Chapter 21
Landslide Susceptibility Map Production of Aden Peninsula – South West of Yemen

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Abstract The slope stability assessment of Aden peninsula which is located at south-western part of Yemen, was carried out. The study area consist of volcanic rocks which affected by number of faults, joints and dykes. All important factors affecting slope stability in the area such as slope angle, slope height, discontinuities measurements, weathering, vegetation cover, rainfall and previous landslide were evaluated. The study was constructed based on integration of field investigation and satellite images in combination with Geographic Information System (GIS). Land use/cover and Landslide susceptibility maps were produced by using satellites images and the Landslide Possibility Index System, the correlation values were computed between the factors measured and Landslide Possibility Index values. Landslide Susceptibility classes derived into six categories while four these categories are recorded in Aden Peninsula: very high, high, moderate and low zone. The results show that rockfall is the main mode of failure in the study area. Some treatments may achieve where it is needed such as removal of rock overhang and unstable blocks, support the toe of the slope and the overhanging parts by retaining wall, erecting well seal drainage conduit and grouting of discontinuities. The outcomes of this research can be helpful for decision makers and future development planners to avoid the zones with high susceptibility during land use planning and urban extension.

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21.1 Introduction

Landslides resulting from large-scale rock slope failures are the major hazard in mountainous regions. In the twentieth century, disasters caused by massive rock slope failures have killed more than 50,000 people on a global basis (Evans et al., 2006). Landslide Susceptibility is one of the most reliable methods to identify landslide- prone areas (Hansen, 1984), i.e. the probability of landslide occurrence.

Landslide susceptibility mapping is essential technique to detract and prevent the landslide detriment. According to Van Westen, 1997, a landslide susceptibility analysis is an analysis that involves the determination of the spatial distribution of landslides, involves four processes: (a) the construction of a landslide inventory map, (b) the assessment of parameters that influence landslides, (c) the implementation of appropriate methods for determining the weights of each parameter and (d) the compilation of the landslide susceptibility map within a Geographic Information System (GIS) environment.

Mostly the susceptibility zonation maps are prepared on a 1:50,000 or 1:25,000 scale (Sarkar et al., 2013). Therefore, assessment of probabilistic slope failure hazard is a one part of decision analytical approach to landslides risk assessment and management.

Many methods have been developed as tools to assess landslide susceptibility, Heuristic approach is one of them, it is based on opinion of geomorphologic experts (Francipane et al., 2014). Generally this approach is divided into two phases: a direct mapping analysis, in which the geomorphologists (or geologist) determine the susceptibility in the field directly on the base of their experience, and a qualitative map combination, in which the experts use their knowledge to determine the weighting value for each class parameter in each parameter (Bartolomei et al., 2006; Puglisi et al., 2007).

Remote sensing and Geographic Information System (GIS) techniques are useful for landslide hazard zonation mapping and can help identify the area best suited for developmental activities (e.g. Saha, 2005; Van Westen et al., 2008; Gupta et al., 2008).

The study area is a volcano mountainous region, a little of landslide was recorded at the region, and it is predictable they are frequently increased due to human activities expansion. The study area is located in the eastern part of Aden governorate which includes the districts of Sirah (or Crater, non-official name), At Tawahi, Al Mu'alla, Khur Maksar, Dar Sa'd, Ash Shaykh Othman and Al Mansurah. These districts represent Aden Peninsula area (Fig. 21.1a).

Aden is an economic capital of Yemen which is located at the south-western part of Yemen, 450 km to the south of Sana'a city; capital of Yemen (Fig. 21.1a). It is characterized by mountainous to coastal area with wet hot climate. The annual average temperature ranges between 22.5 °c in January and 34.2 °c in June, the

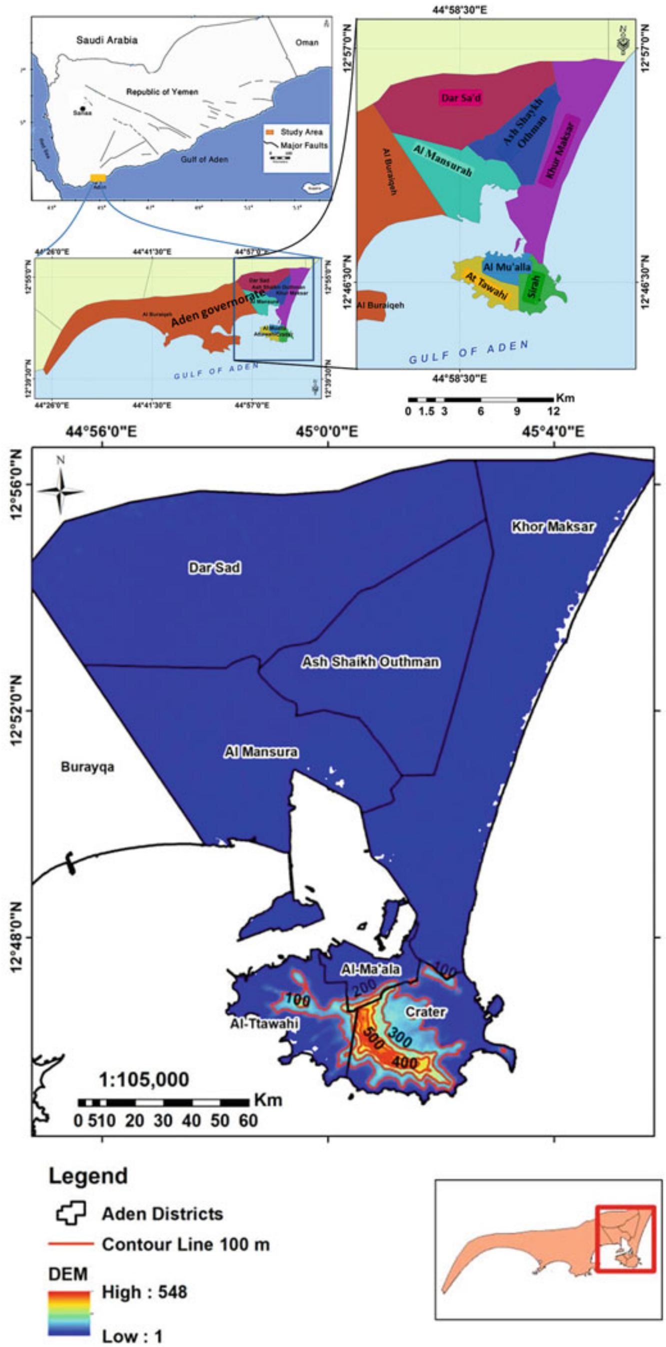

Fig. 21.1 (**a**) Location map shows the districts of the study area, (**b**) Elevation map of the study area

Fig. 21.2 Photo of the historical and archaeological Sirah Fort

annual average precipitation ranges between 56.4 mm/year in June and 304.7 mm/year in August and the annual average humidity ranges from 61.4 in June to 75.2 in August.

This research aims to produce the Landslide Susceptibility Map of Aden Peninsula area, which contain the most important monumentally tourist in Aden represented by the historical and archaeological Sirah Fort (Fig. 21.2) and Aden Tanks (Fig. 21.3), and the most important economic construction represented by the Aden Harbour.

The mountainous area is located at Sirah (or Crater), At Tawahi and Al Mu'alla districts. The elevation map which is produced from digital elevation model (DEM) (Fig. 21.1b) shows that the highest elevation (548 m) is located at the volcanic crater boundary of Sirah district. The other districts are lay's at coastal zone. The geology of the area in general characterized mainly by Cenozoic Volcanics.

21.2 Geologic Setting

21.2.1 Geology/Lithology

The geology of Aden governorate is an integral part of the composition of Yemen and the Arabian Peninsula. Aden governorate is mainly covered by Quaternary-Recent sediments, Sabkhas and Cenozoic Volcanics (Fig. 21.4). The volcanic rocks are represented by three volcanoes: Aden, Little Aden, and Ras Imran, which are belonging to the Aden Volcanic Series. These extinct volcanoes were erupted

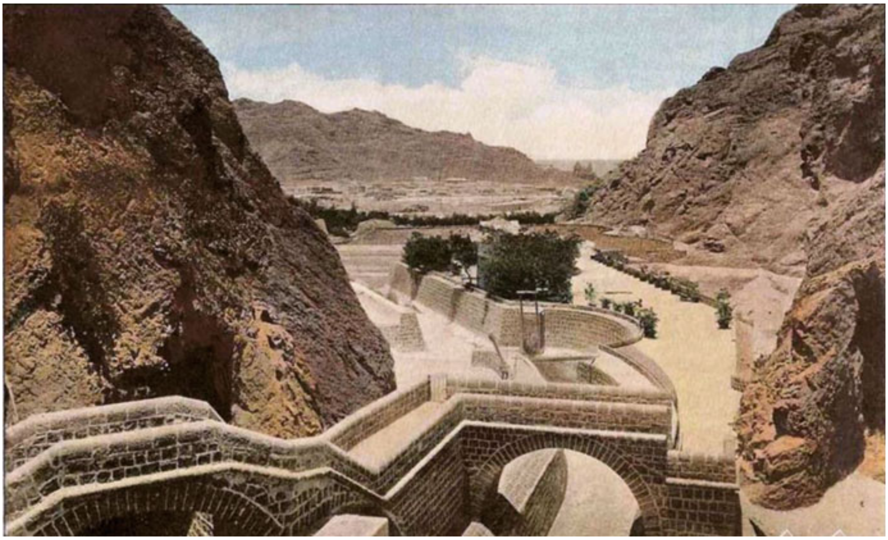

Fig. 21.3 Photo of the Aden Tanks

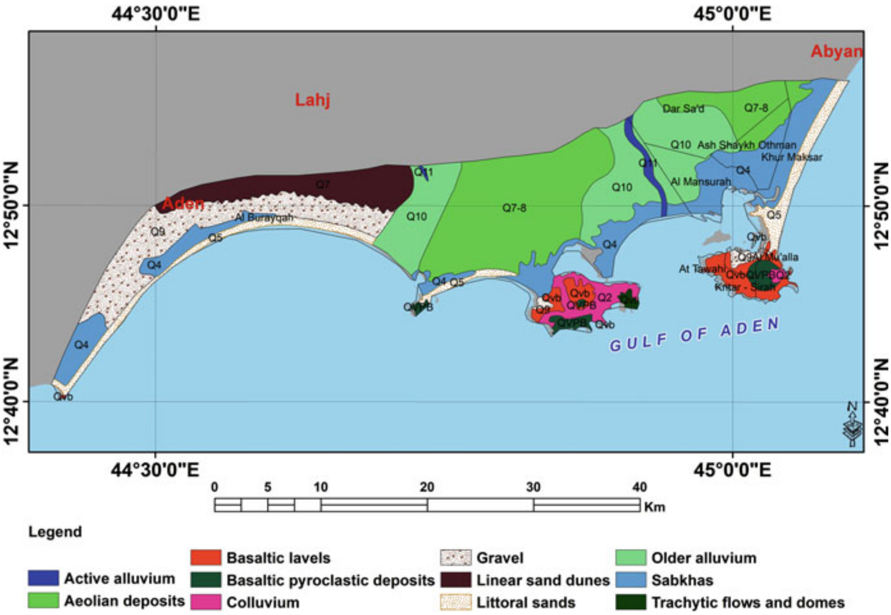

Fig. 21.4 Geological map of Aden Governorate (modified after GSMRB, 1990)

through central-vent, strato-volcanoes about 5 m.y. ago (Dickinson et al., 1969; Cox et al., 1970). Each volcano evolved through a complex cone-building stage during which the predominant rock types were trachybasalt, trachyte and peralkaline rhyolite. This was followed by periods of caldera formation during which trachyandesites, trachytes, and peralkaline rhyolites were erupted (Cox et al., 1968). The major element chemistry of the Aden Volcanic Series is intermediate between the alkaline and tholeiitic associations (Cox et al., 1970). The most acceptable 'parental' magma is mildly alkaline olivine basalt which, on fractionation, produced a series ranging from trachybasalts through trachyandesites and trachytes to rhyolites (Cox et al., 1970). A final stage of parasitic activity included small amounts of olivine-tholeiite amongst the eruptive products (Cox et al., 1968).

21.2.2 Tectonic Setting

Yemen is bounded by two active, young oceanic rifts which are resulting from the movement of the Arabian plate away from Africa in a NE direction since 40 Ma (Beydoun, 1970). The Red Sea is located between African and Arabian plates, and the Gulf of Aden between Somalian and Arabian plates. These two oceanic basins are connected within area of Afar hotspot (Fig. 21.5). The western part of Yemen which is characterized by Tertiary volcanics (Yemen Trap Series) represents a volcanic margin along the Red Sea coast and the western part of the coast of the Gulf of Aden (Khanbari & Huchon, 2010). Tard et al., 1991 show that the southern part of the volcanic margin (Aden margin) presents offshore the characteristics features of a volcanic passive margin. The volcanic activities in Yemen are related

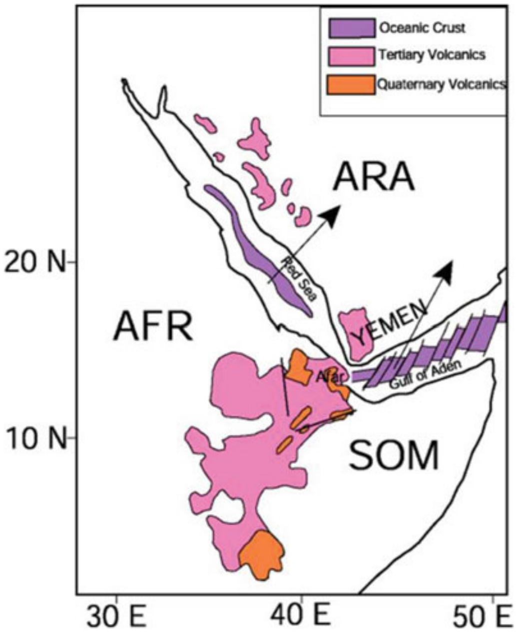

Fig. 21.5 Simplified Tectonic Map of Yemen and the surrounding areas. Arrows show the directions of relative plate motions (modified after Khanbari & Huchon, 2010)

to the Afar mantle plume that impacted the Arabia–Africa area during the Oligocene (Baker et al., 1997).

The volcanoes of Aden Volcanic Series (study area) lie along an east-west lineament parallel to the north margin of the Gulf of Aden which is a young oceanic basin. Its general trend is WSW-ENE (N70°E). The Gulf of Aden is thus oblique to the movement of Arabia toward the north-east (Dauteuil et al., 2001) (Fig. 21.5). The oceanic ridge becomes younger toward the west which reflects its propagation toward Afar hotspot (Fournier et al., 2010). The western part of Gulf of Aden which is located near the study area is characterized by high seismic activities. Although the study area is located near active ridge of the Gulf of Aden, the bibliography does not describe any great earthquakes occurred in the past, but the study area remains under the effect of the very active ridge of the Gulf of Aden (Khanbari, 2020).

In space and time the Aden Volcanic Series represents a relatively minor episode intermediate between the alkaline volcanism of the Lower Tertiary Yemen Trap Series and equally abundant tholeiitic activity in the centre of the Gulf of Aden (Cox et al., 1970). The upper part of the Yemen Trap Series is petrologically similar to the Aden Volcanic Series. Cox et al., 1970 suggest that the magma originated in the mantle.

The volcanoes of Aden Volcanic Series were active between 5 and 10 m.y. ago and remained active over periods of 1–1.5 m.y (Cox et al., 1970). It is at least suggestive that the period of magmatic quiescence between the Yemen Trap Series and the Aden Volcanic Series is coeval with the hiatus in ocean floor spreading in the Gulf of Aden (Laughton et al., 1970) and that the volcanic activity along the Aden volcanic series corresponds to the renewal of ocean floor spreading.

21.3 Methodology

This study presents landslide hazards analysis at Aden Peninsula area by using Remote Sensing, Geographic Information System (GIS) and Field data. The Remote Sensing data include Landsat-8 (OLI) image, high resolution Quick-Bird image with 60 cm resolution dated 2020 (source: Google Earth) and Digital Elevation Model (DEM) with 30 m resolution downloaded from ASTER global DEM. These data were provided by the Yemen Remote Sensing and GIS Center (YRSC). Landslide hazard map was prepared in the study area by processing and interpretation of remote sensing and field data in combination to build GIS database to evaluate the distribution of landslides.

The Landsat-8 image was processed and interpreted to construct a geological map of the study area. Both the Landsat and high resolution images were used to produce a land use/cover map of the study area. Additionally, DEM was used to calculate the slope angle and to create a slope map.

The field data was collected over a period of 20 days with the Geological Survey and Mineral Resources Board (GSMRB) staff. The main features affecting slope stability were measured and estimated in the field at 177 stations (locations) within area of 712.23 km^2 for the eastern part of Aden Governorate which is represented by Aden Peninsula. These included slope height (the vertical distance between the top and the toe of the slope at the station), slope angle, grade of fracture, grade of weathering, gradient of discontinuities, spacing of discontinuities, orientation of discontinuities, vegetation cover, water infiltration and previous landslide. Then the parameters were integrated using a heuristic method (Gemitzi et al., 2011; Francipane et al., 2014; Barahim et al., 2018) as a rating system according to the Landslide Possibility Index chart (LPI) (Bejerman, 1998 and Barahim, 2004) (Fig. 21.6); this is similar to an Analytical Hierarchy Process (AHP) approach, which is a multi-objective, multi-criteria decision-making approach that enables the user to arrive at a scale of preferences drawn from a set of alternatives (Saaty & Vargas, 1991; Saaty & Vargas, 2001; Pour & Hashim, 2017). The correlation coefficient values between each factor and LPI value were calculated by Microsoft excel software in order to understand which factors significantly affect slope instability in the study area.

All interpretations of remote sensing data and field data were implemented in ArcGIS 10.2 in order to evaluate slope instability, and to produce the landslide susceptibility map. The engineering characteristics of the rock mass were described according to the Geological Society of London Engineering Group Working Party (Anon, 1972) and the failure types were recognized.

21.4 Land Use/Cover

Land use/cover data was classified by using unsupervised classification of Landsat image and supporting with visual interpretation of high resolution image. The land use/cover map (Fig. 21.7) has been classified into seven classes such as lithological outcrops, built areas, barren lands, agricultural zones, infrastructures, wet lands and roads. Land use/cover map which represents the distribution of the various surface activities in the study area, shows that lithological outcrops cover 8.3% of the area, and that the built areas cover 14.5%. The barren lands are dominated in the study area and they represent the greatest area with covering of 36.6%. The agricultural zones are covering 15.4% of the area. The infrastructures such as the air-port and sea-ports cover 12.2%. Asphaltic and paved roads are represented in the map by lines. These roads cover an area of 6.6%. Aden Governorate is characterized by wetlands which cover 6.3% of the area. Table 21.1 shows the area and the percentage of each activity of Land use/cover map for each district.

This study will focus on the districts which are characterized by great area of lithological outcrops. They are Sirah, Al Mu’alla and At Tawahi districts. They are located close to the slopes and they subjected to slope stability hazard. These districts are bounded by the sea and the mountains. During the last 30 years, the

Landslide Possibility Index (LPI)							
No.	**Factor**	**Scale**	**Estimation**	**No.**	**Factor**	**Scale**	**Estimation**
1	SLOPE HEIGHT (M)	1 – 8 m	1	2	SLOPE ANGLE (°)	< 15°	0
		9 - 15 m	2			15° - 30°	1
		16 – 25 m	3			30° - 45°	2
		26 – 35 m	4			45° - 60°	3
		> 35 m	5			> 60°	4
3	GRADE OF FRACTURE (Number of Fracture)			4	GRADE OF WEATHERING (Alteration and compressive strength)	Fresh	0
						Slightly Weathered	1
		Sound	0			Moderately Weathered	2
		Moderately Fractured	1			Highly Weathered	3
		Highly Fractured	2			Completely Weathered	4
		Completely Fractured	3			Res. Soil	5
5	GRADIENT OF THE DISCONTI-NUITIES (°)	<° 15	0	6	SPACING OF THE DISCONTI-NUITIES (M)	3 <	0
		15° - 30°	1			3 - 1	1
		30° - 45°	2			1 - 0.3	2
		45° - 60°	3			0.3 - 0.05	3
		> 60°	4			0.05 >	4
7	ORIENTATION OF THE DISCONTI-NUITIES	Favourable 	0	8	VEGETATION COVER (%)	Void (< 20%)	0
						Scarce (20% -60%)	1
		Unfavourable 	4			Abundant (> 60%)	2
9	WATER INFILTRATION (mm/year)	Inexistent	0	10	PREVIOUS LANDSLIDES (m³/year)	Not registered	0
		Scarce	1			Registered Small volume (<3m³/year)	1
		Abundant (>500mm/year) **Permanent**	2				
		Abundant (>500mm/year) **Seasonal**	3			Registered High volume (>3m³/year)	2

1 + 2 + 3 + 4 ± 5 + 6 + 7 + 8 + 9 + 10 = LPI value

The LPI value is obtained by adding the estimations of attributes 1 to 10. If the orientation of the discontinuities is favourable, subtract the estimation of the gradient.

I (Nil)	(0-5)	III (Moderately low)	(11-15)	V (High)	(21-25)
II (Low)	(6-10)	IV (Moderately high)	(16-20)	VI (Very high)	(>25)

Fig. 21.6 LPI chart used in the study area (Bejerman, 1998; Barahim, 2004)

construction of building increases toward the mountainous area which increases the effect of slop stability hazard and threat the life of population.

Table 21.1 shows that the lithological outcrops cover 75.9% of the area in Sirah district, and the built areas cover 13.9% in Al Mu'alla district, lithological outcrops cover 16.5% of the area, and the built areas cover 30.9% while in At Tawahi district lithological outcrops cover 51.1% of the area, and that the built areas cover 25.3%.

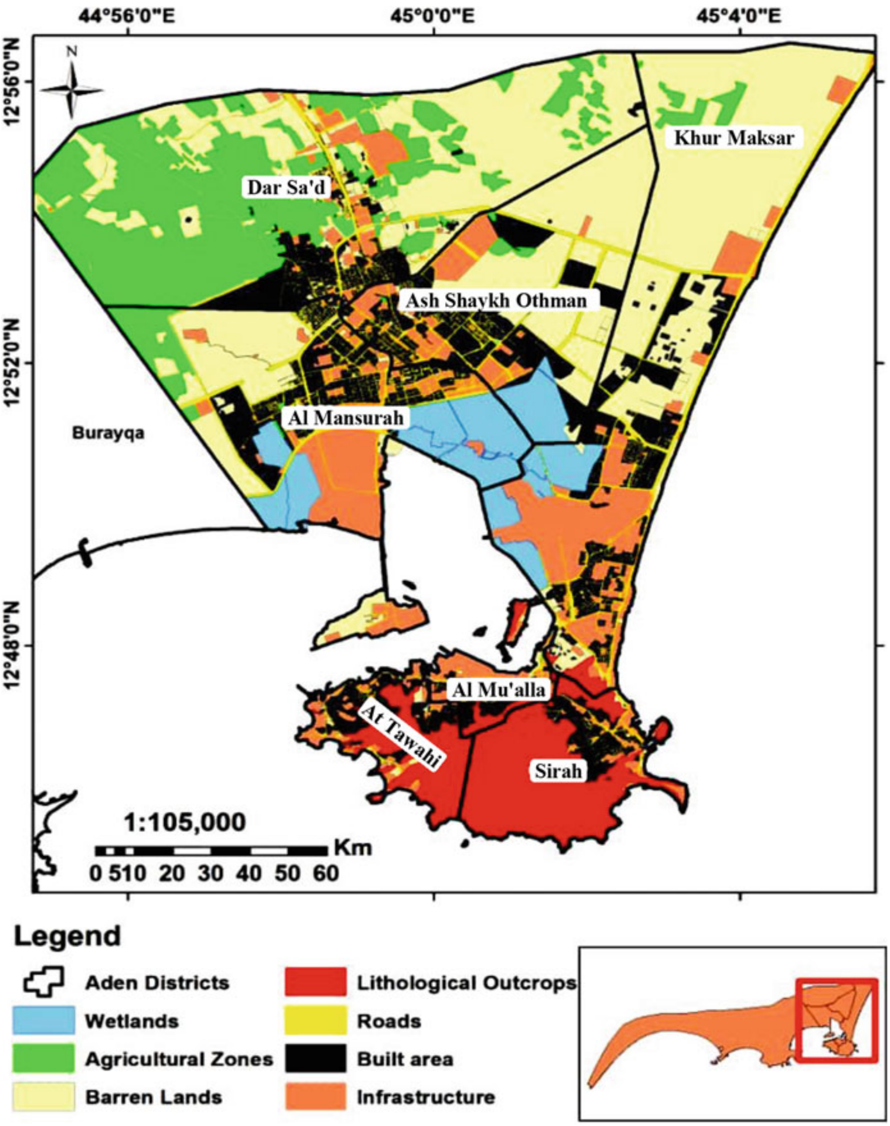

Fig. 21.7 Land use/cover map of the study area

21.5 Landslide Data Analysis, Results and Discussion

21.5.1 LPI Assessment

The total area under investigation is 210.06 km^2 and the rock formations cover an area of 18.78 km^2 which equal to 8.9% of the area. Along the study area 196 stations

Table 21.1 Land use/cover activities in the study area

District		Built area	Lithological Outcrops	Barren Lands	Agricultural Zones	Infrastructures	Wetlands	Roads	Total
Sirah	Area (m2)	2,030,449.2	11,044,224.9	147,253.3	0	925,810.7	0	409,717.4	14,557,455.5
	%	13.9	75.9	1.0	0.0	6.4	0.0	2.8	100.0
Al Mu'alla	Area (m2)	1,269,408.8	680,365.7	167,831.1	7056.9	1,610,130.8	0	376,255.8	4,111,049.1
	%	30.9	16.5	4.1	0.2	39.2	0.0	9.2	100.0
At Tawahi	Area (m2)	2,385,000.3	4,810,634.5	322,803.8	0	1,488,583.3	0	406,604.2	9,413,626.1
	%	25.3	51.1	3.4	0.0	15.8	0.0	4.3	100.0
Khur Maksar	Area (m2)	6,674,127.8	799,008.9	27,703,486.2	1,268,948.7	10,655,915	3,390,380.7	4,217,193.8	54,709,061.1
	%		1.5	50.6	2.3	19.5	6.2	7.7	100.0
Ash Shaykh Othman	Area (m2)	7,134,136.3	0	15,073,095	310,881.9	0	2,117,071.7	2,594,500.4	27,229,685.3
	%	26.2	0.0	55.4	1.1	0.0	7.8	9.5	100.0
Al Mansura	Area (m2)	5,909,449.7	0	9,246,563.5	2,278,731.8	7,939,533.3	7,705,165.7	3,394,080.3	36,473,524.3
	%	16.2	0.0	25.4	6.2	21.8	21.1	9.3	100.0
Dar Sa'd	Area (m2)	4,753,849.8	0	2,3764,944.5	28,320,266.3	2,865,985.4	0	2,374,732.4	62,079,778.4
	%	7.7	0.0	38.3	45.6	4.6	0.0	3.8	100.0
Total	Area (m2)	30,156,421.9	17,334,234	76,425,977.4	32,185,885.6	25,485,958.5	13,212,618.1	13,773,084.3	20,857,4179.8
	%	14.5	8.3	36.6	15.4	12.2	6.3	6.6	100.0

were identified, 117 of them on rock formations exposed at districts of Sirah, At Tawahi, Al Mu'alla and southern part of Khur Maksar. The other 79 stations at sand and Sabkha areas covered the northern part of Khur Maksar and the coastal regions of the Sirah, At Tawahi and Al Mu'alla districts. The distance between each station is 200 and 500 m to the north-south and east-west directions, with exception of some military establishment areas. Dar Sa'd, Ash Shaykh Othman and Al Mansurah districts have a semi horizontal surface covered by sand and Sabkha, and the landslide hazard is nil (Fig. 21.7).

According to the Geological Society Engineering Group Working Party of London (Anon, 1972) the rock masses (rock units) in the study area are identified as black colour and fine grain size, thick bedded to bulky, moderately to widely spaced joints, slightly weathered, basalt, trachybasalt, trachyte and rhyolite, which is moderately permeable and has very strong compressive strength.

Based on the LPI assessment system several plots were created using Microsoft Excel (Fig. 21.8) to show the relationship between the susceptibility category (LPI value) and the different affected features recognized, showing the correlation coefficient (R^2) for each relation. The LPI shows best correlation coefficient value with the orientation of the discontinuities ($R^2 = 0.60$), and with less significant correlation coefficient values with slope angle ($R^2 = 0.28$) and slope height ($R^2 = 0.25$) at linear equations (Fig. 21.8a, b and c), that refer to the direct link of the structure orientation and the slope.

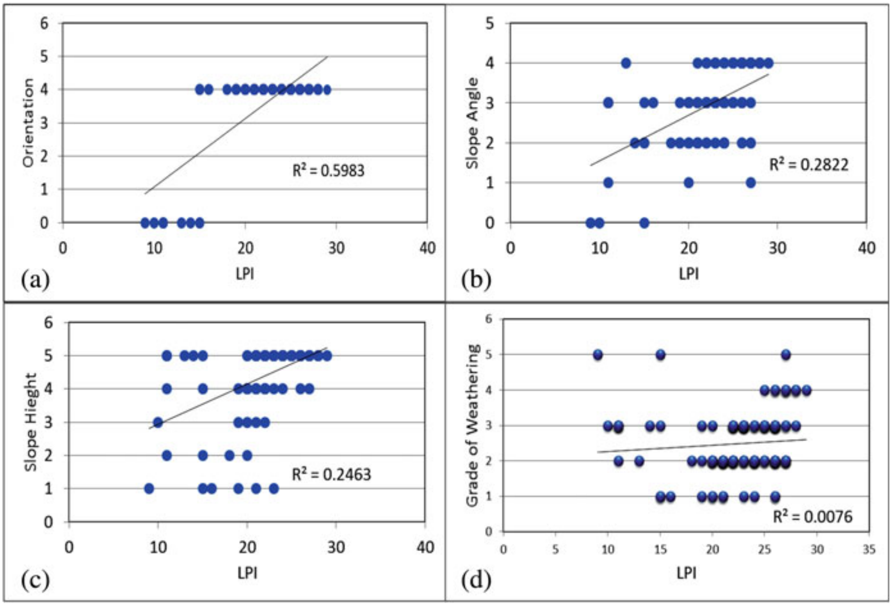

Fig. 21.8 Graphic Relationships between LPI and, (**a**) orientation of discontinuities, (**b**) slop angle, (**c**) slope height and (**d**) grade of weathering in the study area

On the other hand, poor correlations were found with the other factors such as grade of weathering ($R^2 = 0.01$) (Fig. 21.8d). This might reflect the homogeneity of the mineral component of the exposed outcrops within the study area.

The above relationships prove that the LPI in the Aden Peninsula area is mainly controlled by the factors of orientation of the discontinuities, slope angle and slope height. Digital maps were created using ArcGIS 10.2 to show the similarity of these factors (Fig. 21.9a, b and c), and the variation of the other factors i.e. grade of weathering (Fig. 21.9d) with the final LPI value (Fig. 21.9e).

21.5.2 Landslide Susceptibility Map

The LPI rating system was divided to six classes, and the landslide susceptibility classified to six categories based on the LPI values. The number and percentage of each susceptibility category for the Aden Peninsula area were calculated (Table 21.2). High and very high susceptibility zones cover 78% of the study area. Moderate susceptibility zones cover 20%, while low susceptibility zones cover 2% of it (Fig. 21.10). The discontinuities work as an importance factor for failures (Evans, 1981; Hoek & Bray, 1984; Wyllie & Mah, 2004; Sarkar et al., 2013) so the topography represented by slope angle and height.

Landslide susceptibility map in the study area was created (Fig. 21.11) based on the evaluation of landslide susceptibility categories. The susceptibility map and land use map show that the built areas cover 35.6% of the mountainous region. Most of these built areas under moderate and high susceptibility zones, which represent 15% of the total urban zone in study area.

21.5.3 Discussion

The main causes of landslide susceptibility at Aden Peninsula area are discontinuities orientation then slope angle and height; these factors may reflect the effect of topographical caldera shape and the human activities represented by slopes cut. In this study the affected LPI factors have similar correlation coefficient values compared with those computed by the same LPI rating system applied in Wadi Dhahr area which is located in the western part of Yemen and is characterized mainly by Cenozoic Volcanics and Cretaceous sandstone (Barahim et al., 2018), on the other hand, the study of little Aden (Barahim et al., in preparation) have little different correlation coefficient values for the affected LPI factors.

The variation in correlation coefficient values obtained by these three areas (Aden Peninsula, Wadi Dhahr and Little Aden) might be due to changes in the topography, rock type and (or) human activities. However, the results of these studies show that the LPI is acceptable enough to assess landslide susceptibility and furthermore it is have a good pointer for main factor affected the landslide itself.

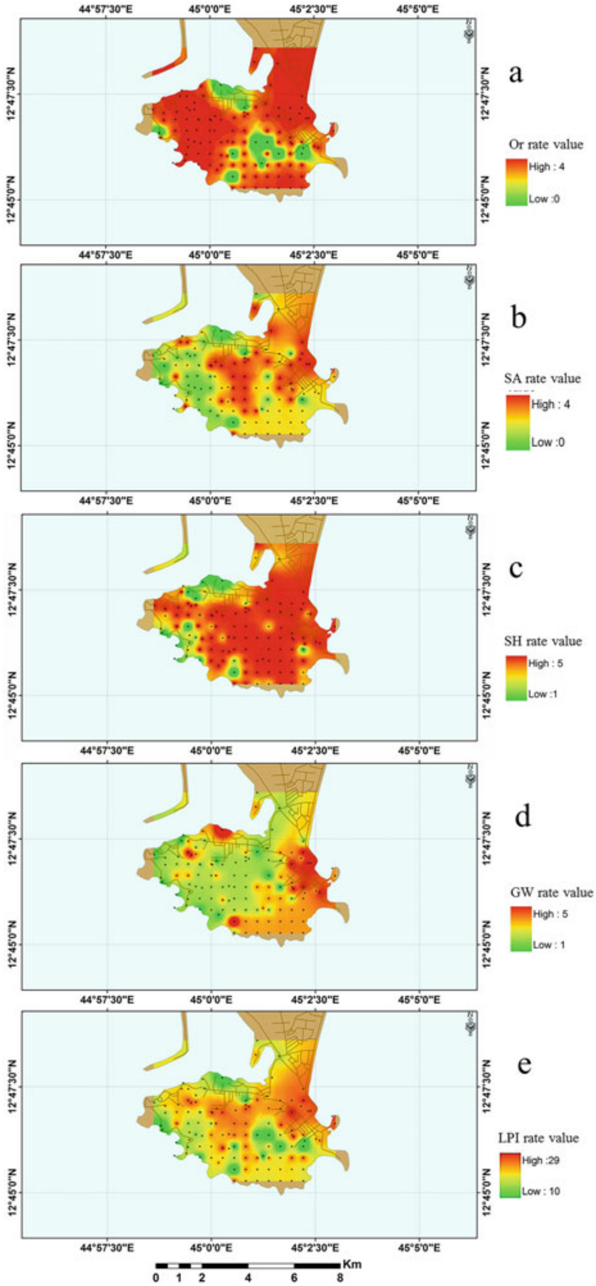

Fig. 21.9 LPI digital maps of the study area showing the distribution of: (a) orientation of the discontinuities, (b) slope angle, (c) slope height, (d) grade of weathering and (e) the final LPI value

The communal failure type in the study area is Rockfall, which is recorded at 60 stations then rolling failure which is recorded at ten stations. Sliding and toppling recorded at local areas with small scale.

Table 21.2 Number and percentage of stations for LPI classes and the susceptibility categories for the rock formation at Aden Peninsula area

LPI value	LPI class	susceptibility category	LPI for rock formation at Aden Peninsula	
			Number of stations	Percentage of susceptibility category
0–5	I	Very low	–	–
6–10	II	Low	2	2%
11–15	III	Moderately low	11	9%
16–20	IV	Moderately high	13	11%
21–25	V	High	56	48%
> 25	VI	Very high	35	30%
Total			117	100%

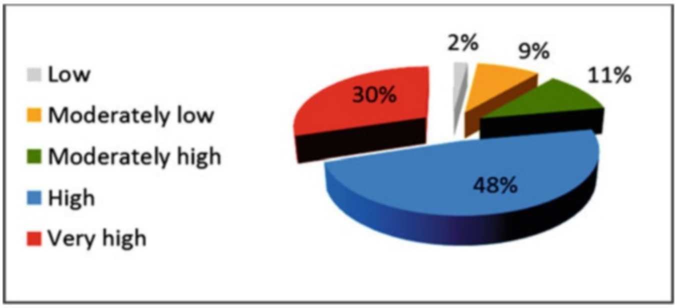

Fig. 21.10 Percentages of the susceptibility categories for rock stations at Aden Peninsula area

The last event of landslide in Sirah district was followed a heavy rainfall on February 2020. Therefore it is necessary to take some construction measures to treat the instability problem of the slopes, most appropriate for the topographical, geological and operational conditions at the site (Wyllie & Mah, 2004). The following treatments may achieve where it is needed:

1. Removal of rock overhang and unstable blocks by trim blasting.
2. Support the toe of the slope and the overhanging parts by retaining wall.
3. Erecting well seal drainage conduit.
4. Grouting of discontinuities by convenient filling material like cement in order to increase the cohesion of the different parts of the rock mass and to prevent water infiltration to the lower part of the slope.

21.6 Conclusion

The results of this research show that the LPI in Aden peninsula is mainly controlled by orientation of the discontinuities, slope height and slope angle factors. The landslide susceptibility map classifies the area into four classes of landslide

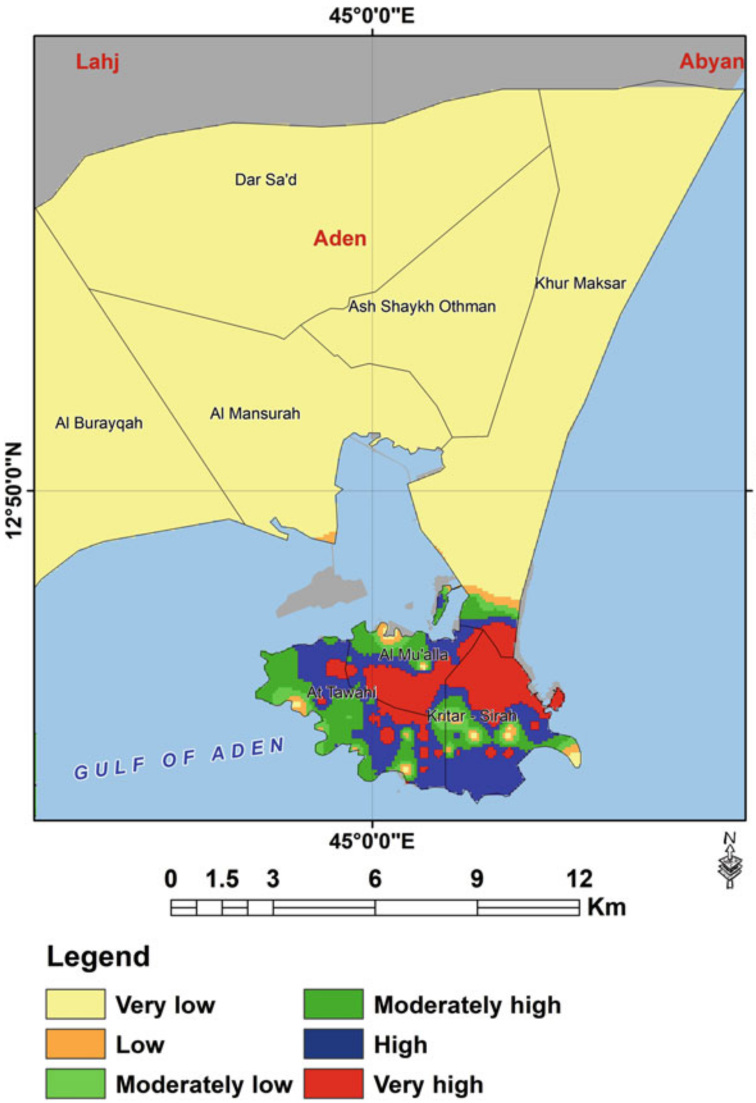

Fig. 21.11 Landslide susceptibility map of Aden Peninsula

susceptibility zones such as; very high and high hazard zones which cover 78% of the study area, the moderate hazard zones which cover 20% and 2% covered by low and nil hazard zones. Rockfall are the main modes of failure occur in the study area. Removing of unstable blocks, retaining wall and grouting are recommended as a treatment for risky unstable slopes. The outcomes of this research can be helpful for decision makers and future development planners to avoid the zones with high susceptibility during land use planning in the study area.

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