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Geomorphological Evaluation for Urban Development Using Remote Sensing and GIS, Southern Coast of Aqaba, Jordan

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Abstract
Recently the Aqaba Region Authority (2003) proposed the southern coast of Aqaba to be a major coastal resort town.The site extends between the container port and the industrial zone just to the north of the Jordan–Saudi international borders. The proposed master plan showed a remarkable lack of understanding regarding the geomorphic characteristics of the area and the associated environmental hazards. Geomorphological evaluation has been conducted for an extremely rugged and arid granite mountains and alluvial piedmont overlooking the Gulf of Aqaba using air photos, SPOT images, field work, remote sensing and GIS. Different terrain units, surface materials, abundant ephemeral wadi channels, and geomorphic problems/hazards were recognized. The presence of high density gullies and ravines, and polished granite boulders suggests that fluvial erosion is a significant agent both past and present. Sharp parallel and elongated ridges are the dominant morphological pattern in the area. The lower parts of the drainage networks are characterized by braided and changing wadi channels which indicate fluvial activity in such a hyper-arid environment. In the light of heavy dissection and active gullying, flat and semi-flat land suitable for urban development and infrastructure construction are not abundant. Available flat and undulating terrain are restricted to a narrow strip (2.5-5 km) of land close to the beach, and are occasionally occupied by large wadi beds with changing channels. 80% of the area is exposed to flood hazards, sediments supply, direct talus and boulder supply from the piedmont and granite mountains watersheds. Following the geomorphological survey, alternative solutions to existing problems are recommended.
Keywords: Jordan, Coastal Aqaba, Alluvial Piedmont, Geomorphological Evaluation, Urban Development.

1. Introduction

On highly dissected alluvial piedmont of hyper-arid environment, urban development is intending to replace the natural setting. Up to the late 1990s, the area under consideration was the domain of changing wadi channels, intensive gully erosion, and sediment transport and deposition. Due to the long intervals between flood events and the lack of field hydrological data, planners and land developers paid little attention to these natural processes, thus ignoring the vulnerability of towns and small coastal resorts to hazardous events and disasters. Past experience from Aqaba (Farhan *et al.* 1989 ; Farhan 1999) and other similar urban areas, such as Eilat southern wadi Araba (Grodek *et al.* 2000), indicate that optimal planning for flood protection became increasingly difficult, since continuous urban development has often resulted in destruction of natural drainage associated with a lack of adequate and efficient passage (natural or artificial) of flood water and sediments. Coral and sand mining during the construction of the coastal road, south of Aqaba, destroyed the 3m level of raised coral beaches. The future urban development associated with tourism pressures, commercial shell collection, sedimentation, and pollution will cause indirect anthropogenic stresses, which contribute to coral reef degradation along the southern coast. Recent and historical earthquakes have been investigated by Al-Tarazi (2000) and Al-Tarazi & Koijenkov (2007). It can be concluded that the Aqaba area is exposed to repetitive seismic hazard**s** which must be taken into consideration to maintain future urban development,present and future infrastructure construction, and public safety. Hydrologic analysis of a severe flash flood that occurred in Aqaba city on 2 February 2006 was carried out. The flood was combined with sediments and debris flow (Murphy 2010). Boulders of 6.5 m^3 were recorded, and rainfall intensities predicted to reach up to 120 mm/hr^{-1} for 10 minutes. The flood caused extensive property damage and loss of life.The combination of high rugged relief, steep and long slopes, wide and narrow wadi channels and extremearidity resulted in a flash flood that caused five fatalities and extensive damage to infrastructure.The flood water disrupted power and water supplies, and damaged the wastewater treatment plant, causing significant environmental degradation and substantial hardship for the people of Aqaba city, Jordan's only shipping port (Murphy 2010).Following the flood, a disaster risk management plan was prepared (including flooding) for the Aqaba Special Economic Zone Authority of the Aqaba Area (ASEZA 2010).Spatially, the port is crucial to the Jordanian economy and protection of the city/port from flood damage is important to maintain future urban and economic development. Flood volumes and sediment loads were estimated for storm events of various return periods. The discharge of wadi Yutum, Aqaba for a single flood is predicted to be 562 MCM/second for a 50-year return period, and 900 MCM/second for a 100-year return period (Nassar & Bany Mustafa 2010).Such an event is comparable with the severe flood of 11 February 1966, where the peak discharge of wadi Yutum reached 500 MCM/second, and was classified as a 50-year return period (Centran Water Authority 1966). The 2006 flood event is of the same magnitude as the 1966 flood, and occurred after almost 50 years. Between 26 January and 6 February 2013, the Aqaba area was also exposed to intense rainfall which resulted in flooding, and hence disruption in transport between the southern coast and the northern neighborhoods of Aqaba. Wadi Yutum and the wadis of the alluvial Piedmont were also flooded, and the bridge installed by the Jordanian army on a wide course on the alluvial fan of wadi Yutum was swept away by the flood water (Alghad daily newspaper, 26 Jan. and 6 Feb. 2013). The yearly total sediment yield from Wadi Mubarak (terminated to the container port) and wadi (9), southern coast of Aqaba, was estimated during the period 1980-2009 using SWAT (Soil and Water Assessment Tool) model (Thneibat 2011). It was found that maximum sediment yield value occurred in 1994, where it reached 0.14 ton/ha^{-1} in wadi Mubrak, while it approached 2.5 ton/ha^{-1} for wadi(9) at the middle of the proposed area for urban development. It is recommended that any future development master plan must be based on geomorphological indicators illustrated by geomorphological maps. The present investigation highlights the geomorphological problems existing along the southern coast of Aqaba (Fig.1), which are typical of those dominating dryland urban areas in the region (Cooke 1982; Cooke *et al.* 1985 and Mohamed *et al.* 2002). Geomorphological survey in this context is considered an important, rapid, and low coast tool to evaluate the site for urban development and land use potential. In light of repetitive geomorphic hazards, it is therefore essential to identify areas exposed to flooding, and terrain constraints against urban expansion. Soil erosion by water and wind, intensive gullying, slumping and mudflow processes have dominated the alluvial piedmont to the east of the southern Aqaba coast (locally called the Teeba area). The changes in wadi channels observed in SPOT images of 1990 and 2003 and 2006, demonstrate that fluvial processes are active at present in such a hyper-arid environment. Subsequently, the present survey intends to:

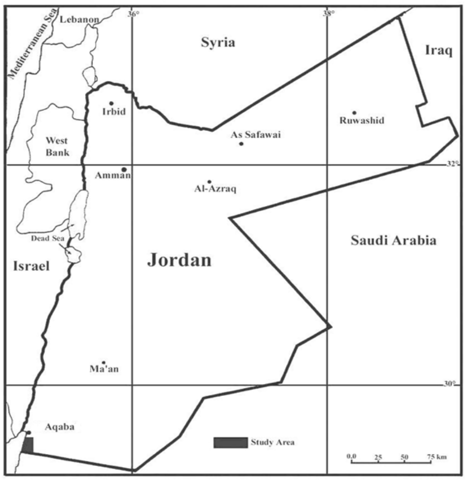

Figure 1. Location of the study area

- delimit the geomorphic units,
- map the dense gullies and drainage networks characterizing the alluvial piedmont.
- record the engineering activities associated with recent urban development following the approval of the development plan in 2003/2004.
- generate a map which illustrates the area liable to flooding, and
- evaluate the development plan in the light of the geomorphic setting of the southern coastal area of Aqaba and flooding.

2. Methodology

A geomorphological survey was conducted to record the geomorphological characteristics and potential future hazards in the area under consideration.The resultant information is intended to help the planners and developers to respond effectively to floods and other environmental hazard**s** in appropriate time (Cooke *et al.*1985; Kesseli & Beaty 1959; Schick 1971; 1974; 1988; Grodek *et al.* 2000 and Jacoby *et al.* 2008). Geomorphic appraisal during and after urban development is similar to appraisals adopted prior to development, but their relative importance changes. Such procedures are occasionally accomplished by establishing long-term observation stations along small arid watersheds. Due to the lack of observation stations in the Aqaba area, the author employed geomorphic mapping and classification of process activity rather than the process itself in order to overcome these difficulties. Such indices were derived through visual interpretation of remote sensing data (aerial photograph and SPOT image) and fieldwork (Cooke *et al.* 1985; Runzi & Banghan 1987; Baker *et al.* 1988).The qualitative flood hazard susceptibility mapping of Suez city, Egypt (Doornkamp *et al.* 1979; Bush *et al.* 1980; Cooke 1982 ; Cooke *et al.* 1985), and of the Aqaba area (Farhan, et al., 1989) exemplify this approach. The present investigation also employed the results of long-term urban flooding and sediment yield monitoring of the Eilat area (Schick 1971; 1974; 1988; 1995; Lekach 1993; Grodek *et al.* 2000;Khana *et al.* 2002) to predict arid fluvial behavior and changes on the basis of spatial analogy.The final maps were digitized using remote sensing (ENVI 4.1 and ERDAS Imagine 8.5) and GIS(Geo Media 6 and Arc GIS 10.1)techniques and the associated packages. ASTER Image of was utilized to establish the Digital Elevation Model(DEM) of 30 m resolution (Fig.2) , and to generate the drainage maps. Geomorphological mapping and field survey was carried out to recognize and record the geomorphic/terrain units, drainage network and gully system,fluvial geomorphic features, areas liable to flooding, and the geomorphic limitations facing urban development and potential land use.

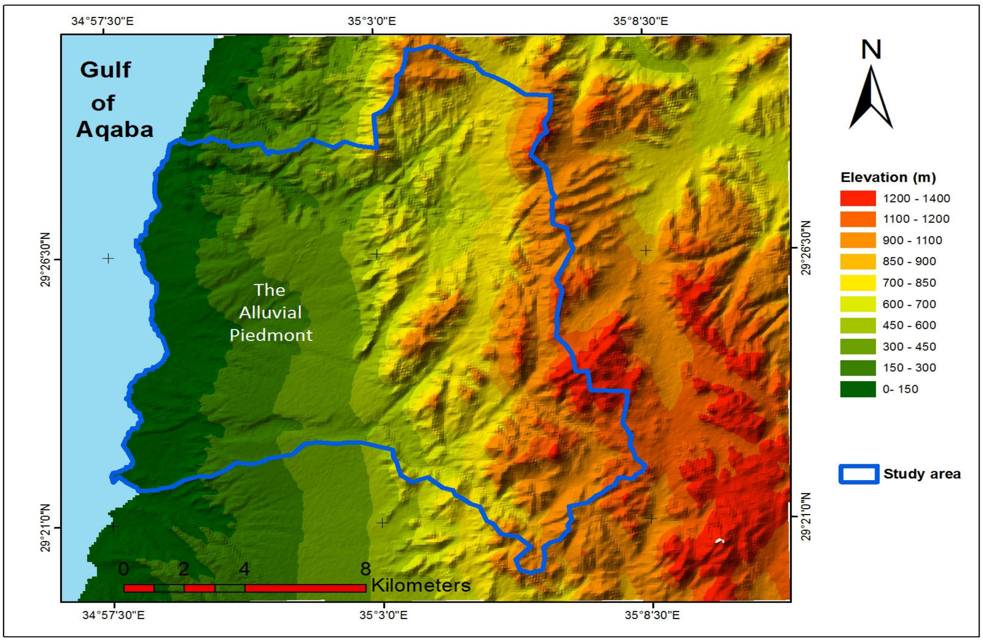

Figure 2. Digital Elevation Model for the southern coast of Aqaba

3. The Study Area

The study area lies on the northern edge of the Arabian shield, overlooking the Gulf of Aqaba.Crystalline basement (the Aqaba granite complex), and the alluvial piedmont dominate most of the area east of the southern coast (Bender 1974; Burdon 1959).The granite mountains here are stripped completely of sandstones, except for a few remnants of Kurnub **s**andstones and Cambrian **s**andstones exposed in the northeastern part of the study area (close to Wadi Mubarak) and to the southeast of the container port, respectively (Fig. 3).The granite terrain is highly weathered , and extensively intruded by dykes of different types, density and rate of weathering (Abed 1985; Osborn & Duford 1981).Thus, rugged mountainous terrain is the persisting topographic expression.The alluvial piedmont consists mainly of recent channel sediments and Pleistocene fan gravel. At the eastern part, lagonal marl and sand are exposed, interbedded with clay. Three major trends for faults are dominant: north-south, east-west, and northeast- southwest (Natural Resources Authority 1987 a & b). The most significant of the north-south fault set is the Quweira fault, which runs parallel to Wadi Araba rift and existed at least from Precambrian – Paleozoic times (Lloyd 1969). The north-south and northeast-southwest fault systems intersect near the spur interchange (east of Wadi Mubarak). Consequently, the area is considered to be a shear zone sub-parallel to the Quweira fault, and seismic activity is a repetitive phenomenon (i.e. the Gulf of Aqaba earthquake swarms of 1983 and 1995 are one example), and may therefore affect the safety of engineering projects in the proposed development area (Al-Tarazi 2000; Al-Tarazi & Koijenkov 2007). Following the 1995 earthquake swarm, cracks were observed in the buildings of Aqaba city and the uplifted coral reefs extending along the southern coast of Aqaba.

Interpretation of SPOT images (1991,2003&2006), aerial photographs (scale 1:7000, 1992) and a field survey led to the identification of four major geomorphic units:

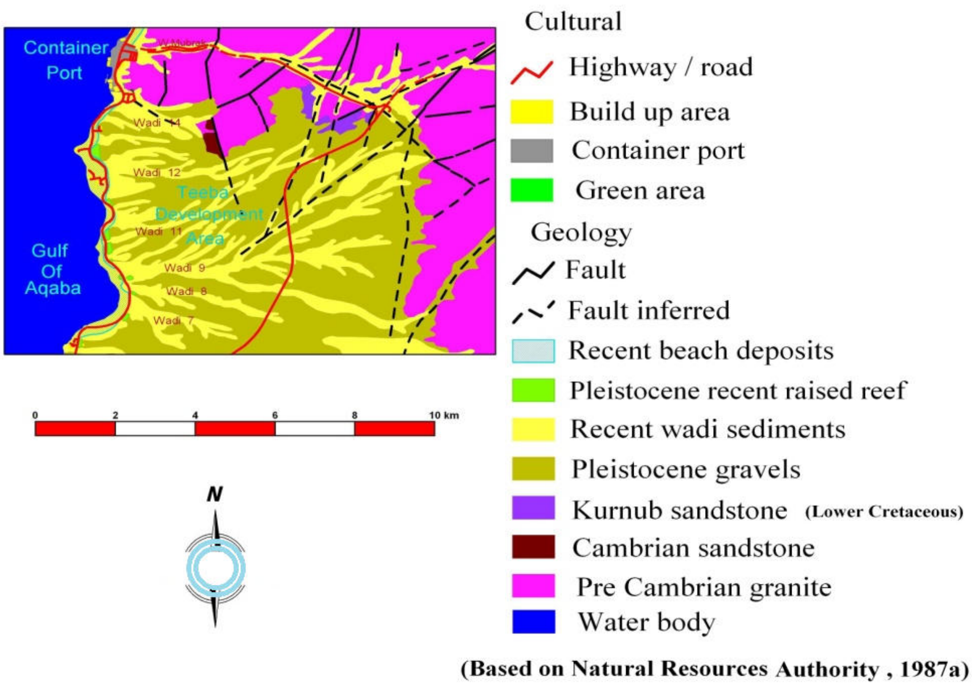

Figure 3. Geology

3.1 The faulted-denudation granite mountains.

Steep and long slopes of 10-20º, 20-30°, and 35-40° are common on granite slopes.The lower slopes are occasionally covered by scree or small recent alluvial fans. Torsand cavernous weathering pits are dominant (Osborn & Duford 1981). The tors are corestones isolated by chemical weathering along orthogonal intersecting joints.Rounded joint blocks become completely detached from the underlying rock, and rest until removed downslope by rainstorms. Boulders are found in steep wadis and ravine courses. Considering the steep wadi gradients, small boulders can easily be transported during flooding, as evident from the 1991, 1993 ,1994 and 2006 floods, which caused severe damage to the Aqaba Back Road (Farhan 1999).

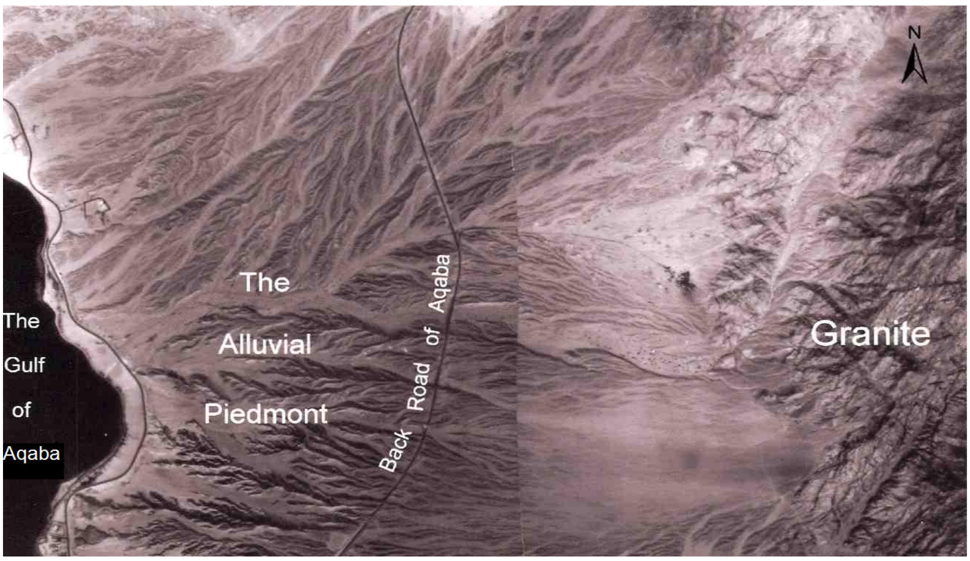

Figure 4. Air photo (stereo model) of the alluvial piedmont(scale: 1:7000,1992,source:RJGC)

3.2 Dissected alluvial piedmont slopes:

Urban development along the southern coast of Aqaba is planned so as to occupy most of this geomorphic unit (Fig.4). This area covers a triangular embayment with a base about 65 km along the coast of Aqaba. It is postulated that the proto Wadi Yutum - Wadi Mabraq drainage system eroded most of the sandstones overlying the granite during late Tertiary, when deposition took place in the embayment mentioned above. Sand interbedded with clay and marl predominates at the base of fan materials; while sand and granite gravel dominate the upper part (Hayward 1985; Farhan *et al.* 1989; Osborn 1985). Uplifted fossil coral reefs (7-8 distinct terraces) are present along the coast, with heights of 3-45 m. An age of 3,800 years is given for the 3m level, and 70–80,000 years for the 40-45m level (Al-Sayari *et al.* 1984 ; Al-Rifaiy &Cherif 1988; Farhan *et al.* 1989; Vita–Finzi 1987). Here rejuvenation produced typical badland topography, with elongated ridges, steep slopes, fine drainage texture (Fig.5), large wadi beds in master channels, and recent embryonic alluvial fans at the base of the granite. Severe gully erosion also indicates unstable conditions during the construction of the Aqaba–Back Road (Section B along the alluvial piedmont),and present development**s** initiate slumping and maximize sedimentation problems at the lower slopes, and the coastal zone of the southern coast.

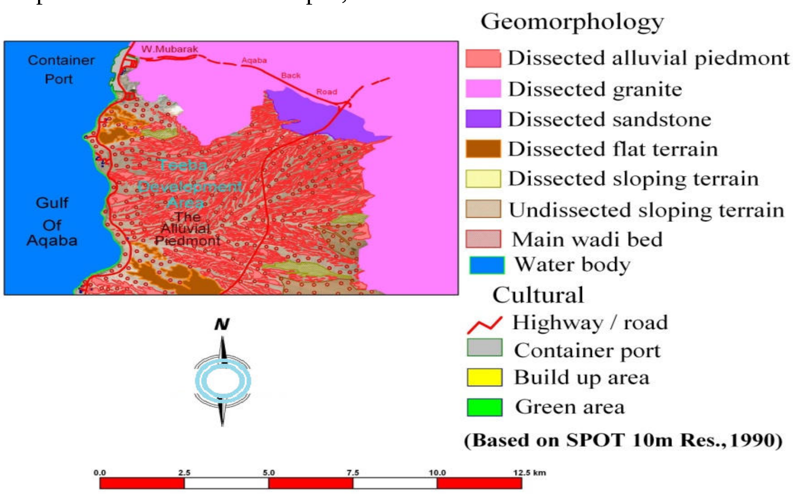

Figure 5. Major geomorphic units

3.3 Dissected Cambrian and Kurnub Sandstones.

Talus slopes and Kurnub sandstone exposure are considered a major sediment source for sand, gravel, cobbles, and boulders which threaten the hydraulic engineering structures. Severe gully erosion on sandstones is also presently active during rainstorms.

3.4 The narrow beach / coastal plain.

In the late Pleistocene, relative lowering of the sea level, possibly associated with further tectonic movement, led to the rejuvenation of wadi systems characterizing the alluvial pi**e**dmont. Drainage incision was associated by deposition of alluvial and wadi sediments, and the formation of fans and mudflats, along with local beach deposits (Natural Resources Authority 1987 a).

4. The Alluvial Piedmont Watershed

Twelve small and large watersheds cross the alluvial piedmont area and are characterized by relatively wide stream and changing channels. The proposed planned area is located between Wadi 2 (drainage area 62.2 km^2) close to the industrial area in the south, and Wadi Mubarak (drainage area 65.1 km^2) close to the container port in the north (Fig. 6).These wadis are named officially from south to north: Wadi 3, Wadi 4, Wadi 5, Wadi 6, Wadi 7, Wadi 8, Wadi 9, Wadi 10, Wadi 11, Wadi 12, Wadi 13 and Wadi 14, which are located just south of the container port.The smallest catchment is Wadi 13 with a drainage area of 0.5 km^2.

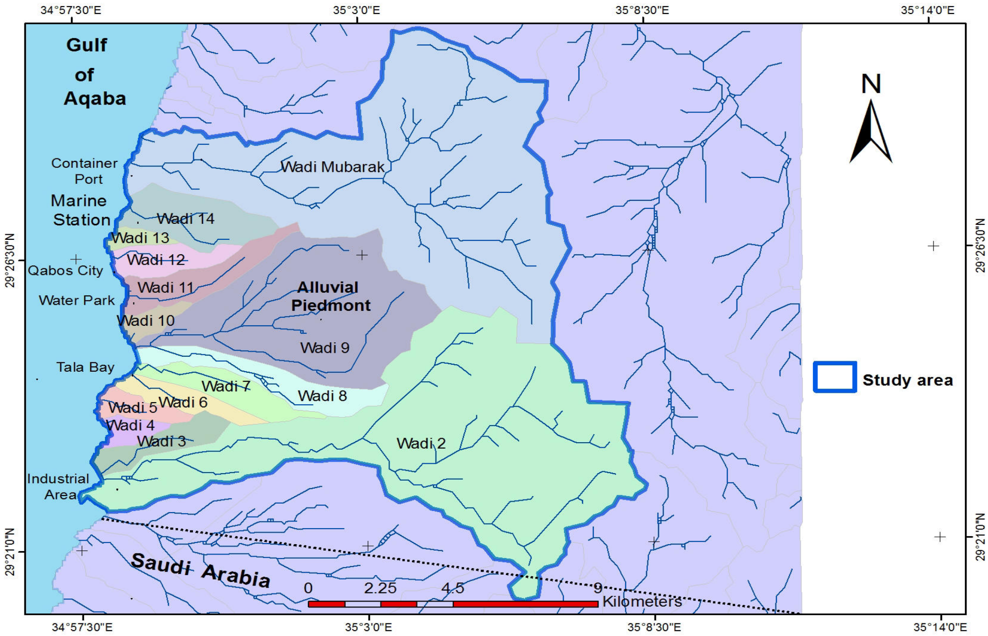

Figure 7. The alluvial piedmont watersheds

The upper divide of these wadis extends to the east along the granite sharp ridges at a height ranging between 1300m and 1350m a.s.l for Wadi 2 and Wadi Mubarak. Meanwhile, the water divide for other wadis ranges between 770m and 1900m a.s.l. None of these wadis is instrumented for hydrological purposes, and the only hydrological study available (Aqaba Region Authority 1987) concluded that the expected peak discharges (MCM/S) are high for such hyper-arid catchments (Table 1). Consequently**,** the only alternative approach is to utilize directly the results obtained from instrumented watersheds in the Eilat area (Grodek *et al.* 2000; Schick 1971; Schick & Sharon 1974; Lekach 1993) to evaluate flood hazard in the area under consideration. Field work investigation indicates that hydraulic structures installed along the present highway are not efficient to transmit the flow and sediments generated through flooding.

Table 1. Expected peak discharge for the piedmont wadis (MCM/S)

Watershed No.	**Drainage Area (km^2)**	**Recurrence Interval (y)**					**Available Culvert Capacity (MCM/S)**
		2	**10**	**50**	**100**	**500**	
Wadi 2	62.2	110	223	418	455	584	62
Wadi 3	0.9	4.3	8.8	12.5	14.2	18.9	0.0
Wadi 4	1.3	3.9	7.8	11.3	12.8	16.9	13.7
Wadi 5	1.5	3.1	6.8	9.9	11.3	15	15
Wadi 6	1.7	3.7	8.2	12.2	13.6	18.4	0.0
Wadi 7	6.2	11.2	26.1	38.5	43.4	57	61.8
Wadi 8	6.5	12.4	30.2	43.9	49.4	65.9	0.0
Wadi 9	37.4	6.2	19.6	34.9	41.9	59.8	0.0
Wadi 10	1.0	2.6	5.6	8.1	9	12.1	6.3
Wadi 11	5.0	9.5	21.1	31.7	35.9	48.6	43.7
Wadi 12	3.5	8.6	8.5	26.5	30.4	39.7	17.3
Wadi 13	0.5	1.6	3.4	4.9	5.6	7.4	0.0
Wadi 14	6.1	13.4	37.8	42.7	48.8	65.9	0.0

Source: Aqaba Region Authority (1987), 2-30& 2-33.

Hence, the coastal highway presents a serious barrier to the natural runoff from the piedmont catchments to the Gulf. Thus, the future urban development of the southern coast of Aqaba must consider this fact, along with the inefficient capacities of present drainage structures constructed along the coastal highway including the industrial area (Aqaba Region Authority 1987). Similarly,the future expansion of the urban/industrial area will increase the peak runoff and sediments associated with expected flooding following urbanization.The industrial area extends 3 km along the coast line and 2 km inland, and is located close to the north of the Jordanian–Saudi Arabian borders. It is planned to enlarge it eastward in the future.The principal industries presently occupying the area are the thermal power plant, a timber products industry, and a potash company.Three ship berths have also been established on the coast to serve the oil, timber, fertilizer and potash industries.The lower part of Wadi 2 has been designed and constructed as a major artificial channel to convey runoff, in an attempt to protect the industrial area against flooding. Fifteen concrete box culverts (typically a twin box: 2.5m * 1.5m) and three pipe culverts are installed along the coastal highway to convey runoff from the industrial area to the Gulf.The capacity of these culverts is only 62 MCM/S. Therefore, the industrial area and other future urban development projects are exposed to anticipated serious flooding.

5. Climate, Hydrology and Flooding Experience

The study area is located 8 km south of Aqaba on the eastern coast of the Gulf of Aqaba. The climate of the area is hyper-arid, with low mean annual rainfall and moderately high temperature. The mean annual rainfall in Aqaba is 37mm, while the mean annual rainfall in the middle and upper catchment of wadi Yutum rang**es** from 100 to 150 mm. Seventy percent of rainfall events occur between December and February, and originate in southerly trajectories of Mediterranean depressions.The spring and autumn rainfall originates in local convective cells associated with an incursion of the Red Sea trough (Grodek *et al.* 2000; Khana *et al.* 2002). The area is characterized by intense rainfall of short duration within limited areas (localized type), where 60 % of the total rainfall come**s** from spotty rain (Sharon 1972). Spottiness is clearly pronounced in the fall and late spring. The storms of March 1991,December 1993 and January 1994, which caused heavy damage to the Aqaba Back Road, are an example (Farhan 1999). Although arid watersheds are dormant for 98 % of the time, when it becomes active, it transports large quantities of sediments both as bed load and suspension load, far outstripping the performance of comparable perennial rivers (Reid *et al.*1998).Similarly, the high relief of the bare rugged granite facilitates the occurrence of extremely destructive floods in the downstream terrain zone chosen for urban development along the coast. Adequate hydraulic structures do not exist to convey the expected high-magnitude,low-frequency flash floods. During the 20th century, the lower Wadi Araba witnessed a number of large rainstorm floods which affected the inhabitants of the region. In 1940, one half of the modern town of Aqaba (built on the alluvial fan of Wadi Shallalah) was flooded and destroyed, as reported by Glueck (1941).Again in 1953, Aqaba town suffered a severe flood.The1960s witnessed a disproportionate number of floods. Three examples are (1) the event of April 1963, in which Aqaba town was flooded and 25 French tourists lost their lives in Petra, southern Jordan. (2) In March 1966, Aqaba was flooded again, and 70 persons lost their lives in Ma'an, with over 250 injured, while hundreds became homeless (Central Water Authority 1966; Schick 1971).(3) In 2006,Aqaba area flooded again, and 5 persons lost their lives, and extensive damage to infrastructure occurred.

Over the last four decades, the Aqaba area ha**s** been exposed to events of maximum rainfall intensities in 24 hours. Examples are: 34mm (1953), 27mm (1955), 36.3mm (1963), 32.8mm (1966), 65mm (1975), 42.5mm (1980).Such figures indicate that high intensity rainstorms are common and frequent in the Aqaba area (Aqaba Region Authority 1987, 2-13).The rainstorms of 21 March 1991, 20 December 1993 and January 1994 resulted in 17mm, 19.2mm, and 21 mm of rainfall respectively (Jordan Consulting Engineering Co. 1993;Thneibat 2011). It is concluded elsewhere that 40 % of the rainfall in similar environments is of intensities exceeding 20mm/hr, and 19 % in excess of 65mm/hr (Schick 1995). Similarly, Wadi Yutum, Aqaba area was exposed to a flood of a 19-year return period on 12 February 2006 (Murphy 2010).The rainfall intensity was estimated at 9.2 mm/hr. Such events affected the industrial zone, the waste water treatment plant and the Airport road. Despite the low annual rainfall average, the spatial and temporal distribution of rainfall in the Aqaba area**,** including the costal area, is such that flooding may cause serious problems, even from very small catchments (i.e. Nahal Yael and Nahal Roded, Eilat area, Israel (Grodek *et al.* 2000). In March 1966, a severe storm was recorded in Ras En Naqab area (70km north–northeast of Aqaba).The average four-hour rainfall was 60mm, which yielded an average intensity of 15mm/hr.The estimated peak discharge of Wadi Yutum during the storm was 500 MCM/s, identified as a 50-year return period (Central Water Authority 1966).

The Aqaba Region Authority (1987) reported that floods having a recurrence interval of 50 years or longer are capable of damaging the Ras En Naqab highway, assuming that surface water will rise to 0.3m above the highway surface, with relative high velocities. Several examples of inappropriate drainage design have been reported in the Aqaba area in general, and in Wadi Mubarak and Wadi 2 (the industrial area, just to the southern part of the coast) in particular, which contain most of the Aqaba Back Road (or the alluvial piedmont). Assuming a storm center over Wadi 9, the point rainfall and hourly rainfall are expected to be high (Table 2) at the center of the development area, and will cause severe damage to the future urban area and any other engineering projects.

Table 2. Point rainfall and basin hourly rainfall for Wadi 9 (Drainage area 37.4 km^2)

Recurrence Intervals	Point rainfall (mm)	Max. hr.	2^{nd} (mm)	3^{rd} (mm)	4^{th} (mm)	5^{th} (mm)	6^{th} (mm)
5yrs	18.1	13.6	3.4	1.8	1.1	0.9	0.7
10yrs	26.1	19.6	5.0	2.6	1.6	1.3	1.0
50yrs	46.5	34.9	8.8	4.6	2.6	2.3	1.9
100yrs	56.0	41.9	10.6	5.6	3.4	2.8	2.2

Source:Aqaba Region Authority (1987), 2-27.

Engineering problems resulting from expected flooding are also posed through the dominance of steep slopes on highly dissected alluvial piedmont, and by high erodibility of materials from which this terrain unit is composed.These conditions promote severe erosion, sedimentation and extreme channel instability in time and space.Infiltration rates of selected geological formations (Table 3) indicate that runoff was generally initiated after the first few minutes of rainfall (Schick 1995).

Table 3. Infiltration rates for selected geological formations in the lower W. Araba

Material	Infiltration rate (mm/hr^{-1})	Time to initiate Runoff (min)	Runoff Coefficient (%)
Granite/gneiss	0.5-2	1-4	52-86
Colluvial surface	20-30	5-10	26-43
Old alluvial surface	10-20	5-8	40-60
Recent alluvial surface	5-15	15-20	40-60

Source: Schick (1995)

Typical concentration of suspended sediments transported by floods generally range between 15000 and 40000 mg L^{-1}, occasionally exceeding 100 000 mg L^{-1}.Sediment yield in the Aqaba-Teeba area is expected to be high for arid wadis draining the alluvial piedmont such as Wadi 7, Wadi 8,Wadi 9, Wadi 11, and Wadi 14 (the major wadis of the alluvial piedmont).Assuming a discharge of 75m ^{3}/s for Wadi Mubarak, the estimated average of transport rates ranges between 7.26 kg m $^{-1}$/s and 28kg m^{-1}/s (Jordan Consulting Engineering Co.1993). More consistent figures may be provided by utilizing results from a fully instrumented arid watershed just to the north of Eilat. Here, Lekach (1993) provided a decadal sediment yield record for Nahal Yael, which has been monitored since 1977 at its outlet with the aid of a 100 % of trap efficiency dam. For the decade (1980-1990), 135 m^3 of fines and 228 m^3 of sand and gravel were deposited in the reservoir.The largest event during the decade is that of 26 December 1980, caused by a rainstorm of 45mm (in part low intensity), which deposited 57 % of this decadal sediment yield.It is evident that high-magnitude low-frequency rainstorms, when centered on the granite mountains east or northeast of the study area, not only yield substantial runoff, but are also capable of transporting a large amount of sediment. In this regard, the alluvial piedmont is considered an extensive sediment source in the proposed development area.Consequently, urban development and the associated engineering structures/hydraulic design must ensure water and sediment transmission. The rainstorms of 1991, 1993, 1994,and 2006 showed that almost all of the drainage structures provided for the Aqaba Back Road were blocked by sediment at their entrances(Farhan 1999).

6. Results and Discussion

The geomorphological survey reveals that geomorphic conditions posed serious problems for future urban development. Geomophologically, the site is considered as highly dissected alluvial piedmont, and topographically, it is a typical badlands (Fig. 4).The area is generally composed of parallel-close arid wadis, named Wadi 3 to Wadi 14, separated by parallel elongated ridges rarely terminated by flat or semi- flat terrain at their summits. The drainage area for these catchments ranges from 0.5 km^2 (Wadi 13) to 37.9 km^2 (Wadi 9). Wadi 2 (62.2 km^2),the largest, separates the southern coastal development area from the industrial zone to the south. From the north, Wadi Mubarak (65.1 km^2) separates the urban development area from the container port. The characteristic local relief of the piedmont terrain ranges from 0.0 (the sea level) to 400-500 meters a.s.l over

6-7 km of distance inland.The general gradient for the wadi courses approaches 5°. Such gradients are high for small and short wadis, which indeed maximize the capabilities for producing flash floods during heavy rainstorms.The surface geometry of the terrain can be summarized as follows:

a - on the plan level, the surface geometry is linear and parallel narrow ridges in the lower and middle-catchments of the alluvial piedmont, and non linear-parallel in the upper reaches.

b - on the profile level, flat to semi-flat, or undulating summits comprise 40-60% of the upper reaches only, but most of these areas are located exterior to the proposed development area. The slope of the ground surface here is less than 6°, but the wadi side slopes approach the 14-20° slope category or greater.Thus, generally, the topographic site of the proposed development area is characterized by a remarkable shortage of flat-semi-flat terrain as a result of dissection by active gullies, and the dominance of sharp elongated ridges(Fig.7) .It can be concluded that 80% of the area to the east of the coast is not suitable for urban development and infrastructure construction, except for a narrow strip of land close to the beach, and occupied by large wadi beds with changing channels. The development plan of the southern coast area suggested a layout of coastal resort, light industry, heavy industry (already existing directly

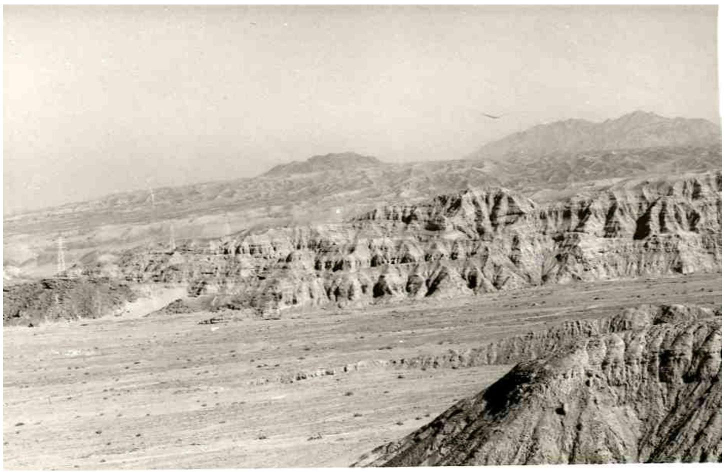

Figure 8. Highly dissected topography (badlands) by dense gullies

south of the present study area, close to Wadi 2), buffer, port, recreational, open spaces, development reserve, and wilderness reserve(Fig. 8). Land use details related to the coastal development plan have not yet been formulated. Table (4) illustrates major economic/tourism activities existing along the southern coast of Aqaba between the container port and the Jordanian–Saudi borders. Adding to the activities illustrated above, the southern coast accommodates eleven sites for diving and six coral gardens. The famous one is the Japanese garden, located off the beach. Several other services are provided on the beach. **A**mong these are:

Table 4 . Economic/tourism activities existing along the southern coast of Aqaba

Distance from the container port (km) towards south-the industrial area	Economic / tourism activity
0.1	Coral reserve
1	Public tourist complex
1.7	Ras Al-Yamaniya beach/camping site
2	Telecommunications building (East)
3	Aqaba marine science station/visitor center
3.4	Qabos City project - under construction
3.7	Bedouin tourist village (East)
5	Tala Bay: Jordan’s first integrated resort and residential community
7.7	Royal diving club
7.8	Telecommunications monitoring tower
8.1	Public security officers’ club
9.2	Marine personnel housing
9.5	Security housing resort
11.4	Three ship births (for oil, timber, fertilizer, and potash industries) Industrial area (East).

camping, car parking, visitor center, boating/jetty, restaurants, sun shades, diving and swimming sports. In addition to the geomorphic constraints illustrated above, the implementation of urban development plan is faced with other geomorphic constraints, such as:

- Steep denudational slopes, steep ravine and wadi courses
- Intensely jointed and faulted geological outcrops, the abundant weathering products, and high sediment supply from arid waters
- High rate of erosion during heavy rainstorms, and expected recurrent flooding events.
- Dense network of gullies and highly dissected piedmont make road crossing and accessibility very difficult.

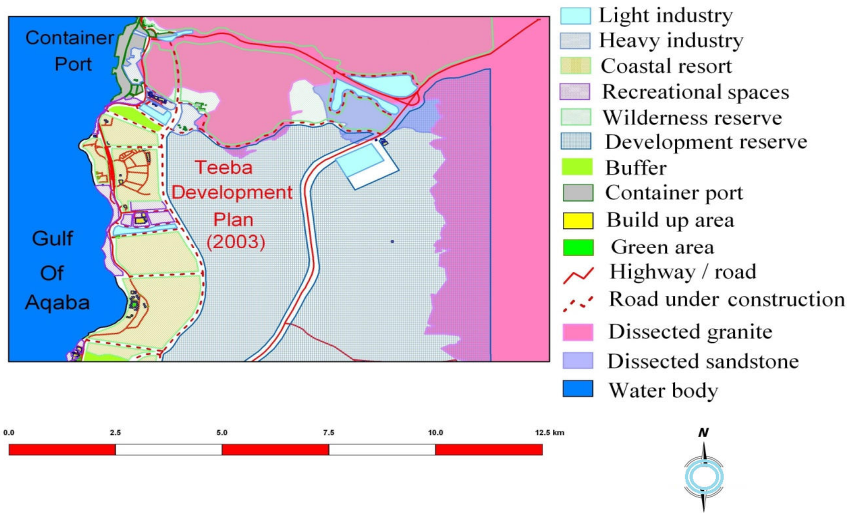

Figure 8 . Proposed development plan(2003/2004)

High magnitude floods in deserts are generated primarily by combination of rainfall characteristics (amount, intensity, duration, and distribution over the drainage basin).Extreme flood events are considered to be the products of the entire basin and tend to be associated with the preferred rainfall pattern. Maximum flood discharge is produced by an optimal combination of watershed morphology/morphometry and storm intensity (Costa 1987).Flooding in the area arises from storm flow along wadi channels descending from the granite mountains. Storm runoff generated by rainfall over the granite mountains reaches the narrow coastal plain and the highway through main wadis/channels extending across the alluvial piedmont (Fig. 9).Steep and long bare rocky slopes of 10-20°, 20-30° and 35-40° are characteristic of the granite mountains. Alternatively, the Kurnub sandstone shows a subdued topography with lower modal slope angles. Steep slopes are characterized by a low rate of infiltration (0.5-2 mm/hr $^{-1}$) and generate storm runoff immediately during the storm (Schick 1995).High velocities are capable of moving weathering products and materials off the alluvial piedmont down slope through wadi channels toward the narrow coastal plain. A geomorphic survey reveals that boulders of 30-40cm diameters were found on the Aqaba Back Road surface and inlets of several culverts following the 1991 and 1993 floods, which were classified as of 6-7 years return period (Farhan 1999).
Analysis of 28 floods generated by a drainage system in the Negev Desert over the last 60 years indicates that desert floods are characterized by high flow magnitudes (Greenbaum *et al.* 2000). An investigation of 52 major floods (for the period 1965-1994) in the same hyper-arid environment concluded that such floods are not the outcome of purely local weather conditions but are rather the result of distinct synoptic-scale events: (a) an active Red Sea trough extending from East Africa through the Red Sea toward the eastern Mediterranean, and (b) a Syrian low, defined as a well-developed Mediterranean cyclone accompanied by a pronounced upper-level trough, both located over Syria (Khana *et al.* 2002).These synoptic conditions and the associated floods are repetitive phenomena in the region.

Table 5. Extreme events in the Ma`an-Aqaba area (Southern Jordan) and Eilat area (Southern Israel)

Date	Catchment	Drainage Area (km^2)	Rainfall Amount (mm)	Storm Duration (hours)	Peak Discharge (MCM/S)	Volume ($10^6 m^2$)
8 April 1963	Wadi Yutum (Aqaba)	1300	36. 6	-	250	-
11 March 1966	Wadi Wuheida (Ma`an, northeast of Aqaba)	170	50-70	4-6	540	7
	Wadi Yutum (Aqaba)	500	30	4	500	4
	Wadi Dilagha (southern Wadi Araba, north of Aqaba)	70	50	4	200	1.3
	Wadi Qilkah. (southern Wadi Araba)	200	55	4	325	1.5
	Wadi Jurdhan (Ma`an)	260	20	4	120	0.7
	Nahal Yael (Eilat)	0.6	22	4	2.2	0.001
	Nahal Roded (Eilat)	38	30	4	100	0.7
1 February 1964	Wadi Yutum (Aqaba)	1300	33. 5	-	336	-
February 1972	Wadi Taba Wadi Morah	18-94	20	-	150	-
18 October 1997	Nahal Yael (Eilat)	0.6	25-42	2	3.7 – 7.4	260 -680
21 March 1991	Wadi Mubarak (close to the container port, Aqaba)	65.1	17	4-12	75	-
20 December 1993	Wadi Mubarak(Aqaba)	65.1	19.2	-	-	-
12 February 2006	Wadi Yutum (Aqaba)	1300	38	6	562	4.25

Based on: (Central Water Authority, 1966; Schick, 1971; Aqaba Region Authority, 1987; Greenbaum et al., 1998; Farhan, 1999; Grodek et al., 2000; Jordan Consulting Engineering Co, 1993; Aqaba Special Economic Zone Authority, 2010 and Murphy, 2010).

Table (5) is an example of extreme flood events recorded in the Ma`an-Aqaba area (**s**outhern Jordan) and Eilat area (**s**outhern Israel), along with their hydrological characteristics. It is clear that destructive flash flood events from small wadis are repetitive phenomena in southern Jordan generally and the Aqaba area specifically. Ninety percent of the Teeba area is located within the drainage areas of Wadi 7, Wadi 8, Wadi 9, Wadi 11, and Wadi 14. According to the flash flood analysis study related to the Aqaba area (Aqaba Region Authority 1987),and the present geomorphological mapping, the existing proposed development plan is totally exposed to severe flash floods (Fig. 9) of 10, 50, and 100 year return periods (Table 1 & Table 5), and it is impossible to avoid hazardous flooded wadis without comprehensive efficient remedial measures and a flood protection plan.

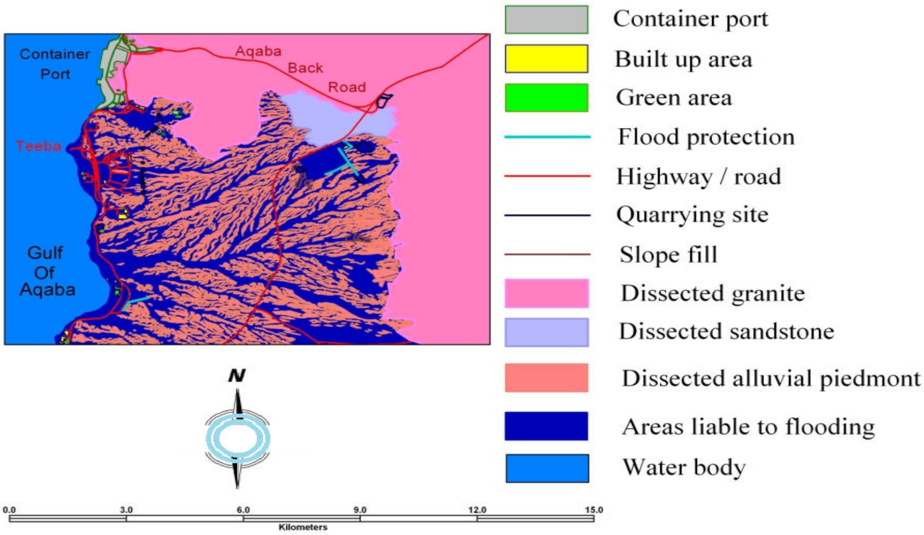

Figure 9. Areas liable to flooding

The only flash flood protection measures existing at the proposed development area are:

a- The light industrial area northeast of the area under consideration. It is an area of one km^2, excavated on an alluvial/scree fan at the base of the granite mountains. The yard was lowered 1-3m below the ravine and tributaries draining the mountain towards Wadi 9. No drainage facilities were provided in this area. Alternatively, an earthbarrier has been built to protect this area against flash flood-runoff descending from the granite mountains to the east.

b- The intensive tourist activities (northeast of the Royal Diving Center).Here an earth barrier was built to protect this cluster from expected flooding of Wadi 8. Not only that the major wadi channels had not been accounted for in that area, but a significant number of major and minor tributary wadis were not considered in the planning stage for this area (Fig.10).It seems that the cut-and-fill procedure was the only measure adopted in the lower channels to provide level land for the present infrastructure (i.e.Qabous city, 2 km south of the container port).Such a procedure is expected to maximize sediment deposition on these flat areas; since natural drainage has been destroyed by engineering activities.The extensive sediment supply revealed by a geomorphic survey reinforces the need for an appropriate drainage design to ensure unimpeded sediment transport. In the light of large areas exposed to future flooding (Fig.10), it is not feasible to construct earth barriers to protect the developed sites from flooding. Alternatively, the most appropriate solution to flood problems is to integrate a flood management and urban development plan. Lessons reported elsewhere (French 1987) concluded that with the increase in urban development on alluvial fans/piedmonts in arid regions, urban areas have become increasingly exposed to unpredictable floods. Due to uncertain flow passages and sedimentation on alluvial fans, total protection is both costly and, being based on uncertain areal differentiation of flood frequencies, may lead to great losses of live and properties (National Research Council 1996).

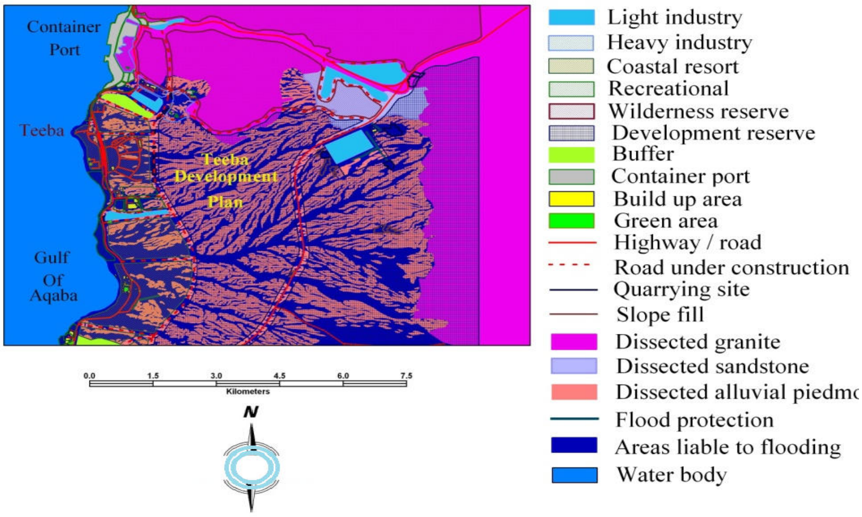

Figure 10. The proposed development plan and areas liable to flooding

Studies in the western Wadi Araba (Schick 1974; 1988; 1995; Grodek *et al.* 2000) and other comparable areas in the U.S. and Australia (Baker *et al.* 1988),are highly relevant to the understanding of the desert flood behavior in southern Jordan and its implications.The present experience from analyzing the southern coast of Aqaba area reveals that proper planning is achieved through incorporating the results of analyzing existing geomorphic units,their characteristics, sediment types and wadi courses along with flooding behavior.

8.0 Conclusion

The geomorphological survey carried out revealed a considerable lack of understanding of the geomorphic, climatic, and hydrological characteristics of the area under consideration. Geomorphological mapping indicates first, that the topographic site proposed for development is characterized by a remarkable shortage of flat-semi-flat terrain as a result of active gullying and changing wadi channels; alternatively, sharp elongated ridges are dominant. Second, the existing development plan is exposed to severe flash floods caused by the alluvial piedmont wadis. Due to the current absence of efficient drainage measures, it is impossible to avoid such hazardous floods and sediment supply.Third, the hydraulic structures installed along the present coastal highway are not efficient to transmit the flow and sediments generated through flooding.Similarly, the future expansion of the urban-industrial area, and the resultant surface conditions(i.e impervious surfaces)will increase the peak runoff and sediments associated with the expected flash flooding following urbanization. Based on the above findings, the most appropriate solution for flood problems in the area, is (i) to integrate flood management and morphologic assessment plans with urban development planning at an early stage of urbanization; (ii) such plans/mapping will enable the construction of proper hydrologic structure capable of accommodating flooding water and ensuring the passage of sediment discharge during flooding; (iii) afforestation and terracing activities could be carried out in middle and upper catchment of Wadi Yutum (Ras En Naqb and north of Quweira) supported with water harvesting construction techniques developed in similar environments elsewhere and proved to be successful (Yair 1982: 1994; Yair & Garti 1994; Yair 1996).The afforestation conditions affect the infiltration–runoff process in the catchment, and reduce the flood peak flow by 24-50% (Al-Weshah & El-Khoury 1999); (iv) the construction of check dams across the ravine/major wadi courses at the upper part of the alluvial piedmont is recommended. This will decrease the sensitivity of the piedmont watersheds to short-duration, high-intensity storms, making it less vulnerable to more frequent flood events and delaying the time to peak (Al-Weshah & El-Khoury 1999); and (v) the installation of upstream sediment control measures is recommended to reduce sediment supply towards the designed drainage system, and to dampen the erosive energy of the flood water. Previous investigations (Schick 1974; Farhan 1999) reported that sediment settling basins (2,560 m^3 in size) are inefficient to control sediment inputs at coastal highway**s** and other road crossings on alluvial piedmont.They tend to fill with sediments during the first few minutes or even seconds of a flood. To be efficient, they must attain a capacity of at least one tenth of the total volume of some typical flood event. For a 50-year return period flood, large settling basins on the order of 15000 m^3 - 50000 m^3 may be needed. However, large holes of such a size are difficult to dig, have to be maintained periodically, and disturb the attractive scenic value of the desert landscape.

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