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Research Article

Fragile Landscape: Impact and Consequences of May 2014 Flash-flood Disaster in the Aqaba Area, Southern Jordan

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Abstract: Flash-flood disasters are common in the Aqaba area. It always has a significant impact on the city and causes immense damages to lives and the infrastructure (highways, roads and dwelling areas). Before the 1990s several flash-floods of medium and high magnitudes were recorded (i.e., the 1963 and 1966 floods). However, low and medium magnitude floods (6-7 and 20 year return period) have been a recurrent phenomena over the last three decades. The city and the port of Aqaba are considered crucial to the Jordanian economy and cosequently the protection of the city/port from repetitive flooding is important to maintain future urban and economic development. Since the 1960s all formulated development plans for the city and the southern coast have suffered from a remarkable lack of appreciation and awareness regarding environmental hazards, where 90% of the Aqaba area is exposed to flood and sediment hazards. An intensive post-event geomorphic survey was carried out following a flash-flood that struck the Aqaba area on 6-7th May 2014 to identify the damages that occurred and to recognize the main hydrological characteristics of the flash-flood, the terrain favoring flooding, fluvial processes which initiate large gullies and finally to gain experience regarding natural hazards. Hydrological studies related to previous flooding events indicate that the Aqaba area is exposed to recurrent floods of different magnitudes, associated with high peak discharge, gully erosion, slumping and high sediment load. These caused serious damages to the properties and infrastructure, loss of life and hardship for the people of Aqaba. The resultant large gullies are considered an additional cause of instability and a sediment source which threatened the Aqaba area.

Keywords: Aqaba area, flood and sediment hazards, fragile landscape, geomorphic survey, Jordan

INTRODUCTION

The fragile and stressful conditions of arid landscape characterized the Aqaba area, necessitate careful site selection for urban development to ensure sustainability (Golany, 1982; Bitan, 1983). Due to long intervals between high-magnitude low-frequency flood events and lack of hydrological data, planners have paid little attention to geomorphic hazards. The vulnerability of the landscape towards geomorphic processes and the resultant hazards have often been ignored (Golany, 1983). Geomorphic investigations executed in arid lands have enhanced the geomorphic techniques which can be employed to avoid the undesirable hazards and have improved levels of awareness regarding the role of geomorphic surveys and information in planning process (Cooke *et al*., 1978; Doornkamp *et al*., 1979; Cooke *et al*., 1985; Potter and Frevert, 2010). Over the last three decades (1981-2011), floods are considered the most recurrent disasters recorded in the Middle East and North Africa including Jordan (Rakhi *et al*., 2014). It has also been reported that a disaster Risk Management Plan (RMP) has not yet been integrated into the development plan of Aqaba (Jordan), which has suffered from flash-floods over the last 30 years. Past experience from the Aqaba area (Farhan *et al*., 1989; Farhan, 1999; Farhan, 2014) and other similar urban areas, such as Eilat at the opposite corner of the Gulf of Aqaba (Grodek *et al*., 2000) and Suez, Egypt (Doornkamp *et al*., 1979) indicate that optimal planning for flood protection has become increasingly difficult, since continuous urban growth has frequently resulted in heavy disturbance of terrain surface and natural drainage. Such procedures are normally associated with a prominent lack of adequate and efficient passage (natural of artificial) of flood water and sediments. Historically, the Aqaba area has experienced low, medium and high magnitude flash-floods since its establishment. Recent floods monitoring (Schick *et al*., 1999) demonstrates that “a small flood occurred every few years, more rarely a large one and perhaps a truly a catastrophic flood once in a few decades”. The southern coast of Aqaba (including the piedmont zone) is at a crucial stage of urban development. Thus, it is appropriate to:

- Approach drainage design and fluvial processes efficiently in formulating future urban and land use plans
- Adopt a sustainable plan by accepting the losses of a disaster and introduce a planning adjustment

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paradigm with environmental hazards rather than planning (or) designing against nature (Farhan, 1999)

However, the intrinsic characteristics of flash-floods in southern Jordan are poorly understood due to a lack of long-term monitoring of fully instrumented arid watersheds and paleoflood studies as compared with Eilat on the opposite NW corner of the Gulf. Long-term hydro-meteorological data are not available. Therefore, due to difficulties in predicting flash-floods, planning adjustment to flooding risk, emergency and proper evacuation plans are of high priority. Post-flood surveys, in this context, are clearly essential in order to:

- Increase the planner's technical knowledge regarding flood events
- Provide more accurate methods for analyzing flash-floods
- Elaborate efficient technical solutions to flood prevention and control (Drobot and Parker, 2007; Gaume and Borga, 2008)

The present investigation is intended to assess the impact and consequences of the May 2014 flash-flood on the Aqaba area, through conducting a conventional field-based post-event geomorphic survey across the entire Aqaba area and analyzing the hydrological studies/reports available on previous floods. Post flash-flood field investigation, notes, intensive photographs and analysis of climatic data pertaining to past events were implemented (Gaume and Borga, 2008). The interaction of geomorphic constraints, fluvial processes, hydrological behavior of wadis, engineering intervention and unplanned development on maximizing flood and sediments were discussed.

The study area:

Flooding problem: The study area is located in the southwestern part of Jordan to the east of the Gulf of Aqaba and lower Wadi Araba. It lies between 29° 21' N to 29° 38' N latitude and 34° 57' E to 35° 5' E longitude (Fig. 1). At the beginning of the 20th century, the

Fig. 1: The study area

modern town of Aqaba was built on the alluvial fan of Wadi Shallalah. Since the1950s, the town has grown rapidly, expanding during the 1960s and 1970s to the north on the alluvial fans of Wadi Al-Shahbi, Wadi Um Jurf and the large Wadi Um-Yutum which is occupied by the present northern part of the city (Hindle, 1966). In a later stage during 1980s and 1990s, the main port facilities and 20 other specialized ports were constructed, as well as construction of the industrial zones and the airport along the southern coast of Aqaba and the bajada of lower Wadi Araba. With reference to the spatial distribution of land use categories, economic and life losses are expected to increase due to continuous exposure of assets and population to risk, the recent building of residential areas across wadi floors, an increase in frequency and intensity of heavy rainfall and probably certain effects of climate change (Al Salihi, 2003; Hamdi *et al*., 2009; Al-Qinna *et al*., 2011), which have all contributed to an increase in precipitation and generated flash-floods. The residential areas, the airport and the industrial zones are concentrated in flood-prone areas on the alluvial fans of

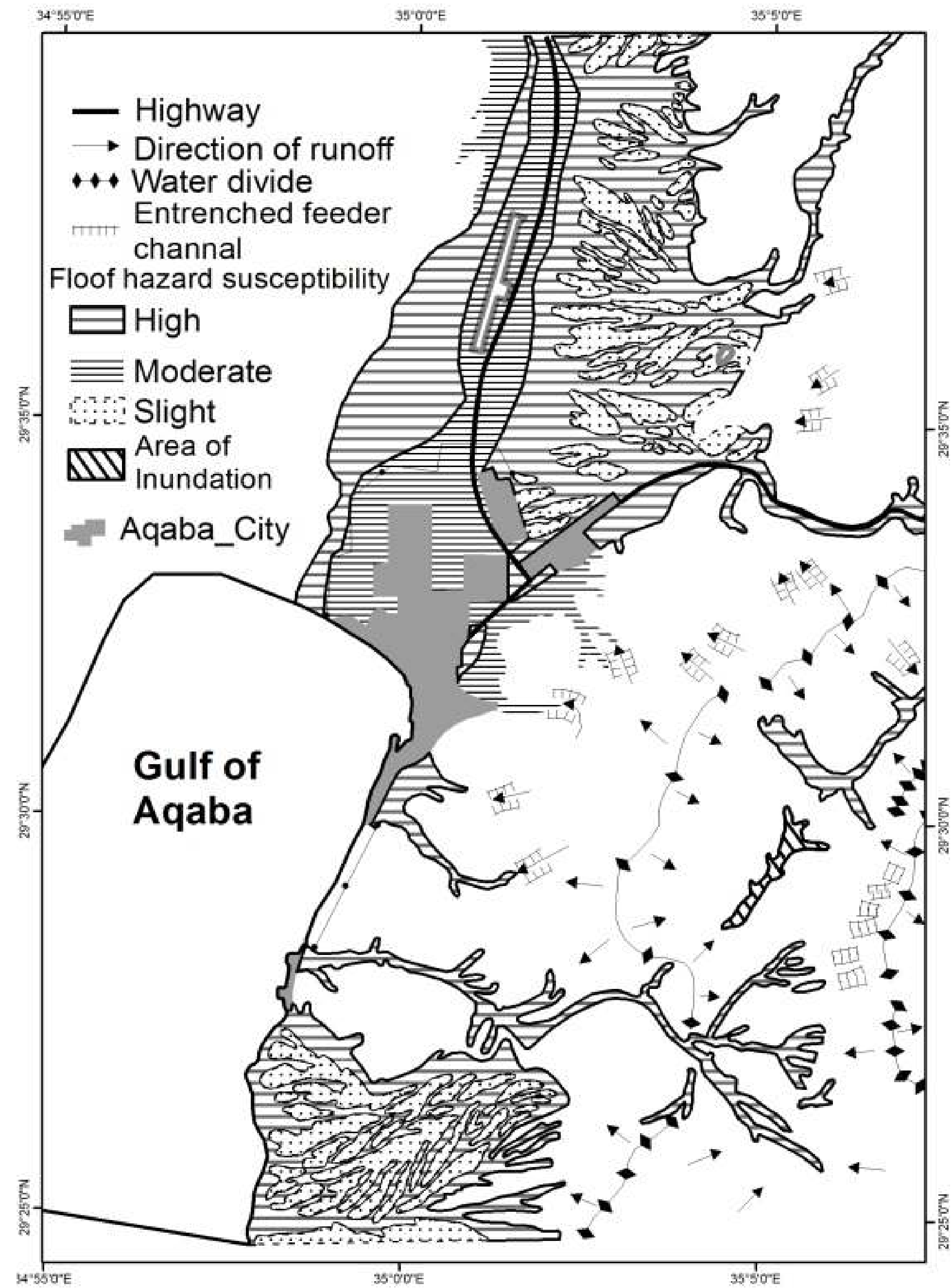


Fig. 2: Flood hazard susceptibility of the Aqaba area (Farhan, 1989)

the bajada and lower slopes of the alluvial piedmont to the south of Aqaba are a particularly challenging task at present and in the future (Potter and Frevert, 2010).

Since the 1960s, several master plans have been generated for the city and the southern coast of Aqaba (i.e., Ministry of Municipal and Rural Affairs, 1981; Aqaba Region Authority, 1985; Aqaba Special Economic Zone Authority, 2003). All previous plans suffer from a prominent lack of appreciation of the morpho-hydrolological setting of the bajada and the piedmont zone and the role of geomorphic information as an input in planning. The main physical criteria considered in earlier plans were: the accessibility of topography related to the bajada; and the availability of water resource at the toe of Wadi Shallalah alluvial fan (the site of the old city) during the 1950s and then from a well installed at the apex of Wadi Yutum large fan until the 1980s and subsequently from the sandstone aquifer "Disa Aquifer", 80 km to the north-east of Aqaba. A prominent lack of attention was paid to low- and high-magnitude flooding events. Scattered hydrological studies on flash-floods were carried out for wadis that dissected the fragile alluvial piedmont (Aqaba Region Authority, 1987) and the Aqaba back road (Jordan Consulting Engineer Co., 1993). These studies, indicate that the Aqaba area has been exposed to recurrent flash-floods over the last three decades. These studies reported that sediment loads during flash-floods are beyond the capacity of hydraulic structures installed across the major roads and the coastal highway. Farhan (1999) assessed a 6-7 year return period for the flash-floods of 1991, 1993 and 1994, which caused substantial damages to the road and the city. We can concluded that a proper crossing design was achieved through analysis of existing geomorphic units, their characteristics and sediment type and sources. The geomorphic parameters derived were considered an essential input for hydraulic design and remedial measures. Adding to that, Farhan (1989) also compiled a qualitative flood hazard assessment map for the Aqaba area (Fig. 2) and recognized four types of flooding susceptibility:

- Terrain of high susceptibility to flooding
- Terrain of moderate susceptibility to flooding
- Terrain of slight susceptibility to flooding
- Areas of inundation

The map generated was meant to help planners understand the spatial distribution of flood hazard conditions. Unfortunately, planners do not pay sufficient attention to such information, or to proper mitigation measures against flooding. Similarly, Murphy (2010) investigated the hydrological characteristics of the severe flood that struck Aqaba on 2 February 2006. The flood was combined with a large amount of sediments, debris flow and slumping. Boulders of 7 m^3 were recorded on the Wadi Yutum alluvial fan and rainfall intensities were predicted to reach up to 120 mm/h for 10 min. The flood caused extensive property damage and loss of life. Following the flood of 2006 (19 year return period), a disaster risk management plan was prepared for the Aqaba Special Economic Authority area (Aqaba Special Economic Zone Authority, 2010). However, due to the lack of technical knowledge and trained manpower, officials failed to respond effectively to the flash-floods of 2012, 2013 and 2014. The role of governmental officials in disaster management should be expanded to regulate, coordinate and develop systems and trained technical staff for disaster management (Ahmad *et al*., 2011). Low magnitude floods of 6-7 year return periods and high magnitude of 50 year return periods have been recorded since the 1950s. The extreme flood event recorded on 11 March 1966 (known as the Ma' an flood) was of 50 year return period. A peak discharge of 500 m^3/sec was achieved, with reported float velocities 6 m/sec and surges up to 12 m^{-1} (Central Water Authority, 1966). Two moderate floods occurred on 8th April 1963 (25 year return period) and on 2 February 2006 (19 year return period). In 1991, 1993, 1994, 2012, 2013 and 2014 floods of 6-7 year return periods were recorded (Jordan Consulting Engineer Co., 1993; Farhan, 1999; Murphy, 2010). It is reported that the northern parts of the Aqaba area are the most vulnerable terrain system against a flash-flood hazard. Without exception, all alluvial fans of the bajada accommodate most of residential areas, the Aqaba International Estate, the King Hussein International Airport and the Northern Light Industrial and Logistic Area (Aqaba Special Economic Zone Authority, 2010). Such a conclusion was ascertained since all developed land use categories are located on the apex, middle and toe part of these alluvial fans and the lower reaches of the alluvial piedmont (Table 1). Unfortunately, two residential areas were constructed recently on the W. Shahbi floor (9th residential area, 2001) and recently the Shamiya neighborhood (2002). Thus additional people have been exposed to a flooding risk. Such terrain units are considered the most hazardous part of the lower W. Araba in terms of flash floods. It is expected that these neighborhoods will be affected by flooding water and sediment discharge whenever a flash flood occurs.

Geomorphic setting: The Aqaba area is located in the southwestern desert of Jordan, on the northern edge of the Arabian plate to the east of the lower W. Araba fault and the Gulf of Aqaba (Zaineldeen, 2013). The area

Table 1: Characteristics of the bajada and the alluvial piedmont watersheds and major developed land use types

Watershed	Area (km^2)	Drainage density (km/km^2)	Avg. slope (degree)	Sediment Size (mm)	Land use type	The part of the alluvial fan utilized
W. Mulghan	24	3.4	3.2	88.2	W. Araba highway, King Husein Airport, Residential areas	Toe part
W. Hweiti	14.5	4.6	3.2	92.6	W. Araba highway, King Husein Airport, Residential areas	Toe part upper part
W. Yutum	870	4.1	2.8	160.2 127.6	Amman-Aqaba highway, Aqaba rail road, light industries, residential and governmental facilities	Toe middle apex
W. UmJurf	4.8	3.2	5.8	82.5	Amman-Aqaba highway, governmental building, residential	Toe middle apex
W. Shahbi	10.5	3.4	6.2	71.8	Amman-Aqaba highway, residential areas	Toe middle apex
W. Shallalah	9.8	5.4	4.6	95.5 74.4 84.8	The coastal highway, port facilities, heavy industry	Toe middle apex
W. Jeishieh	9.1	3.3	6.6	96.3 88.6 84.8	The coastal highway, port facilities, heavy industry	Toe middle apex
W. Mubarak	65.1	3.7	3.4	86.4 75.7	The coastal highway, container port and heavy industry	Toe
Wadi 14	6.1	4.2-6.7	4.7	Granular materials, mostly sand (90%), granite cobbles and boulders	Public beash/tourist complex, mid road, Aqaba back road	Lower catchment middle catchment
Wadi 11	5.0		4.8		Aqaba back road Qabos city project Bedouin tourist village mid road, Aqaba back road	Lower catchment middle catchment
Wadi 9	28.0		5.1		Aqaba back road, light industrial area, mid road wilderness reserve, Aqaba back road	Upper catchment middle catchment
Wadi 8	6.5		5		Aqaba back road, public/governmental building, mid road, wilderness reserve	Lower catchment, middle and upper catchment
Wadi 7	6.2		4.9		Aqaba back road, Tala bay resort and residential community, mid road, Aqaba back road	Lower catchment, middle and upper catchment
Wadi 2	65.5		5.2		The industrial area (southern coast of Aqaba), Aqaba back road	Lower catchment

Avg.: Average

investigated exhibits various geomorphic features characterizing arid lands. Photo-interpretation and fieldwork led to recognizing nine terrain units. The most hazardous units with respect to flash-floods and of significant relevance to engineering problems are (Fig. 3): the faulted denudational granite mountains, the bajada at the lower W. Araba, north of Aqaba and the Quaternary dissected alluvial alluvial piedmont south of Aqaba along the southern coast (Bender, 1974; Burdon, 1959). The granite mountains are stripped completely of sandstone, except for a few remnants exposed in the upper catchment of Wadi Mubarak. Limited areas of Cretaceous sandstone and carbonate rocks are present southwest, south and west of the interchange (leading to the container port) of the Aqaba back road (Natural Resources Authority, 1987a, b; Osborn and Duford, 1981; Osborn, 1985). The bajada is constituteds of several large coalescings alluvial fans at the foot of the granite mountains. The mean slope recorded ranges between 4° and 5°. The alluvial fans are fed mainly by debris flow of ephemeral wadi flowing westward to the inland sabkhas (coastal salt flats). The alluvial fans dislocated from the drainage basins as a result of strike-slip movements along the Dead Sea transform and its subsidiary faults (Makhlouf *et al*., 2010). The fans develop whenever eastern wadis depart from the Granite Mountains and emerge over the W. Araba floor and drop most of their sediments straight away. The fan surface area is found proportional to the drainage basin area because of the greater sediment inputs delivered to the site of deposition. Alluvial fans of the bajada indicated periods of heavy rains or flash-floods with a resultant debris flow and stream flood deposition (Saqqa and Attallah, 2013). The bajada of the lower W. Araba terminated with Qa ed Dafiya, a small flat extended in a narrow strip less than 2 km in width and 12 km of length at the western margin of the bajada. wet playa, where groundwater ascends to the surface through a fault belonging to the same zone reaching Sabkhet Taba to the north. Urban development along the southern coast of Aqaba is planned to occupy the lower part of the dissected alluvial piedmont. This

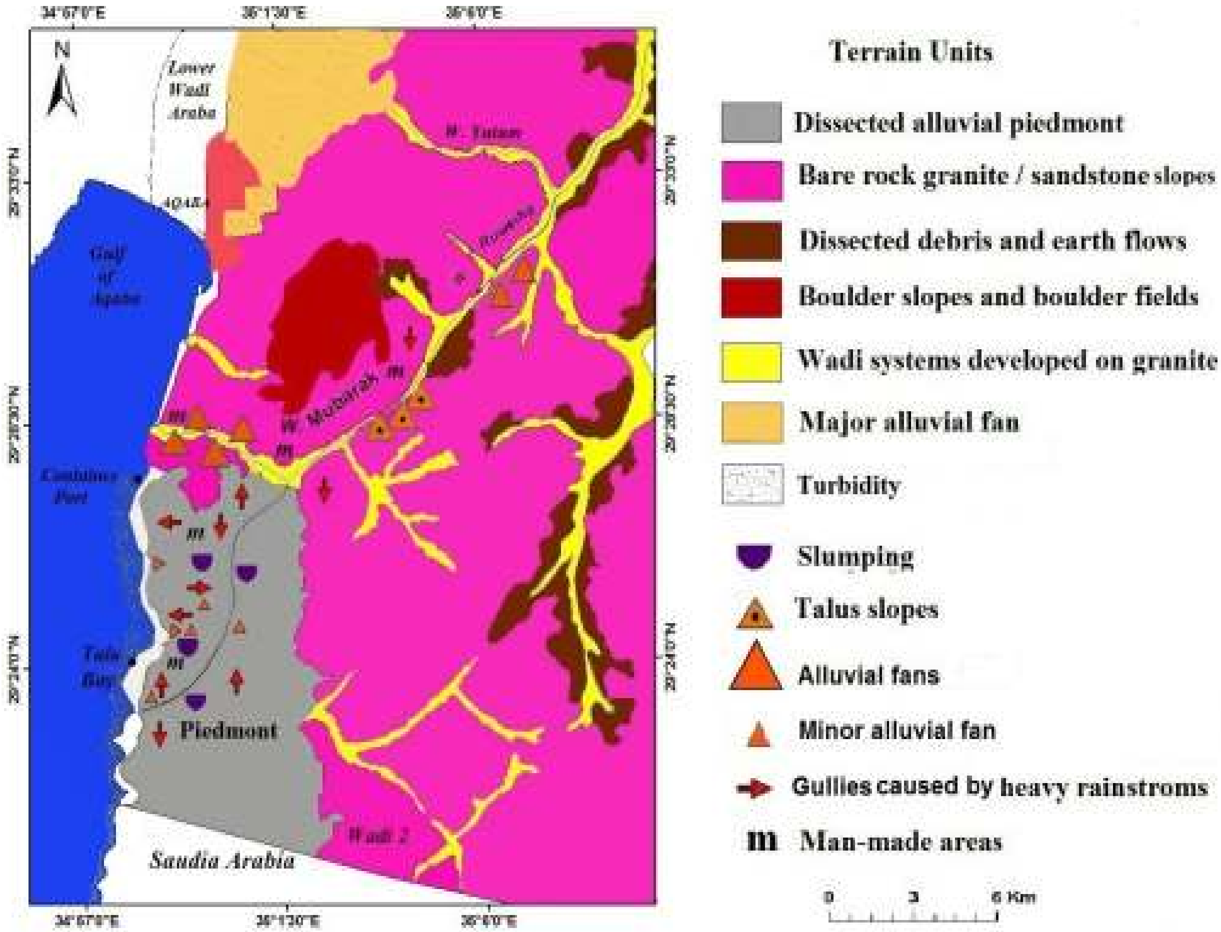


Fig. 3: Terrain units and geomorphology

terrain unit covers a triangular embayment with a base of 65 km along the coast of Aqaba. Sand interbedded with clay and granite gravel/boulders dominate the upper part (Hayward, 1985; Farhan *et al*., 1989). The southernmost sector of W. Yutum fan direct its distributaries towards Aqaba city. These endanger directly a quarter of unplanned dwellings zone. The steep overall slope of the fan (4-5°) facilitates for flood waters to reach any point along an 8 km circumference of the fan sector and together with the smaller fan adjoining to the north, creates flooding hazards for the Aqaba airport with its 3 km long runway. Uplifted fossil coral reefs (7-8 distinct terraces) are present along the coast, with heights of 3-45 m a.s.l. An age of 3800 years is given for the 3 m level and 70000 to 80000 years for the 40-45 m level (Al-Sayari *et al*., 1984; Al-Rifaiy and Cherif, 1988; Vita-Finzi, 1987; Shaked *et al*., 2002). Rejuvenation associated with tectonic uplifting of the granite block, produced typical badland topography with elongated sharp ridges, steep slopes and fine drainage texture, large wadi beds in master channels and recent embryonic alluvial fans at the base of the granite. Severe gully erosion caused pronounced instability conditions during highway and roads construction over the piedmont zone. Present development and flash-floods initiate hundred of gullies, slumping and debris flows thus, maximizing sedimentation problems at the lower reaches of the wadis dissecting the piedmont zone along the southern coast of Aqaba (Farhan, 2014). Other terrain units exist in the Aqaba area (Fig. 3): the dissected remnants of Cambrian and Kurnab Sandstones; dissected debris, earth flow and talus slopes on granite slopes and boulder fields; faulted wadi systems or granite mountains; man-made landforms and disturbed surface materials; and the narrow coastal plain and beach. The high relative relief and bare granite facilitate the background for extremely destructive flooding in the downstream urbanized area developed between the granite horst front and the coast (Schick *et al*., 1999) with large damage potential.

Climatic conditions: The climate of the Aqaba area is hyper-arid with a low mean annual rainfall and moderately high temperature. The mean annual rainfall in Aqaba is 37 mm (with standard deviation of 27.7 for a 30-years record and a coefficient of variation of approximately 70%). Seventy percent of rainfall events occur between. December and January. Rainfall in the southern desert of Jordan varies spatially. Single-storm rainfall totals can be very high and far exceeds the mean annual rainfall, thus, rainfall intensities are very high. Rainfall is usually of the convective type with some effect of orography (Schick, 1971, 1974). The convective rains usually occur during warm months such as October, March and April and are characterized by intense rainfall of short duration similar to that which occurred, for example, in 1991, 2006, 2010 and May 2014, respectively. A localized pattern of rainfall is also characteristic of the Aqaba area, where rainfall affected limited areas. Here, 60% of the total rainfall comes from spotty rain (Sharon, 1972). Spottiness of rainfall is clearly pronounced in the fall and spring thunderstorms, which occur at an annual average of four events/year in southern Jordan (Shehadeh, 1990). Most of the annual rainfall might fall during one event and concentrated in few hours (or less) or a days. Therefore, rainfall intensity is predicted to be high and it may reach 120 mm/h for 10 min (Murphy, 2010). Over the last five decades, the Aqaba area has been exposed to events of maximum rainfall intensities in 24 h. Examples are: 34 mm (1953), 27 mm (1955), 36.3 mm (1963), 32.8 mm (1966), 65 mm (1975), 42.5 mm (1980). The highest rainfall in Aqaba was recorded in 1974/1975. Such figures indicate that high intensity rainstorms are common and frequent in the Aqaba area. Thus high rainfall intensity occasionally has resulted in severe flash-floods associated with large sediment load. The high relief of bare rugged granite mountain and dense gully network facilitate the occurrence of extremely destructive floods in the downstream over the bajada, Aqaba city and the piedmont zone along the southern coast of Aqaba, a terrain zone which has been planned for urban development. During the storm of 11 March 1966 for example, Aqaba recorded 37 mm (the same mean annual total). Ras En Naqb 71.2 mm, Ma'an 39 mm and Ras En Naqb highlands over looking Ma'an from the west recorded 60 mm falls in 4 h, with an intensity of 15 mm/h, while the mean annual rainfall of Aqaba is 37 mm, Ras En Naqb 149 mm and Ma'an 44 mm. The resultant flash-flood of the 1966 storm is classified as 50-year return period. The rainfall recorded during the thunderstorm of May 2014, was high for southern Jordan generally (in Tafila for example: 80 mm, in Shawbak 45.6 mm, in Wadi Musa and Petra 32.8 mm and in Ma'an 24 mm, all of them north of Aqaba). Aqaba city received only 3.6 mm in 20 min, therefore, rainfall intensity was high and recorded 13 mm/h in 10 min. Fieldwork investigations following the 1991, 1993, 1994, 2012 and 2013 flash-floods indicate that most of the hydraulic structured installed along the coastal highway, the Aqaba back road, the mid-road and other roads networks constructed recently on the piedmont zone, are not efficient for transmitting the flow and sediments generated through flooding (Aqaba Region Authority, 1987; Jordan Consulting Engineer Co., 1993; Farhan, 1999; Murphy, 2010). Therefore, the industrial area, urban development projects and the public beach (and other facilities) are exposed to anticipated serious flooding.

MATERIALS AND METHODS

Flash-flood disasters are common in the Aqaba area. Effective documentation of flash floods through direct post-flood geomorphic survey is essential to increase our knowledge about flash-floods and to provide proper information which can help in executing planning adjustment procedures with environmental hazards and the construction of efficient flood prevention structures (Borga *et al*., 2007; Rusjan *et al*., 2009; Roca and Davison, 2010; Arghius *et al*., 2014). Due to time constraints, mapping was carried out at medium scale using a topographic map (1:25000) and Enlarged Google Earth photo as a base to locate features resulting from fluvial processes, instability features and damage to the infrastructure and properties. The adopted mapping method consisted of a combination of analytical and synthetic geomorphic mapping techniques (Verstagppen and van Zuidam, 1991; Brunsden *et al*., 1975a, b; Doornkamp *et al*., 1979; Aly *et al*., 2002). Extended research is intended to carry out on a latter stage using Quick Bird image and GIS and to establish a monitoring program to obtain detailed information on the actual frequency of different processes and temporal changes due to rainfall variation. Terrain units were recognized and mapped for the Aqaba area according to the method elaborated by Meijernk (1988). The objective of the field survey is to record the following:

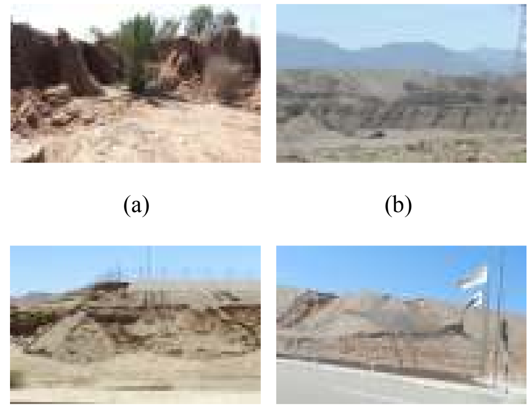
- Shape and extent of terrain units (i.e., alluvial fans, debris slopes, talus slopes, denudation granite slopes, the piedmont zone and the bajada) where road network, residential areas, recreational and governmental facilities and other infrastructures have been initiated since the 1950s
- Surface materials, sediment size, fluvial erosion processes, sedimentation and changes in wadi channels (natural or artificial) affecting the infrastructure including roads
- Characteristics of the wadis of the bajada and the piedmont zone. Types of drainage crossing, disturbance of natural drainage, drainage structures and its performance and artificial channels (roadside ditches and hills lope drainage and major wadi channels) associated with main roads. Evaluation of hydrological and climatic information related to previous flash-flood events

- Engineering activities during construction (i.e., cut and fill in fragile surface materials (the piedmont zone, the fluvial terraces, talus and debris cores), continuous accumulation of earth tips close to the coastal highway, Aqaba back road and the industrial zone, which activate severe gullying and maximize sediment discharge, instability and minor fans building affecting roads. Heavy disturbance of wadi sediments and continuous extraction of building materials from wadi floors which activate serve gullying and maximize sediment discharge, instability and minor fans building which affect roads and highways
- Type and frequency of damages and the affected infrastructure and land use category. Samples of muddy water were taken from the beach of the southern coast and two standing muddy pools to estimate the suspended sediment sediments transported by flooding water

RESULTS AND DISCUSSION

Following the thunderstorm of 6-7 May 2014, an intensive geomorphic field investigation was carried out three days after the event. A completed record of fluvial process features and the associated engineering problems and damages were made. The most remarkable fluvial process initiated and (or) reactivated due to the intense rainfall is gully erosion. Adding to the natural erosion gullies persist (Mazaeva *et al*., 2014) in the upper part of the piedmont zone and the faulted denudation granite slopes. Typical anthropogenic erosional gully landforms were excessively developed following the 1991 flash-flood which caused serious damage to the Aqaba back road (Farhan, 1999). Heavy disturbance of surface materials, cut and fill due to unplanned engineering activities associated with roads construction and repetitive heavy rainstorms, are the main causes of the newly developed gullies. Generally, gullies in the Aqaba area can be classified into three categories:

- Gullies in wadi catchments draining the faulted denudational granite mountains towards the lower W. Araba. These gullies are initiated on granite slopes, often by erosion along the dykes, joints and materials of low resistance against erosion.
- Gullies developed on large alluvial fans created by wadis descending towards the lower W. Araba, Aqaba city and the container port south of the city. It is dominated by large alluvial fans, remnants of fluvial terraces, slope cuts, disturbed minor alluvial fans and talus slopes due to construction activities.
- Gullies of catchments draining the alluvial piedmont, which extends between the container port to the Jordanian-Saudi borders. Severe gully erosion and changing wadi channels prevail. Two types of gullies are recognized: Natural gullies dominate the upper reaches of the wadis dissecting the alluvial piedmont (Wadi 2 in the south to Wadi 14 close to the container port), where erosion has taken place mainly in the granular sandy and boulder matrix. Here, gullies formed and incised due to heavy intense rainstorms. These gullies expand mainly by gully head erosion. Through this process, gullies move upslope releasing sediment to the channels, thus exposing new channel walls to erosion and threatening roads and other infrastructure. Anthropogenic erosional gullies often began as rills (Fig. 4a) and their length, width, shapes of cross profile and long profiles are varied. The length of the gully depends on the artificial slope length (cut and fill) and areas leveled for construction purposes and recurrent intense rainfall.



(a) (b) (c) (d)

Fig. 4: (a) new gullies initiated close to the marine station, (b) gullies activated and threatening the mid-road, (c) severe gullying on areas leveled for construction and development of minor alluvial fans, (d) severe gullying on leveled areas near the industrial zone

Hence, the morphometric of gullies changes and generally is enlarged and deepened following repetitive rainstorms. V-shaped and U-shaped gullies which characterized the scarps of cuts and fill slopes around the coastal highway and the mid-road start directly. These developed gullies are considered a major threat to the shoulders of the highway and roads (Fig. 4b to d). The lower part of the alluvial piedmont consists mainly of clayey and marly materials. Therefore, gullies accelerated normally by overland flow influenced by runoff generated upslope on the granite mountains (Shit *et al*., 2013). It delivers a significant amount of sediments including debris and mudflow materials, thus depositing it on road surfaces and in buildings close to slope cuts and tends to damage houses leaving families

Table 2: Type and frequency of damages

Damage	Mid highway	Aqaba back road	Coastal highway	Other roads	Residential areas
Slumping in alluvial cut slopes	1	6	3	-	-
Gully erosion in alluvial cut slopes	7	12	3	5	4
Collapse of artificial channel	2	3	-	-	-
Lack of protection measures against erosion	2	14	-	6	12
Blockage of side ditches	1	3	2	8	-
Flow overtopped road pavement	6	13	2	12	
Pooled water during flooding	4	6	3	15	3
	The level of water reached 60 cm in several locations of the city				
Sedimentation and debris on road surfaces	Most of the roads in the city suffer from siltation during flooding				
Gully erosion on spoil heaps	All spoil heaps (›35˚) suffer from gully erosion				
Subsidence of residential area under construction	-	-	-	-	1
Erosion of embankment slopes	3	2	2	1	5
Formation of minor alluvial fans	8	6	6	2	-
Siltation of sea water along the shore	Siltation affects the shore to the south of the container port and the public beach (100 m off shore)				

homeless. It is clear that developed gullies are considered an additional significant source of sediment production and supply. Annual variations of rainfall spatially and in quantity significantly influence the development of cracks and depositing of sediments below the head cut of a single gully, a process which leads to better explaining the development of gullies and to estimating long-term sediment production rates (Ghimire *et al*., 2006; Vandekerckhove *et al*., 2001). Consequently, proper conservation measures, appropriate drainage design and effective flood protection plan must be implemented so as to ensure free drainage and unimpeded sediment transport towards the Gulf of Aqaba and the sabkhas of the lower W. Araba. A systematic survey combined with a detailed photographic record was conducted to evaluate the conditions of major and secondary road including the hydraulic structures and the residential areas and other properties on the piedmont zone. The type and frequency of damages are illustrated in Table 2. Sediment concentration in the flooding water during the thunder-storm was extremely high, since hourly rainfall intensity is likewise expected to be high, when assessing a storm center over the granite mountains bordering the alluvial piedmont zone (Aqaba Region Authority, 1987), thus, severe damages is predictable in the Aqaba area. Geomorphological problems in the piedmont zone also, posed by the presence of long steep slopes (partially oversteepend due to engineering activities, absence of vegetation and permeable detritus), associated with excessive development and high erodibility of surface materials. Such conditions promote severe erosion, sedimentation and extreme channels and slope instability in time and space in such a fragile arid landscape. Infiltration rates for granite (0.5-2 mm/h), old alluvial surfaces (10-20 mm/h) and recent alluvial surfaces (5-15 mm/h), along with time to initiate runoff (1-4, 5-8 and 5-15 min for the previous materials, respectively) exemplify that runoff generally is initiated following the first few minutes of rainfall (Schick, 1995). It is reported that in similar areas such as Eilat (Greenbaum *et al*., 2006; Morin *et al*., 2009)

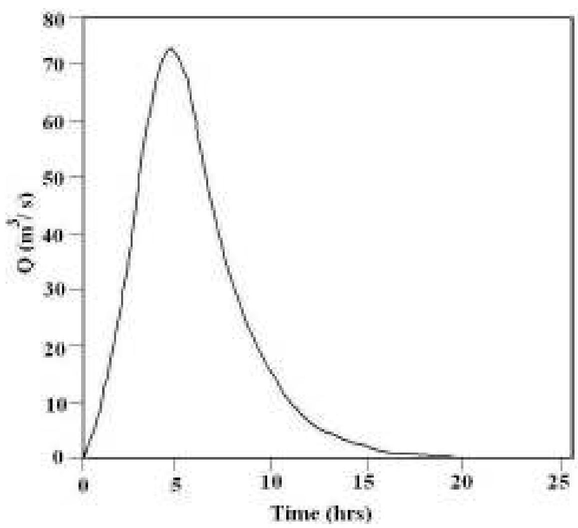


Fig. 5: Flash-flood hydrograph for Wadi Mubarak (1991 flood)

runoff events in small catchments might be generated as a response to only 5 mm of rainfall while in larger catchments, runoff is usually the consequence of at least 10-20 mm of rainfall. The morphological setting of the study area promotes the development of flash-floods with high peak discharges and sediment load that can damage properties and pose a serious threat to human life. Discharge records for flash-floods are not available for the wadis of the bajada and the piedmont zone, except scattered and inconsistent measurements for W. Yutum. Therefore, Synthetic Unit Hydrographs are crucial in this regard and available information is restricted to miscellaneous hydrological reports (i.e., Aqaba Regoin Authority, 1987; Jordan Consulting Engineer Co., 1993; Murphy, 2010). Previous results on flash-flood events of W. Mubarak (close to the container port) as an example showed that in 1991, in a flash-flood (which struck the Aqaba back road and the container port), the UH time to peak discharge was 4.3 h and the UH peak discharge quantity was predicted to be 73.4 m^3/sec (Fig. 5). The predicted maximum

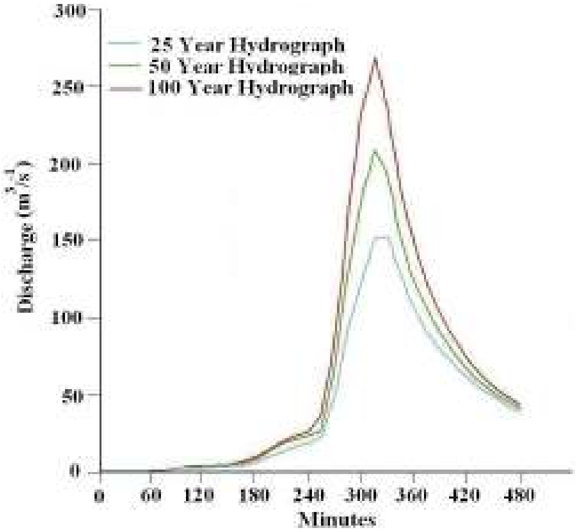


Fig. 6: Predicted maximum discharge (25, 50 and 100 year return periods, respectively) for Wadi Mubarak (1991 flood)

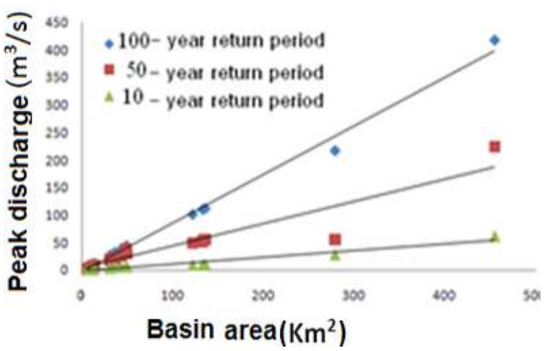


Fig. 7: Relation between the basin area and unit peak discharge for different wadis of the piedmont zone

discharge for flash-floods of a 25 year return period was 135.3 m^3/sec (Fig. 6), for 50 year return period was 210 m^3/sec and for 100 year return period was 269.2 m^3/sec (Jordan Consulting Engineer Co., 1993). The sudden rise in peak discharge is occasionally influenced by the blockage of culverts installed along channel crossing of the Aqaba back road and the mid-road by debris materials in the upper reaches of the wadis, thus accelerating runoff, roads and property damages. Field observations indicated that the maximum intensity of the flash-floods occurred in the upper and middle reaches of the wadis, while maximum inundation and standing water after rain were achieved at the lower reaches and toes of alluvial fans. Located here are most of the residential areas, the airport, container port, public beach, green areas and large yards and light industry area. Considering the predicted maximum discharge related to wadis crossing the piedmont zone (Wadi 2 to 14) and the bajada (W. Mubarak until W. Yutum to the north), most hazardous catchments are: Wadi 2; Wadi 7; Wadi 9; W. Mubarak; W. Jeishieh; W. Shallalah; W. Shahbi and W. Yutum (Aqaba Region

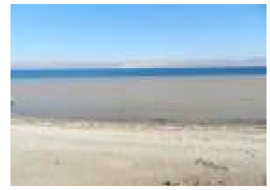


Fig. 8: Turbidity of the sea shore

Authority, 1987; Jordan Consulting Engineer Co., 1993; Central Water Authority, 1966). Plotting the predicted UH peak discharge of flash-floods pertained to the main wadis of the Aqaba area, against catchment areas (km^2) (Fig. 7) for different return periods (25, 50, 100 year return period, respectively), illustrates that the Aqaba area is seriously threatened by flooding water and sediments discharge. Moreover, in case of flash-floods of different magnitudes, there is no sufficient time to evacuate residents of Aqaba, or to apply precautionary safety procedures. Thus, comprehensive and efficient flood protection measures are urgently needed.

These shortcomings where described by officials in several short unpublished reports concerning previous flood events and printed media. It is argued that a warning system, emergency plans and precise information regarding flash-floods are often not available. The response of officials to the hazard and the management of crisis after it emerged are nearly deemed quite inefficient and are managed incidentally and poorly. Muddy flooding water invaded the sea up to 50-100 m along the southern coast of Aqaba. Suspended sediment transported by flooding water ranges between 30000 and 80000 mg/L at the Yamanieh coral reef area south of the marine research station. These sediments caused environmental degradation to the public beach of the southern coast and increased the turbidity of the water along the shore (Fig. 8), which might cause a loss of aquatic habitat such as corals and definitely harm the visitors of the public beach who enjoy observing these corals through glass boats.

At the lower reach of Wadi (7), close to the coast, Tala Bay residential and recreational village was recently constructed. The flood protection measures installed caused a remarkable disturbance of terrain surface and drainage in the upper reaches. The natural drainage is disrupted by the mid-road combined with heavy disturbance of surface materials. An artificial channel was constructed (5 m width and 2.5 m height) to divert natural drainage/runoff away from the village and at a right angle close to the mid-road (Fig. 9). The main wadi channel was replaced under the road by a three box-culvert (2×2 m). During fieldwork, it was observed that the artificial channel was already cleared of fine sediments deposited with 10 cm of thicknes. It is obvious that this channel function is solely for small flows and it is expected to be filled mainly by fine sediments during a large-scale event. Gully erosion and

Fig. 9: Artificial channel to protect Tala bay

Fig. 10: Slope cut in the wadi bottom and severe gullying, mid-road

sedimentation indicate that the channel gradient is not suitable for efficiently passing flooding water and suspended sediments especially in the case of high-magnitude floods. The shoulder of the highway is heavily eroded by gullying and the wadi floor which has been cut for mid-road alignment is intensively gullied (Fig. 10).

All terrain units recognized in the study area are characterized by the abundance of sediment supply of all sizes from the surroundings. Parts of the alluvial piedmont, the granite slopes and the fluvial terraces were heavily disturbed during construction of the Aqaba back road (1990/1991), the mid-road located between the coastal highway and section (B) of the Aqaba back road (2006-2007) and other road networks already constructed between the coastal highway and the mid-road).

Sections of these roads were affected by the flood. Continuous leveling of the piedmont surface in several sites (between the coastal highway and the mid-road) to prepare appropriate sites for building construction, maximize sediment supply and gully development (Fig. 10) during flooding. However, wadi systems developed on granite with long alluvial fans and man-made areas are the most critical terrain units for flooding and resultant engineering problems. Most of the problems recognized on the mid-road, secondary road network, leveled surfaces with steep-side slopes and spoil heaps are found on these units. Sediment sources, rill and gully erosion, slumping, mud and debris flows and subsidence are characteristics of the piedmont terrain zone. In several sites, on the coastal highway, mid-road and other roads network, slumped materials and debris overrode the road surfaces (Fig. 11). Mini alluvial fans were initiated and covered the road surfaces (Fig. 4c and 12). Uplifted corals in several areas were also exposed by gully erosion.

The assessment of terrain units can be carried out on the basis of identifying areas of relative flood danger. In this regard, terrain units and components

Fig. 11: Slumping (mid-road)

Fig. 12: Minor alluvial fan, severe gullying, road covered with debris and subsidence of a housing plot

which are evaluated as the safest areas must be considered for urban development and other desert installations such as the residential areas, industrial zones, ports and airports, roads and railways and other infrastructures. Such procedures could be more efficient if terrain assessment for flood hazards is combined with regular hydrological measurements from a monitored catchment (Schick, 1971, 1978), where basic data on rainfall intensities, peak flows, fluvial process parameters and other factors can be provided and analyzed. Following that, the developer or planner can do as little as possible to control the flood, or to minimize its negative impact. Adding to that, the adoption of sensible control measures must be designed for sites where high flood risk cannot be avoided. The implementation of a sensible informed land use planning is essential.

It is worth referring here to a comment (during an interview with Director of the Permanent Scout Club, Ministry of Education, on 10th of May 2014) which reflects the mistrust of the government and to some extent the fear of expressing this mistrust. Speaking to the director of the Club:

> "I spoke several times to the civil engineer of the Ministry to build a retaining wall parallel to a slope cut close to road leads to the club, to protect the building against flooding water and sediments…, the engineer replied, ‘Well it is costly to built such a wall. It cost at least 100 000 JD's … Surprisingly again, the engineer commented: ‘How much rain does Aqaba received? There is no rain in Aqaba"… It is clear that the engineer represents a typical example of poor perception regarding

environmental hazards. The basic characteristics of rainfall in an arid environment and the fluvial processes action etc., are not known and that's why geomorphology and flood hydrology are totally ignored by the engineers of arid Jordan''.

CONCLUSION AND RECOMMENDATIONS

The present investigation indicates that the Aqaba area is seriously threatened by repetitive flash-floods of different magnitudes. Planners must therefore, learn how to delimit the appropriate sites for development and avoid sites exposed to geomorphic hazards. Proper flood protection measures must be executed to protect developed sites against flooding, sediment discharge and other geomorphic processes. Limited or even poor perception of flood hazards among planners, engineers, developers, managers and the inhabitants as a whole is obvious in the Aqaba area. As Schick (1971) postulated over four decades ago, perhaps because of the "inexorable monotonous dryness", the dryland urban population does not expect and is usually not prepared for flood hazards. Urban development is often executed with complete ignorance of the potential threat of flash-flooding and the accompanying sediment discharge. As a first priority, therefore, urban planners, engineers and inhabitants of dry land cities such as Aqaba should be provided with technical information and fruitful advise on flood risk related to the areas they live in and be given Extreme Rainfall forecast Alerts (ERA) through the Meteorological Office of Jordan (Aparicio *et al*., 2009; Hurford *et al*., 2012).

A framework for a disaster management system for the Aqaba area was suggested, taking into consideration that disaster management is a multidimensional field that requires a high level of solid up-to-date technical knowledge and coordination. Several governmental and non-governmental agencies, the army and security forces can play a distinctive role in all regional and national calamities. Pre-and post-disaster management efforts could be provided through a wide range of bodies and agencies. The available systematic resources in the country can be employed to respond efficiently to flood hazards in the Aqaba area. The army capacities can participate in pre-and post-disaster activities such as rescue, relief and recovery. Furthermore, technical assistance can be provided to other governmental agencies involved with infrastructure services and voluntary assistance associations and NGOs during disasters. A research program should be launched to investigate gully erosion, sediment production and other hillslope processes. The growth rate of natural gullies and those developed recently since 1991, must be thoroughly monitored and studied. Large wadi floors with changing channels, gully erosion, slumping and spoil heaps rising several meters above natural undisturbed surfaces, act as a sensitive indicator of landscape change caused by intensive human and engineering activities. Such phenomena must be examined to assess areas destroyed gradually by gully erosion and damage that might affect the present and future infrastructure. The rates of gully erosion and development in critical areas, can be determined using sequential aerial photographs to explore the extent of the problem. Rates of gully head expansion can be estimated using repeated field measurements and monitoring overtime, to produce sediment budgets with high accuracy (Ghimire *et al*., 2006). Aerial photos also permit the survey of gully erosion to be extended in time. The results of the present intensive survey are useful for planning and executing appropriate control measures and for generating a sediment hazard map at the catchment scale (for Wadi 2 and other Wadis crossing the piedmont zone up to Wadi 14). At present high resolution remote sensing techniques, have led to a dramatic increase in terrain information, better understanding of geomorphic processes and precise recognition of anthropogenic signatures on topography (changes in terrain surfaces due to human activities) (Tarolli, 2014). It is also possible to assess flooding risk and to map spatial potential flood hazards using geospatial techniques (Nkeki *et al*., 2013; Peng *et al*., 2010).

Nevertheless, the last thunderstorm of May 2014 and the associated flash-flood substantiate that the piedmont zone and the southern coast of Aqaba are exposed to additional geomorphic problems. This zone is dissected by an ephemeral flow-network and dense gullies that occasionally convey high-velocity flows combined with high suspended sediments through steep slopes in the upper parts and potentially unstable slopes in the upper parts and potentially unstable slopes composed of weak materials in the middle and lower parts. Unfortunately this zone has been earmarked as a site for urban and suburban development in the near future (Aqaba Special Economic Zone Authority, 2003). The flash-flood caused severe disruption to the residents of Aqaba, where flood water invaded several sectors of residential areas and two lives were lost. All the streets, highways, roads, yards and roundabouts were converted into muddy pools, bridges were dislocated and retaining walls were destroyed. The high level of muddy water reached 60 cm in the city centre and other parts of the city. Flooded water with high sediment concentrations also invaded the beach of the southern coast to a distance of 50 to 100 m into the sea. Severe gully erosion, debris flows, slumping, subsidence and the creation of minor fans were recorded almost everywhere on the piedmont zone. Inundation of the lower reaches of the piedmont wadis is predicted even with low-magnitude flash-flooding similar to that which has occurred since 1991. The geomorphic hazards and problems existing due to May 2014 flash-flood indicate that the piedmont zone is more vulnerable to flood hazards and the associated fluvial processes than the bajada north of Aqaba. Anthropogenic factors such as the destruction of the natural drainage system, inefficient drainage or lack of artificial drainage, heavy disturbance of specific landforms/terrain units, wadi floors, extraction on construction materials and poor land use control are key factors responsible for maximizing flooding and sediment discharge in the Aqaba area. The combined effect of geomorphology (fluvial processes, gullying and slumping), hydro-meteorological conditions, anthropogenic factor, poor response to flood disaster management and lack of adaptation strategies will increase the negative impact of flood disaster on the flood-prone areas of Aqaba. Hence careful flood protection procedures should be integrated with present and future land use patterns essential to achieve proper adjustments with the natural fragile landscape of Aqaba (Jones, 1983). Although slight progress has been made in flood risk management recently by Aqaba Special Economic Zone Authority (2010), it is not yet integrated into the Aqaba land use plan. A national strategy of flood management plan and a national insurance system against environmental hazard are as yet unattainable.

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