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Hydrological problems of flash floods and the encroachment of wastewater affecting the urban areas in Greater Cairo, Egypt, using remote sensing and GIS techniques

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Abstract

Background: This paper discusses the hydrological problems assessment of flash floods and the encroachment of wastewater in selected urban areas of Greater Cairo using remote sensing and geographic information system (GIS) techniques. The integration of hydrogeological and geomorphological analyses with the fieldwork of drainage basins (Wadi Degla) hosting these urban areas endeavors to provide the optimum mitigation measures that can be feasibly taken to achieve sustainability of the urban areas and water resources available.

Results: Landsat 5 and Sentinel-2 satellite images were obtained shortly before and after flash flood events and were downloaded and analyzed to define the active channels, urban interference, storage areas, and the natural depressions response. The quantitative flash flood estimates include total GSDMap meteorological data sets, parameters of rainfall depths from remote sensing data, active channel area from satellite images, and storage areas that flooded. In GIS, digital elevation model was used to estimate the hydrographic parameters: flow direction within the catchment, flow accumulation, time zone of the catchment, and estimating of the water volume in the largely inundated depressions.

Conclusions: Based on the results obtained from the study of available satellite images, it has been shown that there are two significant hydrological problems, including the lack of flash flood mitigation measures for urban areas, as the wastewater depressions and sanitary facilities are dotting in the downstream areas.

Keywords: Flash floods, Wastewater, Remote sensing, GIS, Urban areas, Egypt

Background

Populated areas in dryland regions have experienced great difficulties in better managing inhabited lands, which are usually under severe hydrological stress (Arzani 2010; El Bastawesy et al. 2013a, b). According to the hydrological systems, surface water supplies to urban areas can be a significant factor limiting the degree of land use (El-Baz et al. 2000; Rubin 1991; Tooth 2000). However, economic expansion has led to the creation of

important urban and industrial centers in many dryland areas where there is an adequate supply of surface water (Hutchinson and Herrmann 2008).

Urban areas' growth and their infrastructure networks take place to the detriment of the surrounding landforms which differ in their geological and hydrological properties. The most suitable locations for urban development are the low relief areas of alluvial fans, wadi beds, and piedmonts (Dunne 1991). Notwithstanding, these areas in drainage basin outlets usually contain potential aggregate and row deposit supplies for building materials as well as groundwater resources fed by periodic rainstorms and flash floods (Blair and McPherson 1994).

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Consequently, flash floods' impact on urban areas may vary from catchment to catchment and even within the same catchment themselves depending on sediment loads (El Bastawesy et al. 2009). Besides, the encroachment of urban features on alluvium beds increases surface runoff coefficients due to laying down on the surface of impermeable parcels and pavements (El Bastawesy et al. 2013a, b).

Flash floods are one of Egypt's principal natural disasters that cause cutting roads, sweeping away homes, and damaging power lines. Flash floods occur mostly in the Eastern Desert and Sinai regions, where high terrain and incised wadis are present (Yousif and Hussien 2020; Mahmoud et al. 2020).

Recently, in urbanized areas within dryland countries, the creation of a perched water table, wastewater seepage, and wastewater ponds has become common (El Bastawesy et al. 2012; Bahabri 2011). Indeed, dealing with wastewater, which is released at a rate faster than its proper disposal, is a major challenge for most urban areas in the dryland (Abuzaid and Fadl 2016, 2018) and it is very harmful to the groundwater quality (Farrag et al. 2019; Megahed and Farrag 2019).

Therefore, the importance of understanding the hydrological processes of these drainage basins is to avert the negative impact of flash floods, prone areas to wastewater seepage and pond (Chin and Gregory 2001; Cooke et al. 1982). Unfortunately, dryland hydrological measurements remain insufficient to establish a detailed description of these systems. Moreover, the hydrological procedures are not fully understood and the hydrological models are uncalibrated (El Bastawesy et al. 2009). Nevertheless, most of these data are also limited and obtained by individuals or organizations during pilot projects and case studies which cannot reflect the diversity of dryland

processes (El Hames and Richards 1998; Robinson 1994). This is why sudden flash floods often lead to devastation, and the wastewater impact is gradually increasing (White 1995).

Remote sensing provides a fast data collection tool using multiplied spectrum wavelengths, allowing for accurate diagnosis at different time intervals of the different land use and land cover. Hydrological data indices include water ponds, waterlogged areas bodies, and active channels within a specific catchment which can be achieved using the multi-temporal sets of satellite images. (Subyani et al. 2009; El Bastawesy et al. 2008). Data sets have been widely obtained using GIS due to its ability to handle remote sensing data and thematic maps (Foody et al. 2004; Maidment 1993; Robinson 1994).

This research uses remote sensing and GIS with field measurements to study the effects of recent flash floods that affected several urban areas in Greater Cairo. Wadi Degla was included as the chosen catchment for this research, representing various types of flash floods in terms of wadi system distribution and response.

Description of study area

Location and climate

The study area is occupied by numerous wadi systems, but Wadi Degla has a particular significance as its hydrological regime affects large urban areas and roads in the southeast part of Greater Cairo. Wadi Degla is one of the important wadis with a length of 30 km. It is located between latitudes 29° 51' 51" N to 30° 00' 34" N and longitudes 31° 16' 03" E to 31° 39' 11 E (Fig. 1). It passes through the limestone rocks in the Eastern Desert that had remained in the marine environment during the Eocene Epoch. Therefore, it is fossils rich. The height of these rocks is about 50 m along the wadi. The rainwater

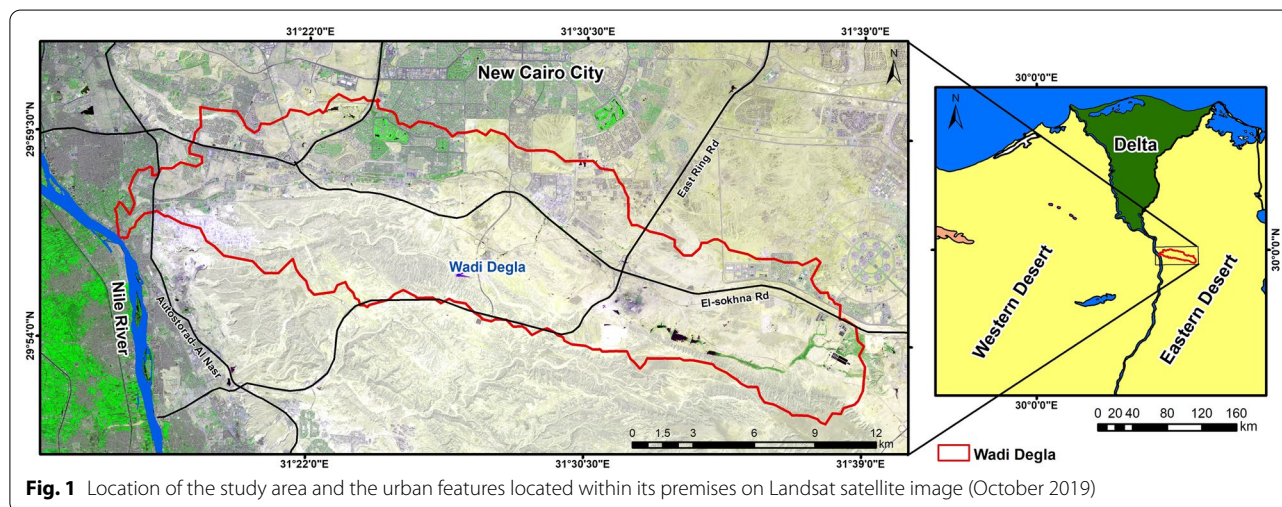


Fig. 1 Location of the study area and the urban features located within its premises on Landsat satellite image (October 2019)

dropping from the waterfalls affected the limestone rocks over the years. Wadi Degla catchment was selected for the hydrological analyses which exceeds area about 200 square kilometers, and its main wadi floor is occupied by the Al Qattameyah–Ain Al Sukhna Road numerous urban areas in Al Maadi area. The climatic data are the most essential hydrological parameters to assess the flood risk in the study area. Generally, the mean annual rainfall precipitates about 23 mm in winter season in the study area according to the Egyptian Metrological Authority (EMA 2019). The mean maximum temperature is recorded about 34.7 °C in June, while the mean minimum temperature is recorded in January about 9 °C and the relative humidity ranges between 40 and 56% (Table 1).

Geological and geomorphological setting

According to digital elevation model (DEM) and topographic map, the geomorphologic map of the study area illustrates that it contains three main geomorphologic units including Nile flood plain, piedmont plain, and structural plateau (Fig. 2). The Nile flood plain including the delta of Wadi Degla constitutes an area of about 355 km², and it was originated by a tectonic depression. It is almost flat having elevations less than 50 m above mean sea level (asl). Piedmont plain is a transition zone between the Nile flood plain and the plateau units. It dominates an area of about 500 km² with elevation ranges from 50 to 350 m asl. The structural plateau is formed up mainly of limestone and is dissected by several sets of normal faults. It has an area of about 700 km² with

elevations between 250 and 615 m asl. It represents the upstream of the different Wadis.

Geologically, the study area is dominated by sedimentary rocks of tertiary and quaternary ages. The southern part of Wadi Degla contains the oldest exposed rock outcrop which is represented by the Tertiary Eocene limestones of Mokattam Group. The clastic shale sediments of Maadi formation cover a considerable area of Wadi Degla underlying Mokattam limestone. The Maadi formation is then overlain by the Oligocene rocks comprising the Gebel Ahmar Formation, which dominates a wide area of the New Cairo City and made up of sandstones and gravels. The basaltic sheet flows cap the Gebel Ahmar Formation in some parts (Moustafa and Abd-Allah 1991). The Miocene Hagul Formation is represented by non-marine deposits of fluvial sands and gravels, while the Pliocene sediments are represented by Kom El-Shelul Formation that is made up of calcareous sandstone (2–5 m) (Said 1990). Moreover, undifferentiated Pliocene deposits are found overlying Kom El-Shelul formation in some localities (CONOCO 1987). Finally, the Quaternary deposits dominate the floor of the wadis, which drains to the Nile. It covers all the area around the Nile as well as the cultivated lands. It is made up of silt and clay with sand interbeds (Fig. 3).

Methods

Two satellite images of the Landsat Enhanced Thematic Mapper (ETM) and Sentinel-2 were acquired (www.usgs.com) to detect land-use/land-cover changes and flash floods indices from 1984 to 2019 (Fig. 4a, b). Enhanced images were interpreted using ArcGIS 10.1

Table 1 The average climatic records of the study area during the period (EMA 2019)

Month	Temperature C°			Rainfall (mm)	Evaporation (mm/day)	Humidity (%)
	Maximum	Minimum	Mean			
Jan	19.7	9	14.35	25	5.5	56
Feb	22.3	7	14.6	17	7.6	48
Mar	25.4	9.9	17.7	13	10.9	41
Apr	30.2	13.8	22	8	15.7	46
May	33.9	17.4	25.6	2	18.4	45
Jun	34.7	20.3	27.5	19	20.1	46
Jul	26.9	20.1	23.5	5	17.7	43
Aug	26.6	21.5	24.05	6	16	47
Sep	24.9	20.2	22.5	9	15.6	47
Oct	21.2	16.6	18.9	23	11.8	49
Nov	25.4	12.3	18.8	12.5	7.9	40
Dec	21	7.5	14.2	10	5.7	44
Total	354.5	172.1	263.1	149.5	152.9	552
Mean	37.7	14.3	21.9	12.5	12.7	46

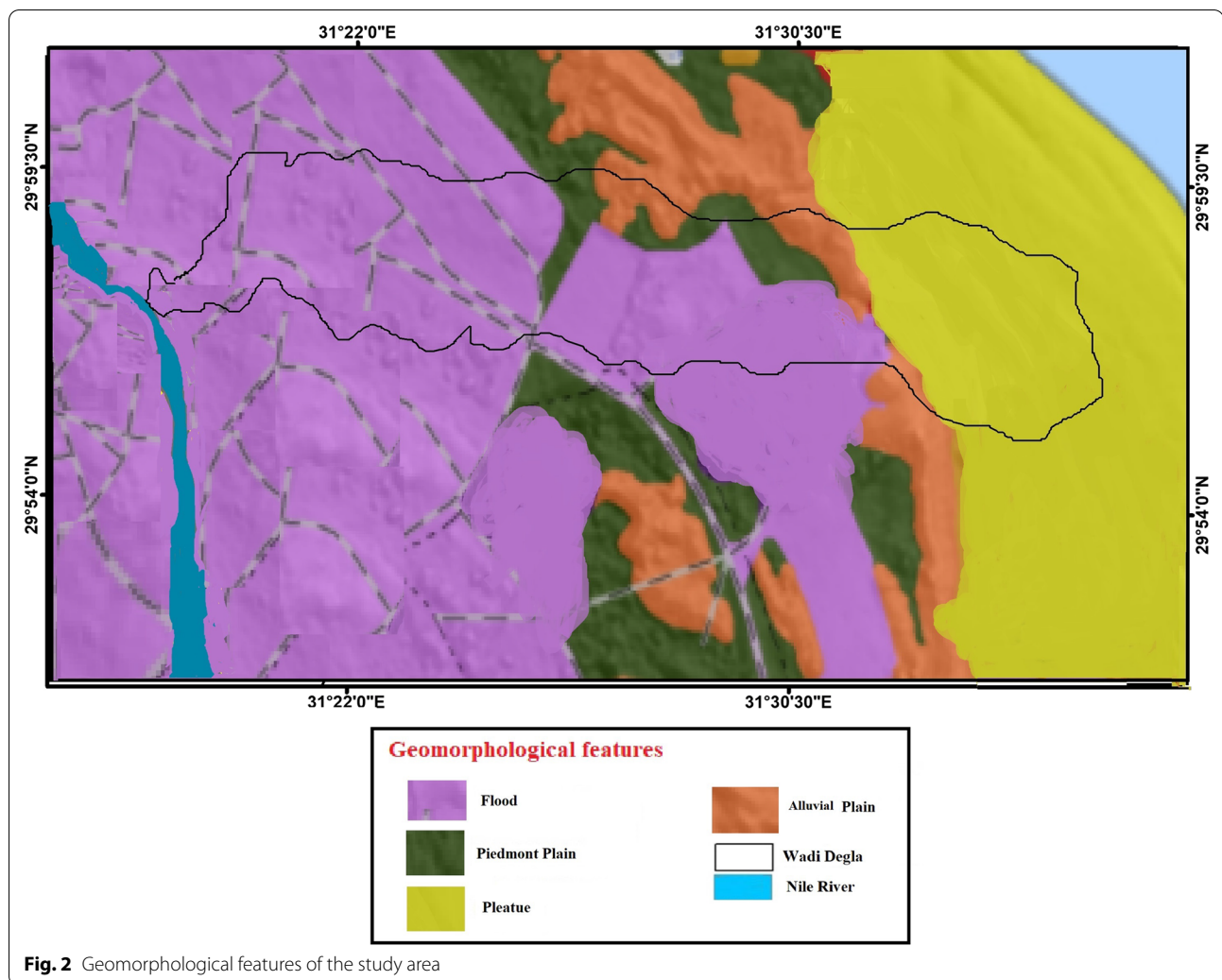
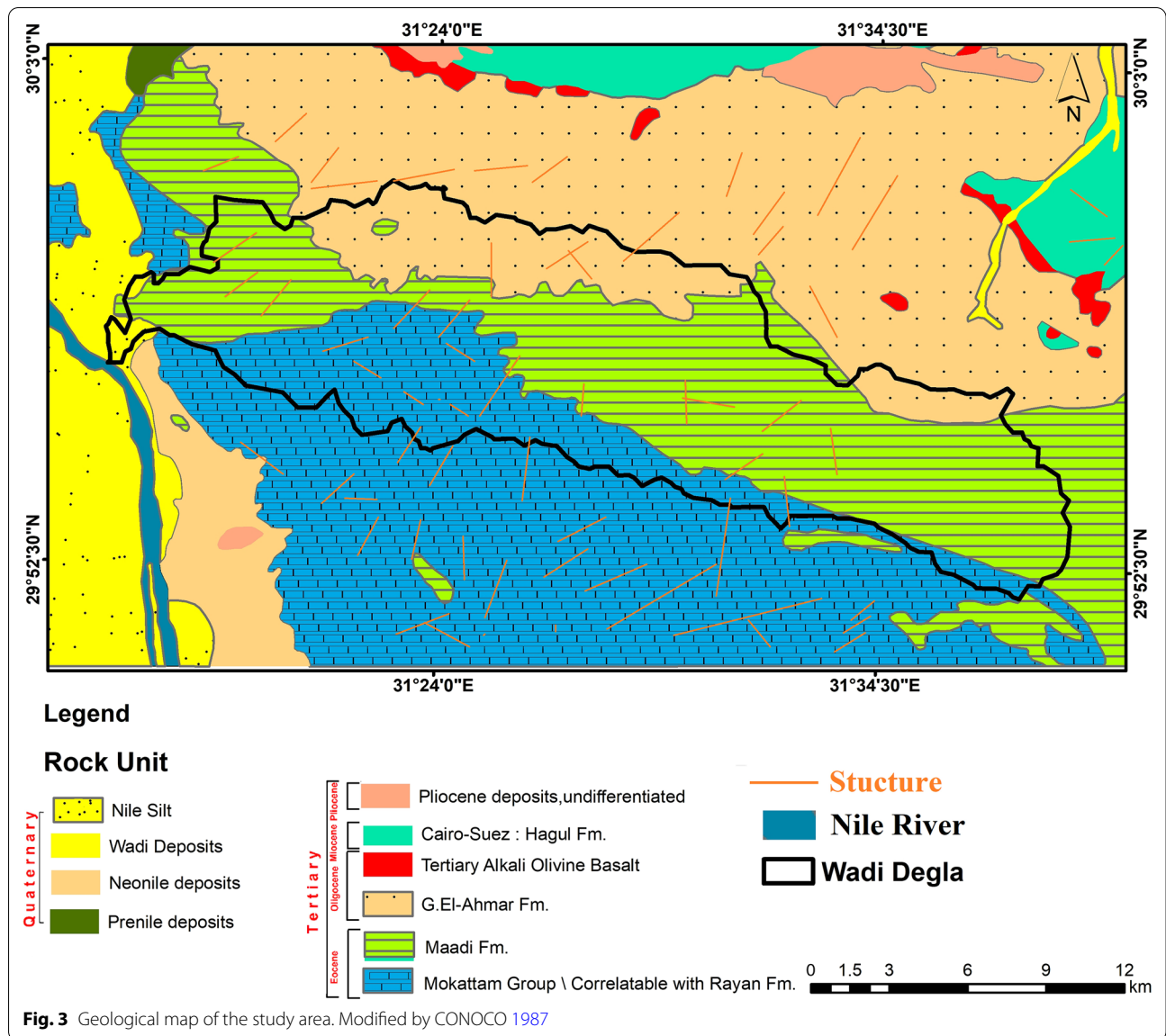


Fig. 2 Geomorphological features of the study area

software (ESRI 2006) to produce the thematic maps, urban features, active channels to determine the active contributing areas within the catchment, wastewater ponds, and road networks and their intersections. The automatic classification techniques for these images have been ignored because features sites select in older dates during unsupervised classifications are difficult. Then, different features were digitized from the various images to quantify changes and the active channels in the study area. The land cover map obtained shows that flash floods in this area have environmental, economic, and social impacts.

Thereafter, the topographic maps of scale 1:50,000 (EGSA 1991–1997) were scanned and digitized to create a 20 m resolution digital elevation model (DEM) for the western part of the study area. The digitized map sheets are of Cairo, East Cairo, Jabal Al Anqabayah, Bir Gindaly, and Helwan (Fig. 5a). The

created DEM was processed to extract the hydro-graphic parameters for the catchment of Wadi Degla affecting the Al Maadi area using ArcGIS 10.1 software and Erdas/Imagine 9.2 (2014) for maps analysis (rectification, subset, and mosaic) (Fig. 5b, c). The embedded “D-8” algorithm enables the automated extraction of these parameters through multiple steps including sink filling in the DEM to calculate the direction of flow in one of its eight adjacent cells for each cell in the elevation matrix. In the context of the downstream gradient, the flow accumulation for each cell depends on the flow directions. The drainage networks and watershed divides were delineated and then compared against their equivalents on satellite images for accuracy assessment. The slopes of both the channels and hillslopes were obtained from the DEM data and were implemented in Manning’s equation (Eq. 1) to estimate the runoff velocities:



$$V = \left(\frac{(R^{0.67} S^{0.5})}{n} \right) \tag{1}$$

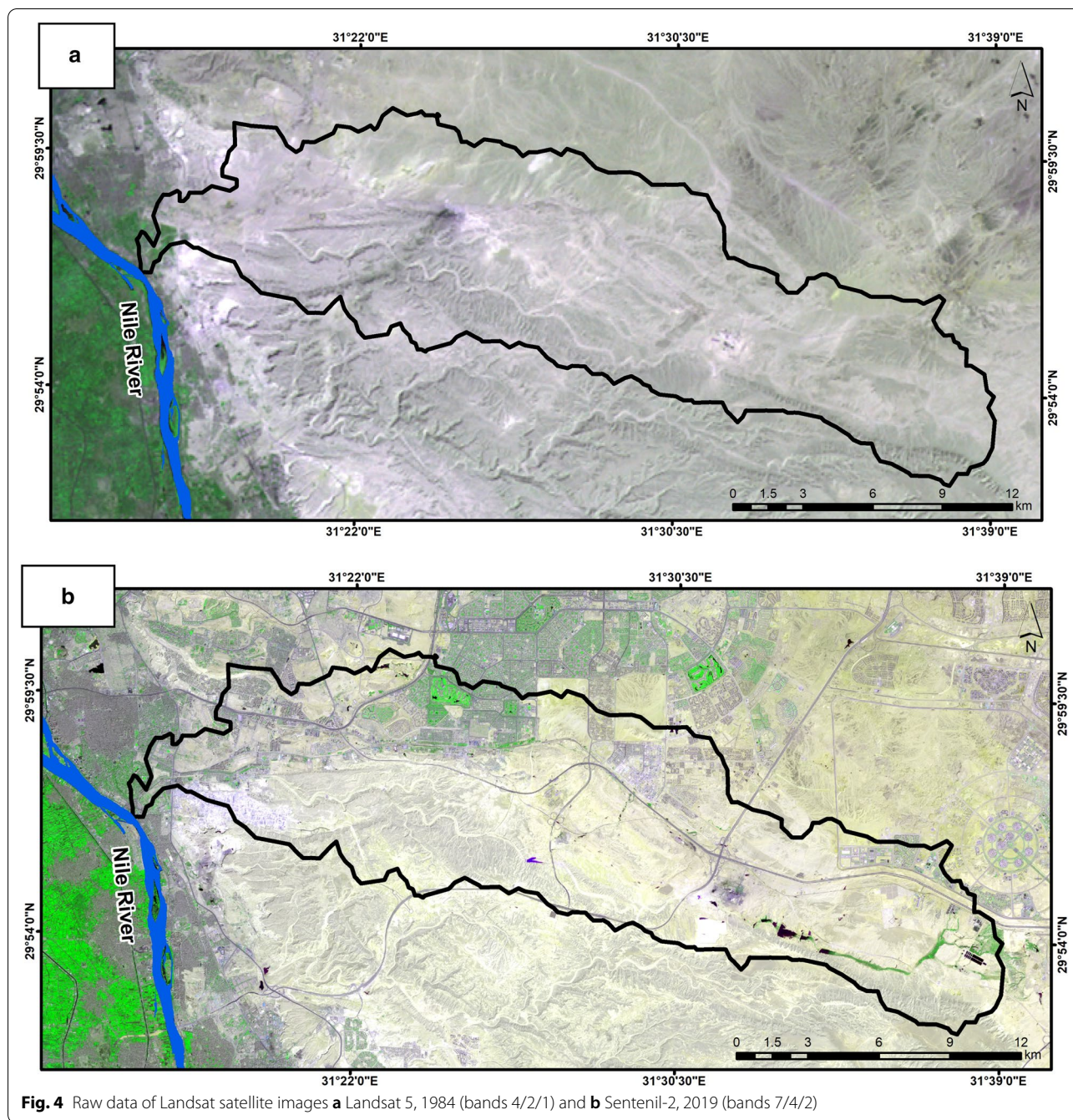
where V is the mean velocity in m/s, R is the hydraulic radius, which is defined as the cross-sectional area of the flow, A , divided by the wetted perimeter, P , S is the slope gradient of its water surface, and n is the Manning coefficient.

It is quite straightforward to obtain the digital map of the flow travel time given the velocity and the flow lengths using Arc GIS 10.1 software (Eq. 2). In downstream flow directions, the time required for the flows

generated at any point to reach the outlet is obtained from the accumulation of cell travel times. These values can be grouped into sets of time-area zones at unique time intervals (i.e., hours, minutes, etc.) required to deliver their outlet flows (Maidment 1993).

$$vij = \sum_p cp \times dp \tag{2}$$

where Vij is the output result of the convolution for cell (I, j) , d the slope distance between the centers of two adjacent cells along the minimum-cost path, c the unit-distance cost value, and p the minimum-cost path.



Results

The land cover map obtained from satellite images (Fig. 6) shows that drastic change in land cover has occurred within the catchment due to the urban expansion of New Cairo over the expanse of surrounding barren areas. These changes will affect the runoff coefficients and the flash flood magnitudes delivered to the main conveying channels. Even though the capacity of the conveying channels is large enough to safely discharge the

flash floods into the Nile, thus minimizing the impact on urban areas on both banks of that channel, the installation of a pressure pipeline for municipal water supplies has created additional pressure on the need to mitigate flash flooding.

The occurrence of wastewater pools in the area catchments creates more hydrological problems in the urban areas downstream. Wastewater seepage into the near-surface soil resulted in widespread waterlogging within

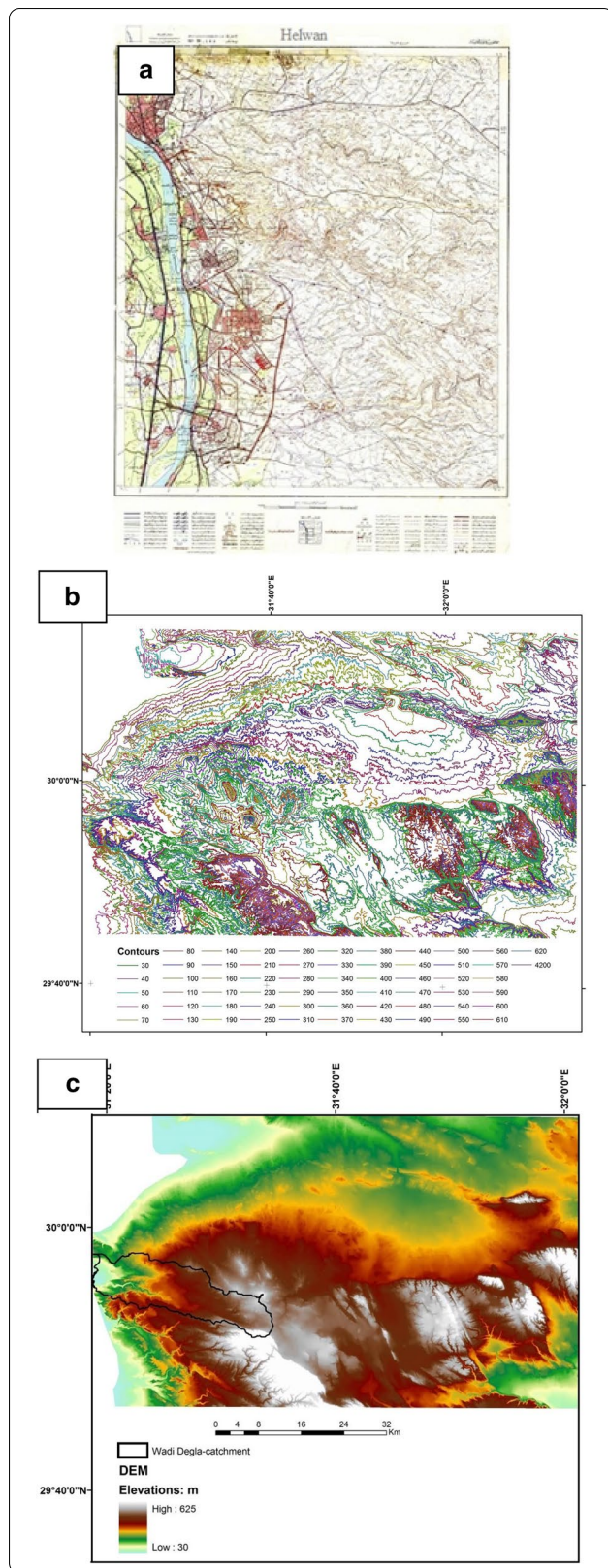
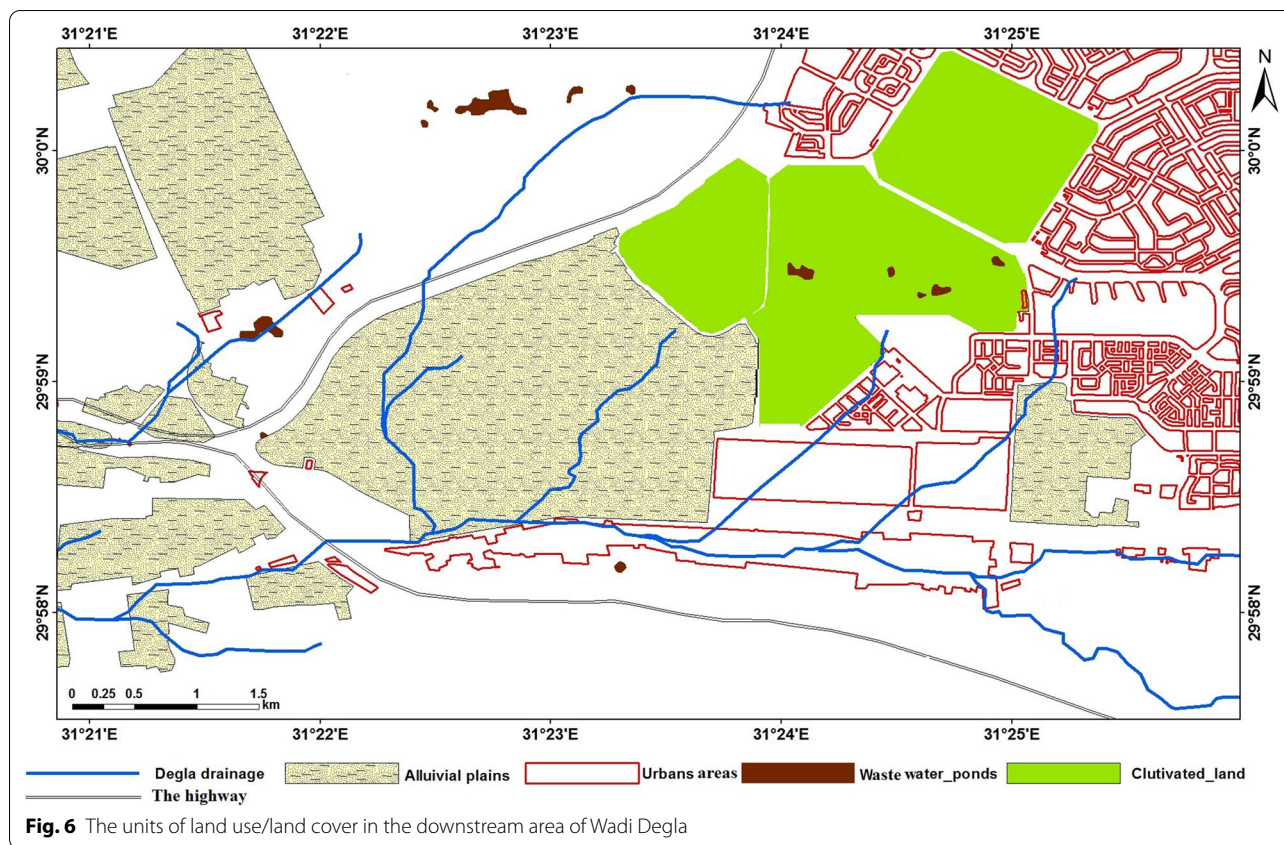


Fig. 5 a A sample of the scanned 1:50,000 topographic maps used to create a 20 m resolution DEM and to map the alluvial channels now concealed by the urban areas, **b** the digitized contours of the study area, and **c** the created DEM from the topographic contour maps, note the extent of Wadi Degla catchment

the rural and urban areas in the area (Fig. 6). Consequently, flash floods and wastewater pools in these areas will have high a negative impact on urban infrastructure and human life (Elsayed et al. 2020).

The time-area zones map (Fig. 7) is a representation of the spatially distributed unit hydrograph, which is necessary for determining the hydrography for any given event once the rainfall and runoff parameters are given. The scarcity or absence of rainfall/runoff data for the catchment decreases the accuracy of estimation for the hydrograph. A hypothetical storm with effective rainfall of 20 mm was proposed to estimate the resulting flash flood hazard in the area. The rating curve and its equivalent hydrograph were determined for this specific event. Consequently, scenarios could be developed for the flow parameters and their likely impact on the areas downstream. Finally, the areas occupied by wastewater ponds have been analyzed in the context of active channels with urban areas downstream. The flash flood parameters and hydrological analyses of the DEM of the study catchment area have been used to estimate the hydrographs. The geomorphological setting of catchments also is necessary to identify the optimum storage area capacities and to determine pathways required to ensure that the discharges of flash floods create minimal impact on the surroundings. The application of the spatially distributed unit hydrograph (Maidment 1993) for the study catchment area showed that the total flow duration would be six hours and the peak discharge would occur during the second part. The runoff coefficient for the catchment would be of high great magnitude as a result of the recent urban development of the alluvium areas within the drainage basin (Fig. 7).

The estimated runoff coefficient from the nearby from the study area (Helwan and Al Saaf areas) during the flash flood event of October 2019 fell in the range of 20–25% of the total precipitation. For those catchments, images were used to measure the active channels (i.e., the peak discharge), the storage areas (the developed water ponds), and the pathways of the flash floods within the catchment. Unfortunately, those estimated parameters cannot be retrieved for the study area as the remote sensing indicators for the flash floods (such as slack deposits and active channels) were not found on the investigated



available satellite images. Given the high similarity in relief and geology between Wadi Degla and the Wadis in the Helwan area, which were observed in the field shortly after the recent flash floods, we have, therefore, used the same runoff coefficient and rainfall scenarios. The runoff hydrograph has been computed from the time-area zones and the effective rainfall of 20 mm based on topographic surveys of the storage areas and the transmission loss was neglected (Table 2 and Fig. 8). The estimated peak discharge from the pools from the flash floods produced approximately 110 m³/s. Investigating the allocated channel for conveying the flash flood showed that the dimensions of the cross sections and the culverts under the main roads are not sizable enough to safely discharge this water into the Nile. Therefore, it is strongly recommended that locations suitable for the construction of retention and storage dams be ascertained.

Discussion

The original landscape fluvial setting of the study area has been altered by anthropogenic activities, such as the widespread excavation of quarries which were very common in large areas, and therefore increased the aggregates, sand, and clay materials found within. Urban encroachment has been associated with the leveling of

the land parcels and the preparation for terracing of the plateau areas; therefore, the outlets of drainage basins, particularly in the western part of the area, have been concealed under the existing urban sprawl. It is also possible that the gradient and aspect of the original drainage lines have been modified through urban development. The use of topographic maps is very essential to showing flash flood risk results, and it is one of the alternative methods due to lack of hydrological data. The analyses of 1:50,000 topographic maps of 1984 revealed some important information on the drainage basins because large areas were barren in the study area.

Problems definition

The study area was exposed to the rainfall storm causing a flash flood in October 2019 with values around 30.3 and 33.27 mm. This flood caused many damages in the study area in which the runoff water flooded most of the main roads and many urban areas were submerged. From available satellite images showed, main hydrological problems include a major pipeline for freshwater supplies to New Cairo that has been installed into the active channel of this wadi, which was originally allocated for conveying inundations to the Nile near Al Maadi area (Fig. 9). Another hydrological problem in the Wadi Degla area

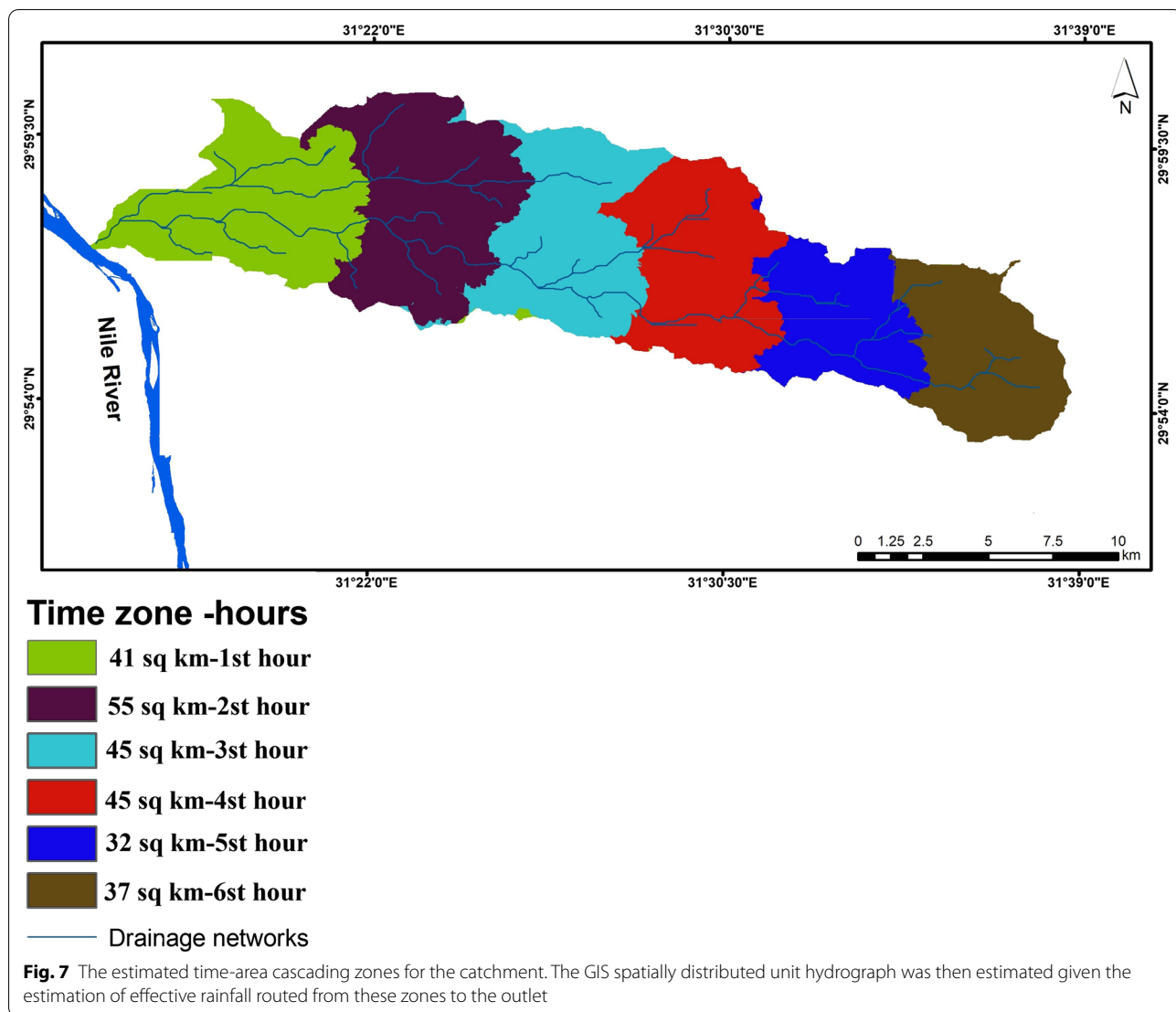
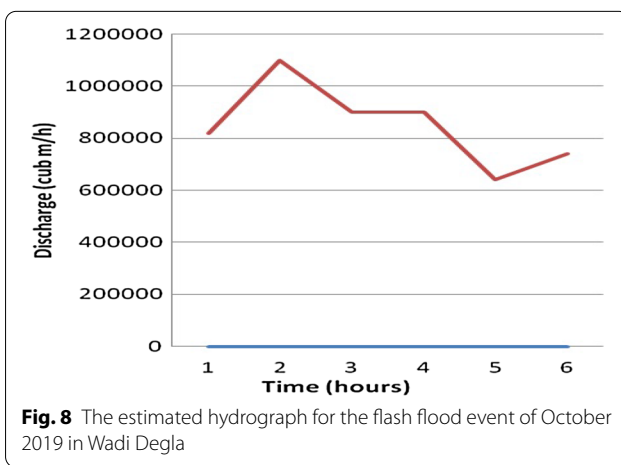


Table 2 Calculation of effective rainfall, resulting runoff, and time zones from outlet to upstream

Time zones from outlet to upstream (hours)	Area (square kilometer)	Effective rainfall (mm)	Resulting runoff (cubic meters)
1	41	20	820,000
2	55	20	1,100,000
3	45	20	900,000
4	45	20	900,000
5	32	20	640,000
6	37	20	740,000
Total	255	20	4,800,000



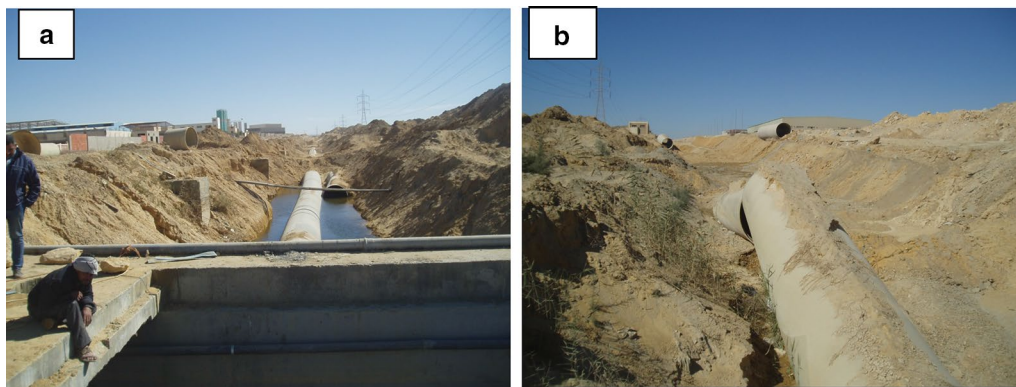


Fig. 9 Field photographs for the pipeline in Wadi Degla (**a, b**, respectively)

is the development of wastewater ponds in the resulting depressions from quarrying, which are intercepting the seepages from land uses upstream onto a thick impermeable substrate of the Tertiary shale and marl (Figs. 10, 11). The problem of wastewater ponding is closely associated with the development of the perched water table in neighboring urban areas; therefore, the sustainability of urban assets is greatly affected. Given these challenges, analyses of the interplay of the land uses and hydrogeology of the wadi system will define optimum management strategies for flash floods and the groundwater problems.

Hydrological analysis

GIS which is of great benefit in the hydrological analysis is estimating the flow parameters in the catchments of urban areas (El Bastawesy et al. 2009) to determine the pathways prone to flash floods activity and wastewater for urban areas. Analysis of DEM has been commonly used to determine various hydrographic parameters integrated with GIS, such as flow directions, accumulations, lengths, and drainage networks (Fig. 12).

From hydrological analysis results, it was observed that the main wadi floor is dotted by few depressions of the quarrying activities, and these depressions acted as storage ponds that attenuate the lag time and peak discharge. The different land uses downstream remain vulnerable to flooding risk as the dimensions of the designed channel in the outlet areas are not capable to safely discharge the estimated peak flows into the Nile. Therefore, it is necessary to consider the construction of the main dam in the upstream area not only to prevent significant amounts of the flash flood reaching the downstream but also to control the resulting peak discharge. The site selection of this dam is controlled by the local geological setting, drainage

patterns, and contributing areas and the characteristics of the groundwater aquifer in the area. Selected storage dams that are constructed in the main wadis upstream may be more efficient based on the properties of near-surface groundwater aquifers which are controlled by subsurface geological structures (Fig. 13).

Conclusion

Remote sensing techniques are proved very useful to define active channels and vulnerable areas of flash flood effects. It is strongly recommended to obtain specific field measurements for the runoff and transmission loss to better estimate the flash flood parameters. The hydrographical analyses for the drainage basins in the study area were performed using the available DEM, remote sensing images with fieldwork. The hydrographic and hydrologic parameters including (drainage networks, catchment areas, etc.) were automatically extracted from the DEM using the hydrological analysis functionalities of ArcGIS. One of the main conclusions in this research is that the flash flood poses a threat to the infrastructures downstream as the existing mitigation measures were very limited and insufficient. Some urban areas in Greater Cairo were completely destroyed during the flash flood of October 2019. Also, the incompetence of their cross-sectional areas to pass the delivered flows allowed the rapid accumulation of runoff and the crossing of torrential flows on top of the road surface. Consequently, the road in this area has been destroyed. Finally, the alleviation of flash flooding in the study area should be given more significant, as large amount of wastewater flows in the quarrying depressions in the lower parts of the wadis. In conclusion, flash floods can have a devastating impact when not adequately controlled. Therefore,

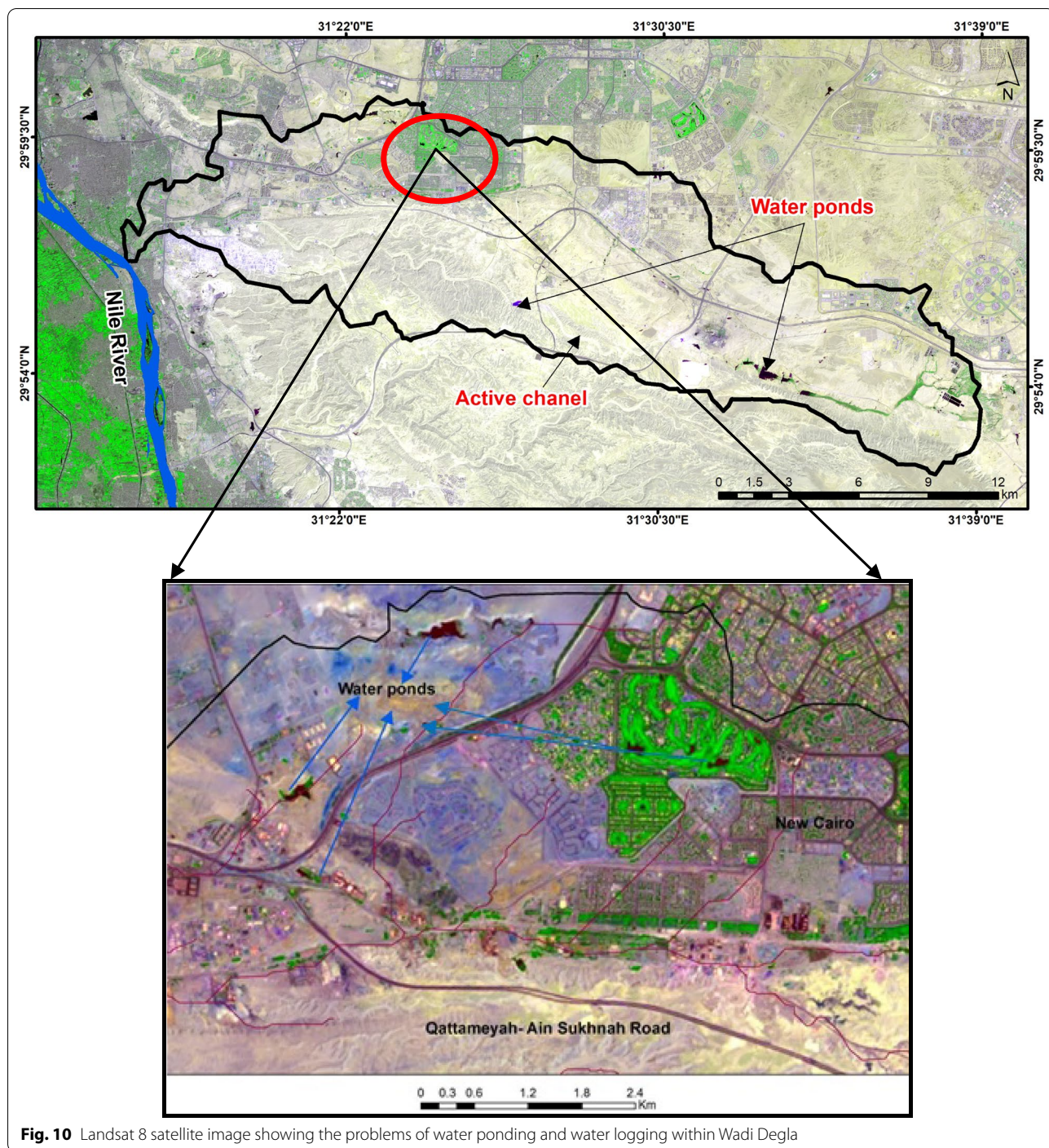


Fig. 10 Landsat 8 satellite image showing the problems of water ponding and water logging within Wadi Degla

the planning of flash flood controls is paramount. The present study recommends management to control the seepage of wastewater from the study area as well as the

strict supervision of wastewater treatment plants, thus protecting the area around the outlets of potable water treatment plants.

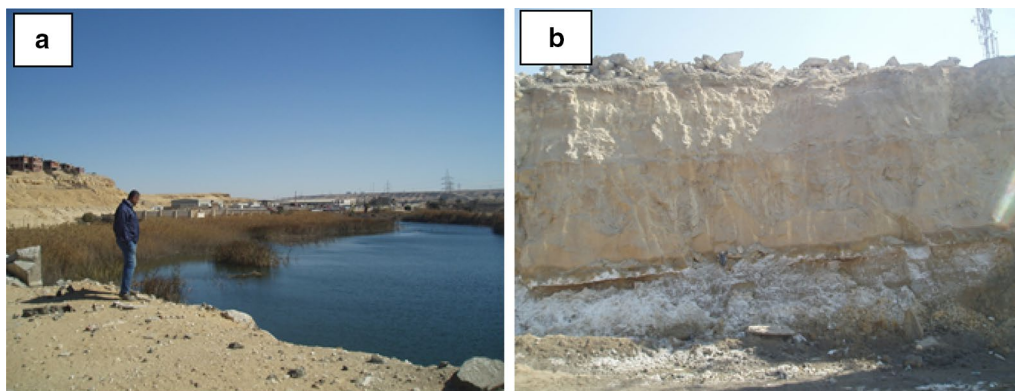


Fig. 11 Field photographs showing a wastewater pond in Wadi Degla area from the seepage of land uses upstream and the impact of seepage on waterlogging and salt weathering in the outcrops in the study area (**a, b**, respectively)

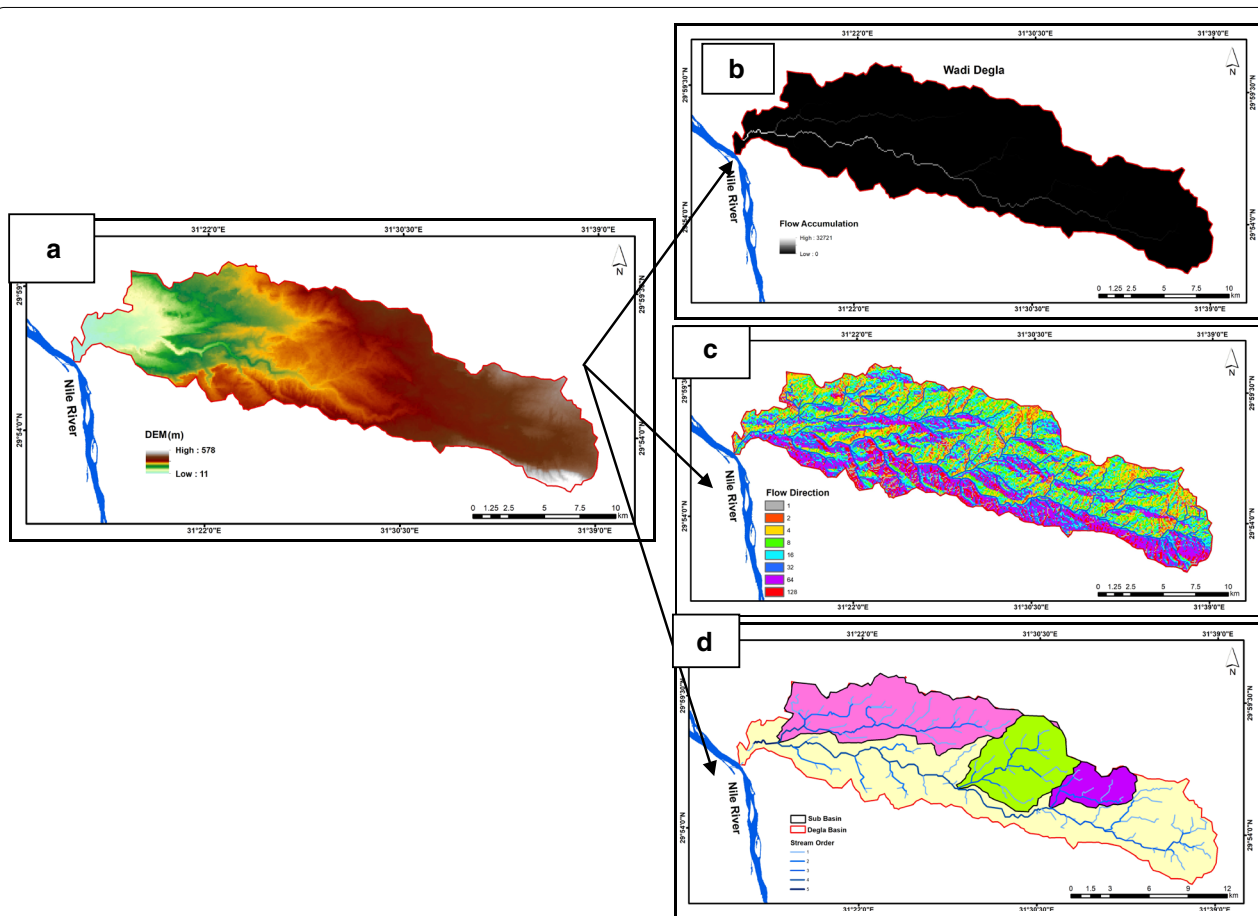
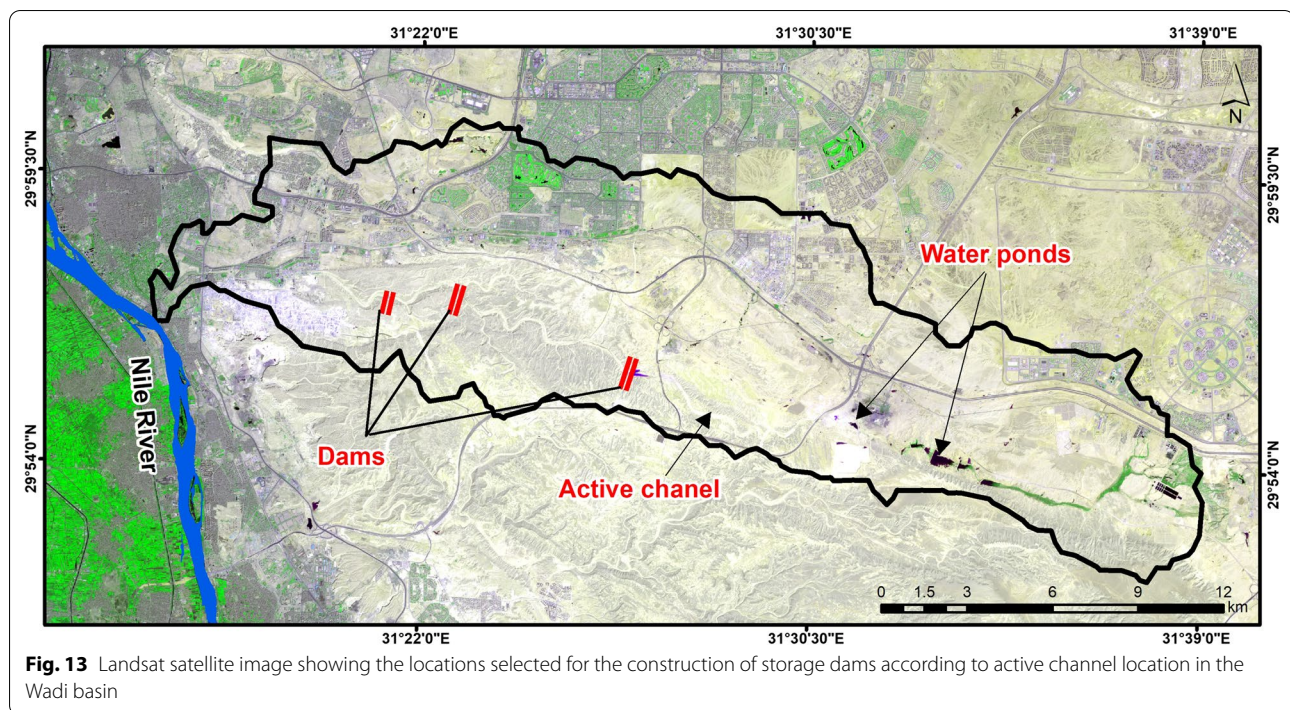


Fig. 12 a Digital elevations model (DEM) of the study area to estimate, b flow accumulations, c flow directions, and d drainage networks



Abbreviations

RS: Remote Sensing; GIS: Geographic Information System; GMap: Global Satellite Mapping of Precipitation; DEM: Digital Elevation Model; asl: above sea level; EMA: Egyptian Metrological Authority; ETM: Enhanced Thematic Mapper; EGSA: Egyptian General Survey Authority; ESRI: Environmental System Research Institute.

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Authors' contributions

HAM contributed her idea, studied geology, provided description of the study area and analysis, and interpreted different satellite images. MAEB assessed flash floods and hydrological analyses of the study area. Finally, Both authors reviewed and wrote the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this manuscript.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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