore, terrain and lithology are decisive in sediment accumulation and erosion risk in the study area. The present study demonstrates the hydrologic and morpho-tectonic parameters with remote sensing data set are efficient tools in evaluating flash floods, potential erosion, and management, supporting the urban planner for future development.

Keywords Flash flood · Erosion and accumulation · Hydrologic indices · Morpho-tectonic parameters · Fuzzy k-means clustering · Wadi Gharandal

Introduction

Most of Egypt located in arid to semi-arid zone, experienced scattered and torrential rainfall, causing flash flood events. However, such flash flood events recently appear to be more frequent than in the past and their impacts become much serious, causing human life, livestock losses, and infrastructure damages, drastically increasing the flash flood events in last decades, with both effects of climate change and human activities. The study area is perpendicular to the Gulf of Suez, extending from east to west and running to the west (Fig. 1). Since the eastern tributaries of their steep sloping channels drain the high lands of central and south Sinai, where high concentrations of rainfall prevail (Gad 1996), the hydrographical basins of the study region have high surface water potentialities. Furthermore, due to the steep slopes in these tributaries, the chance for infiltration is limited. Several approaches, methodologies, and hydrological models were used for flood mapping and prediction as a result of an unclear standardized approach for flood mapping. Topography, geomorphology, irrigation, infrastructure systems, and climate conditions are all factors that contribute to and lead to flash floods. Several studies have recently been published concerning the use of GIS tools for the study of natural risk and hazards assessment (Youssef and Hegab 2005; Yousef et al. 2005; Mason et al. 2010; Youssef and Maerz 2013; Youssef et al. 2009, 2014a, b, c; Pradhan et al. 2014; Abu El-Magd et al. 2021a; Ali et al. 2021; Abu El-Magd et al.

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Fig. 1 Location map of the study area
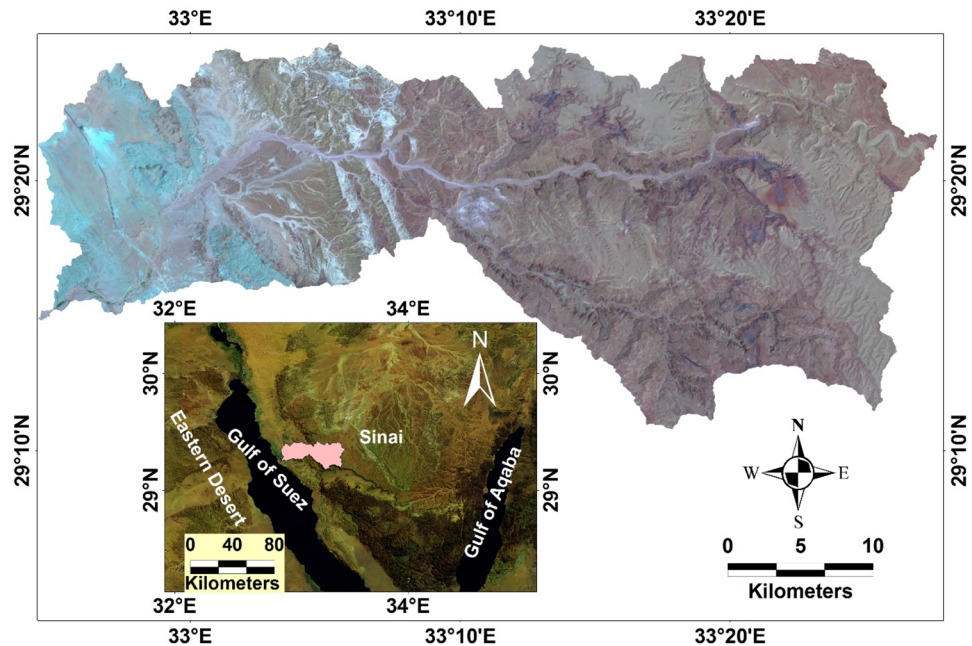
2021b; Vojtek and Vojteková 2018). Abd El-Aziz (2018) combining the remote sensing data with topographic maps integrated with GIS techniques to describe the drainage basin characteristic of Wadi Gharandal. In his study Abd El-Aziz (2018), the ASTER DEM data with georeferenced topographic maps (scale 1:50,000) were used to extract drainage network characteristics. Thus, different hydrologic indices have been proposed to be implied in natural hazard prediction and monitoring, such as basin catchment areas, basin flow accumulation, in addition to stream power (SPI), compound topographic (CT), and stream transport (STI) (Moore et al. 1993; Dymond and Harmsworth 1994). Accordingly, remote sensing data and GIS environment provide a better understanding of the hydrological process related to natural hazards, where the field-based investigation is limited and/or unavailability of regular dataset measurements. One of the advantages of using satellite imagery is that you can get a high-resolution, up-to-date view of the drainage pattern (El-Behiry et al. 2005). It is thought that the automated extraction of the drainage network from satellite imagery improves the network precision and reducing measurement errors.

Generally, landforms morphometric analysis presented by many scientists and researchers (Horton 1945; Smith 1950; Strahler 1952, 1954a,b, 1964; Melton 1958; Schumm 1954, 1956; Chorley 1957; Morisawa 1958; Carlston 1963; Sherve 1966), contributes to the fundamentals in geomorphological and quantitative techniques applied to morphometric studies. Stream network and stream orders have been done according to the classification developed by Strahler. In fact, the arid and semi-arid conditions in the study area cause the unavailability of vegetation cover. Therefore, the flash floods

may have been eroded many streams due to the non-existence of vegetation cover and the increase of first, second, and third orders in these dry climatic conditions. Since the morpho-tectonic analysis approach has played an important role in understanding the hydrology of the drainage basin (Strahler 1952 a, b; Bishop, 2002), the hydrologic indices help to identify the susceptible zones for flash floods. Over the past years, the integration of remote sensing and GIS with spatial and non-spatial information have been used in different studies in order to understand the catchment morphometry (Mesa 2006; Grohmann et al. 2007; Maeda et al. 2014). Furthermore, the contribution of hydrologic indices and morpho-tectonic parameters in sediment flash flood, sediment accumulation, and erosion, is the concept behind the development of the present approach. Therefore, the integrating approach provides a suitable solution for understanding and identification of sediment accumulation, erosion, and flash flood zonation. Hence, these kinds of integration approaches are significant for watershed development and management. Scientists have proposed and applied different approaches and methodologies for the analysis and prediction of flash floods and their associated erosion and accumulation of sediments, among applying the morphometric and morpho-tectonic analysis approach in their studies (Pant et al. 2020), GIS and remote sensing (Youssef et al. 2005; Bannari et al. 2017; Dano et al. 2019; Wang et al. 2019; Ali et al. 2019; Ali et al. 2020), Heuristic and statistical models (Chen et al. 2011; Sar et al. 2015; Abu El-Magd 2019; Abu El-Magd et al. 2020; Pham et al. 2021). Other researchers were applying to inundate flood models (Pal and Pani 2016; Abdelkarim et al. 2019). There are few studies carried out on morphometric and hydrology of Wadi Gharandal and

areas around (Hasanein 1989; Misak et al. 1995; Abdel-Latif and Shereif 2012; Morad 2016). Morphometric analysis of Wadi Gharandal mostly derived from thematic elevation layer (30 m resolution) and verified with topographic map (1: 50,000 scale).

In this paper, the integration of hydrologic indices and morpho-tectonic parameters represents a new approach implemented for the detection of flash flood's risk and potential erosions. This work aims to focus on the determination of the flash flood sediment accumulation and erosion perspective. Furthermore, to understand the capability of hydrologic and morpho-tectonic parameters in flash flood risk and mitigation, the present work has drawn attention to the importance of the integration of hydrologic indices, morpho-tectonic parameters, and GIS for such studies.

Site description and geology

The Sinai Peninsula (SP) is a part of the Arabo-Nubian shield foreland and gradually dips northward (Said 1962). The study area is located on the western side of the Gulf of Suez in Sinai Province side. The study area is located between latitude 29° 10′ to 29° 10′ and longitude 32° 54′ to 33° 27′ E (Fig. 1). The elevation of the study area can be observed from the digital elevation thematic layer and shows that the elevation in Wadi Gharandal ranges from 17 to 1199 m AMSL. Geologically, the Gharandal basin and area around are almost a series of exposures exclusively of Miocene in age (Fig. 2). On the north and northeast, recent gravel deposits recorded to form a natural boundary to Miocene outcrops, to the south are either the rock units of the pre-Miocene age lie unconformably below the Miocene or faulted against. The Miocene succession exposed in Wadi Gharandal was classified into Gharandal Group and Evaporites Group (Heybroek 1965; EGPC 1964; Gawad et al.

1986). The lower is Gharandal Group comprising clastic, marl, and carbonates which become increasingly arenaceous toward the east. It is overlain by a series of interbedded gypsum and anhydrite and intercalated shale, known as the Evaporite Group. The structural setting of the west Sinai area shows that the faulting system is much pronounced more than folding (Abdallah et al. 1992).

Materials and methods

Data sources and their roles

There are many factors that are associated with and responsible for flash floods occurring and sedimentation. But mostly used factors in flash flood susceptibility and sediment accumulation include topographic parameters, such as digital elevation model (DEM), slope, curvature, stream power index (SPI), topographic wetness index (TWI), stream transport index (STI), land use, lithology, soil, distance from rivers or stream network, all these factors prepared in thematic layers (Table 1). The thematic layers were constructed with a resolution of 30 × 30 m and processed in a GIS environment and R software (Fig. 3). The morpho-tectonic parameters were used to construct a flash flood hazard map, whereas topographic datasets were used to generate sediment accumulation and erosion maps.

Morpho-tectonic parameters

Different parameters were applied to evaluate morpho-tectonic including basin parameters and calculated parameters according to traditional basin morphometric assessment (Table 2). Generally, morphometric characteristic correlates with surface runoff and potential flooding and this
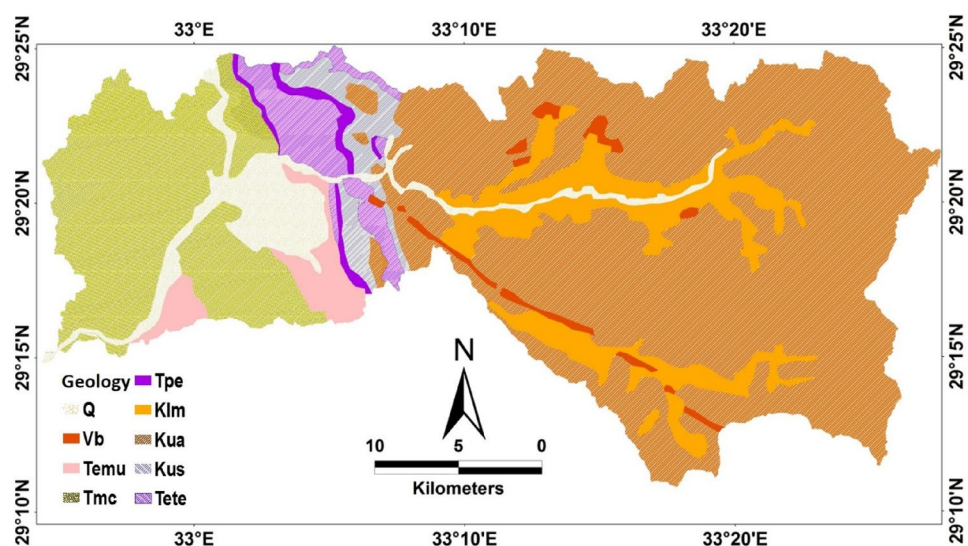
**Fig. 2** Lithological units of the study area (CONOCO 1987)

Table 1 Data sources used in the present study

Category	GIS data	Extracted data	Output data
Digital elevation model	Raster	Slope, drainage network	Grid data
Geology	Vector	Lithology	Grid data
Drainage map	Vector	Drainage density	Grid data
Stream power index	Raster	SPI (calculated in GIS)	Grid data
Stream transport index	Raster	STI (calculated in GIS)	Grid data
Topographic wetness index	Raster	TWI (calculated in GIS)	Grid data
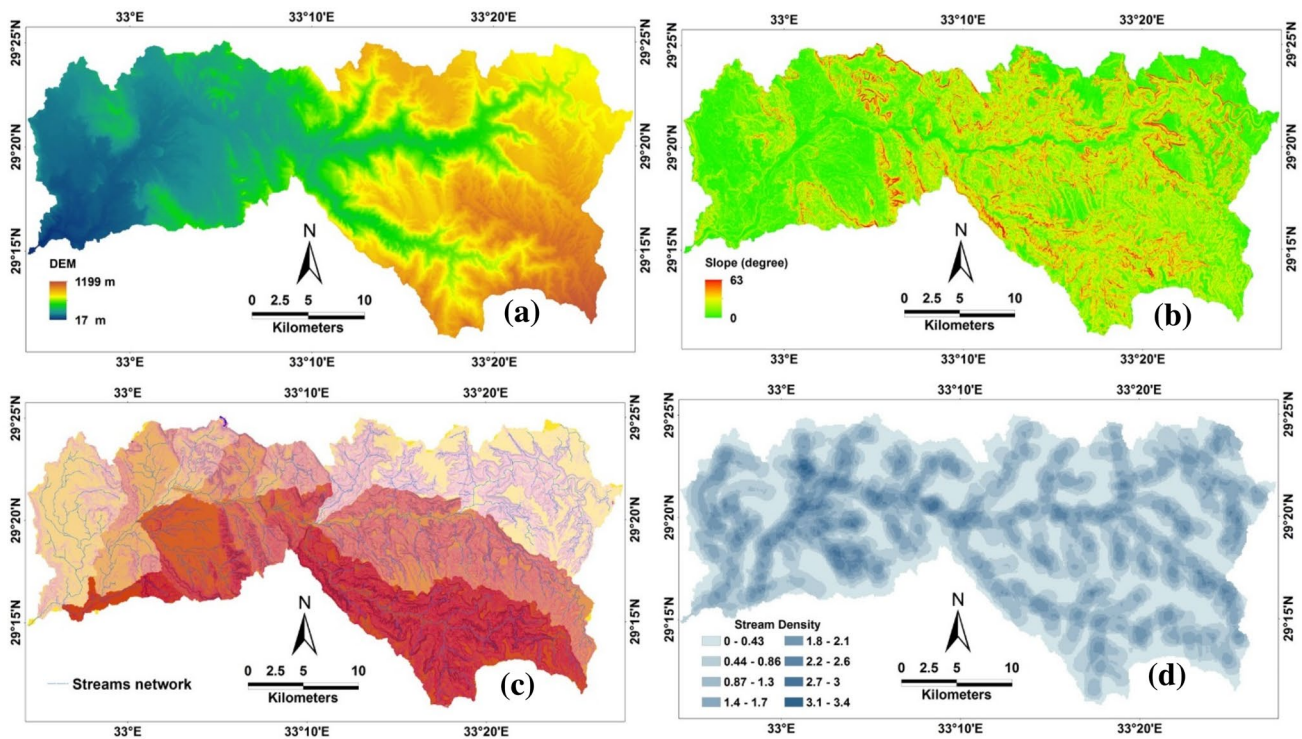
Fig. 3 Thematic layers **a** DEM, **b** slope, **c** streams network, **d** stream density

correlation with storm events leads to soil and rock deterioration. Basin geometry, basin network, drainage relief, and texture are the main morphometric characteristics of the basin (Horton 1945; Strahler 1964). Under the aforementioned four classes, about 21 different parameters were evaluated and calculated (Table 4). Furthermore, morphotectonic parameters were calculated (elongation ratio, hypsometric integral and shape factor) for the Wadi Gharandal basin (Fig. 4).

Stream lengths (L_s) are calculated as the summation of all the lengths of tributaries of individual orders of the watershed. The lengths of tributaries of individual orders are measured using ArcGIS. According to Ahmed (1997), the stream numbers (N_s) for individual orders are counted for the considered basin and expressed as Table 2. Areas of circularity ratio (CR) near to 1 normally are of regular shape and associated with low terrain and high flooding

risk. Whereas, Wadi Gharandal basin is far from the regular shape indicated elongated watershed. Strahler (1964) concluded that the elongation ratio (ER) values near to 1 are of areas of very low terrain, moreover, values between 0.60 and 0.80 are associated with high terrain and steep slopes. According to the definition of Horton (1932), form factor (SF) is described as a ratio of the watershed area and the square length of the basin. Bifurcation ratio (BR) is defined as a ratio of segments of a certain order Nu and the next higher-order (Nu + l) and is expressed by the following formula BR = Nu/Nu + l. The small values of the bifurcation ratios indicate that the difference between stream numbers from one order to another is not large. Moreover, the similar values of basin bifurcation ratios indicate that the evolution conditions for the studied basins are the same. According to Strahler (1952), the BR exhibits only

Table 2 Hydrologic indices and morphometric parameters formula applied in the present study

| Hydrological indices and morpho-tectonic parameters		
Parameter	Formula	References
Stream number N_s	$N_s = N_1 + N_2 + N_3 + N_4 \ldots \ldots .. (1)$	Strahler (1964)
Stream length L_s	$L_s = L_1 + L_2 + L_3 + L_4 \ldots \ldots .. (2)$	Strahler (1964)
Frequency ratio	$F = N_s/A$ (3)	Horton (1932)
Stream density	$D = L_s/A$ (4)	Horton (1945)
Elongation ratio	$ER = 2/Lb \times (A/\pi)^{0.5}$ (5)	Schumm (1963a, b)
Circularity ratio	$CR = 12.57 \times A/P2$ (6)	Horton (1945)
Shape factor	$SF = Lb2/A$ (7)	Horton (1945)
Texture ratio	$TEXR = N1/P$ (8)	Smith (1950)
Hypsometric integral	$HYP = \dfrac{(z_{mean} - z_{min})}{(z_{max} - z_{min})}$ (9)	Pike and Wilson (1971)
Relief ratio	$ReRa = H/Lb$ (10)	Schumm (1956)
Relative relief	$ReRe = ReRa \times 100/P$ (11)	
Stream Power Index	$SPI = \left[\ln(A_s + 0.001) \times ((\beta/100) + 0.001)\right]$ (12)	
Stream Transport Index	$STI = \left[(m + 1) \times (A_s/22.13)^m \times (\sin\beta/0.0896)^n\right]$ (13)	Moore and Wilson (1992)
Topographic Wetness Index	$TWI = \left[\ln(A_s + 0.001)/((\beta/100) + 0.001)\right]$ (14)	Beven and Kirkby (1979)
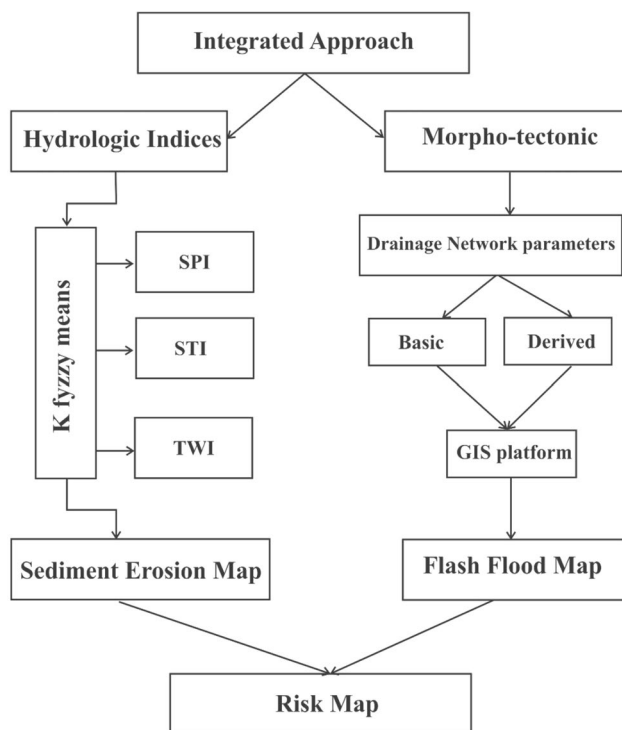
Fig. 4 Flowchart of the integrated approach in the present work

minor variation in various regions where the geological formation is not well controlled.

Frequency ratio (F) is defined as the number of stream network segments per watershed area (Horton 1945). The small values of drainage frequencies are attributed to the small area of these basins. Furthermore, a high value of drainage frequency tends to give more possibilities for run-off. Stream density (D) is denoted by the length of streams (L_s) per basin area (Horton 1945). Areas of high drainage density are associated with large flood flows and a low proportion of groundwater contribution. D is a key indicator of the landform aspect since it provides a numerical measurement for the potentiality of run-off and landscape dissection. The product of stream density (D) and stream frequency (F) describes the texture ratio (TEXR) (Horton 1945). TEXR is also known as the measure of the stream segment's total number divided by the watershed area (Table 2). Horton concluded that infiltration is the single most significant factor shaping texture ratio. Generally, watershed relief is determined by the geology of the study area, geomorphology, and characteristics of the drainage network. Basin relief is considered the most accurate predictor of any river basin erosional phases. Length–width ratio (LWR) is the ratio between the width and length of the basin. A small value of LWR indicates an elongated shape which led to surface run-off potentiality. Compactness coefficient (CmF) refers to the ratio between the perimeter and circumference of the basin (Horton 1945). The relief ratio (ReRa) refers to the proportion of total reliefs to the length of the main drainage line (Lindsay and Seibert 2013). Strahler (1964) defined the Ruggedness degree (RugD) as a product of drainage density and basin relief which defines the slope steepness with its length.

Hypsometric integral (HYPS) is one of the most effective instruments of the relative strength of the effect of the key element in Landform Evolution processes, such as geomorphic development divided stages, inspection tectonic movement, and lithology. The Ruggedness degree

(RugD) is calculated as the product of stream density by relative relief. RugD reaches its maximum value when both values of relative relief and stream density are high (Ansari et al. 2012). The higher value of the RugD of a given area, the more likely it is in the early stages of denudation activity or geomorphic development.

Hydrologic indices

To study the sediment accumulation and erosion developed and caused by flash floods, hydrologic indices were applied (Fig. 5). The implemented approach considered in this work includes an integration of TWI, SPI, and STI

Fig. 5 Hydrologic indices—**a** Stream power index (SPI), **b** Sediment transport index (STI), **c** Topographic wetness index (TWI)
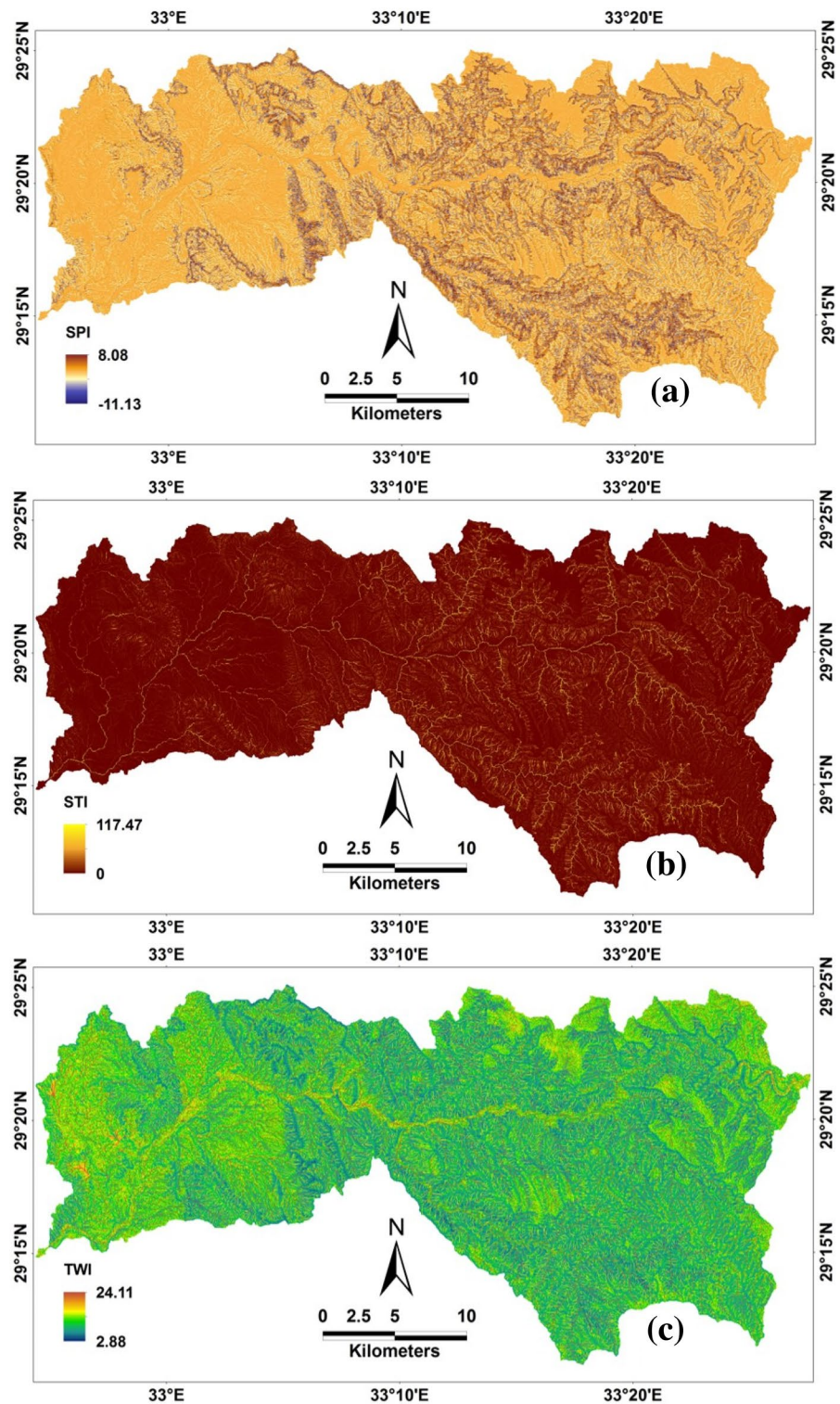
with morpho-tectonic parameters to generate flood risk and potential erosion maps. The fuzzy K-means classification of the calculated indices was adopted to produce sediment accumulation and erosion potentiality.

Sediment power index (SPI)

It can be defined as a semi-empirical model that was proposed to depict the ability to load and transfer the sediment thought out the hydrological basin. In addition, the SPI was used to assess the flash flood risk in stream channels. SPI can be calculated mathematically as shown by Eq. 12 (Table 2).

$$\text{SPI} = \left[\ln\left(A_s + 0.001\right) \times ((\beta/100) + 0.001)\right], \tag{12}$$

where A_s is the basin flow accumulation, β is the basin slope, and "ln" is constant refers to the Napierian logarithm. The flow accumulation demonstrates regions that contribute to the overland flow.

Stream transport index (STI)

It is defined by considering the transport potential limiting sediment flux and catchment evolution erosion theories, and it is a non-linear function for particular discharge and slope (Moore and Wilson 1992). SPI can be calculated mathematically by Eq. 13 (Table 2).

$$\text{STI} = \left[(m + 1) \times \left(A_s/22.13\right)^m \times (\sin\beta/0.0896)^n\right], \tag{13}$$

where $m = 0.4$ and $n = 1.3$.

Topographic wetness index (TWI)

It is also named compound topographic index; this index was originally proposed by Beven and Kirkby (1979) and it was used extensively to describe and quantify the topography effects on hydrological processes. TWI was used to describe the topography effects of the hydrological process and can be expressed by the following equation (Eq. 14).

$$\text{TWI} = \left[\ln\left(A_s + 0.001\right)/((\beta/100) + 0.001)\right]. \tag{14}$$

Integration of hydrologic indices with morpho-tectonic parameters to generate flash flood risk and potential erosion map

The present study used the hydrologic indices, such as TWI, SPI, and STI, which were extracted from the digital elevation model, slope, and basin flow accumulation of the study area. The generation of sediment erosion model using STI, TWI, and SPI as input for the erosion model involves two steps of procedures. The first procedure step entails creating a sediment erosion model. The second step of procedures in the sediment erosion model is the unsupervised classification of the resulting map, sediment accumulation, and sediment erosion classes. Data extraction and analysis of the drainage network are carried out from DEM of resolution 30 m using Arc Map 10.5. Morpho-tectonic parameters of Wadi Gharandal were calculated using DBAP (Youssef and Hegab 2005). Moreover, watershed and sub-watersheds were delineated based on the catchment polygon processing and adjoint catchment polygon processing function in Archydro. Two types of data were relied upon to generate a flash flood map; the first is the basic network parameters including (basin geometry, stream orders, stream length, etc.). The second is the calculated parameters including morphometric and tectonic parameters. The derived parameters like stream frequency, drainage density, elongation ratio, bifurcation ratio, shape factor, circulatory factor, texture ratio, relative relief, lemniscate, hypsometric integral, and compactness coefficient are calculated from the basic parameters. Derived morpho-tectonic parameters with hydrologic indices were integrated into the GIS platform to generate flood risk and sediment erosion maps (Fig. 4).

Fuzzy k-means clustering algorithm

The approach applied in the current work is based on developing a continuous watershed using the fuzzy k-means method. The goal of clustering is to be partitioning of the dataset (X) into the number of clusters by obtaining low within-cluster and high between-clusters heterogeneity. The fuzzy k-means approach of clustering, also this approach known as c-means (Bezdek 1981; McBratney and deGruijter 1992; Odeh et al. 1992; Burrough et al. 2000, 2001), is analogous to traditional cluster analysis. Ruspini (1969) proposed fuzzy clustering as an alternative to conventional cluster analysis by assigning membership values to points between clusters as an inverse function of distance from cluster centers. By choosing a series of random cluster points and constructing clusters around each seed, the clustering technique employs a repeated process. This is achieved using distance measurements, such as Euclidian, Mahalanobis, and Diagonal distance, to allocate each point in the data set to its nearest seed. The fuzzy k-means clustering technique is the most widely used and has been used in a variety of fields, including geologic modeling, climatic modeling, environment modeling, and soil and landscape modeling (Bezdek 1981; McBratney and Moore, 1985; Fisher and Pathirana, 1990; MacMillan et al. 2000; Burrough et al. 2001).

For a set of x individuals classified into y classes with conventional (Boolean) classification, the membership function equals $M = \mu_{ij} = 1$, where individual i belongs to class j, and $M = \mu_{ij} = 0$, when individual i does not belong to

class j. There are three conditions to ensure that conventional sets are exclusive and jointly exhaustive:

First that the sum of membership of an individual across all classes is 1

$$\sum_{j=1}^{y} \mu_{ij} = 1 \quad 1 \le i \le x. \tag{15}$$

Second ensures that at least one individual belongs to each class, so the classes are not empty.

$$\sum_{i=1}^{y} \mu_{ij} > 0 \quad 1 \le j \le y. \tag{16}$$

Third, it implies that an individual belongs to a class or does not belong at all

$$\mu_{ij} \in \{0,1\} \quad 1 \le i \le x; 1 \le j \le y. \tag{17}$$

Equation (17) is relaxed in fuzzy set theory, so class memberships can be partial and have any value between and including 0 and 1 (Eq. 18).

$$\mu_{ij} \in [0,1] \quad 1 \le i \le x; 1 \le j \le y. \tag{18}$$

Minimization of the objective function to satisfy the conditions in Eqs. (15), (16), and (17) yields the best fuzzy classification (3). The generalized objective function is given in Eq. 19:

$$J_F(M,Y) = \sum_{i=1}^{x} \sum_{j=1}^{y} \mu_{ij}^{\varnothing} d_{ij}^2, \tag{19}$$

where μ is the membership of the ith object to the jth class; $Y = (Y_{jv})$ is donating $y \times p$ matrix of class centroids with Y_{jv} refers to the centroid of class j for variable v; p donating the number of attributes; d_{ij}^2 refers to the square of the distance between the individual i and the class center j, and ϕ determines the amount of fuzziness or overlap and is known as the fuzzy exponent.

Results and analysis

To detect the flash flood, sediment accumulation, and erosion, a new integrated insight of hydrologic indices and morpho-tectonic parameters was applied. The current approach suggests considering the hydrologic and morpho-tectonic variables for analysis of the potential erosion and sediment accumulation. Thus, the morpho-tectonic and hydrologic indices are comprehensively used as an indirect tool for sediment accumulation and erosion of the basin. In the context of flash flood and erosion map, analysis of hydrologic indices and morpho-tectonic characteristics estimate the flash flood risk and potential erosion of Wadi Gharandal, Sinai,

Egypt. The Wadi Gharandal and its sub-basin exceed an area of 800 km^2; thus, it can be considered as a large-sized basin that has a great potential to collect a huge quantity of water in comparison to small-sized basins. The drainage pattern in the study area is mainly dendritic which is characterized by less percolation and high surface runoff, particularly in high-elevated areas. In most cases, it has been found that the main channels and their sub-streams are affected by the lithological structure and lineament density. The Wadi Gharandal and its sub-basins have a value of bifurcation ratio (BR) greater than 1.5, which indicates dissected areas and elongated-shaped basins where the values of elevation range between 17 and 1199 m (Fig. 3a).

Based on the elevation and slope of the area under consideration, it has been noticed that complex and undulating topography plays a significant role in occurring flash floods and the potentiality of erosion. The study area is characterized by three distinguished groups of elevation:

i. The western and south-western groups with very low elevation ranging from 17 to 100 m, where the slope is very low, i.e., less than 3 degrees.
ii. The central group with moderate elevation ranges between 100 and 500 m, where also moderate slope is found, i.e., 3°–15° (Fig. 3b).
iii. The eastern and south-eastern groups with very high elevation (500–1199 m) and a high degree of slope (15–63).

Generally, flash flood events occur in highland areas where undulating topographic features are observed as shown in the eastern and south-eastern groups, which led to high erosion at that places and very high sediment accumulation in areas as shown in the western and south-western groups. Along with elevation and slope, different morpho-tectonic characteristics and hydrologic indices having a great role in occurring, affecting, and controlling the areal extension of flash floods, erosion, and sediment accumulation that have been discoursed as follows:

Morpho-tectonic characteristics

The area under consideration covers an area of 862 km^2 having a perimeter of 210 km. Total stream orders length and numbers are 760 km and 565, respectively (Table 3). For computing the morphometric parameters, the formula after Strahler (1964) was applied. Morphometric and morpho-tectonic parameters of Wadi Gharandal were calculated and analyzed. Estimation of areal stream characteristics (Table 2) includes drainage basin area, perimeter, width, and length (Horton 1945), which have been calculated in ArcGIS. The linear stream characteristics were calculated (Table 4), which include stream ordering (Strahler 1952);

Table 3 Areal drainage basin characteristics of Wadi Gharandal main basin

Basin	Drainage network					Perimeter (km)
	Stream order	Stream number	Stream orders length (km)	Basin area (km^2)	Basin width (km)	
Gharandal	5	565	760	862	24	210

Table 4 Morpho-tectonic characteristic of the Wadi Gharandal main basin

Morpho-tectonic parameters

Parameter	Value	Parameter	Value	Parameter	Value
ER	0.49	D	0.88	Relf	1184
CR	0.25	SR	1.13	ReRe	0.56
SF	0.18	BR	1.73	ReRa	0.02
CmF	0	MBR	387.85	TSN	564
LmF	1.35	SlopD	0.99	TSL	760.18
LWR	2.85	SlopR	1.73	TEXR	2.69
F	0.65	RugD	1.04	HYPI	0.73

ER is the elongation ratio, CR is the circulation ratio, SF indicates the shape factor, CmF is the compactness coefficient, LmF describes the lemniscate ratio, LWR is the length width ratio, F is the basin frequency, D is the stream density, SR is the stream retaining, BR refers to the bifurcation ratio, MBR refers mean bifurcation ratio, SlopD is the slope degree, SlopR is the slope ratio, RugD depicts the ruggedness degree, Relf is the relief, ReRe is the relative relief, ReRa is the relief ratio, TSN is the total stream number, TSL refers to total stream length, TEXR is the basin texture ratio, HYPI refers to hypsometric integral

mean of the bifurcation ratio; total stream length; drainage frequency ratio (Horton 1945); and drainage density ratio (Melton 1957). In the present study, the drainage network analysis has been carried out using a geographic information system (GIS) package, which deals with the determination of stream orders, stream numbers, bifurcation ratios, channel lengths, stream frequencies, texture ratios, and drainage densities. Moreover, the correlation and interrelationships between these elements were considered.

The value of elongation ratio (ER) near to 1 indicates the round shape of the basin. The ER value has been estimated as 0.49. Based on the ER value, the basin shape of Wadi Gharandal is elongated. Since the ER value is such a significant predictor of measuring the basin tectonic activity (Cannon 1976; Bull and McFadden 1977), with arid to semi-arid climatic conditions, the overall Wadi Gharandal has an ER value of < 0.5, signifying tectonically active. The presence of different geomorphic events, such as faults, joints, and some landslides, suggests the tectonic setting, whereas the ER value > 0.75 is considered a tectonically inactive setting.

The circularity ratio (CR) shows the dendritic pattern of the basin. The computed value of CR is 0.25 which reflects the elongation nature of the Wadi Gharandal, whereas the shape factor (SF) was estimated as 0.18. The CmF depends on the slope and is indirectly associated with the elongation of the basin. The value of CmF in the present analysis is calculated as 0. The lower value of CmF indicates more elongation of the basin area. Lemniscate ratio (LmF) is generally used to determine the slope of the basin and the number of stream orders (Chorely 1957). In the present study, the value of LmF was estimated as 1.35 (Table 4). This reveals that the maximum area of the Wadi Gharandal occupies streams of higher order. The value of LWR was calculated as 2.85 for the Wadi Gharandal.

According to Vijith and Satheesh (2006), drainage density (D) is one of the most important indicators for potential runoff and generally correlated to lithology, climatic condition, and vegetation (Straher 1954a, b, c; Melton 1957). Moreover, the drainage frequency (F) is sensitive to basin relief, infiltration capacity, and permeability (Horton 1932; Bali et al. 2012). The values of drainage density (D) and drainage frequency (F) have been estimated as 0.88 and 0.65, respectively (Table 4). A relatively high value of drainage frequency specifies that the basin is of low infiltration capacity of the bedrock associated with coarse stream texture of value 2.69. Using El Shamy's model for the determination of flash flood degree, the Wadi Gharandal basin comes under a high degree of flash flood possibility.

Horton (1945) defined the Bifurcation ratio (BR) as an index of relief and dissections. BR is inversely correlated with soil permeability, i.e., higher value of BR indicates lower soil permeability. The calculated BR in Wadi Gharandal is 1.73, whereas the mean bifurcation ratio (MBR) was valued as 387.85, both the values of BR and MBR are suggesting a high potential flash flood for the study region. The slope degree (SlopD) and slope ratio (SlopR) have been used for assessing the character of surface runoff of a basin. For Wadi Gharandal, the SlopD has been calculated as 0.99, whereas SlopR was found as 1.73, both the values of SlopD and SlopR are the indications of relatively higher surface run-off. The value of the RugD has been calculated as 1.04 (Table 4). The higher value of RugD is an indication of the high potential for soil erosion. The basin Relief (Relf) of the study area is 1184 m. Based on the basin Relief (1184 m), the Relative relief (ReRe) was calculated using Schumm (1956), which is 0.56, while the Relief ratio (ReRa) was found as 0.02. The ReRa controls the rate of energy conversion between the potential and kinetic of the flowing water through the basin. These all relief parameters are directly related to flash floods and potential erosion.

In this study, the total stream number (TSN) and the total stream length (TSL) have been computed based on Horton's low. These two parameters are important for defining hydrological features and surface runoff characters. Streams with smaller lengths are commonly revealed areas with steep slopes, whereas streams with longer lengths denote smoother slopes. Generally, total stream lengths are higher in the first-order stream which is further inversely proportionate with the stream order. The estimated values of TSN and TSL for Wadi Gharandal are 564 and 760.18, respectively, that indicate neither too steeper nor too smoother slope. The stream length is an indicator of climatic condition, vegetation cover, and resistance of bed-rock to soil erosion. The study area as an arid and semi-arid region shows higher drainage densities because of the flash flood occurrence and scarce vegetation cover. Basin texture ratio (TEXR) is also an important parameter for drainage morphometric analysis. This parameter is dependent on infiltration capacity, underlying geological structure, and relief aspect of the basin (Schumm 1956). The value of TEXR in the present analysis has been calculated as 2.69, which is categorized as lower. Hypsometric integral (HYPI) is commonly used as an estimator of the erosion status of watersheds (Singh and Sharma 2008). The hypsometric integral reflects the stages of landform erosion. Lower values of hypsometric integral indicate ancient and more eroded areas, whereas higher values indicate early and less eroded areas. As per the present analysis, the HYPI value of the Wadi Gharandal was found as 0.73, which reveals that the considered area falls under the mature stage of erosion, where more chances of sediment accumulation are there.

Generally, the asymmetry and similarity of the drainage pattern and catchment area reflect tectonic geomorphology (Wilson and Dominic 1998; Van der Beek et al. 2002). Therefore, between structural geology, geomorphology, and hydrology, there are several disciplines (Odeh et al. 2016; Othman et al. 2020, 2021). Meanwhile, the asymmetry and similarity of the drainage network and catchment area have a significant impact on surface water hydrology, particularly runoff processes (Rodrıguez and Rinaldo 1997; Stephenson 2003; Subramanya 2006; Vivoni et al. 2008; Wade et al. 2012). Thus, it is necessary to understand the asymmetry and similarity of the drainage network and catchment area for a better understanding and analysis of the interaction between surface deformation and underlying structural geology. The structural pattern of west-central Sinai shows that faulting is much more pronounced than folding. The region underwent minor folding in the Late Paleozoic (Abdallah et al. 1992) and then rifting of part of the Gulf of Suez, which began in the Early Miocene and continues to the present (Purser et al. 1993). Faults are the result of successive movements which affected the area at different ages. Said (1962) proposed the age of this faulting as Oligocene and/or Early Miocene. However, El-Gammal (1984) showed that the faulting has taken place periodically since the Late Paleozoic, increased in intensity and areal extension progressively, and reached its climax in the Oligo–Miocene period. Figure 6 shows the rose diagram of the lineaments in the study area.

Hydrologic indices

The Wadi Gharandal basin, which has an elongated watershed and a low form factor, maintains flat peak flows for a longer period of time. Furthermore, because of the basin's elongated shape, the measured value of elongation ratio suggests that the basin is typically associated with high relief and steep ground slopes. Accordingly, a high possibility of flash floods could be expected in the study area. Within the runoff model, the STI, SPI, and TWI used in this analysis are semi-empirical indices. According to Moore and Wilson (1992), the SPI is a non-linear function of discharge and slope, consequently, STI is an important factor in the Universal Soil Loss Equation (USLE). The SPI value in the present study ranges from -11 to 8, with high values toward the positive indicating potential erosive process. Usually, the SPI was used to evaluate the sediment rate and describe the ability to transport the sediment in the basin. TWI originally describes the hydrological balance between drainage conditions and water accumulation. The calculated value of TWI in the study area ranges from 2.8 to 24.1 indicating a high TWI value in the mainstream channels.

Potential flash flood risk map

A flash flood is an event generated due to high rainfall in a very short time, which floods the drainage of the basin and causing impoundment of the stream network and resulting in extremely high discharge at the basin's outlets (Al-Rawas et al. 2001; Wahid et al. 2016). In general, the study area receives small amounts of rainfall due to its location in arid and semi-arid regions. But intensive rainfall in seasonal variation, along with its geomorphological and geological structures, makes havoc flash floods in the Wadi Gharandal basin, causing potential land erosion and sediment accumulation.

Flash flood risk is an indicator of the morpho-tectonic parameters and hydrologic response of a basin to the extreme rainfall in its watershed. The risk map helps in identifying susceptible areas to flash floods and structural planning accordingly. The generated flash flood risk map has been shown in Fig. 7. The higher risk value points to the high morpho-tectonic and hydrologic response for flash flood-prone. The analysis of streams network, DEM and slope, proposed dams was suggested in the present work for better management and mitigation of water resources (Fig. 8). The result reveals that western parts of the study area are highly

Fig. 6 represents **a** lineaments map and **b** rose diagram of Wadi Gharandal
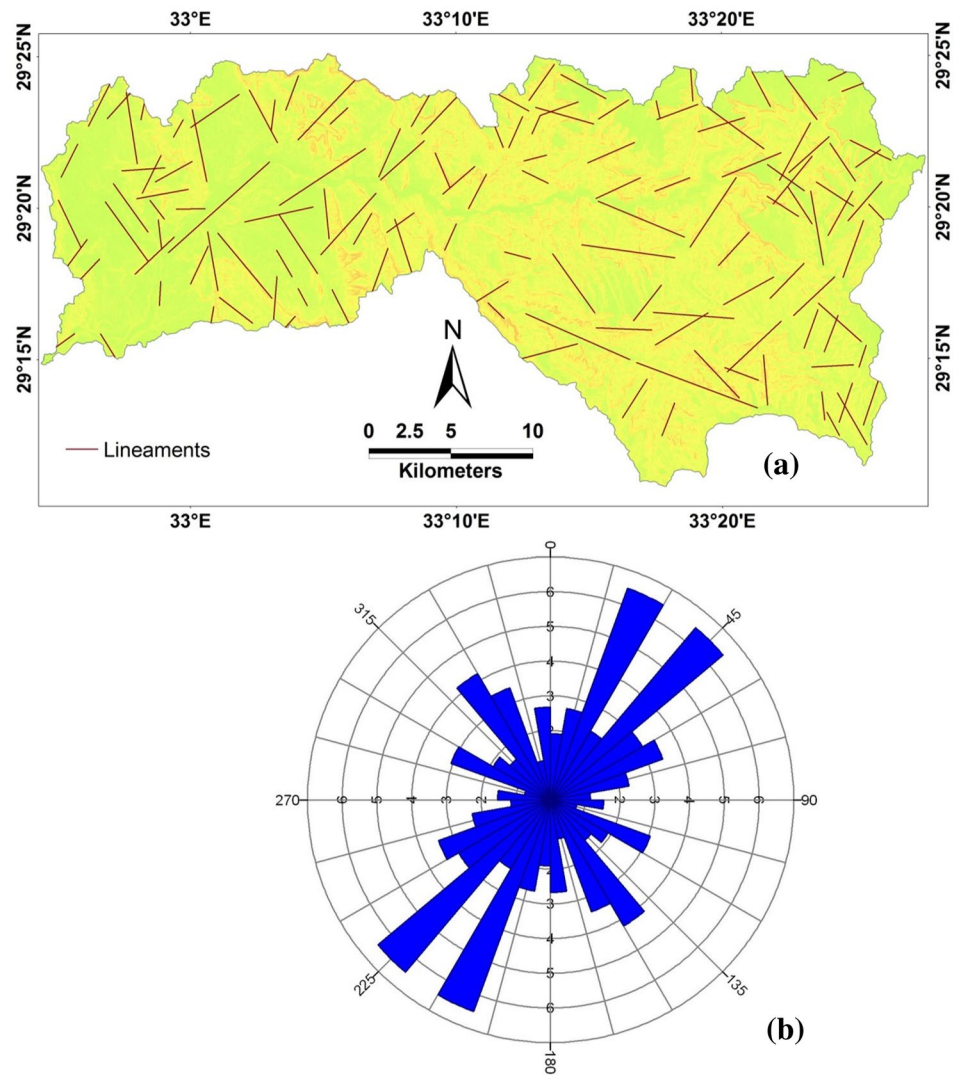
prone to flash flood, where both the elevation and the land slope are lower. So, it could be determined that the low-elevated and gentle-slope areas of arid and semi-arid regions like the study area are relatively prone to flash floods, followed by excessive erosion and sediment accumulation in those portions in comparison to higher elevation and steeper slope areas.

Potential erosion index and sediment accumulation

To improve the flash flood and associated risk management, there is a need to develop such an integrated methodology to maximize the analysis and prediction of risk zonation. Morpho-tectonic parameters along with hydrologic indices have been incorporated as a tool for sediment erosion and accumulation characteristics. The results obtained using the fuzzy K-means clustering classification of hydrologic indices and morpho-tectonic parameters

have been shown (Fig. 9). It has been come to know from the local people in the study area that during the rainfall events, the main basin channel brings large quantities of vegetation, sediments, and boulders. High topographic condition with less vegetation cover is the main reason behind the erosion susceptibility of the area. Accordingly, the drainage density largely correlated to the erosion, high drainage density with low infiltration rate indicating high surface runoff that supporting erosion capability. The output result shown in Fig. 9 reveals that sediment accumulation is mainly confined in low-lying areas with smother slope, it is the result of erosion in high-elevated steep slope regions and sediment transportation in low-elevated areas. Further, the potential erosion map has been classified into three classes, namely sediment accumulation, moderate erosion, and low erosion, and the result shows that about 48% of the basin area comes under low to moderate potential erosion susceptibility.
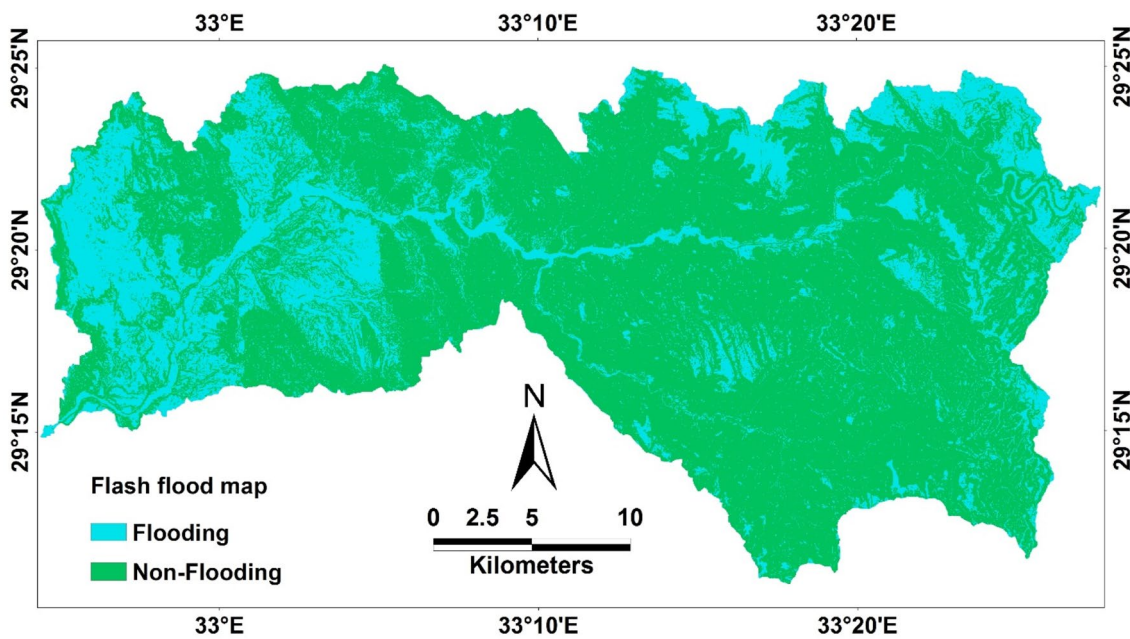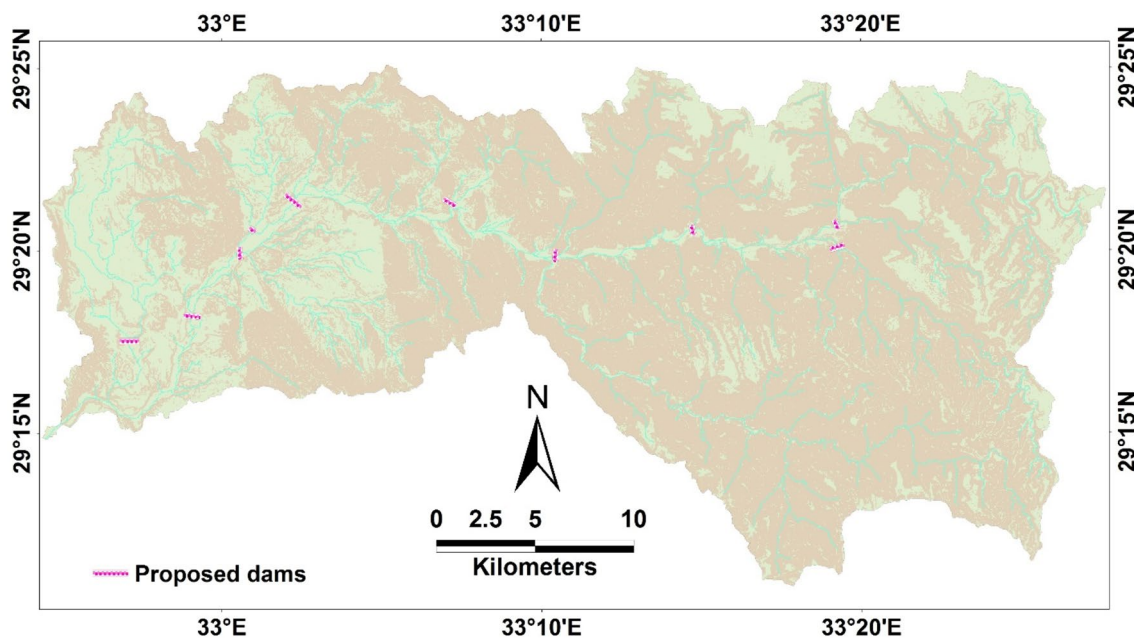
Fig. 7 Flash flood map of Wadi Gharandal basin

Fig. 8 Proposed dams of Wadi Gharandal basin

Discussion

It is a crucial task to understand the topographic characteristics, geomorphological structure, and its control on the pattern of surface channel to reduce the risk of flash flood hazard within a given area (El Bastawesy et al., 2013). So,

the present study aimed to assess the hydrologic indices and morpho-tectonic parameters for flash flood susceptibility and potential erosion mapping. In the present analysis, twenty-one morpho-tectonic parameters, such as ER, CR, SF, CmF, LmF, LWR, *F*, *D*, SR, BR, MBR, SlopD, SlopR, RugD, Relf, ReRe, ReRa, TSN, TSL, TEXR, and HYPI, were considered which have a direct influence on
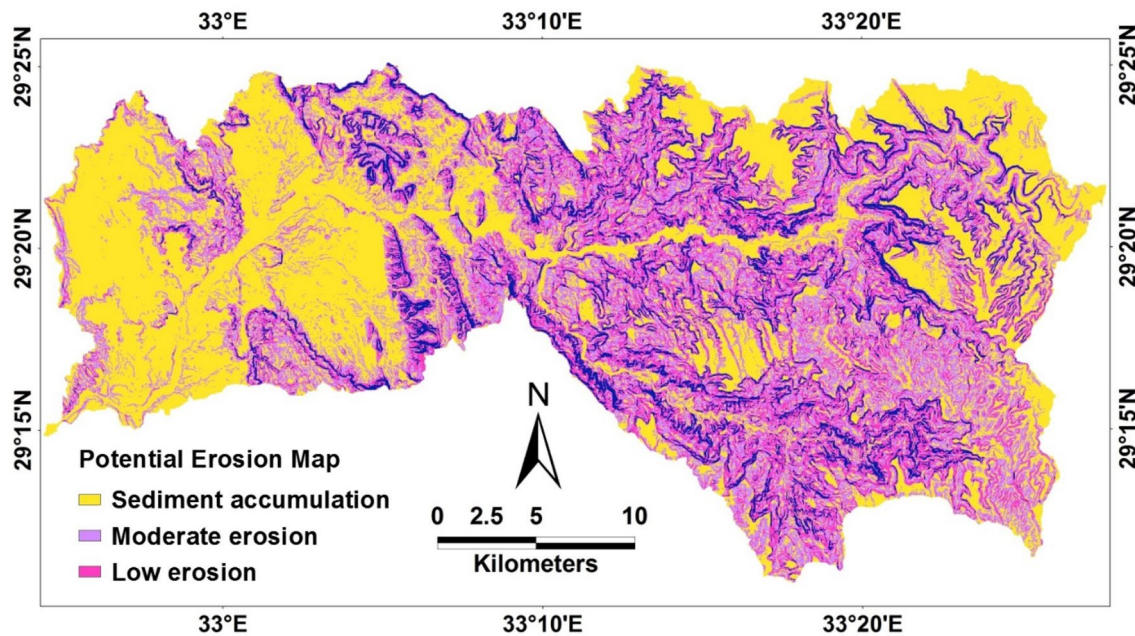
Fig. 9 Potential erosion and sediment accumulation map

hazard mapping. Further, three hydrologic indices, such as stream power index (SPI), sediment transport index (STI), and topographic wetness index (TWI), were incorporated to evaluate the flash flood risk and erosion potentiality of the concerned area.

Gabr and El Bastawesy (2015) identified the role of hydrological parameters for flash floods in Sinai using SRTM DEM and geographic information systems. Their study revealed that hydrological parameters have a significant role in discharge rate and flash flood events, but they have estimated the susceptibility rate. Masoud et al. (2014) attempted flash flood hazard mapping based on physiographic features and GIS technique for Wadi Fatimah, Saudi Arabia. Their result showed that topography is an important factor that controls the hydrological response to flash floods in the study area, but the result suffering from scarcity of data. Bajabaa et al. (2014) highlighted quantitative assessment of hydrology and geomorphology of Wadi Al Lith, Saudi Arabia for hazard mapping of the flash flood. They used ASTER data in the assessment of linear, areal, and relief aspects of morphometric parameters and found similar results as that topography acts in controlling the hydrological response to flash floods.

Unlike the above-mentioned studies, the present study not only showed an interlink between hydrologic indices and morpho-tectonic parameters in flash flood susceptibility, but also showed the potential erosion and sediment accumulation. This study integrated hydrologic and morpho-tectonic parameters which would be a useful tool to manage flash floods and plan for water harvesting.

More recently, some studies focused on hybrid models using statistical measures and machine learning algorithms. For example, Costache et al. (2020) used bivariate statistics and their hybrid integration with machine learning models for flash flood susceptibility within a small mountain basin; Costache (2019) applied a number technique including logistic regression, frequency ratio, weights of evidence, and support vector machine and their hybrid models to assess potential flash flood in Romania; Pham et al. (2020) identified flash flood susceptibility areas based on hybrid machine learning methods including bagging based-credal decision tree, dagging based-credal decision tree, credal decision tree, and single credal decision tree.

All of these studies emphasized the capability of the model's efficiency and prediction rate for flash flood susceptibility. But these studies did not evaluate any hydrologic or morpho-tectonic indices and also not highlighted erosion potentiality or sediment accumulation due to flash floods. Thus, unlike those studies, the present study emphasized these all issues which would be beneficial for flash flood control and erosion mitigation strategies in the study area.

Conclusion and recommendations

Hydrologic, morpho-tectonic parameters and GIS were integrated in the present study which are useful in planning and flood management. In this study, the implementation of hydrologic indices and basin morpho-tectonic parameters was used for the assessment of the basin's potential erosion and

sediment accumulation. Twenty-one morpho-tectonic parameters and three hydrologic indices were utilized to understand and evaluate the accumulation and erosion susceptibility. Morpho-tectonic characteristics indicate a high possibility of flash floods in the area due to low infiltration capacity and high overland flow. Additionally, morpho-tectonic indicates a relatively active tectonic setting in the region linked to geomorphic structures. Generally, the lower value of stream power index (SPI) indicates a potential deposition process that characterized the basin downstream and main channel, whereas the higher values of SPI indicate a potential erosive process in the study region. Indeed, the key indicators for erosion and sediment accumulation are lithological units associated with hydrologic indices and morpho-tectonic parameters. Three classes were identified as a result of fuzzy k-mean clustering that illustrates the areas of similar potential sediment accumulation and erosion. Consequently, high run-off aggressiveness is linked to the areas of high slopes and upstream. The low runoff encountered with an area of low slope is associated with sediment accumulation. Finally, this study demonstrates that the application of remote sensing data connected with morpho-tectonic and hydrologic data is an efficient tool for understanding flash floods, erosion, and their management strategies.

Flash flood risk estimation is very important for watershed management, particularly managing water resources for sustainable development in arid and semi-arid regions and protecting vulnerable zones. Proper assessment of flash flood risk areas and appropriate managemental strategies can reduce the rate of hazard degree. Thus, it is recommended to construct a sufficient number of dams downstream of flash flood risk areas. This management practice can erect the surface runoff which leads to recharge groundwater. Additionally, this strategy can also be taken into consideration for planning rainwater harvesting and watershed management to sustainable uses of floodwater and reduce land erosion in the Wadi Gharandal.

Declarations

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