Egyptian Journal of Geology

https://egjg.journals.ekb.eg

Assessing Vulnerability to flash floods in Greater Khartoum, Sudan: An integrated approach

Noreldeen Abakar[1]**, Mohamed Ibrahim El-Anbaawy**[1]**, El Sheikh Mohamed Abdelrhman**[2] and **Tamer Nassar**[1]

[1] *Geology Department, Faculty of Science, Cairo University, Giza, Egypt*

[2] *Faculty of Petroleum and Minerals, Al Neelain University, Khartoum, Sudan*

THE RESEARCH paper investigates the vulnerability of Greater Khartoum to flash floods triggered by intense rainstorms, which may become more frequent due to climate change and sand dunes/encroachment. The study uses geo-environmental mapping, observational fieldwork, Remote Sensing, GIS techniques, watershed analysis, and climatic data interpretation to identify the area as more susceptible to flash floods than to river flooding and sand dunes/encroachment. A multi-hazard impact assessment was performed using natural and human causative factors. Integrated geological, climatic, and land use factors were discussed. The growth of the Khartoum, Omdurman, and Khartoum Bahri areas without proper urban and agricultural plans has created severe negative impacts on public communities and cultural heritage in archaeological sites west of the White Nile banks. The paper proposes two geomorphological risk models: Nile floodplain/terraces (N) and hilly deserts (H) for risk assessment. The complex nature of risk assessment due to changeable environmental factors necessitates an integrated approach. The study also suggests multiple management procedures to mitigate the predicted negative impacts of runoff floods due to the area's changeable land use and climate conditions.

Keywords: Greater Khartoum, geohazards, landforms, controlling factors, sand dunes, integrated causative factors, human activities impact, watershed analysis, multiple risk assessment, integrated models.

1. Introduction

Sudan, including the Greater Khartoum megacities of Khartoum, Omdurman, and Khartoum North (Bahari), suffers from integrated natural and anthropogenic or induced man-made hazards that lead to severe environmental problems. Natural hazards are mainly represented in this study by flash (runoff) floods and sand dunes/encroachment, which are associated with torrential rains and sandstorms, respectively. The Greater Khartoum cities and surrounding area are still very vulnerable to flooding triggered by intense convectional rainstorms, which may be more common and increased within future natural phenomena like climate change.

The development of Greater Khartoum is a planetary issue, involving many disciplines that include urban planning, social organization, and assessment of the vulnerability to geohazards of infrastructure (Zerboni *et al.*, 2021). They discussed the impacts of the uncontrolled urban and agricultural development to the west of the Nile bank on the natural and cultural heritage sites. Furthermore, political instability and economic degradation, in addition to natural hazards, may exceed the environmental problems to be potentially managed (Ibrahim and Adam, 2022). It is indicated that anthropogenic (human) factors (e.g., lack of proper urban planning) are the main causes of frequent recurrences of floods and desertification rather than the natural factors. According to Bhalotra (1963), a four-fold division of the climatic year in central Sudan is suggested, and one of them is June to September. These rainy seasons are one of the main causes of flash floods in the area.

With further climate and land use change, the study area will expose more flash floods and sand dunes hazards. This paper is an attempt to evaluate the hazards that induce severe impacts on the environment in the Greater Khartoum and surrounding areas with an emphasis on the discussion of the geomorphological, climatic, and land use causative factors. Based on the available data and the revealed environmental parameters, an integrated impacts assessment model could be constructed. According to the assessment categories, an effective management procedure and practical adaptation plans

*Corresponding author e-mail: noreldeenart@gmail.com
Received: 24/03/2025; Accepted: 01/05/2025
DOI: 10.21608/EGJG.2025.370827.1108
©2025 National Information and Documentation Center (NIDOC)

are proposed to mitigate the potential negative environmental impacts, particularly in the shadow of climate change.

2. The study area

The study area (about 5250 km²) is located between latitude 15° 20 and 16° 05' N and between 32° 10 and 32° 55 E, occupying the southern central part of the Khartoum State. The State ranges in elevation between 380 meters and 420 meters above sea level (Oliver, 1965), with a general slope towards the Nile River Corridor. The Greater Khartoum is divided by the Blue Nile, White Nile, and main River Nile into three cities: Khartoum, Khartoum North (Bahri), and Omdurman. Each of these cities has its own physiographic characteristics (fig. 1c).

Physiographically, the study area is characterized by a hot desert climate (hot arid), extremely dry for most of the year. July and August are the only months with the highest precipitation, with an average of 121.3 mm of precipitation falling each year (Ibrahim and Adam, 2022). The topography is somewhat undulating at Omdurman and flat at Khartoum and Khartoum North (Bahri) with an elevation of 381 meters above sea level (Haj mousa, 2019). Khartoum is a mega-city with a continuously increasing population of more than 5.1 million (Zerboni *et al.*, 2021).

Monthly totals for rainfall in the study area (Greater Khartoum): July (~30 mm), August (~65 mm), and September (~123 mm), (Table 1c). These brief, intense convective thunderstorms frequently result in flash floods in the area with insufficient drainage. While wind patterns: Light to moderate winds, with occasional gusts during storms (Table 1a &b).

Each city (Khartoum Bahri, Omdurman and Khartoum) represents a distinct area with its own physiographical and geomorphological features, allowing for easier navigation and organization within the study area, making it more efficient to analyses and assess the different risk parameters (fig. 1c).

The Greater Khartoum (The study area) major geological units are classified chronologically, including the Basement Complex, Lower Omdurman Formation, Upper Omdurman Formation, Wad Madani, Lower Gezira Formation, Upper Gezira Formation, and superficial deposits (Farah *et al.*, 1997). Basement Complex overlain by the formation known as the Nubian Sand- stone, and later covered by a blanket of post-Cretaceous deposits continuing up to the Pleistocene (Whiteman, 1971). The study area rock units are arranged from oldest to youngest, including the Proterozoic Basement Complex and Mesozoic granite (Bas), Nubian Sandstone (Omdurman Formation) (KM), Tertiary Volcanics (Basalt), Umm Ruwaba Formation (TQ), Gezira Formation (QT), Gravelly Sand Sheet & Sand Dunes (QB), Wadi Deposits (QW), and Nile Silt (QN). As shown in (fig. 2). The study area's geology is influenced by the sedimentary cover, volcanics, and other geological features. The basement complex and Mesozoic granite are exposed in the north-eastern corner of the study area, while the Nubian Sandstone Formation (Omdurman Formation) crops out in the majority of the western sides of the main Nile and White Nile courses. The Omdurman Formation crops out across much of the Khartoum State and consists of the Umm Badda and Merkhiyat members (Awad, 1994). The Umm Ruwaba Formation (TQ) overlies the Nubian Sandstone and crops out on the east bank of the main Nile and Blue Nile courses as well as on the western bank of the White Nile near the Touti Island. The Gezira Formation (QT) is composed of sandy alluvial deposits, which usually show rapid lateral and vertical changes of lithofacies (fig. 2).

3. Methodology

This methodology describes the use of Remote Sensing techniques and ArcGIS Pro software to map and assess the risks associated with geomorphological and flash flood hazards. The method combines data collection, spatial analysis, and risk assessment to produce useful results for effective hazard management and mitigation. The use of satellite data to map urban land cover is not new (Howarth and Boasson, 1983; Patino and Duque, 2013, Reba and Seto, 2020). Satellite imagery (such as Landsat 5 and Sentinel-2) is collected for land use/cover and geomorphological analysis. Topographic analysis and watershed delineation will be performed using Digital Elevation Model (DEM) data with a resolution of 30 m, and sentinel-2 with a resolution 10 m. Figure (3b and 4) depicts examples of existing features for DEM products derived from RS and GIS data.

Therefore, identifying and categorizing geomorphological features like slopes, valleys, ridges, and rivers. Geomorphological features are characterized by analyzing terrain attributes from DEMs (e.g., slope). and using topography and land use to assess the potential for flow accumulation and surface runoff. Finally, this methodology outlines a structured approach for using Remote Sensing and

GIS software to identify, assess, and map the risks associated with natural and anthropogenic factors.

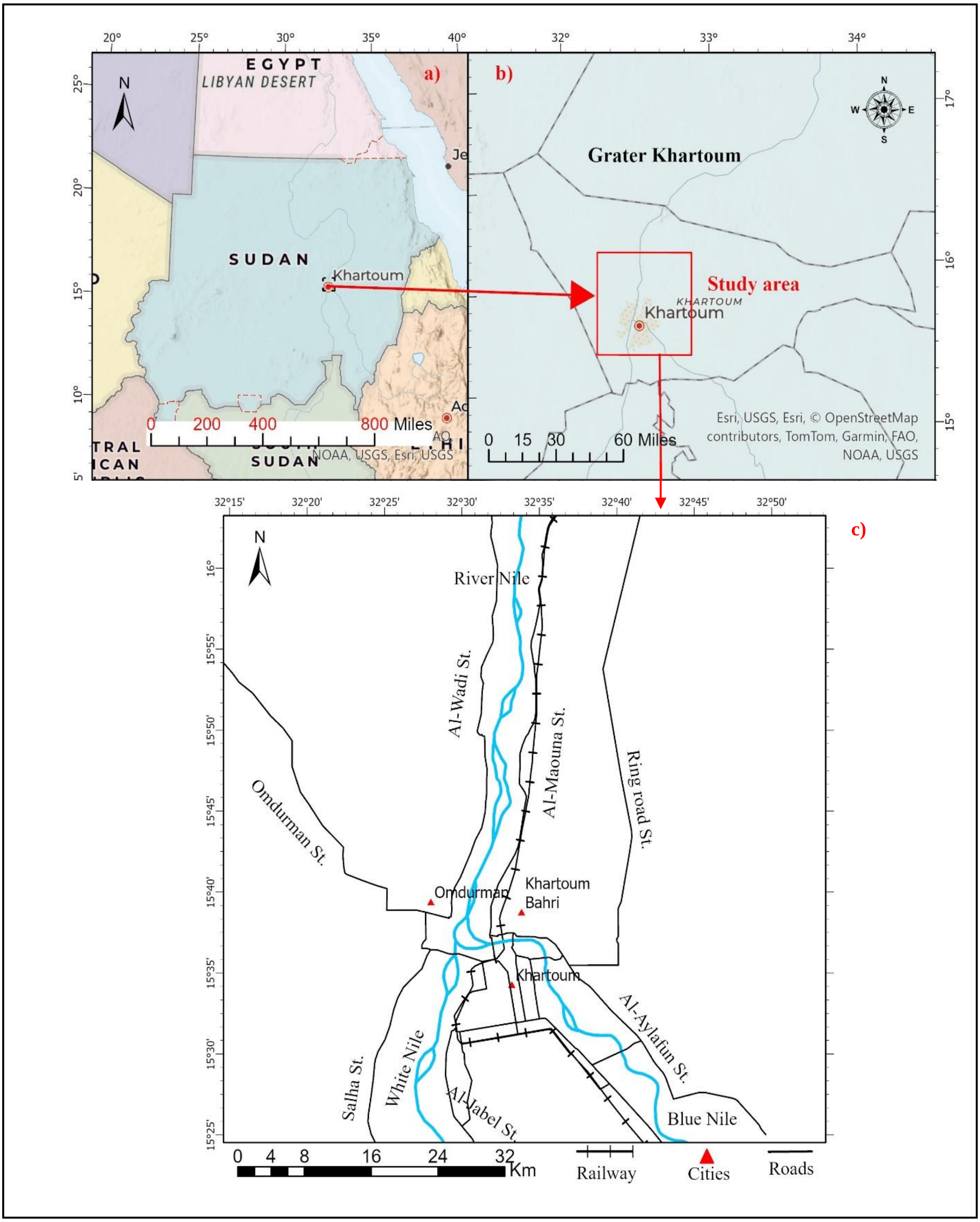


Fig.1. Location and base maps of the study area and a, b & c) Sudan, Greater Khartoum, and the study area.

Table 1. a) Mean monthly wind speed in knots, b) mean monthly wind direction, c) monthly rainfall (MM) in Shambat Station from 2018-2022, (Meteorological Authority, 2023).

a)

Year	1	2	3	4	5	6
2018	5	4	4	4	4	5
2019	4	4	4	4	4	5
2020	5	4	4	4	4	5
2021	4	5	5	4	4	6
2022	6	6	6	6	5	6
Year	**7**	**8**	**9**	**10**	**11**	**12**
2018	5	4	4	3	3	4
2019	4	5	4	3	4	4
2020	5	4	4	3	4	4
2021	6	5	4	5	5	5
2022	6	6	6	4	5	5

b)

Year	1	2	3	4	5	6
2018	N	N	N	N	N	S
2019	N	N	N	N	N	S
2020	N	N	N	N	N	SW
2021	N	N	N	N	S	S
2022	N	N	N	N	N	S
Year	**7**	**8**	**9**	**10**	**11**	**12**
2018	S	S	S	N	N	N
2019	S	S	S	S	N	N
2020	S	S	S	N	N	N
2021	S	S	S	N	N	N
2022	S	S	S	N	N	N

c)

Year	1	2	3	4	5	6
2018	0.0	0.0	0.0	0.0	0.0	0.2
2019	0.0	0.0	0.0	0.0	15.7	5.0
2020	0.0	0.0	0.0	0.0	1.7	5.4
2021	0.0	0.0	0.0	0.0	0.1	TR
2022	0.0	0.0	0.0	0.0	0.0	0.2
Year	**7**	**8**	**9**	**10**	**11**	**12**
2018	1.1	4.1	1.5	0.1	0.0	0.0
2019	10.0	64.6	31.0	25.0	0.0	0.0
2020	25.6	29.4	44.9	0.0	0.0	0.0
2021	29.1	55.3	124.0	0.0	0.0	0.0
2022	21.6	44.3	45.9	15.0	0.0	0.0

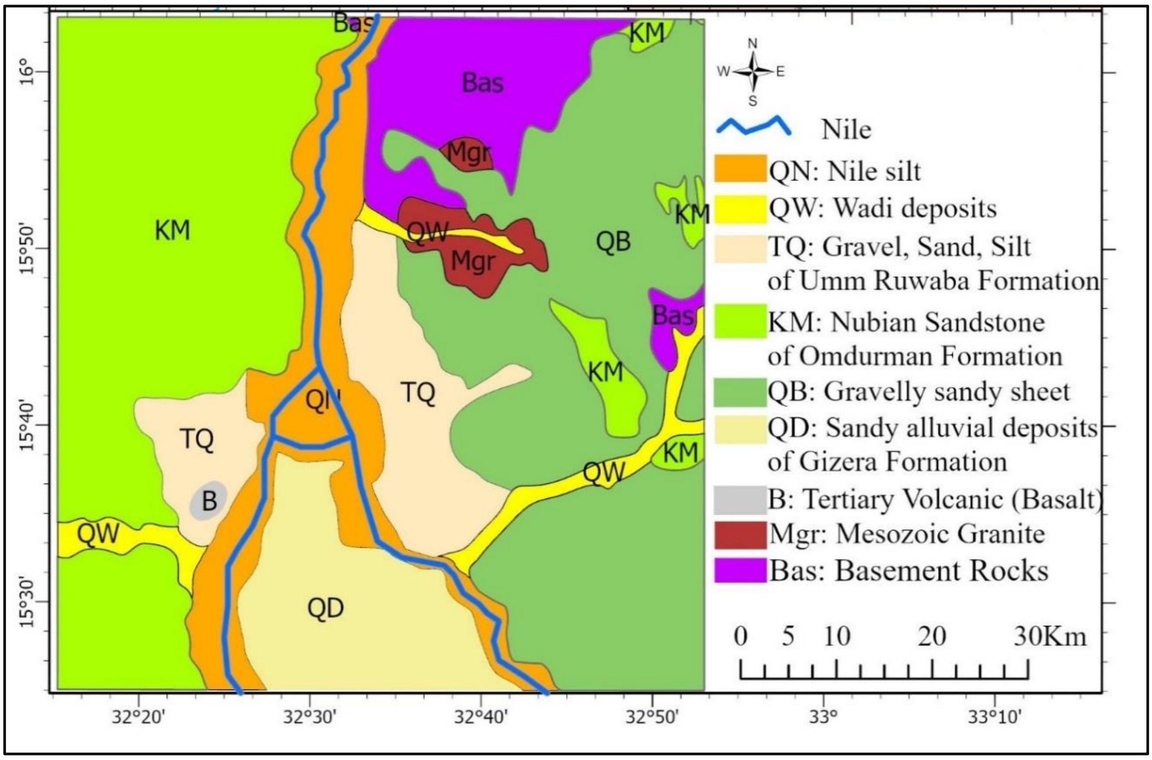
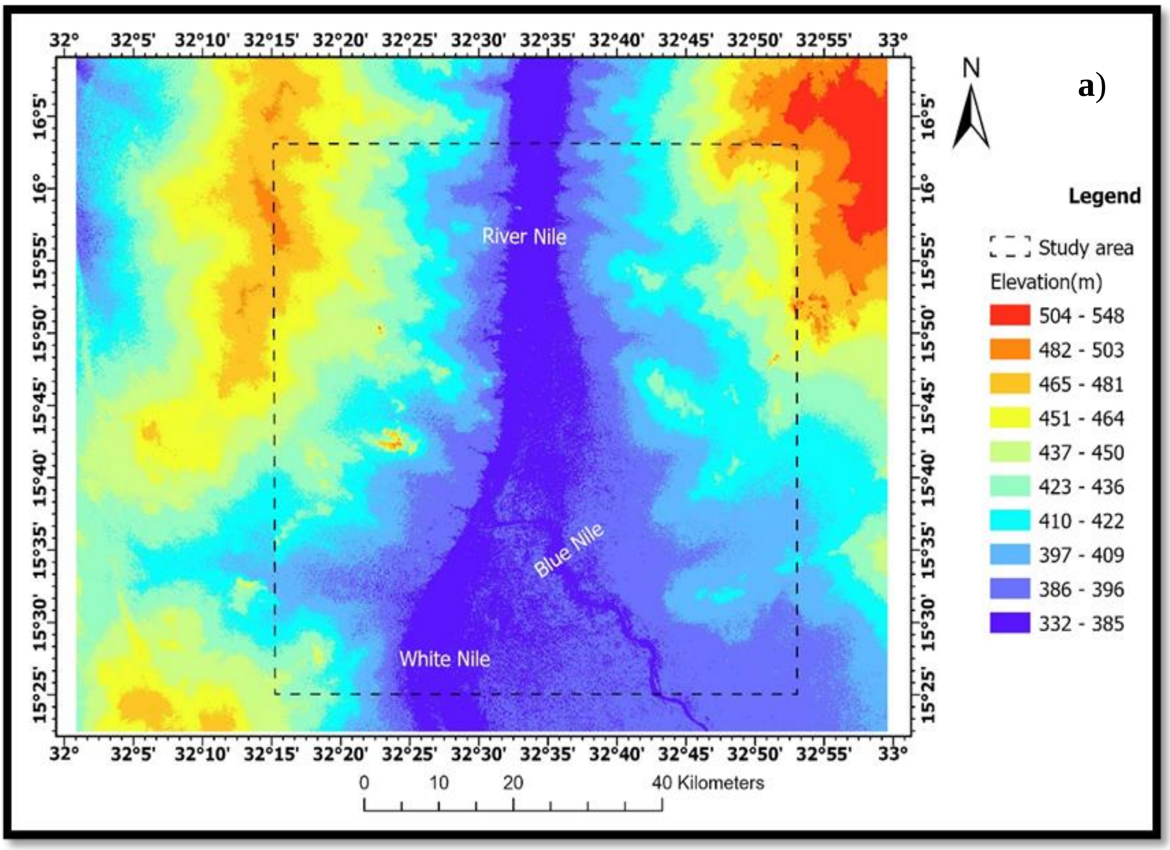


Fig. 2. Simplified geological map of the study area, based on the geological map of the Khartoum area, Khartoum State (GRAS, 2016).



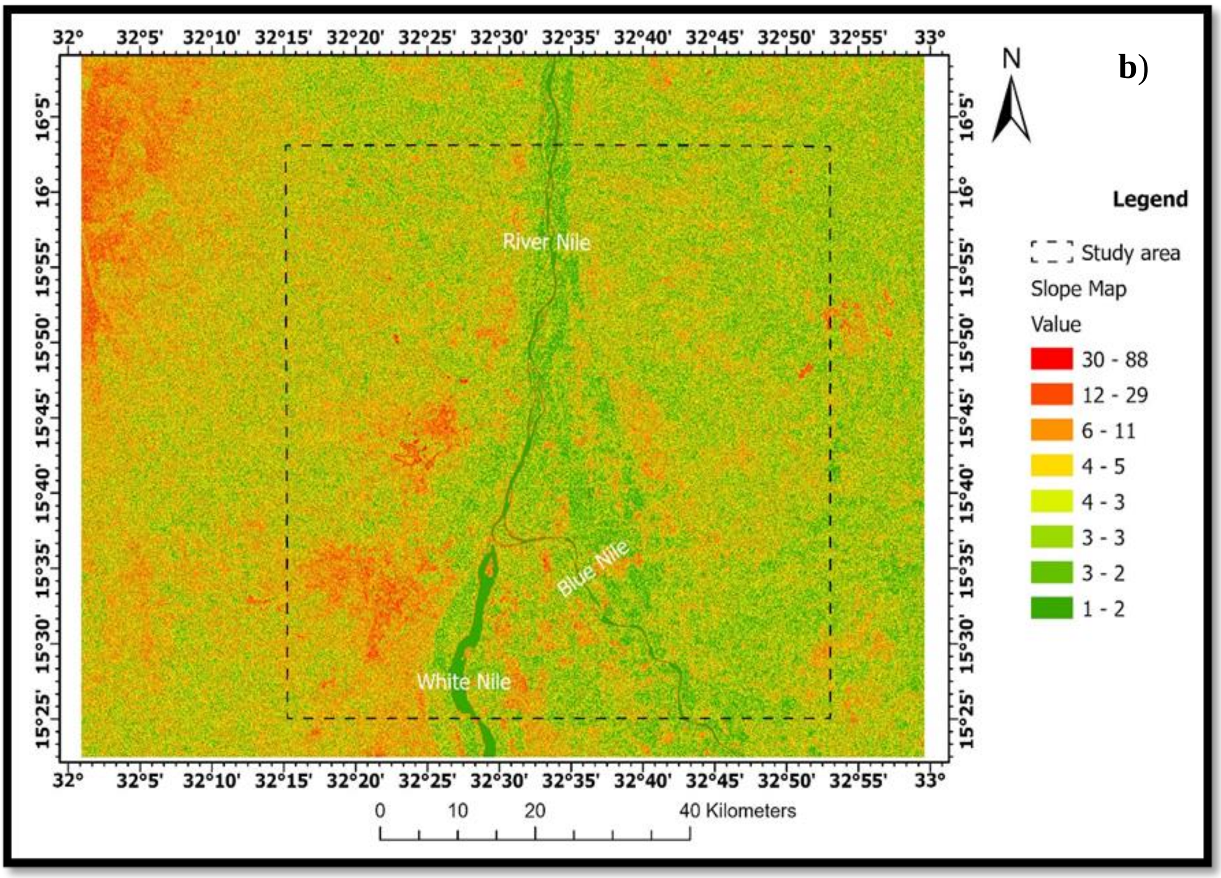


Fig. 3. a) The digital elevation model (DEM), and b) slope maps of the study area.

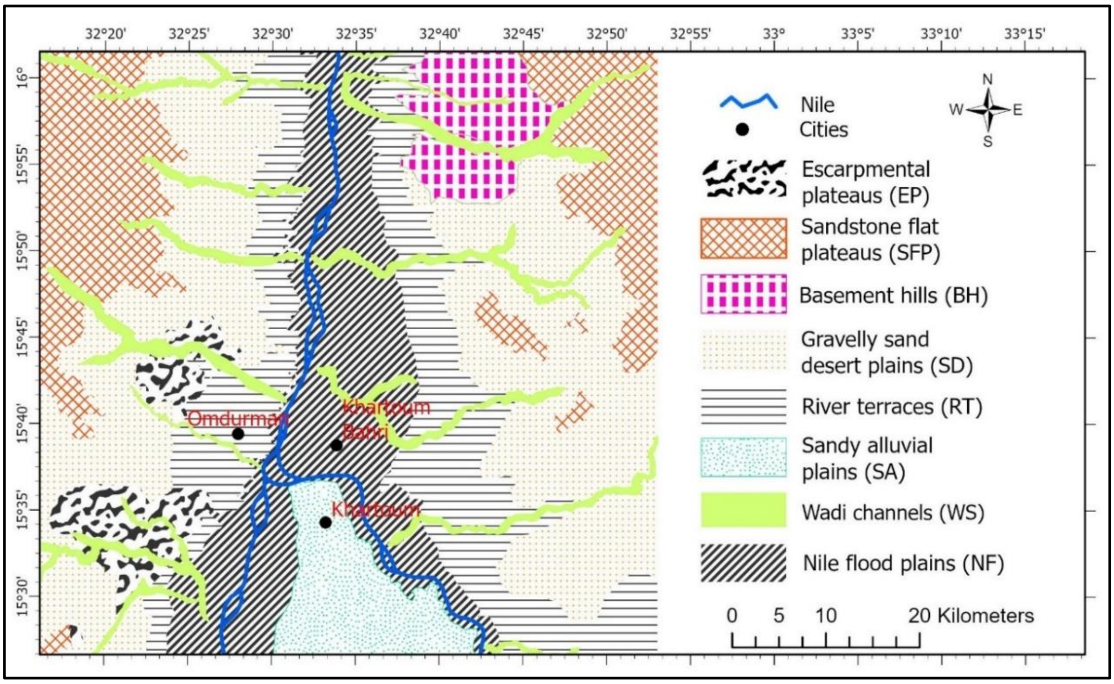


Fig. 4. Geomorphological map showing the landforms distribution in the study area.

Table 2. Hydromorphmetric parameters of the study bus-basins in Grater Khartoum (the study area) and surrounding area.

Aspects	Parameters	Western Nile Sub-Basins				Eastern Nile Sub-Basins			
		4	11	8	6	10	3	15	5
Liner	u	4	3	3	4	3	5	2	4
	Lu	291.23	81.74	126.84	275.59	103.70	433.84	74.47	284.39
	Lb	35.52	30.23	30.86	38.5	30.37	43.87	14.82	37.18
	Wb	18	8.1	9.19	17	6.85	24.28	9.89	18.57
	Rb	2.6	1.60	1.53	2.43	1.6	3.44	3.13	2.49
	A	433.54	131.49	205.63	393.34	151.31	633.78	104.06	414.16
	P	133.77	97.36	107.69	139.31	103.38	166.68	60.81	149.23
Areial	Texture ratio	1.13	0.44	0.72	0.97	0.55	1.41	0.61	0.89
	Dd	0.67	0.62	0.62	0.70	0.69	0.68	0.72	0.69
	Fs	0.35	0.33	0.37	0.34	0.38	0.37	0.36	0.32
	Ff	782.54	203.25	312.94	772.35	284.28	1187.90	213.18	781.14
	Rc	0.30	0.17	0.22	0.25	0.18	0.29	0.35	0.23
	Re	0.67	0.43	0.53	0.58	0.46	0.65	0.76	0.56
Relief	Bh	100.98	107.92	103.94	108.88	149.79	161.98	65	142.48
	Rr	135.67	134.17	128.22	152.57	205.32	221.77	93.04	195.68
	Rn	67.83	67.09	64.11	76.29	102.66	110.88	46.52	97.84
Aspects	Parameters	Eastern Nile Sub.		West White Nile		East White Nile		East Blue Nile	
		14	7	9	1	13	12	2	16
Liner	u	2	4	3	5	3	3	4	2
	Lu	84.40	239.11	106.47	893.86	73.72	88.52	556.72	26.61
	Lb	17.93	33.58	22.06	48.13	17.87	19.04	47.05	14.71
	Wb	10.44	14.64	11.66	48.62	10.89	9.72	39.47	6.25
	Rb	2.22	2.58	3.61	3.39	1.56	1.74	2.52	2
	A	117.04	338.40	157.51	1273.45	117.11	131.46	737.82	54.25
	P	64.97	125.57	75.12	226.16	66.68	90.41	216.99	49.13
Areial	Texture ratio	0.38	0.87	0.65	1.90	0.67	0.45	1.03	0.26
	Dd	0.72	0.71	0.68	0.70	0.63	0.67	0.75	0.49
	Fs	0.21	0.32	0.31	0.34	0.38	0.31	0.30	0.24
	Ff	243.43	675.80	287.88	2509.64	185.62	238.42	1680.29	26.61
	Rc	0.35	0.27	0.35	0.31	0.33	0.20	0.20	0.28
	Re	0.69	0.68	0.64	0.84	0.69	0.63	0.66	0.57
Relief	Bh	48.02	41.03	65.38	65.04	7.19	13.45	130.90	16.98
	Rr	69.25	57.99	88.38	91.31	9.05	18.11	197.55	16.65
	Rn	34.62	28.99	44.19	45.65	4.53	9.05	98.77	8.17

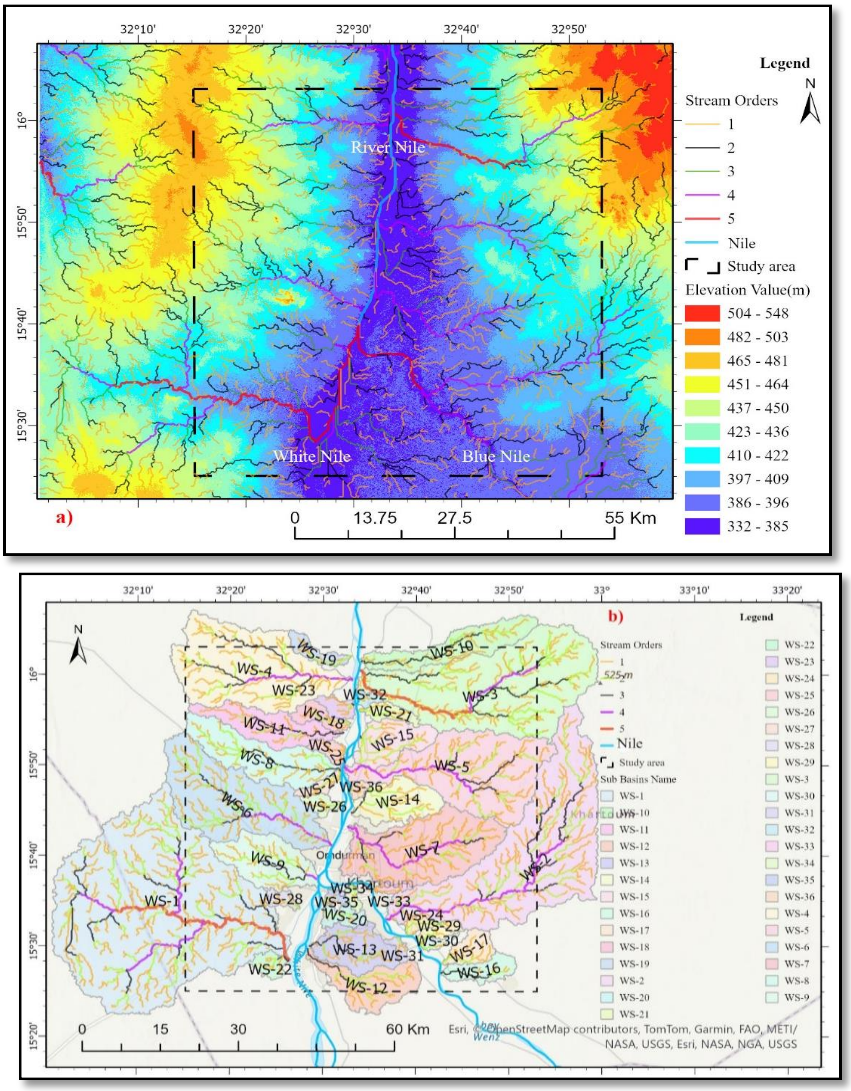


Fig. 5. a) The drainage system of the area under DEM layer, b) the sub-basins that selected form wadi basins in the study area.

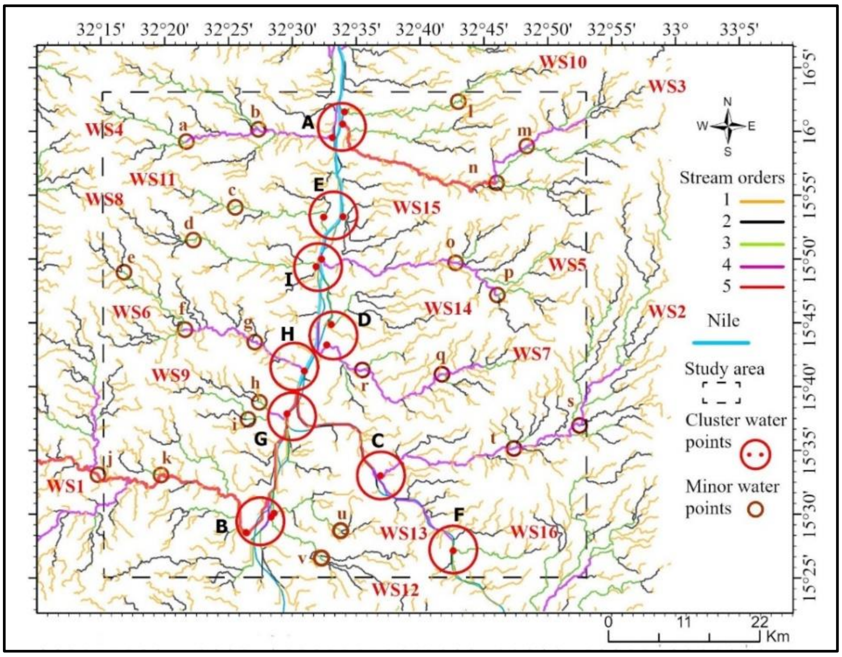


Fig. 6. Flash (Run off) flood hazard map of the study area.

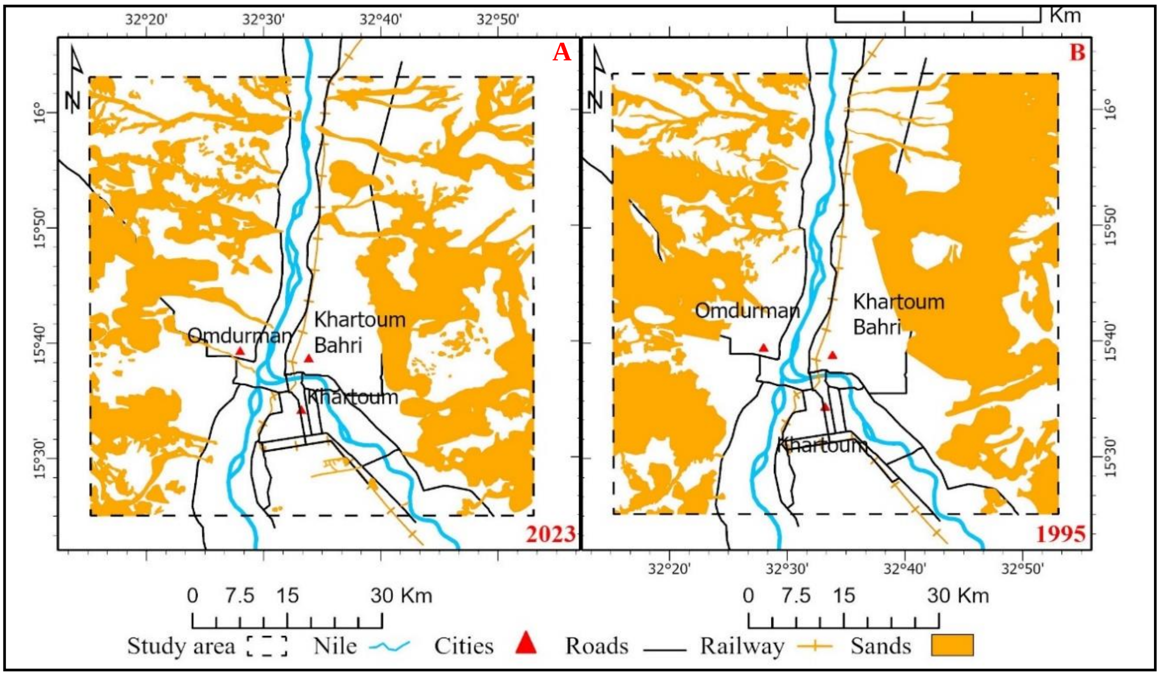


Fig. 7. A) Sand dunes/accumulation bodies through the study area in recent time (2023), and B) shows sands in period (1995).

Table 3. Geomorphological characteristics of wadi channels with land use site.

Location	WS No.	Cluster points	Minor point	Strem length	Strem order	Near land use sites
West Nile (WN)	WS 4	A	a & b	291	4	Sheih-Altiib
	WS 11	E	c	82	3	Sururab
	WS 8	I	d	127	3	El Nofalab
	WS 6	H	f & g	276	4	North Omdurman
East Nile (EN)	WS 10	A'	l	104	3	Wawise
	WS 3	A"	m & n	434	5	Al-Gaili
	WS 15	E'	-	74	2	El-Kabashi
	WS 5	I'	o & p	284	4	Al-Zakiab
	WS 14	D'	-	84	2	El Eziregab
	WS 7	D"	r & q	239	4	Halfia Elmouluk
West White Nile (WWN)	WS 9	G	h & i	106	3	Omdurman
	WS 1	B	j & k	894	5	Salha
East White Nile (EWN)	WS 13	B'	u	74	3	Mayo
	WS 12	B"	v	89	3	Al-Kalakla
East Blue Nile (EBN)	WS 2	C	s & t	557	4	Soba
	WS 16	F	-	27	2	Um Dowwanban

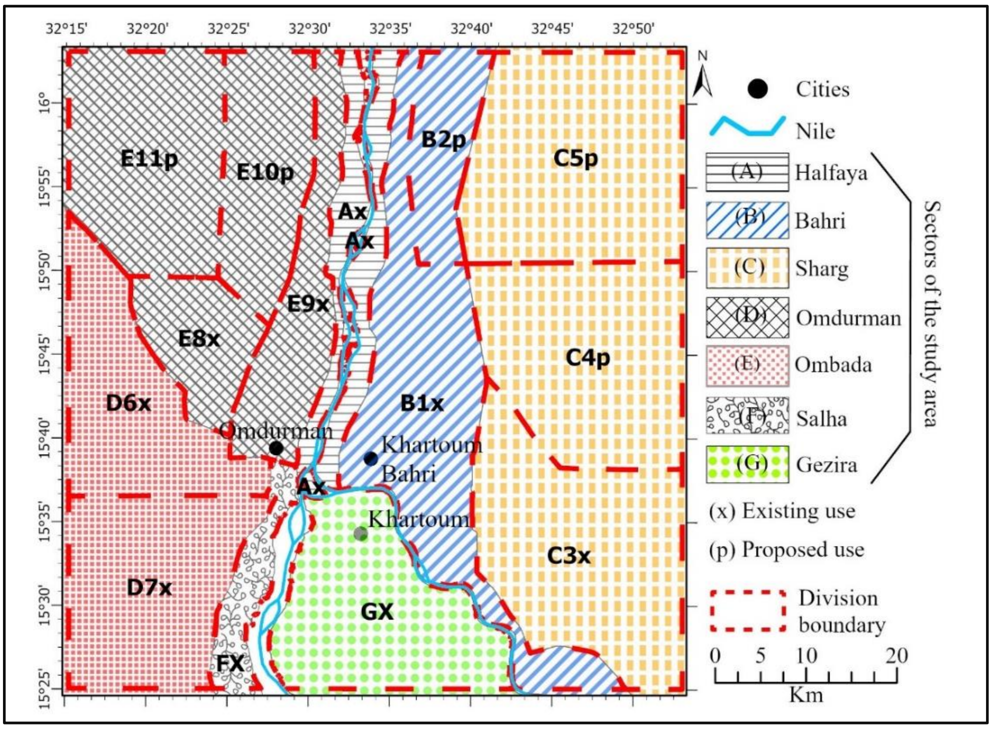


Fig. 8. land use map of the study area.

Table 4. Assessment of the risk levels and categories for the physiographic sectors and land units.

	Geomorphic risk parameters	A	B		C			D		E				F	G
		Ax	B1 x	B2 p	C3 x	C4 p	C5 p	D6 x	D7 x	E8 x	E9 x	E10 p	E11 p	Fx	Gx
Physiography	Elevation	10	10	6	7	3	0	8	8	9	10	2	0	10	8
	Distance Nile	10	10	4	3	2	0	5	7	9	8	2	0	10	8
Landforms	EP	-	-	-	-	-	-	5	4	6	8	-	-	-	-
	SFP	-	-	-	-	4	8	6	5	7	-	-	10	-	-
	BH	-	-	10			3	-	-	-	-	-	-	-	-
	SD	-	-	9	3	6	2	8	9	10	7	2	-	-	-
	RT	10	10	4	7	-	-	-	5	-	10	2	-	9	5
	SA	-		-	-	-	-	-	-	-	-	-	-	9	10
	WS	10	10	6	5	2	3	7	8	7	6	3	1	10	2
	NF	10	8								4			10	7
Watershed Characteristics	Cluster points	10	7	-	-	-	-	-	-	-	8	-	-	10	8
	Minor points	-	3	5	1	2	3	5	5	6	8	3	1		5
	Stream orders	10	10	5	2	7	8	6	7	6	9	3	1	10	7
Lithology	Bedrocks	-	7	7	0	6	3	6	4	8	7	6	6	7	7
	Soils	10	10	3	5	2	1	5	3	5	8	0	0	8	9
Environmental Hazards:	Flash flood	10	10	7	5	0	2	9	8	9	10	0	0	10	10
	Sandstorms	10	10	7	6	5	1	8	7	8	10	3	0	10	7
	Instability	-	-	0	-	-	-	3	5	7	7				
	Ground water rise	10	10	0	5	-	-	0	5	0	8	-	-	10	8
Land uses	Agriculture	10	8	0	5	-	-	5	5	8	10	2	-	8	7
	Urban built	10	10		3			8	7	7	10			10	10
	Archeological site	-	-	-	-	-	-	-	4	-	-	-	-	10	-
	A. Average risk level	10	9	5	4	3	2	6	6	7	8	2	1	9	7
	Risk categories	V. High	V. High	Medium	Low	Low	V. Low	Medium	High	Medium	High	V. Low	V. Low	V. High	High
	Model (N& H)	N	N	H	H	H	H	H	H	H	N	H	H	N	N

4. Discussion

4.1 Geomorphological features

The Digital Elevation Model (DEM) can reveal the geomorphological features and landforms distribution of the study area (Greater Khartoum), based on the constructed slopes, as well as field investigations (fig. 3). The study area could be divided into two major groups of landforms: high landforms include escarpmental plateaus, sandstone flat plateaus, and basement low hills, while low landforms include gravelly sand desert plains, river terraces, sandy alluvial plains, wadi channels and Nile flood plains, and islands (fig. 4).

The escarpmental plateaus, about (480 m a.s.l), represent isolated, structurally controlled Nubian Sandstone blocks in the western desert near Omdurman and White Nile regions. The sandstone flat plateaus (380-400 m a.s.l.) constitute the largest highlands, with the western plateaus generally steeper than the eastern ones. Basement law hills, gravely sand desert plains, river terraces, sandy alluvial plains, and flowing Nile flood plains are all found in the region (fig. 4). The basement law hills are particularly covered granitic blocks with low relief. West and east of the Nile terraces are the gravely sand desert plains, which are made up of sandy, gravelly wadi plains on a bed of rocks. The ancient and higher banks of the Nile River courses may be represented by the river terraces, which are a gravelly decrease in breadth northward. Khartoum is the capital of Gezira (G) province, which is made mostly of the sandy alluvial plain between the Blue and White Niles (fig. 4). All landforms are traversed by the wadi channels, which split the plains, hills, and plateaus along the Nile Rivers. The Nile Course occupies the western side of the Nile Valley, while the Nile floodplains are the topographically lowest areas of the valley (fig. 4). The White Nile occupies a wide, mostly straight bed due to low-energy forming temporary bars and islands that parallel the riverbanks. The only permanent river island is Tuti Island, a half-moon-shaped strip of land where the While and Blue Nile rivers converge. The Blue Nile is narrow, with sedimentary materials deposited at the bends in front of more stable agricultural land (fig. 4).

4.2 Multi-hazard impacts of the flash floods

The study area, including Greater Khartoum, is highly susceptible to flooding and sand dune/accumulation actions, resulting in significant losses for people and property. The area is susceptible to two types of flooding risks: fluvial and plume floods (Davies and Walsh, 1997; Mahmood *et al*., 2017; and Ibrahim and Adam, 2022). Fluvial floods occur when water in the Nile rises and overflows, while plume floods result from intense rainstorm water running downwards through local ephemeral wadi channels. The study aims to assess the role of these basins in the collection and flow direction of rainstorm water and their runoff hazards by studying their geomorphological characteristics and watershed analysis (fig. 5b, 6a, and Table 2).

4.2.1 Hydro-morphometric parameters

The wadi basins and their cluster and minor outlet points are divided into sixteen major basins, WS1-WS16, which receive surface water runoff during rainstorms. These water points are considered prone areas for flash flood hazards. The basins can be divided into five spatial categories: west Nile (WN), east Nile (EN), west White Nile (WWN), east White Nile (EWN), and east Blue Nile (EBN). The most potentially influenced wadi basins within Greater Khartoum (the study area) are WS6, WS9, WS2, and WS1 (fig. 5b and Table 2). The study calculates morphometric parameters like the relief aspect parameters (e.g., Bh and Rr) as well as the areal morphometric parameters (A, P, Ff, Dd, Rc, and Re) representing area, perimeter of basin, form factor, drainage density, circularity ratio, and elongation ratio, respectively) are mainly related to the basin dimensions and to some extent to some relief parameters (e.g., ruggedness number; Rn).

And it observed that the stream order (u) is more or less proportional to the other linear parameters (e.g., Lu, Lb, Wb, and Rb, representing stream length, basin length, basin width, and bifurcation, respectively), as given in (Table 2 and Fig. 5b). The stream order is a measure of the position of a stream in the hierarchy of tributaries (Strahler, 1964). The order (u) is proportional to the total stream length (Lu). The stream ordering designates the relative position of stream segments in an erosional drainage network (Golts and Rosenthal, 1993). Drainage provides a basic to understand initial gradient, variation in rock resistance, structural control, geological and geomorphologic history of the drainage basin or water shed (Rai *et al*., 2017). As Longer and flatter larger wadis (e.g., WS1 and WS3) have higher stream orders than shorter and smaller ones (fig. 5b and Table 2). Furthermore, the short stream length describes steep slopes while longer lengths indicate relatively flatter gradient (Withanage *et al.,* 2015). The difference in parameters values between larger, moderate, and smallest basins may support their variation in lithology, infiltration rate, and slope gradient, rather than climatic conditions and land use factors. This is supported by ArcGIS software and standard formulas (Table 2).

4.2.2 Hazard impacts

Khartoum State has been the second worst-hit by floods in 1988, 2013, and 2014, with flash flooding risk from wadi channels (Walsh *et al*., 1994, and Mahmood *et al.,* 2017). These channels collect runoff water to the Nile River during rainstorms, causing severe damage to urban settlements (fig. 6). The impacts include widespread street flooding and damage to infrastructure, industry, public services, schools, and transport routes. Heavy rainstorms and flash floods have also affected the Omdurman and Omm Badda areas, washing away thousands of homes, damaging infrastructure, interrupting public services, and increasing the risk of epidemic diseases due to lack of clean potable water (Davies and Walsh, 1997, and Mahmood *et al.,* 2017). Basins WS1, WS2, and WS3 in the White Nile, Blue Nile, and main Nile courses are considered the most hazardous, causing severe flash flooding (fig. 5b and 6, Table 2 and 3).

Observation of Walsh *et al*., (1994) at Khartoum during summer rainstorms suggests that all storms > 10 mm tend to produce overland flow and flooding of local topographic hollows. More widespread road, street, and house flooding starts to occur in larger rainstorms as surface depression storages are exceeded, local pools coalesce, and diffuse runoff is generated. Confirming the conclusion of Mahmood *et al*., (2017), during the field trip, several planning problems were observed, including uncontrolled building of informal embankments and barriers across the floodwater path away from some basins (e.g., Wadi Seba (WS2), WS1) as well as the unsuitable design of box culvert and tunnel sites.

4.3 Sand dune/encroachment

The sand dune and sheet change detection are of great importance in the documentation of the recent landscape dynamics and their negative impacts on the cultivation and urbanization activities in the study area (Greater Khartoum); see figure (7a &b). Sand dunes of various kinds and densities can be found in the Sudanese and Saharan deserts, especially in the northwest of the Northern State (El Gamri, 2020). Although sand dunes in the country can be either fixed or mobile, mobile sand dunes pose a serious risk to residential areas and agricultural lands (El Gamri, 2020).

Consequently, the present study focused on assessing sand dune bodies spatial modification over time, which may provide environmental data for land use planning. The study area, based on the use of Remote Sensing and GIS techniques over the past decades, was supported by field checks.

According to Gamri (2003), the Sudan affected by drought and desertification amounts to about 50.5% of the total area of the country. The detection of the sand dunes (bodies) over almost 30 years is based on the interpretation of the 1995 Landsat image (fig. 7), the 2023 Landsat image, and the Sentinel-2 image satellites. The change detection is the monitoring of the differences of the state of a phenomenon and of an object by supervising them at different times (Mohamed and El-Raey, 2019).

The rate of these changes is not equal and homogeneous. During the 1995 to 2023 period, no considerable spatial changes are recorded and documented on the sand bodies in the wadi basins, while major changes are detected in the sand bodies of the gravelly sand desert landform. It is found that the sand dunes/bodies are the most changeable and consequently will be the most hazardous source area.

4.3.1 Spatial distribution and impacts

One of the geomorphological hazards related to sand dunes, which result in wind erosion and sand accumulation, is the analysis of which is critical for interpretation of environmental hazard and future desertification potential. Based on RS and GIS-interpreted data that support field investigation, the sand dunes/accumulations occur in two major landforms, namely wadi channels and gravelly sand deserts.

In the gravelly sand desert landform, scattered sand dunes/encroachment occur as different types and sizes of dunes and linear dunes. Many sands encroachment act as stable base cover on which sand dunes may migrate. On the other hand, the morphological features of these sand bodies may indicate that they have been formed under past sandstorm regimes with a strong north and northwestern wind vector (Table 1 a and b). In spite of this dominant orientation, some dunes seem to be affected in flat desert by more than one wind direction (Table 1a & b). Furthermore, the field study reveals that most of the sand dunes are established upon the Nubian Sandstone bedrocks, which are occasionally exposed as plateau landforms (see figs. 4 & 7).

In the majority of the western wadi basins, sands are partially stabilized by little vegetation, and consequently they are considered a source of hazardous movable sand encroachment, particularly within their margins and surrounding areas (fig. 7). However, some of the channel sands are highly vegetated, like those of the southeastern corner of the study area, and consequently became stable sand bodies. These shifting sands could erode the banks of the Nile River and destroy its agricultural lands.

4.3.2 Impacts of the sand dunes/encroachment

Revealing different forms of sand dunes, sand encroachment has negative impacts on cultivated lands along the Nile banks and residential areas in Greater Khartoum (the study area). sand encroachment is the most serious environmental problem affecting different ecological and socio-economic aspects particularly in northern regions as triggered by the north-easterly winds that mostly prevail during February - May (El Gamri, 2020). Sand encroachment deteriorates fertile riverbank soil and reduces productivity.

The development of unstable sand dunes and sheets threatens cultivated lands, paved roads, and railways. Mobile sands may cause Nile River bank erosion and destroy cultivated lands. Dune movement and migration represent an environmental hazard to agriculture, railway, roads and human settlement (Hidore and Albokhair 1982; Watson 1985; Al-Harthi 2002; Abu Seif and El-Khashab 2019). These factors contribute to the negative impacts on the Nile River and the surrounding areas.

4.4 Integrated natural causative factors

The accumulation of runoff water (flash flood) and sand dune hazardous impacts are primarily controlled by heavy rainstorm intensity, topographic slope, bedrock infiltration rate, and wadi basin system characteristics. Climatic changes and land uses, such as population pressure and human interference, also trigger these impacts. Flash floods are only damaging after large local rainstorms, with an average frequency of at least 40 millimeters in Khartoum being 1.6 and 0.7 days per year (Walsh *et al.*, 1994). Changes in heavy rainstorm magnitude and frequency and urbanization changes will influence flash flooding frequency and severity. Sudan, a region prone to climate change, is experiencing increased rainfall and sandstorms, leading to severe aeolian activities and a lack of soil moisture and vegetation growth. This has increased the risk of weather-related hazards like storms, runoff water, and wind erosion. The bedrock and lack of vegetation significantly influence drainage patterns and sand dynamics, affecting runoff, wind erosion, and desertification potential. The main bedrock in Sudan is moderately sloped ferruginous Nubian sandstone, which borders wadi basins (e.g., WS9, WS6, and WS1), triggering slope instability and flash floods.

Hazards in wadi basins depend on bed soil infiltration rate and hydro-geomorphological characteristics. Infiltration rate is influenced by impermeable bedrocks' texture and depth, as well as permeability. Ferruginous sandstone bedrocks have low retention potential, increasing flash flood potential, while scattered sand dune have high infiltration rates, partially reducing surface runoff potential.

4.5 impacts of human interference factors

The rise in natural hazards is a result of climate change, global warming, and human interferences like land use change, rapid population growth, and urban growth (Villarini *et al.*, 2011; Agbola *et al.*, 2012; Mohmood *et al.*, 2017). The rapid population growth in Greater Khartoum, from 1.7 million in 1956 to over 5 million in 1983 (Davies and Walsh, 1997). Has led to uncontrolled urban expansion into vulnerable sites, increasing susceptibility to flash floods and sand dune dynamics. Factors contributing to this include lack of urban planning, mismanagement of natural and human resources, and lack of experience and preparedness for environmental hazards (Table 3).

Poor urban planning in Greater Khartoum has led to settling in unsuitable lowlands, exposing people to natural hazards. Urbanization near cultivated lands, mobile sand dunes, and escarpmental plateaus can cause severe damage unless mitigation measures are taken. Construction of unpaved roads and excavation for foundations can trigger further natural hazards. Constructed settlements near major channels, such as Khor Shambat and Khor Abu Anga (WS6&WS9), are at the highest risk of severe flash floods, damaging urban infrastructure and disrupting natural drainage (fig. 6). Flood impacts will be exacerbated by disruptions to natural drainage caused by roads, railways, and buildings (Walsh *et al*., 1994).

Human activities can change natural drainage and vegetation patterns, increasing the risk of runoff water and flood impacts (Table 3). Urban expansion in low-lying floodplain areas, like Khartoum North, can cause infiltration of floodwater, rising groundwater tables, chemical erosion, and land subsidence. The situation is unplanned due to inadequate runoff drainage infrastructure and urban drainage systems. Poorly constructed storm drains, lack of maintenance, and sediment accumulation contribute to blockages and malfunctions (Ibrahim and Adam, 2022). Local drainage is also inefficient in responding to erratic rain, making rainstorms and floods dangerous hazards in the area; the situation is unplanned and needs improvement (Zerboni *et al.*, 2021).

The expansion of illegal settlements in the Nile region, replacing flood-prone cultivated lands, and the misuse of fertile Nile mud soils are causing irreversible loss of resources. This is also affecting the archaeological heritage of the west White Nile region, with invasive buildings disrupting natural landscapes. An integrated geo-environmental management plan is needed to prevent or reduce environmental degradation in Greater Khartoum (Table 3 and 4).

4.6 Integrated environmental risk assessment of land use units

4.6.1 Land units definition and limitations of assessment

The Greater Khartoum area's risk assessment is a complex process that involves dividing the area into seven sectors and fourteen land units. These sectors are based on physiographic and geomorphological features, land uses, and existing and proposed land uses (Table 4). The study area is divided into sectors A, B, C, D, E, F, and G, with further land units numbered Ax, B1x, B2p, C3x, C4p, C5p, D6x, D7x, E8x, E9x, E10p, E11p, Fx, and Gx (fig. 8). Sector A (Halfaya); located between Al-Wadi Road and Al-Maouna Road, includes the floodplain and cultivated lands along the Blue Nile (fig. 3b), which reaches its peak between July and September. Sector B (Bahri), located between the Ring Road and Al-Maouna Road, includes Khartoum North's urban and agricultural extension. It is situated on a flat alluvial plain and Nile terraces deposits, with an elevation of 381 meters. This sector could be further subdivided into existing urban and cultivated land units (B1x) and narrow barren strip terraces west of Basement Hill (B2p). Sector C (Sharg), east of the Ring Road, is a flat desert with sand sheets, plateaus, and Wadi channels (e.g., units C4p and C5p), except(C3x) for reclaimed cultivated land and scattered urban areas (fig. 8).

Sector D (Ombada) is located west of the Omdurman area and Salha Road and is a sandy desert with scattered escarpmental plateaus and hills. It could be subdivided into D6x and D7x. Sector E (Omdurman), west of Al-Wadi Road, includes Omdurman city and is on higher undulating ground under Nubian Sandstone bedrock. It could be subdivided into four land units: E8x, E9x, E10p, and E11p. Sector FX (Salha) is west of the White Nile, is an elongated desert belt bounded by Salha Road, and is almost entirely occupied by an important archaeological prehistoric site. The sector GX (Gezira sector), between the Blue and White Niles, occupies the Gezira cultivated area and Khartoum city (fig. 8).

The spatial distribution of the risk assessment of the physiographic sectors and their human activities survey data were used as the source key for land use units' evaluation. However, several limitations and difficulties have been faced for their assessment processes due to the high environmental sensitivity, misleading proper land use change data, and lack of local large rainstorms and sand dune frequency data. Therefore, it is difficult to assess the flash floods and sand dune hazards and controllers.

Field investigations are recommended for mitigation measures. Despite limitations, the risk levels of the study area were estimated based on all available data, and further studies are recommended to improve its potentiality.

4.6.2 Risk parameters and levels

This assessment analyzed five risk parameters, including physiographic, geomorphological, geological, environmental hazards, and land use considerations, and twenty-two parameters derived from natural and anthropogenic influences (Table. 4). The risk level associated with land use and human activities was evaluated by analyzing the spatial distribution of cultivated lands and built-up areas, as well as the spatial distribution and magnitude of environmental hazards parameters. The risk level is expected to escalate with the increase in negative environmental impacts, with each land unit having its average risk level. A semi-quantitative flexible risk assessment was developed, guiding ongoing monitoring and adaptive management to mitigate risks in each land use unit. A semi-quantitative flexible risk assessment scale, ranging from 0 to 10 (approximately average), was developed to prioritize ongoing monitoring and adaptive management in each land use unit to mitigate risks (Table. 4).

4.6.3 The geomorphological risk models

Two geomorphological models, (N) and (H), are formed by the integrated geo-environmental risk assessment, which finds notable differences between land units in the Nile floodplain, terrace landforms, and hilly desert land units. The (N) model is distinguished by its low topography, closeness to Nile courses, and growing risks from both natural and man-made hazards (Table 4). Reduced arable land due to urbanization has resulted in environmental deterioration processes such as weathering, waterlogging, soil liquefaction, salinization, and structural weakening. These land units are the focus of risk management and remediation because they are thought to be more vulnerable to environmental threats.

The model (H) is characterized by its distance from the Nile courses, high altitude, and increasing vulnerability to natural hazards. It is particularly threatened by hazard-prone land units, such as C3x, C4p, D6x, D7x, and E8x (Fig. 8). These land units are prone to land degradation due to sand encroachment, wind erosion, and flash flood hazards, which are predicted to increase with climate change. The model (H) is classified as low to medium on average and can be further refined into four risk zones.

The study categorizes land units into medium- to high-risk zones, with higher potential for environmental degradation due to flash floods, instability, and land use hazard conditions. Medium-risk zones include D6x and B2x, with lower magnitude hazards. Low-risk zones C3x and C4x are low-risk, while very low-risk zones E10x, C5x, and E11x are low-risk. Higher elevation, stable areas are proposed for urbanization, while lower desert areas require moderate mitigation measures (Table 4).

4.7 Integrated management procedures

In addition to the previously mentioned geohazards, Greater Khartoum is experiencing unchecked urban and agricultural growth. Weak institutional arrangements, inefficient management systems, low expert personal capacity, and fragmentation in public policy and decision-making are characteristics of the Khartoum region's environmental situation and protection measures. For example, Khartoum's current urban drainage system is obstructed by waste, resulting in inadequate management (Mahmood *et al.,* 2017). Several mitigation measures and strategies are suggested as an integrated part of the land use vulnerability to flash floods and sand encroachment management plan in order to prevent or lessen hazards, as well as to enhance the potentiality of the preservation of urban and cultivated lands.

Greater Khartoum needs to increase and redesign existing structural mitigation measures, such as culverts and water tunnels, to improve flood flow capacity. Regularly removing obstacles and solid waste from storm drains can improve water flow potential. Houses built on natural drainage channels should be removed and relocated to non-runoff-prone areas. Mahmood *et al*., (2017) suggest connecting vulnerable areas with proper sewerage networks to reduce health hazards during floods. Improving facilities before and during flood events is crucial.

At significant water points, especially west of the Omdurman region, protective measures like zigzag barriers are advised in order to lower runoff water velocity and flood risks during intense downpours. Shallow aquifer recharge and downward infiltration are made possible by these barriers. In order to safeguard homes and agricultural areas from the dangers of flash floods and sand dunes, remediation techniques like planting vegetation and creating shelterbelts are also required. Natural stabilizers, like those in Khartoum, have proven to be more effective than fences or artificial chemicals (Watson, 1985). Public awareness of flood-prone areas and pathways is essential to reducing flood risks and improving adaptive capacity. It is crucial to set up emergency response plans, flood warning and monitoring systems, and ongoing runoff drainage network maintenance. Additionally, it is essential to advocate for political support, community involvement, and awareness-raising.

5. Conclusions and recommendation

The Greater Khartoum area faces environmental hazards due to inadequate urban planning and mismanagement, affecting institutional, technological, and cultural components. Although efforts have been made, the region is still susceptible to sand dune/encroachment and wadi channel flash floods. exacerbated by climate change, population pressure, and human interference. The study suggests an integrated approach to understand the causative factors controlling these hazards and determine mitigation measures. Uncontrolled urban expansion and climate change threats should be considered in management plans, as human interference can alter natural drainage patterns and increase flash flood risks.

Uncontrolled settlement growth is causing a reduction in Nile flood fertile lands and destruction of White Nile archeological sites, which are crucial for cultural tourism. To address this, a multi-risk analysis using remote sensing, GIS, and DEM data was conducted on proposed physiographic sectors and their subdivisions. Two geomorphological risk models, Nile floodplain/terraces (N) and hilly deserts (H), were developed to evaluate the spatial distribution and impacts of these factors. The risk assessment is complex due to changeable environmental factors like climate and land use changes. Strengthening regular monitoring capacities and increasing public awareness about climate change impacts are recommended. Sufficient data is also recommended for environmental impact assessment reports for each urban development project to avoid unnecessary environmental problems.

6. Acknowledgments

We would like to express our sincere gratitude to Geology department at Cairo University and Geological Research Authority of the Sudan (GRAS) for their outstanding technical facilities. Our success has been greatly aided by your support, which has been essential to the advancement of our research.

7. References

Abu Seif, E. S. S., & El-Khashab, M. H. (2019). Desertification risk assessment of sand dunes in middle Egypt: a geotechnical environmental study. Arabian Journal for Science and Engineering, 44, 357-375.

Agbola B.S., Ajayi O., Taiwo O.J. & Wahab B.W (2012). The August 2011 floods in Ibadan, Nigeria: anthropogenic causes and consequences. Int J Disaster Risk Sci 2012, 3, (4), 207–217.

Al-Harthi, A. (2002). Geohazard assessment of sand dunes between Jeddah and Al-Lith, western Saudi Arabia. Environmental geology, 42, 360-369.

Awad, M. Z. (1994). Stratigraphic, palynological, and paleoecological studies in the East-Central Sudan (Khartoum and Kosti Basins), late Jurassic to mid-Tertiary. Ph.D. thesis, Free Uni. Berlin, pp. 149.

Bhalotra, Y. P. R. (1963). Meteorology of the Sudan. memoir Nr. 6. Sudan Meteorological Department.

Davies, H. R. J., & Walsh, R. P. D. (1997**).** Historical changes in the flood hazard at Khartoum, Sudan: lessons and warnings for the future. Singapore Journal of Tropical Geography, 18(2), 123-140.

El Gamri, T. (2020). Sand Dunes: Mechanisms, Impacts and Control Measures in the Sudan. Environment and

Natural Resources International Journal (ENRIJ), 5, 01-16.

Ibrahim, E.M. & Adam, E.A. (2022). The Crisis of Runoff Control in Greater Khartoum. GSJ: Volume 10, Issue 10, October 2022, online: ISSN 2320-9186.

Farah, E. A., Abdullatif, O. M., Kheir, O. M., & Barazi, N. (1997). Groundwater resources in a semi-arid area: a case study from central Sudan. Journal of African Earth Sciences, 25(3), 453-466.

Gamri, T. E., & Nasikh, E. E. (2003**).** Desertification Studies in the Sudan. Annals of Arid Zone, 42(3 & 4).

Geological Research Authority of Sudan (GRAS), (2016). Geological map of Sudan. https://gras.gov.sd.

Golts, S. & Rosenthal, E. (1993). A Morphotectonic Map of the Northern Arava in Israel, Derived from Isobase Lines. Geomorphology, 7, 305-315.

Haj mousa M. M. (2019**).** The impact of perched groundwater bearing layers on the engineering performance of civil structures, Omdurman Old District, Khartoum, Sudan (unpublished, MSc).

Hidore, J. J., & Albokhair, Y. (1982). Sand Encroachment in Al-Hasa Oasis, Saudi Arabia. Geographical Review, 72(3), 350-356.

Howarth, P. J., & Boasson, E. (1983). Landsat digital enhancements for change detection in urban environments. Remote sensing of environment, 13(2), 149-160.

Mahmood, M. I., Elagib, N. A., Horn, F., & Saad, S. A. (2017). Lessons learned from Khartoum flash flood impacts: An integrated assessment. Science of the Total Environment, 601, 1031-1045.

Meteorological Authority. (2023). The Ministry of Irrigation and water resources, Khartoum, Sudan.

Mohamed, S. A., & El-Raey, M. E. (2019). Land cover classification and change detection analysis of Qaroun and Wadi El-Rayyan lakes using multi-temporal remotely sensed imagery. Environmental monitoring and assessment, 191(4), 229.

Oliver, J. (1965). The climate of Khartoum province. Sudan Notes and records, 46, 90-129.

Patino, J. E., & Duque, J. C. (2013). A review of regional science applications of satellite remote sensing in urban settings. Computers, Environment and Urban Systems, 37, 1-17.

Rai, P. K., Mohan, K., Mishra, S., Ahmad, A., & Mishra, V. N. (2017). A GIS-based approach in drainage morphometric analysis of Kanhar River Basin, India. Applied Water Science, 7, 217-232.

Reba, M., & Seto, K. C. (2020). A systematic review and assessment of algorithms to detect, characterize, and monitor urban land change. Remote sensing of environment, 242, 111739.

Strahler AN (1964). Quantitative geomorphology of drainage basins and channel networks. In: Chow, V., Ed., Handbook of Applied Hydrology, McGraw Hill, New York, 439-476.

Villarini, G., G. A. Vecchi, T. R. Knutson, M. Zhao, & J. A. Smith (2011). North Atlantic tropical storm frequency response to anthropogenic forcing: Projections and sources of uncertainty, J. Clim.

Walsh, R. P. D., Davies, H. R. J., & Musa, S. B. (1994). Flood Frequency and Impacts at Khartoum since the Early Nineteenth Century. The Geographical Journal, 160(3), 266–279. https://doi.org/10.2307/3059609.

Watson, A. (1985). The control of wind-blown sand and moving dunes: a review of the methods of sand control in deserts, with observations from Saudi Arabia. Quarterly Journal of Engineering Geology and Hydrogeology, 18(3), 237-252.

Whiteman, A. J., & Whiteman, A. (1971). The geology of the Sudan Republic.

Withanage, N. S., Dayawansa, N. D. K., & De Silva, R. P. (2015). Morphometric analysis of the Gal Oya River basin using spatial data derived from GIS. Tropical Agricultural Research, 26(1).

Zerboni, A., Brandolini, F., Mariani, G. S., Perego, A., Salvatori, S., Usai, D., ... & Williams, M. A. (2021). The Khartoum-Omdurman conurbation: a growing megacity at the confluence of the Blue and White Nile Rivers. Journal of Maps, 17(4), 227-240.

تقييم مدى التعرض للفيضانات المفاجئة في الخرطوم الكبرى، السودان: نهج متكامل

نورالدين حسن ابكر [1] ، ومحمد إبراهيم الأنبعاوي [1]، والشيخ محمد عبدالرحمن [٢]، وتامر حسن نصار [١]

[١] قسم الجيولوجيا، كلية العلوم، جامعة القاهرة، الجيزة، جمهورية مصر العربية

[٢] كلية النفط والمعادن، جامعة النيلين، الخرطوم، جمهورية السودان

تبحث هذه الورقة البحثية في مدى تأثر منطقة الخرطوم الكبرى بالفيضانات المفاجئة الناجمة عن العواصف الممطرة الشديدة، والتي قد تصبح أكثر تواتراً بسبب تغير المناخ والكثبان الرملية/التعديات. تستخدم الدراسة رسم الخرائط الجيولوجية البيئية، والعمل الميداني الرصدي، والاستشعار عن بُعد، وتقنيات نظم المعلومات الجغرافية، وتحليل مستجمعات المياه، وتفسير البيانات المناخية لتحديد المنطقة على أنها أكثر عرضة للفيضانات المفاجئة من فيضانات الأنهار والكثبان الرملية/التعديات. تم إجراء تقييم لتأثير المخاطر المتعددة باستخدام العوامل المسببة الطبيعية والبشرية. تمت مناقشة العوامل الجيولوجية والمناخية وعوامل استخدام الأراضي المتكاملة. أدى نمو مناطق الخرطوم وأم درمان والخرطوم بحري دون خطط حضرية وزراعية مناسبة إلى آثار سلبية شديدة على المجتمعات العامة والتراث الثقافي في المواقع الأثرية غرب ضفاف النيل الأبيض. تقترح الورقة نموذجين للمخاطر الجيومورفولوجية: سهل/مدرجات النيل الفيضي (شمال) والصحاري الجبلية (ح) لتقييم المخاطر. تتطلب الطبيعة المعقدة لتقييم المخاطر بسبب العوامل البيئية المتغيرة نهجًا متكاملًا. وتقترح الدراسة أيضًا إجراءات إدارية متعددة للتخفيف من التأثيرات السلبية المتوقعة لفيضانات الجريان السطحي بسبب الاستخدام المتغير للأراضي في المنطقة وظروف المناخ.