# 8 Geo- and Environmental Hazard Studies in Kuwait

Jasem Mohammed Al-Awadhi, Abd el-aziz Khairy Abd el-aal, Raafat Misak, and Ahmed Abdulhadi

**Abstract**

Low magnitude Earthquakes are the most natural hazard facing Kuwait, while other environmental challenges such as flooding, dust fallout, land degradation, and aeolian sand movement often arise from human impact as well as natural factors. Because of the rapid socio-economic development in the last five decades in Kuwait, these issues cause environmental and social problems as well as economic disturbance; they are also considered natural disasters for country. The scale and intensity of the geological environment hazards are considerably increasing especially land degradation, and impacting on the harsh structure of desert ecosystem. Due to fragility of the desert environment, human activities exceeding the carrying capability of the geo-environment system can easily lead to geological and environmental hazards; such as runoff, sand and dunes movements and dust fallout causing serial environmental and health impacts. Geographic Information System (GIS) has been used to evaluate the degrees of geological hazard and risk by producing maps for each hazard; seismic, sand potentiality, hydrologic risk, land degradation, and sand drift severity maps are produced.

J. M. Al-Awadhi (✉)
Department of Earth and Environmental Sciences, Faculty of Science, Kuwait University, Kuwait City, Kuwait
e-mail: jasem.alawadhi@ku.edu.kw

A. el-aziz K. Abd el-aal · A. Abdulhadi
Kuwait Institute for Scientific Research (KISR), Safat, Kuwait

A. el-aziz K. Abd el-aal
National Research Institute of Astronomy and Geophysics, Helwan, Egypt

R. Misak
Desert Research Center, Al Matariyyah, Egypt

## 8.1 Earthquake Hazard in Kuwait

The earthquakes potentially affect the surrounding environment including man-made structures and human life. In general, earthquakes are either classified as tectonic or natural earthquakes or man-made earthquakes (Abd el aal et al., 2020; Bath, 1979; Bormann, 2012). Seismic activity around and inside Kuwait has been studied by some researchers, for example (Abd el-aal et al., 2020; Abd el-aal et al., 2021a, 2021b, 2021c; Al-Enzi et al., 2007; Gu et al., 2017, 2018). The nature of the occurrence of earthquakes near places of oil extraction and production in Kuwait has been studied by these researchers. There are some researchers linking the oil production process and the occurrence of earthquakes in those places, especially since the earthquakes that are recorded near the places of oil production have a shallow depth and also small/medium magnitudes (Abd el-aal et al., 2020, 2021a; Gu et al., 2017).

Kuwait as a result of its proximity to one of the most active places and seismic belts in the world, which is the Zagros seismic belt, moreover, the occurrence of local earthquakes near the places of oil extraction, makes Kuwait more vulnerable to seismic hazards and must be studied in details to reduce its effects on infrastructure and local community. The seismic hazard assessment in and around Kuwait is studied through the well-known and common methods of assessing the seismic hazard, which are the probabilistic (PSHA) and the deterministic (DSHA) seismic hazard approaches.

### 8.1.1 Probabilistic Seismic Hazard Analysis (PSHA)

The PSHA method employs the principal achievable amount of dataset, including seismic, geophysical, and geological data to construct models of the earthquake producing processes. The probability that the value Z will be exceeded


A. el-aziz K. Abd el-aal et al. (eds.), *The Geology of Kuwait*, Regional Geology Reviews,
https://doi.org/10.1007/978-3-031-16727-0_8

within t years will be obtained through the following formula:

$$P_t(z) = \sum_{j=1}^{k} \int_{m=M_{min}}^{m=M_{max}} P_t(m) \int_{r=R_0}^{R_{max}} P(r)(P(A \geq Z)m, r)dmdr \tag{8.1}$$

where $j$ refers to the seismogenic zone,
*m symbol* refers to the moment magnitude,
$r$ represents the distance to the earthquake source.

$P_t$(m) refers to the probability of occurrence of a magnitude $m$ earthquake in zone $j$ within $t$ years which can be obtained through the following equation:

$$P_t(m) = 1 - \exp\left[\frac{-t}{n(m)}\right] \tag{8.2}$$

To carry out Probabilistic seismic hazard computation at a particular place, the subsequent input coefficients are required (Cornell, 1968; Reiter, 1990).

1. Updating historical and instrumental earthquake catalogues are fundamental.
2. Seismic zones which describes areas of equal seismic activity and also the faults (Fig. 8.1).
3. The recurrence parameters for the detected earthquake zones, where every seismic zone is represented by a seismic recurrence relation. This relation mentions the chance of seismic event of a given magnitude which occurs anywhere within the seismic source during a certain interval of time. The maximum magnitude is selected from every seismic source, representing the biggest earthquake to be estimated.
4. A ground motion-attenuation models express the attenuation of the seismic waves as a assignment of magnitude and distance. For more details on the inputs of the seismic hazard assessment process, please read (Abd el aal et al., 2015, 2022; Mostafa et al., 2018).

The main products of the process of evaluating and calculating the seismic hazard in the State of Kuwait are maps and curves of the spectral acceleration values with period (Abd el aal et al., 2021c). Spectral Seismic acceleration maps have been drawn to illustrate variation of the level of the

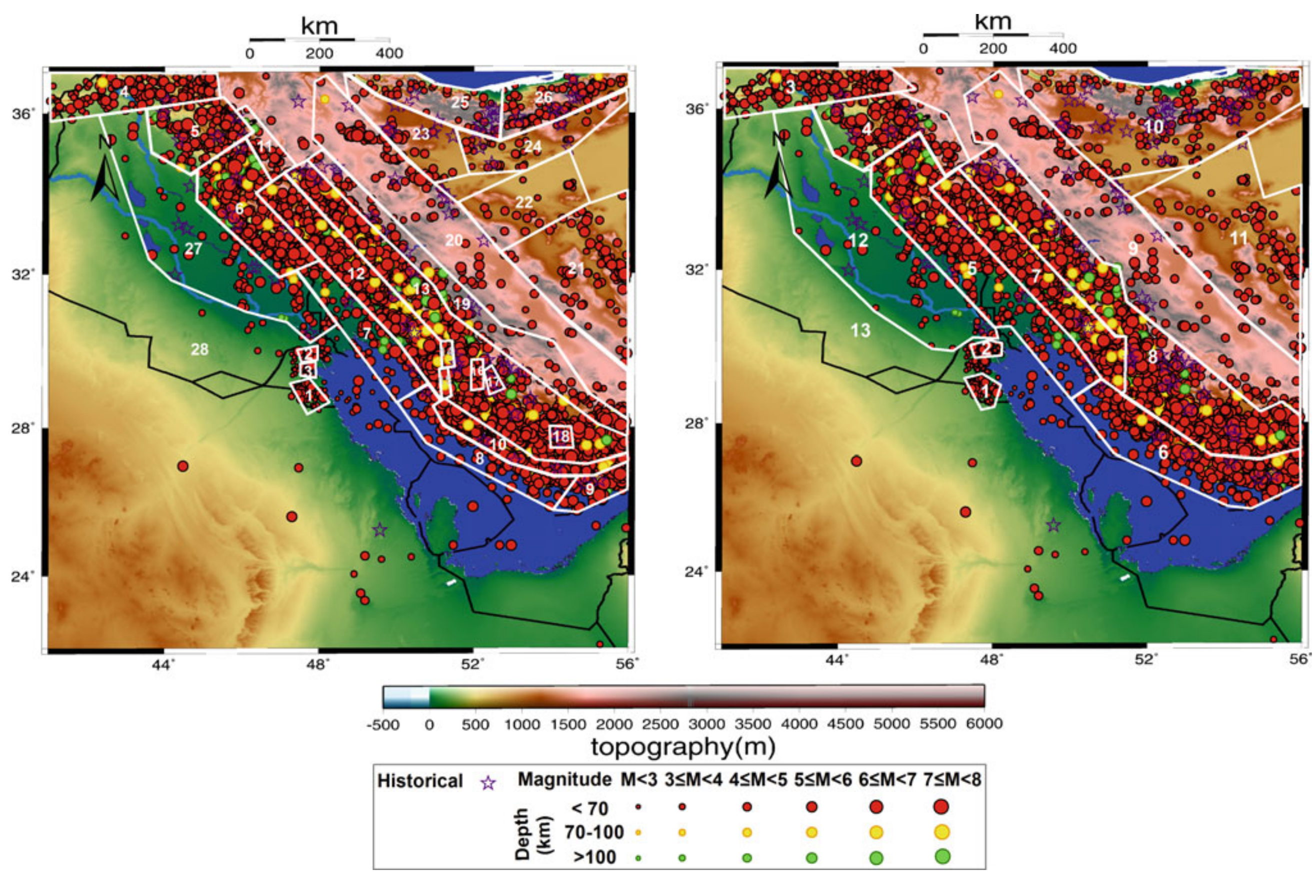


**Fig. 8.1** **a** Shows a detailed seismotectonic zones. **b** illustrates the regional seismotectonic zones used in seismic hazard calculation for Kuwait region

calculated seismic parameters considered with either probability of exceedance within specified period or with return period (Abd el aal et al., 2022). The computation was performed at 4 different periods including PGA, 0.1, 1.0, and 4 s (Fig. 8.2).

Abd el aal et al. (2021c) calculated the uniform hazard spectrum (UHS) in the following six main cities in Kuwait, basically in Sabah Al Ahmad, Mubarak Al-Kabeer, Hawally, Al Farwaniyah, and Al Jahra (Fig. 8.3). UHS is mainly used to establish a seismic hazard maps or charts at spectral periods range from 0 to 4 s at return periods of 75, 475 975, and 2475 years on bedrock conditions.

Abd el aal et al. (2021c) calculated the deaggregation charts of seismic hazards to identify the involvement of both source and earthquake magnitude to site location to the hazard calculation at return period of 475 years for six main cities in Kuwait at spectral periods of 0.1 s. The deaggregation calculations are very helpful in detecting prevailing hazardous seismic event at a certain location for use by the civil engineer. The deaggregation charts of ground motion hazards at six sites in Kuwait at the period of 0.1 s for return period of 475 years for the detailed seismotectonic source model are shown in Fig. 8.4. The deaggregation results show that most of the seismic hazardous occur from moderate seismic events with Mw ranging from 4 to 5 situated at very short location from these cities (Abd el aal et al., 2021c).

### 8.1.2 Deterministic Seismic Hazard Analysis (DSHA)

The hazard was also calculated by deterministic approach method (Abd el aal et al., 2021c). The calculations were made in 6 important places in Kuwait, which are the governorates of Kuwait. Figure 8.5 shows the results obtained by Abd el aal et al. (2021c).

Comparing the DSHA results to the PSHA results for six governorates of Kuwait, it is clear that the results of DSHA are relatively higher as a result of this method being the worst case.

## 8.2 Dust Fallout in Kuwait

Drought and recurring strong winds increase the frequency of dust fallout in Kuwait. Frequency and intensity of dust storms vary with climatic conditions. Dust and sand storms originating in the flood plain in the south part of Iraq, upwind of Kuwait, are major contributors to the sediments in Kuwait (Khalaf et al., 1980). The drainage of Mesopotamian Central marshes and Lake Hammar was accelerated after the First Gulf War (1991) and by 2003 they were drained to nearly 10% of their original size. This created a vast region of dried-up areas, creating a new potential dust source. Though the Second Gulf War (March–April 2003) inflicted a massive destruction to the surrounding environment yet a positive aspect was the restoration of the drained marshlands and lakes thus eliminating a potential dust source in proximity to Kuwait's northern border. The Iraqi-Kuwaiti war in 1990 followed by the liberation of Kuwait in 1991 was a localized environmental disaster never witnessed previously in this area. The extensive destruction to the Kuwait desert environment augmented pre-existing sources and created new local dust sources.

Dust fallout is observed in Kuwait throughout the year (13% of daytimes), while during the summer months (April to August) it rises to 25% of daytime. Meteorological data from the Kuwait Airport (July 2000 to March 2010) analyzed by Al-Dousari and Al-Awadhi (2012) for the monthly average dust storm days is shown in Fig. 8.6. In general, dust fall increased during the drought years and decreased during the years with higher rainfall. Except for the Sahara Desert, Kuwait experiences higher dust fall in comparison with the surrounding regional and global areas (Al-Dousari & Al-Awadhi, 2012).

### 8.2.1 Dust Regional Sources

Five major regional dust sources surrounding Kuwait were identified by Al-Dousari and Al-Awadhi (2012) (Fig. 8.7). These are as follows:

1. Iraqi desert surrounding Kuwait border.
2. The Mesopotamian Flood Plain in Iraq.
3. Saudi Arabia's desert surrounding Kuwait border.
4. Drainage of the southern Iraqi marshes.
5. Iranian dry marshes (*Sabkhas)* at northern coastal area of Arabian Gulf.

### 8.2.2 Amount of Dust Fallout

Significant quantities of dust are deposited along the trajectory of moderate to strong dust storms blowing across Kuwait that originate from the west, northwest, and north of Kuwait from sources identified in the previous section. Modified dust traps designed by Al-Awadhi (2005) were installed at 42 sites covering eight zones in Kuwait, at a height of 2.4 m above the sediment surface level. The dust fallout data was collected for 14 months from November 2006 till December 2007 (Al-Dousari & Al-Awadhi, 2012) (Table 8.1). Total annual dust fall at the eight zones was 395 tons/km$^2$ and the monthly average was 33 tons/km$^2$.

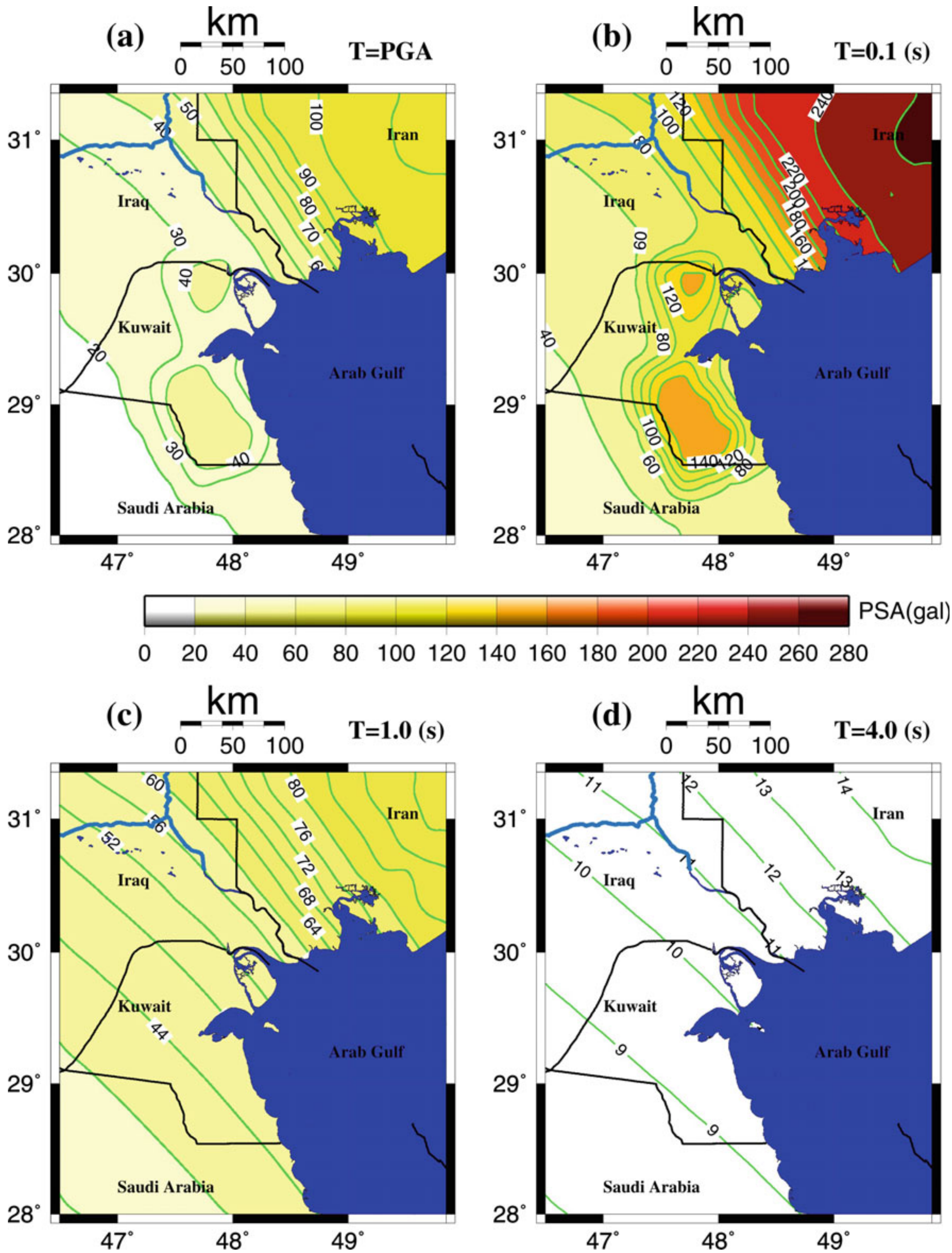


**Fig. 8.2** Seismic hazard calculation maps for Kuwait area at periods PGA, 0.1, 1, 4 s for 475 years return period

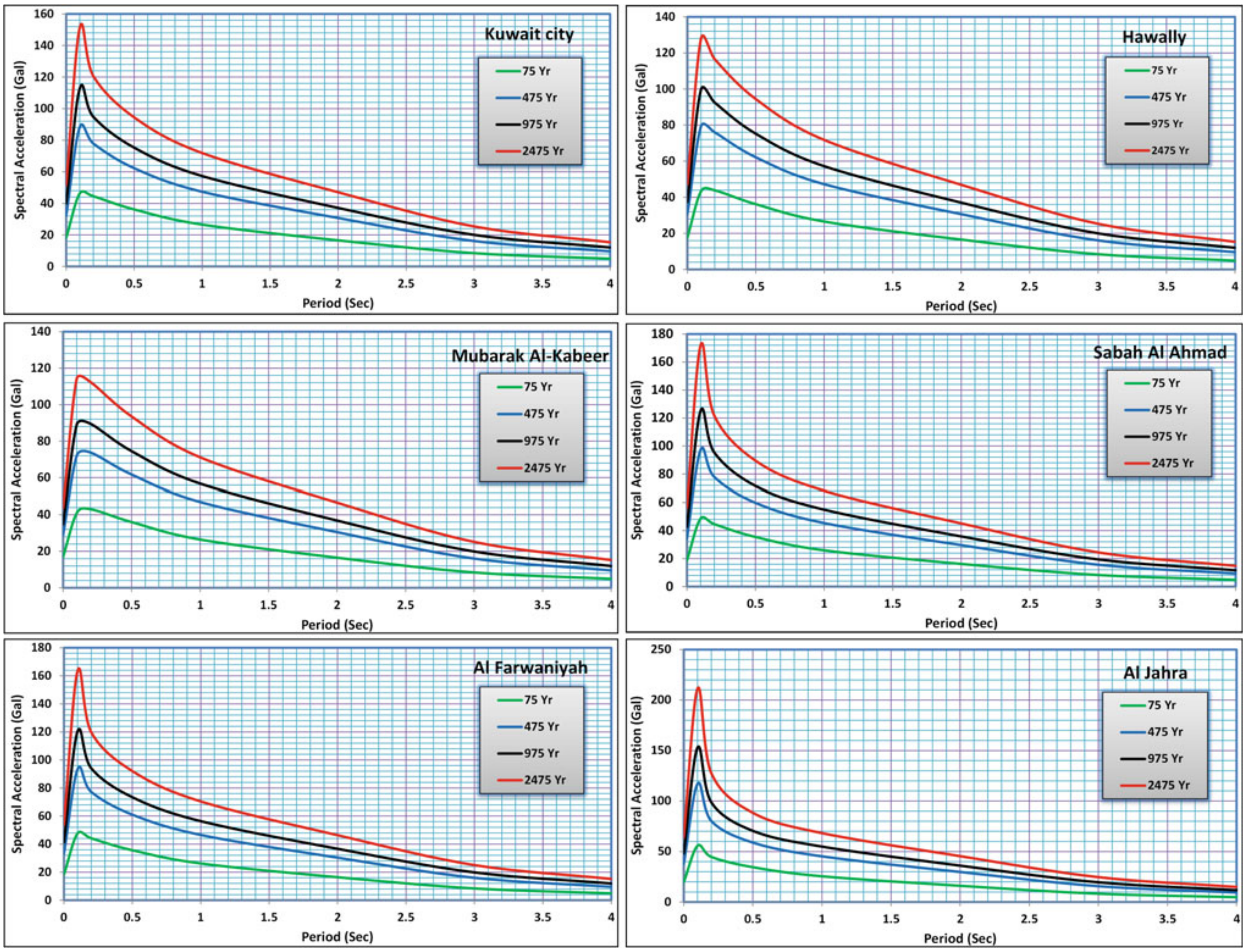


**Fig. 8.3** Uniform hazard spectrum (UHS) for six governorates in Kuwait at return period 75, 475, 975 and 2475 years

There is strong quantitative and temporal correlation between the trajectories of major dust storms and the dust deposition recorded within the path at the eight zones. Local topography, existing vegetation, and meteorological conditions at any local region significantly affect the dust fall within and at the vicinity of these zones. Other probable explanation could be related to.

1. Proximity to regional sources (mainly for southwestern desert of Iraq).
2. Massive quantities of mud within depressions, *sabkhas,* and intertidal zones.

Accordingly, grain size and composition vary over dust samples collected from the eight zones. Such variations are primarily due to the origin and accumulation of the sand from a single source or multiple sources, local and regional. For example, analysis of Bubiyan Island dust reveals that it is trimodal with three dominant fractions of coarse silt, very fine silt, and clay; the trimodal distribution suggests several sources. Dust from the open desert in western Kuwait is unimodal with a dominant very coarse silt size fraction. It is coarse with heavy fractions, large size (100 µm), and smooth with sub-angular quartz grain with a few adhering carbonate particles (Fig. 8.3b), while Bubiyan Island dust is fine carbonate (30 µm) mixed with gypsum and bassanite (Fig. 8.8c). Generally, sand particles with size of fine and very fine originate from local sources since they usually transport either by creeping or saltation over short distances only.

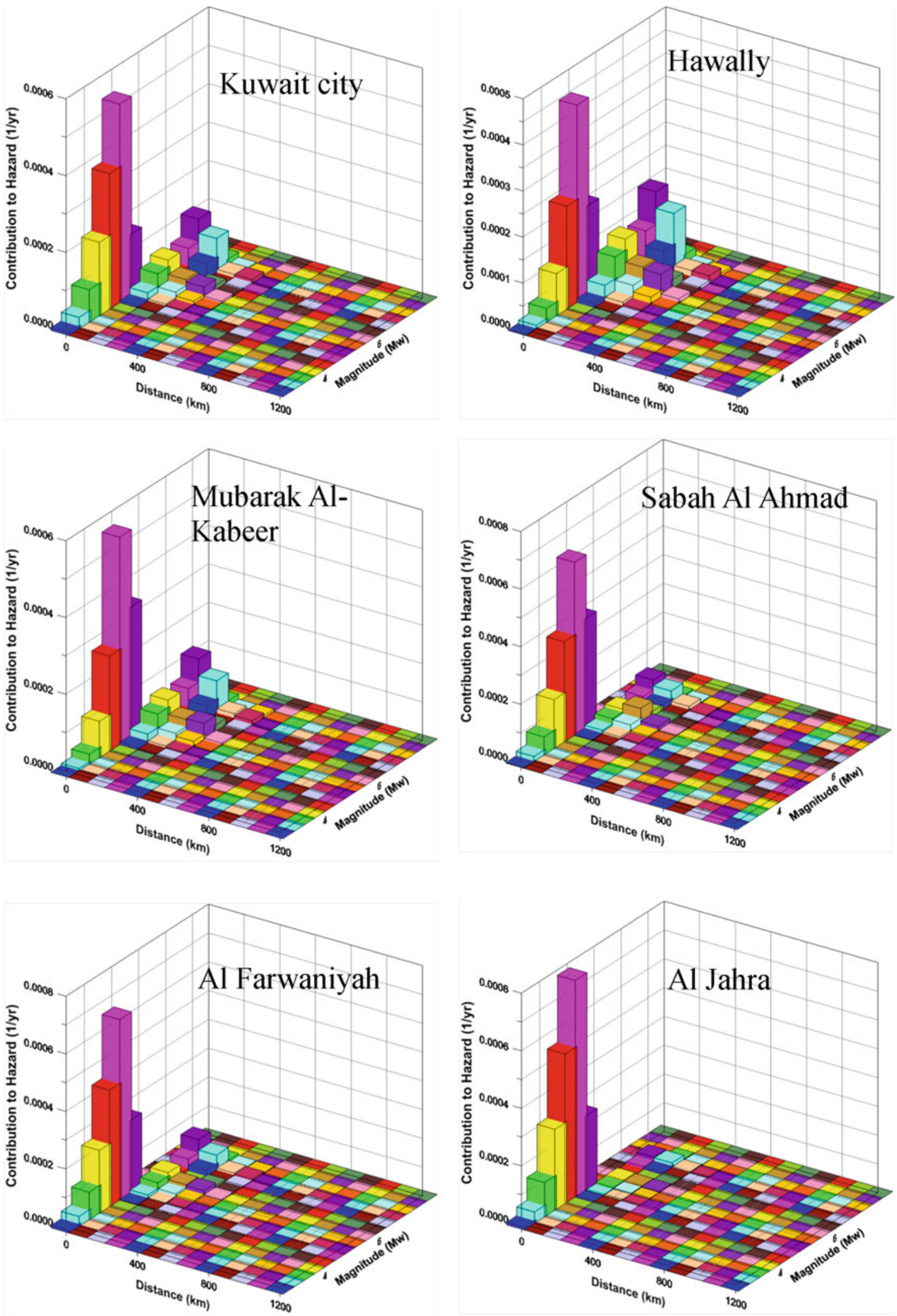


**Fig. 8.4** The deaggregation charts at the six governorates of Kuwait for the short spectral period of 0.1 s for return period of 475 years for the detailed seismotectonic source model

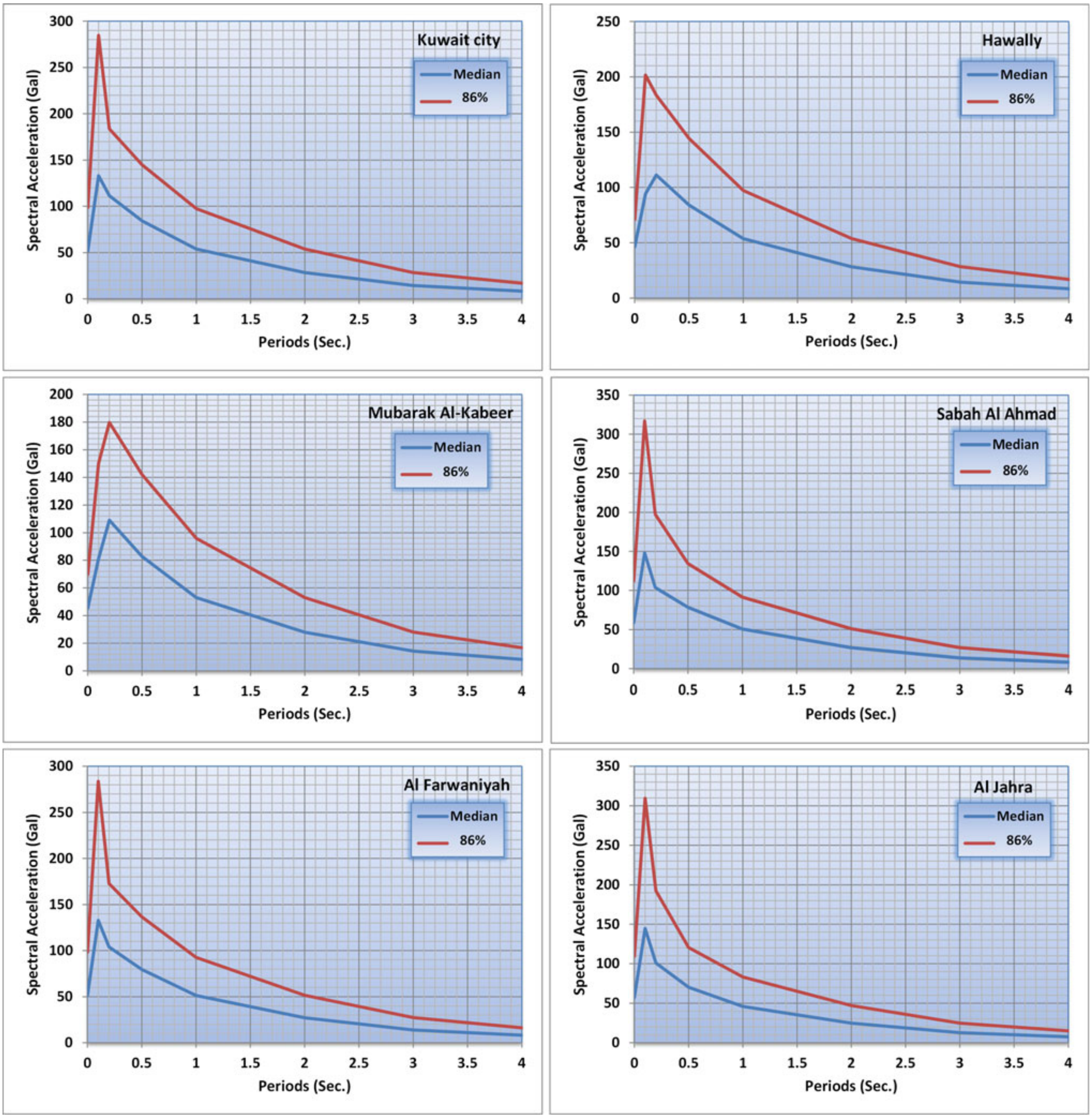


**Fig. 8.5** The seismic hazard estimation by DSHA approach at the six governorates of Kuwait (after Abd el aal et al., 2021c)

### 8.2.3 Mineralogical Characteristics of the Dust

Kuwait dust samples, collected by Al-Dousari and Al-Awadhi (2012), from 5 sectors in Kuwait, investigated by XRD for mineralogical analysis, the results reviled that the dust fallout contains Quartz (35.2%), Calcite (28.5%), Dolomite (10.7%), Carbonates (39.5%), Feldspars (12%), and Clay (4.5%) as the major constituents. Other minerals in the dust were found in trace or small quantities such as anhydrite, basanite, gypsum, and heavy minerals (Table 8.2).

### 8.2.4 Elemental Concentration in Dust Fallout

Al-Awadhi and AlShuaibi (2013) collected samples of dust falling over Kuwait city for 12 months from March 2011 to

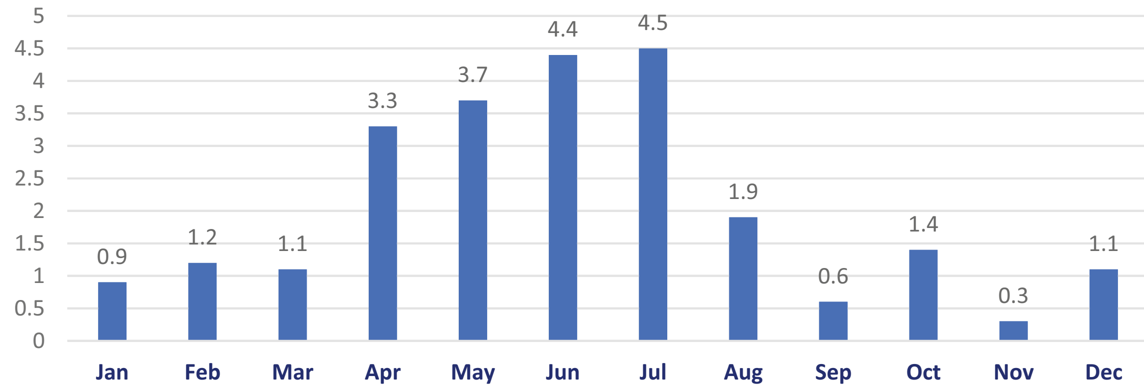


**Fig. 8.6** The monthly average number for dust storm days in Kuwait (2000–2010) (after Al-Dousari & Al-Awadhi, 2012)

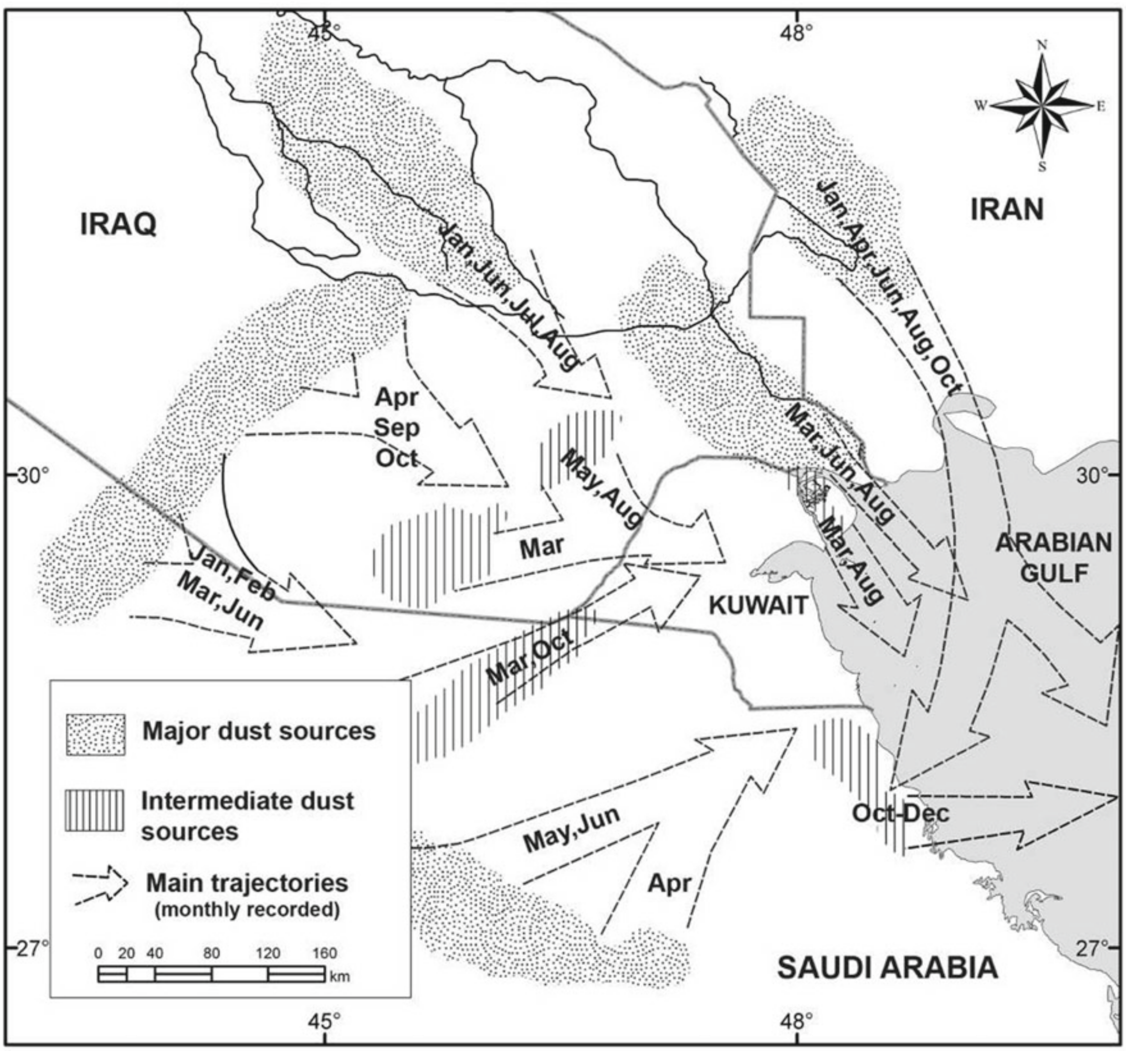


**Fig. 8.7** Major and intermediate source areas of dust storms and trajectories for the north-western areas of Arabian Gulf including the study area in reference to dust storm days in Kuwait and satellite images from 2000 to 2010

**Table 8.1** Variations of monthly and annual dust fall in eight zones (tons/km$^2$)

| Months↓ Zones→ | National Park | Al-Mutla | Al-Liyah | Al-Jahra | Shuwaikh | Warba | Sabiya | Bubiyan | Monthly Total |
|---|---|---|---|---|---|---|---|---|---|
| Jan | 0 | 1 | 3 | 2 | 2 | 7 | 6 | 13 | **34** |
| Feb | 0 | 3 | 5 | 3 | 3 | 1 | 6 | 7 | **28** |
| Mar | 0 | 2 | 3 | 3 | 3 | 4 | 6 | 6 | **27** |
| Apr | 1 | 4 | 5 | 4 | 3 | 9 | 6 | 15 | **46** |
| May | 0 | 2 | 2 | 2 | 6 | 3 | 3 | 7 | **25** |
| Jun | 0 | 2 | 2 | 4 | 9 | 1 | 5 | 4 | **27** |
| Jul | 1 | 7 | 3 | 10 | 8 | 2 | 8 | 8 | **47** |
| Aug | 0 | 2 | 2 | 3 | 5 | 3 | 7 | 9 | **32** |
| Sep | 0 | 2 | 2 | 2 | 4 | 4 | 6 | 9 | **29** |
| Oct | 0 | 1 | 1 | 1 | 2 | 3 | 3 | 6 | **17** |
| Nov | 0 | 1 | 3 | 1 | 2 | 16 | 10 | 10 | **43** |
| Dec | 0 | 1 | 2 | 1 | 2 | 5 | 21 | 8 | **40** |
| Total | **2** | **28** | **33** | **36** | **49** | **58** | **87** | **102** | **395** |

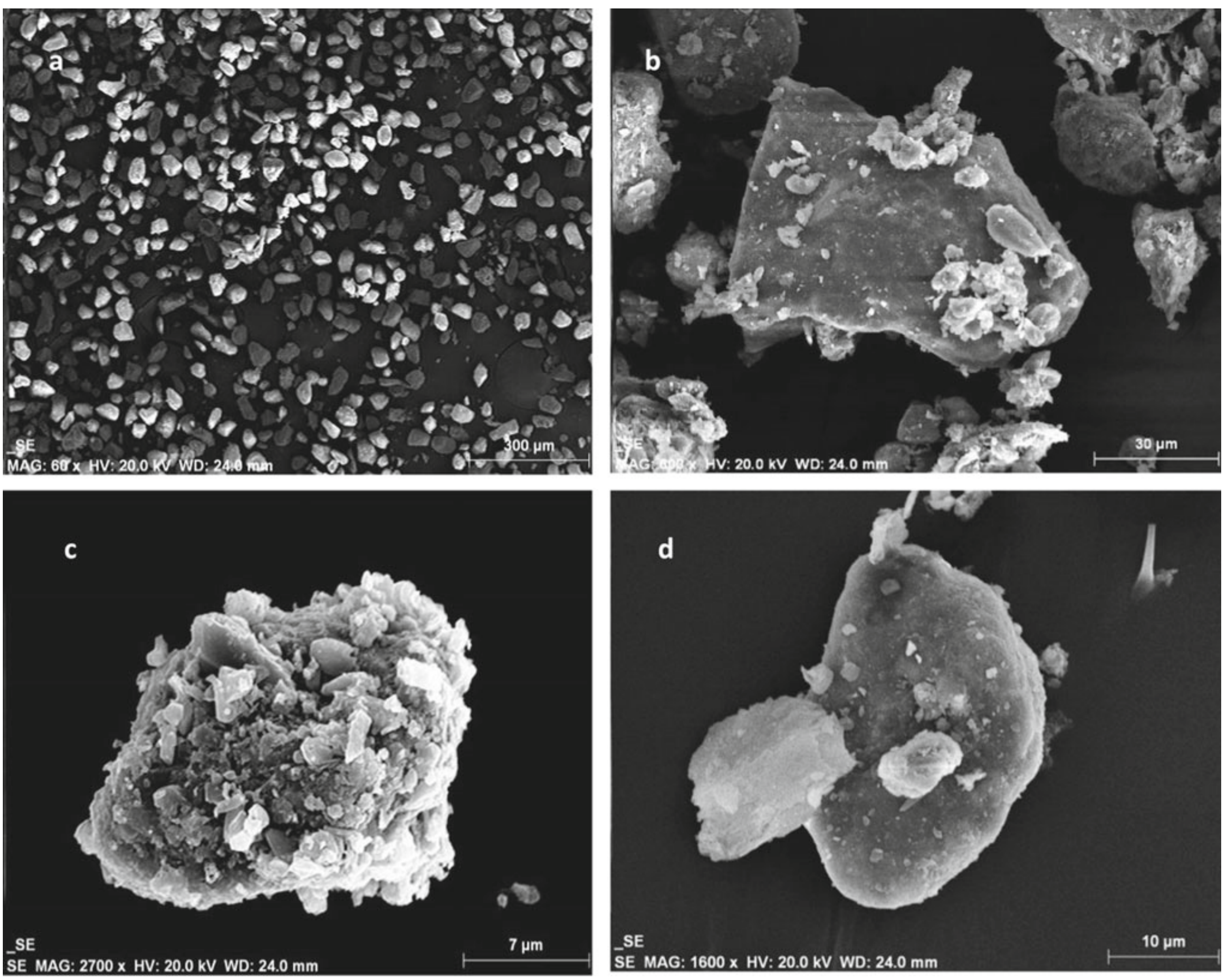


**Fig. 8.8** Smooth dust particles within Wester zone. **a** very coarse silt, **b** adhering carbonates particles, (**c**, **d**) adhering gypsum and bassanite particles

**Table 8.2** Kuwait Dust samples analysis by XRD for minerals

| Sector | Area | Quartz | Calcite | Dolomite | Carbonates | Feldspars | Clay | Other |
|---|---|---|---|---|---|---|---|---|
| Bubiyan | East Kuwait | 28 | 20 | 14 | 34 | 18 | 5 | 14 |
| National Park | North Kuwait | 38 | 38 | 7 | 45 | 10 | 2 | 5 |
| Warba | NE Kuwait | 36 | 30 | 11 | 42 | 8 | 5 | 9 |
| Sabiya | East Kuwait | 39 | 26 | 11 | 37 | 12 | 6 | 5 |
| | **Average %** | **35.25** | **28.5** | **10.75** | **39.5** | **12** | **4.5** | **8.25** |

**Table 8.3** Elemental contents in dust fallout in Capital city of Kuwait and its surface sediments (mg/kg)

| mg/kg | Soil (N = 184) | Dust (N = 120) |
|---|---|---|
| V | 19.2 | 56.3 |
| Cr | 25.6 | 131.0 |
| Co | 3.7 | 24.0 |
| Ni | 25.6 | 193.6 |
| Cu | 22 | 97 |
| Zn | 18.4 | 213 |
| Zr | 5.1 | 14.5 |
| Mo | 0.2 | 2.2 |
| Ba | 51.6 | 150 |
| Pb | 4.6 | 32.1 |
| Sr | 191 | 232 |
| Fe | 4162 | 16,136 |
| Mn | 121 | 315 |
| Ti | 178 | 524 |
| Cd | 0.4 | 0.4 |

February 2012 and analyzed the samples for mean annual elemental concentrations (Table 8.3). They used these data for enrichment factor (EF) analysis, which is indicative of the potential impact of dust falls to the elemental composition of surface sediments where dust from local or regional sources is deposited. The following equation of Sutherland (2000) is used for the computation of EF:

$$EF = (M/N)_{sample}/(M/N)_{baseline} \tag{8.3}$$

EF is the concentration ratio of a metal (M) to its normalizer (N) for both investigated samples and baseline reference samples (i.e., surface sediments).

Magnesium (Mn) was selected as the reference element (normalizer), and $M_{baseline}$ was determined using mean elemental concentrations of the Kuwait soil. Accordingly, Table 8.4 shows the EFs of 16 elements.

Based on contamination degrees using the EF values (Table 8.4), which were suggested by Sutherland (2000), Loska and Wiechuya (2003), the dust is significantly contaminated by Mo and Zn ( mean EF > 5), while it is moderately contaminated by Ni, Pb, Co, Fe, Cr, Cu, Ti, Zr, Ba, and V (2 < mean EFs < 5). In general, the dust is less contaminated by Cd and Sr.

## 8.3 Land Degradation in Kuwait

Land degradation in the country can be attributed to uncontrolled overgrazing, off-road driving, camping, and quarrying. Gulf war in 1990 and its subsequent military movements added more environmental damages including soil compaction and soil pollution in the form of oil lakes. Several reports on land degradation are available (e.g., Khalaf, 1989; Omar, 1991; Zaman, 1997; Brown & Porembski, 1997, 1998; Howle, 1998; Misak et al., 1999; Shahid et al., 1998, 1999, 2003; Al-Dousari et al., 2000; Al-Awadhi et al., 2001; Omar et al., 2005). Aeolian (wind) and fluvial (water) processes, causing soil erosion, soil compaction, sealing and crusting and depletion of desert vegetation cover, are the two principal causes of land degradation in Kuwait. Misak et al. (1999) reported 44% moderate and 32% severe land degradation of the Kuwait desert ecosystem. Al-Dousari et al. (2000) studied the soil compaction in Al Salmi area adjacent to the western border with Saudi Arabia. A map for soil compaction was prepared, which shows that 89.5% was non-compacted whereas 8.8% was highly compacted and only 1.7% was slightly

**Table 8.4** Determined Enrichment factors in the dust fallouts in Kuwait city

| *Enrichment factor* | | | |
|---|---|---|---|
| Elements | Mean | Max | Min |
| V | 2.0 | 8.4 | 0.2 |
| Cr | 3.1 | 10.3 | 0.5 |
| Co | 3.9 | 12.9 | 0.4 |
| Ni | 4.4 | 32.5 | 0.0 |
| Cu | 2.4 | 19.1 | 0.4 |
| Zn | 6.8 | 39.9 | 0.7 |
| Zr | 2.0 | 8.1 | 0.0 |
| Mo | 5.3 | 29.3 | 0.4 |
| Ba | 2.0 | 8.0 | 0.2 |
| Pb | 4.2 | 39.1 | 0.0 |
| Sr | 0.5 | 1.4 | 0.1 |
| Fe | 3.6 | 16.4 | 0.4 |
| Mn | 1.0 | 1.0 | 1.0 |
| Ti | 2.0 | 9.6 | 0.4 |
| Cd | 0.3 | 8.3 | 0.0 |

compacted. Generally, loss of land productivity is a major factor while assessing land degradation. However, in Kuwait protection of desert ecosystem is of prime importance with a view to preserve environment quality and biodiversity. Cattle grazing in the desert area is historically a cultural activity with hardly any financial benefits. Harshness of Kuwait climate has resulted in minimal pedogenesis with hardly any changes to the sand and gravel parent material.

### 8.3.1 Manifestation of Land Degradation

#### 8.3.1.1 Vegetation Cover Deterioration

Perennial desert shrubs (*Haloxylon salicornicum*), in the western and southern parts of Kuwait desert and open farmland areas, were recorded in abundance prior to the occupation of Kuwait on August 2, 1990. Coalescence of *Nabkhas* developed rugged vegetative sand sheets, which resulted in dense to moderate vegetation cover. Another survey during February 2010 showed severe degradation with vegetation cover only in the protected areas such as oil fields, military areas, and nature reserves.

#### 8.3.1.2 Soil Erosion

Soil erosion in Kuwait is attributed to Aeolian processes mainly and to Fluvial processes to some extent. The fragile desert ecosystem is prone to degradation by the uncertain, unpredictable, and varying climatic conditions as well as to uncontrolled anthropogenic activities. Soil erosion in the desert areas is accelerated due to scarcity of vegetation cover that provides soil stabilization by deep-rooted shrubs and trees, and the higher susceptibility of deposits to aeolian and fluvial processes (Khalaf & Al Ajmi, 1993; Al-Awadhi & Misak, 2000).

During the dry season in 2008, for example, with rainfall less than 30 mm, wind erosion caused loss of 10 to 15 cm of topsoil at an estimated rate of around 1,000 $m^3$ $ha^{-1}$. Previous studies show that during the 1980s the deposition and erosional areas in the desert was in equilibrium (Khalaf & Al Ajmi, 1993). Previously sand sheets, with dense coverage of perennial shrub *Cyperus conglomeratus,* enhanced the depositional aeolian processes in the southern part of Kuwait, acting as a stabilizing agent to form well-developed sandy soil. Nowadays, these areas have been subjected to severe erosion processes and replaced the surface of the areas by thin smooth sand sheets covered with desert pavements. Also, during the early 1980s several small 3 m high *barchan* dunes were observed in the north areas. In 2010 survey revealed the formation of higher 10 m *barchan* dunes.

Soil erosion due to Fluvial processes is dependent on the rainfall, which averages around 125 mm $year^{-1}$, with extremes of 20 mm to 325 mm $year^{-1}$. Rare intensive precipitations (20 mm $day^{-1}$) over degraded natural drainages may lead to erosive surface runoff. Fluvial erosion by rain, in Kuwait, formed several gullies with depth ranging from 50 to 150 cm and rills inter-spacings ranging from 20 to 50 m (Misak et al., 2001).

#### 8.3.1.3 Soil Degradation Vulnerability

Three classes (high, moderate, and low) of vulnerability to degradation of eight soil types have been characterized in

Kuwait (KISR, 199): (1) *Torriorthents* (1%) and *Torripsamments* (27%) are classified as highly vulnerable, (2) *Aquisalids* (7%) is moderately vulnerable to degradation, and (3) *Haplocalcids* (8%), *Petrocalcids* (11%), *Haplogypsids* (0.5%), *Calcigypsids* (6%), *Petrogypsids* (33%), and others (7%) are classified as low vulnerability.

#### 8.3.1.4 Enhancement of Sand Encroachment

Droughts, sediment loses and strong winds are the main causes of aeolian sand movements in Kuwait. The prevailing wind direction in Kuwait is NW–SE. Sandstorms, lasting for days and weeks, result in massive sand encroachment and widespread soil loss due to wind erosion. A field survey in 2010 revealed that shifting sands were encroaching farms, oil flow pipelines, roads, and a water storage facility existing across the prevailing wind direction. The thickness of the drifting sand accumulation ranges from 50 to 120 cm.

#### 8.3.1.5 Disruption of Surface Runoff

Building bund walls along desert roads and highways form dams at the upstream side resulting in obstructing the surface runoff flow and disturbing the existing hydrological system, and consequently in recharging of shallow groundwater reservoirs. In addition, when the accumulated mud dries up, it forms a potential source of dust storms during windy days. For example, when the catchment and drainage systems are disturbed, the loss of about 40% of surface runoff water to reach discharging areas is expected.

### 8.3.2 Causes of Land Degradation

#### 8.3.2.1 Anthropogenic Activities

Significant increase in annual population growth rate, currently at around 3.8%, calls for a delicate balance between population welfare, socio-economic growth and land use to prevent or minimize land degradation and overexploitation of desert resources. Anthropogenic activities include overgrazing (Omar et al., 1999), sandy roads (Al-Awadhi, 2001; Al-Dousari et al., 2000), traditional camping (AlSudairawi & Misak, 1999) and using sand and gravel quarries (Al-Awadhi, 2001). The short and long terms of the impacts related to anthropogenic activities are presented in Table 8.5.

#### 8.3.2.2 The Gulf War

The occupation (August 2, 1990) and liberation (February 26, 1991) war activities destroyed most of the Kuwait desert ecosystem (Holden, 1991; Karrar et al., 1991; Al-Ajmi et al., 1994). The heavy bombing, trench digging, war maneuvres, off-road heavy vehicles including tanks movements during the war resulted in the destruction of the native shrubs and plants, soil compaction and high degree damage to the desert topsoil, making the desert vulnerable to frequent sand movements and dust fallouts. During the war, 727 oil wells were burned, which released massive quantities of $SO_2$ causing acid rain and form oil pits (Al-Besharah, 1992). In addition, extensive destruction of topsoil and biomass in the Kuwaiti desert resulted due to the removal of mines and unexploded ordinance after the liberation.

**Table 8.5** Summary of the anthropogenic activities on land degradation

| Activity | Short-term impact | Long-term impact | Nature of the impact |
|---|---|---|---|
| Over-grazing | Reduction in the biomass, soil and sediment disturbance. Potentiality to originate dust fallout and sand movement | Increasing evaporation rate leading to loss of the vegetation species | Over-grazing is mainly associated with camel and sheep in the desert of Kuwait |
| Off-road vehicles (sand roads) and camping | Soil compaction, decrease in permeability, and lowering vegetation cover. Increase the potentiality erosion by wind and water | Potentiality of sand movement and creating active sand sheets. Reduction fertility of soil | Impacting at least 45% of top soils in the open areas by various degrees of compaction |
| Gravel quarrying | Disturbing of the armor layer of pebbles and gravel Disruption and rupture of surface and near surface sediments Exposing finer grains to be easily carried by wind Vanishing the vegetation cover | Creating new sources for dust and sand. Disturbance of natural drainage system and loss of running water in quarries | Extensive gravel quarrying operations commenced, without any planning, regulation or governmental oversight |

#### 8.3.2.3 Climatological Factors

Land degradation processes are influenced by the following climatological factors:

1. The scarcity and low rainfall (approximately 115 mm/year).
2. High frequent of drought periods (years with lower rainfall than the average). During the drought periods the soil temperature increase and the vegetation cover depletes.
3. The strength of the prevailing NW winds (reaching 30 m $s^{-1}$) during the summer season. This exceeds the rates of sand transport and topsoil erosion (Al-Awadhi & Misak, 2000).

### 8.3.3 Assessing Land Degradation Indicators

#### 8.3.3.1 Field Assessment

Al-Awadhi et al. (2005a, 2005b) assessed the extent and magnitude of land degradation in four open areas and recognized seven indicators for land degradation in Kuwait: (1) soil erosion by wind, (2) soil erosion by water, (3) deterioration of vegetation cover, (4) soil crusting and sealing, (5) soil compaction, (6) soil contamination by oil, and (7) soil salinization (Fig. 8.9). The four assessed areas (Al Mutlaa, Al-Sabiya, Sulaibiyah, and Ahmadi-Al-Dahr) showed noticeable variations in vegetation cover, soil erosion by wind/water and soil compaction. Comparing with the extend and magnitude of land degradation in the nearby

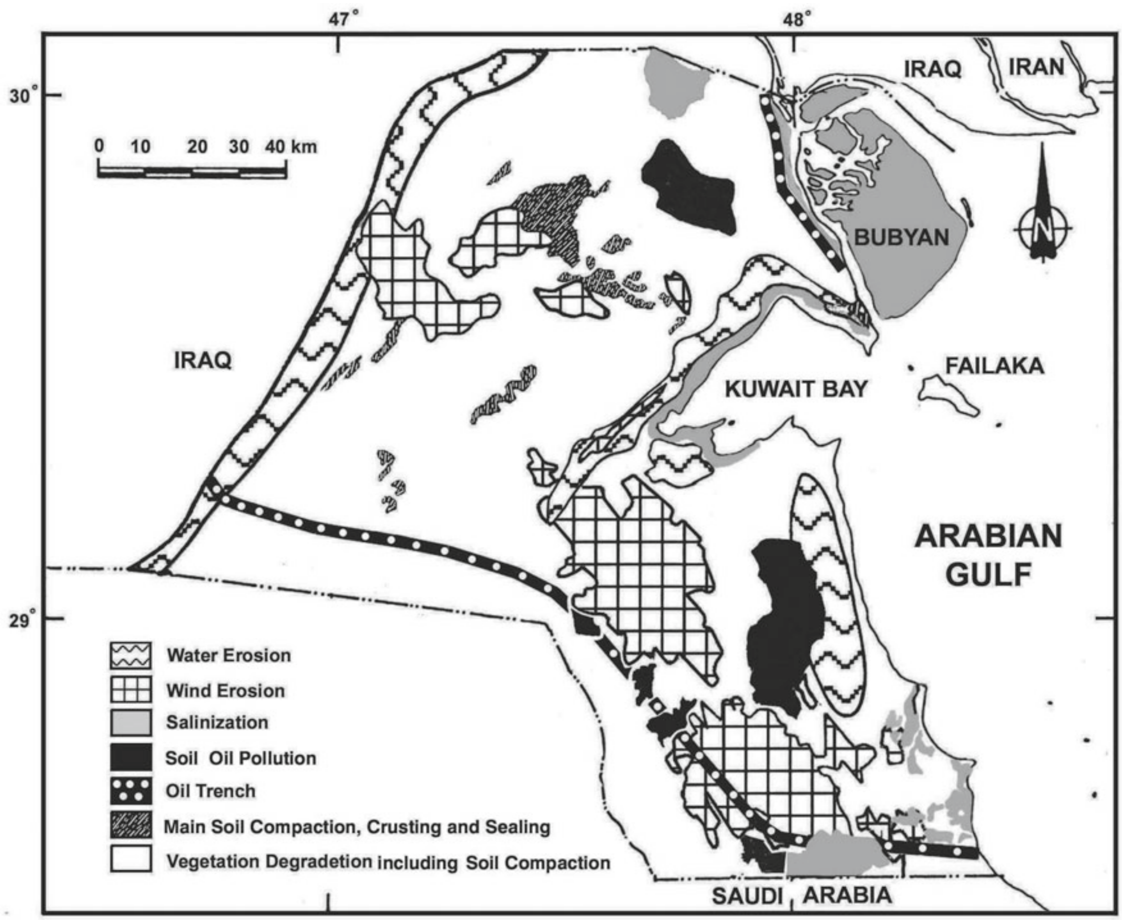


**Fig. 8.9** Mapping main Indicators of land degradation in Kuwait (after Al-Awadhi et al., 2005a, 2005b)

protected areas, the bulk density of soils and compaction rate increased with average values of 17 and 61.8%, respectively. Heavy vehicle movement caused soil compaction with remarkably high values with impermeable layers at about 22 cm depth. As a subsequence result, the average infiltration rate in the open areas decreased with an average value of 52.7%.

#### 8.3.3.2 Mapping Land Degradation Hazard Using GIS

Al-Awadhi (2008) integrated a March 2001 Landsat image and nine other Kuwait maps of physical attributes to compose a Geographic Information System (GIS) composite land degradation hazard map. The nine maps are (1) sand drift potential, wind energy, (2) surface sediment type, (3) vegetation density cover, (4) land use type, (5) drainage type, (6) topography change, (7) vegetation type, (8) iso-salinity contour, and (9) salinized areas. The relative weightages of the criteria to land degradation, assessed by Delphi and Analytical Hierarchy Process (AHP), with input from the professional knowledge of local experts, resulted in the map (Fig. 8.10) showing four degrees of land degradation hazard such as very high (15%), high (36.6%), moderate (35%), and low (13.4%).

Table 8.6 shows a comparison between the overall model assessment of land degradation and the field assessment.

## 8.4 Aeolian Sand Movement

Kuwait land surface was formed during the early pluvial period. Fluvial processes formed water courses and land depressions, which were covered by alluvial sediments in subsequent epochs. Kuwait weather is characterized by hot and dry summer months (May to September), with prevalent north-westerly strong winds (30 $m.s^{-1}$) and several sandstorms, resulting in aeolian sand depositions, from the upwind high deflation area of the Mesopotamian flood plain, and instability of the fragile ecosystem. The scarcity of deep-rooted shrubs and trees across the open central desert areas results in significant aeolian processes that accelerate soil erosion, extensive and intensive sand encroachment, formations of sand dunes, sand sheets, and sand drifts over areas reserved for defence facilities, oil exploration, groundwater fields, electrical transmission stations, cattle farms, road network, and residential projects. This is a major environmental and socio-economic issue. The annual total sand drift measured in Kuwait is $7.8 \times 10^4$ $kg.m^{-1}$-width

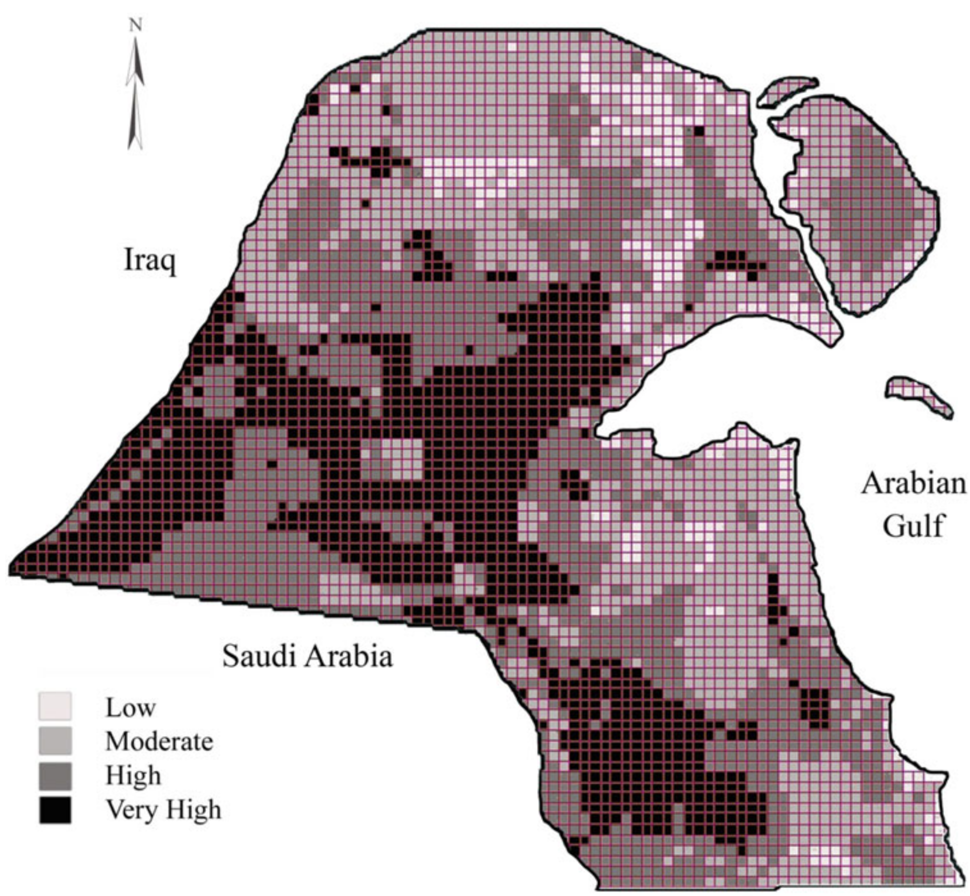


**Fig. 8.10** Land degradation hazard map of Kuwait (after Al-Awadhi, 2008)

**Table 8.6** A comparison between the overall model assessment of land degradation and field assessment

| Land degradation classes | Model Assessment (Al-Awadhi, 2008) | Field assessment (source: Al-Awadhi et al., 2005a, 2005b) | |
|---|---|---|---|
| | Class (%) | Class (%) | Plant coverage (%) |
| High | 36.6 | 25–40 | <5.5 |
| Moderate | 35 | 35–45 | 5.5–25 |
| Low | 13.4 | 10–25 | >25 |

(Al-Awadhi & Misak, 2000). Al-Awadhi and Al-Awadhi (2009) developed a sand transport model, which computed the summer monthly sand transport rate 5,900 kg.m$^{-1}$ towards southeast. The highest sand transport rate occurs within the Al Huwaimiliya sand dune corridor, which crosses the country from NW to SE (Fig. 8.11).

### 8.4.1 Vulnerability of Soil Classes to Drifting

Kuwait Institute for Scientific Research (1999) used USDA Soil Taxonomy to map eight soil types in Kuwait, namely, in order of abundance, Petrogypsids (33%), Torripsamments (27%), Petrocalcids (11%), Haplocalcids (8%), Aquisalids (7%), Calcigypsids (6%), Torriorthents (1%), Haplogypsids (0.5%), and other miscellaneous types (7%). Vulnerability to degradation and drift during the drought periods varies among the soil types, which can be classified as (a) High: Torriorthents and Torripsamments; (b) Moderate: Aquisalids (7%); and (c) Low: other types.

### 8.4.2 Enhancement of Sand Encroachment

Al-Awadhi and Misak (2000) identified 13 mobile sand bodies in Kuwait (Fig. 8.12) and estimated Kuwaiti Dinars (KD) 1.68 million as the annual cost of removal of $4.39 \times 10^6$ m$^3$, 50 cm to 120 cm thick, accumulated sand from facilities within the main passage of the wind corridor, classified as high to very high encroachment zones. Kuwait Oil Company (KOC) expenses for sand removal over a five-year period (2003–2008) were KD 6.2 million. Most facilities are located at the downward side of the Al Huwaimiliya-Wafra wind corridor with the upwind sandy plain as the source of shifting sand.

The socio-economic development of Kuwait associated with the oil boom has come at the cost of damage to the

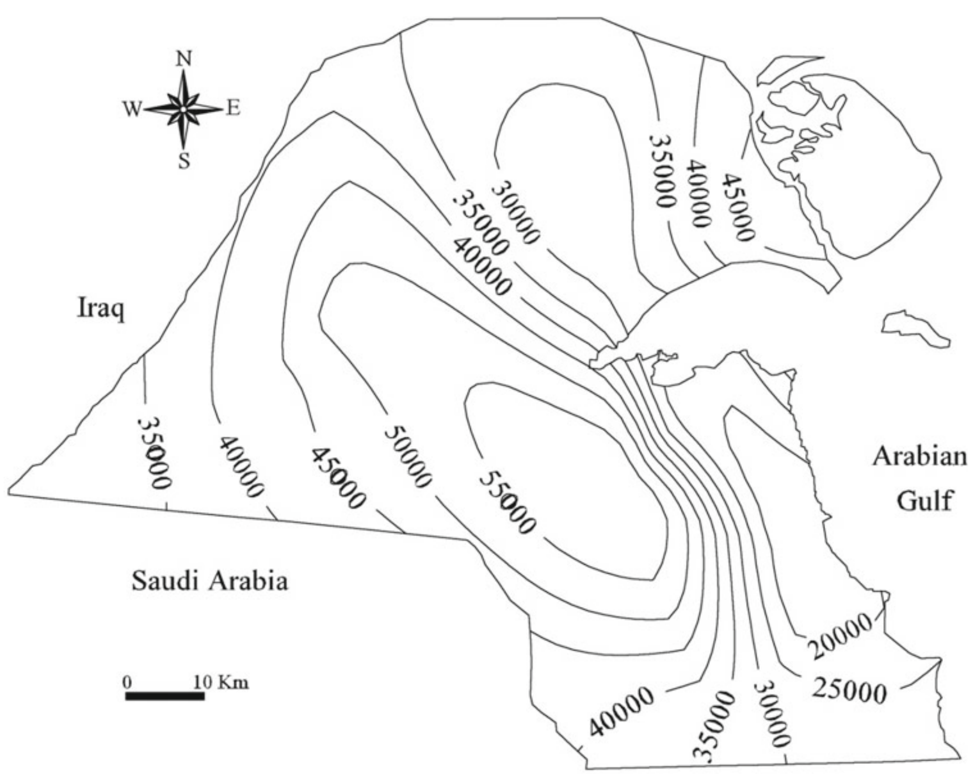


**Fig. 8.11** Spatial variation of sand transport rate (kg.m$^{-1}$) in Kuwait. Letters indicate zones of sand transport rate; **a** severe, **b** moderate, and **c** slight (after Al-Awadhi & Al-Awadhi, 2009)

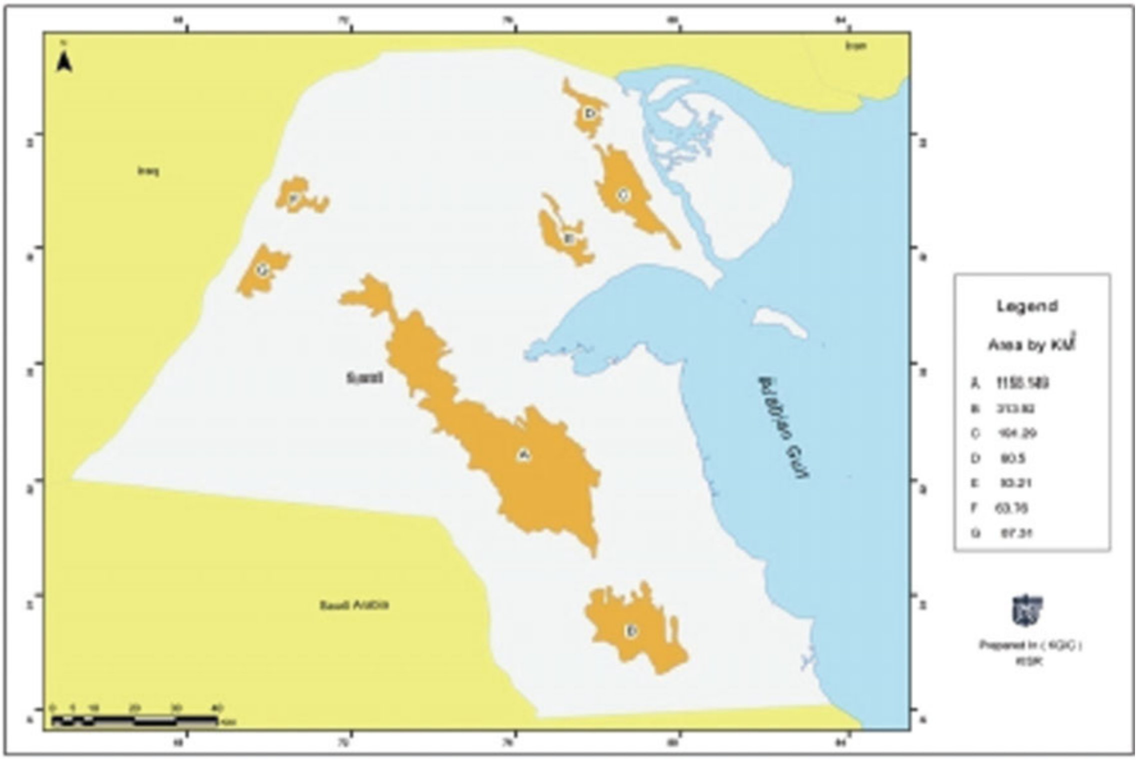


**Fig. 8.12** Mobile sand bodies in Kuwait (after Al-Awadhi & Misak, 2000)

fragile ecosystem of the Kuwaiti desert land. The extensive use of gravel from the quarries for infrastructure development damages the vegetative cover, depletes fauna, and disperses fine sand during transportation from the quarries to the construction sites. Existing gravel quarries are estimated to cover an area of 383 $km^2$ or 2.14% of the total land area of Kuwait. Traditional overgrazing in unprotected areas has resulted in almost total loss of vegetation cover whereas the protected areas are flush with vegetation. Major plant species native to Kuwaiti desert are cyperus conglomeratus, Rhanterium epapposum, Zygophyllum qatarense, Halaxylon salicornica, Panicum turgidum, and Stipagrostis plumose (Fig. 8.13) Omar et al. (2001).

### 8.4.3 Natural Factors Controlling Aeolian Processes

**Surface sediments**. Khalaf et al. (1984) estimated that the Kuwait desert, covering 80% of the surface area, is covered by several types of surface sediments. Significant deposits are aeolian (50%), residual gravel, and playa (35.1%). Tidal flats, Coastal *sabkhas*, sand dunes, plain deposits, sandstone, clay, and calcareous rocks cover the other areas.

**Wind**. Surface wind velocity is critical to aeolian processes and downwind movement of deflated sand over short distances (saltation). During summer months prevalent wind direction (60%) is north-westerly with wind speed reaching 29 $m.s^{-1}$. Average wind speed in Kuwait is 4.3 $m.s^{-1}$ with highest average 5.1 $m.s^{-1}$ in June and lowest average of 3.2 $m.s^{-1}$ in January (Al-Awadhi & Misak, 2000). Al-Awadhi et al. (2005a, 2005b) analyzed wind data recorded by 8 meteorological stations in Kuwait and computed a value of 354 vector unit (VU) for the sand drift potential (DP). Fryberger's (1979) classification places Kuwait in the intermediate wind energy deserts (DP between 200 and 400 VU).

**Surface roughness**. Flat residual gravel deposits in the northern areas of Kuwait contribute to the surface roughness, which has a bearing on the sand movement due to wind flow aerodynamics. Surface topography (Fig. 8.14) is a flat to gently rolling desert plain interspersed with low hills, ridges, scarps, and *wadis*. When wind speeds exceed the sheer threshold (>5 $m.s^{-1}$), finer particles are airlifted from the windward side and residual gravel grains accumulate on the leeward side (Figs. 8.15 and 8.16).

**Drainage System**. Drainage basins in Kuwait follow regional topography (Fig. 8.17). Northern drainage networks

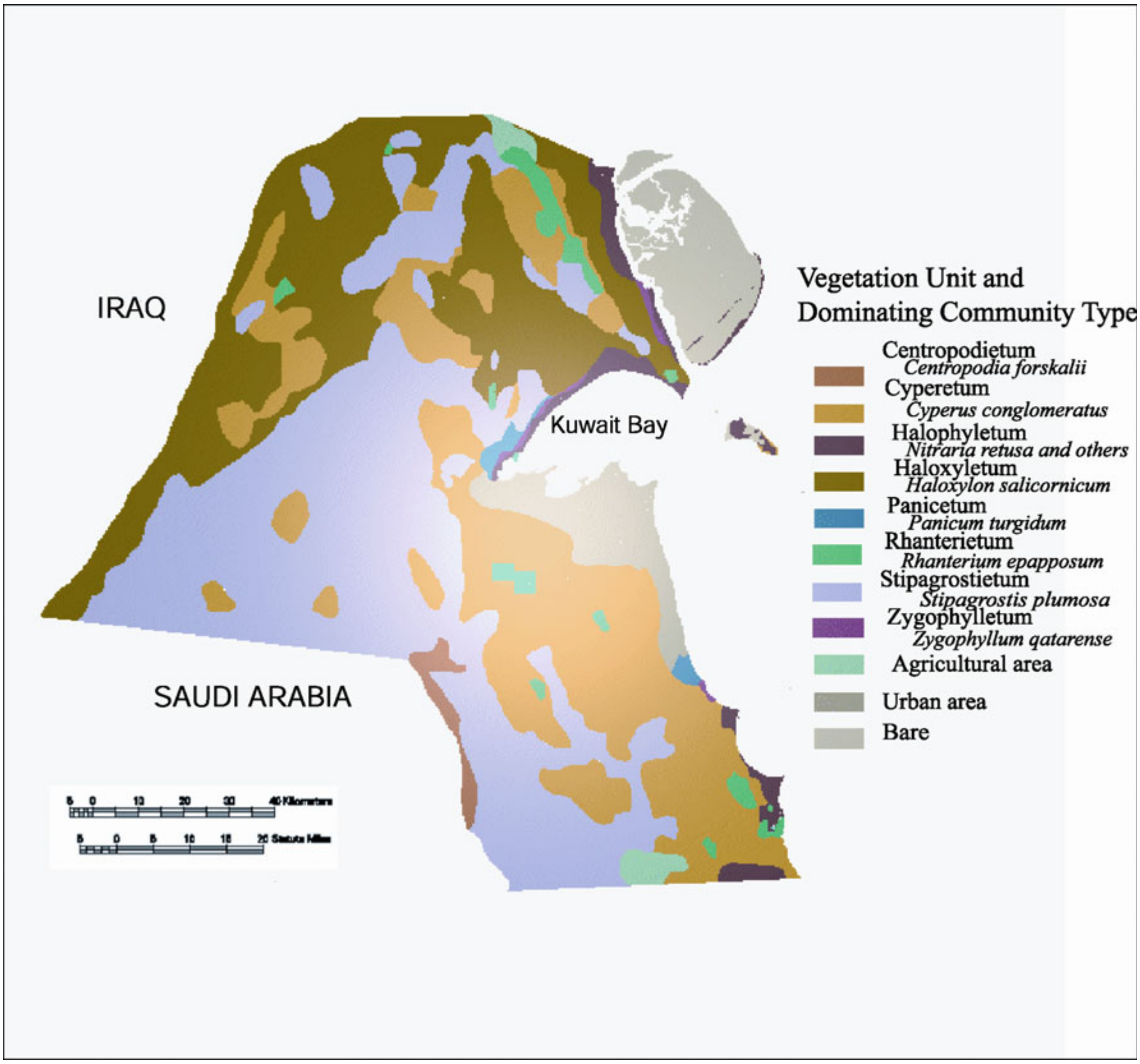


**Fig. 8.13** Vegetation map of Kuwait (after Omar et al., 2001)

are well-defined large areas, developed on the gently sloping northeast plain aligned in NW–SE direction. The fine texture, low relief, high-density northern drainage network basins flow into a shallow depression. Southern Kuwait is devoid of any significant drainage network.

While annual rainfall in Kuwait is only 115 mm, wet season (October to March) can experience occasional cloud bursts with rainfall exceeding 20 mm/day with surface runoff transporting sediments within the drainage network. During the hot summer months, the sediments dry up and are used as local sand supply sources.

### 8.4.4 Mapping Sand Encroachment Hazard Using GIS

Sand encroachment in Kuwait is a perennial problem that requires professional planning by experts to identify all related causes to devise ways to combat it. Considering the spatial extent of sand encroachment issue over all of Kuwait, excluding the urban areas and the islands, Geographical Information System (GIS) technology was used to develop a map showing sand encroachment. Delphi and Analytical Hierarchy Process (AHP) were used by local experts, with

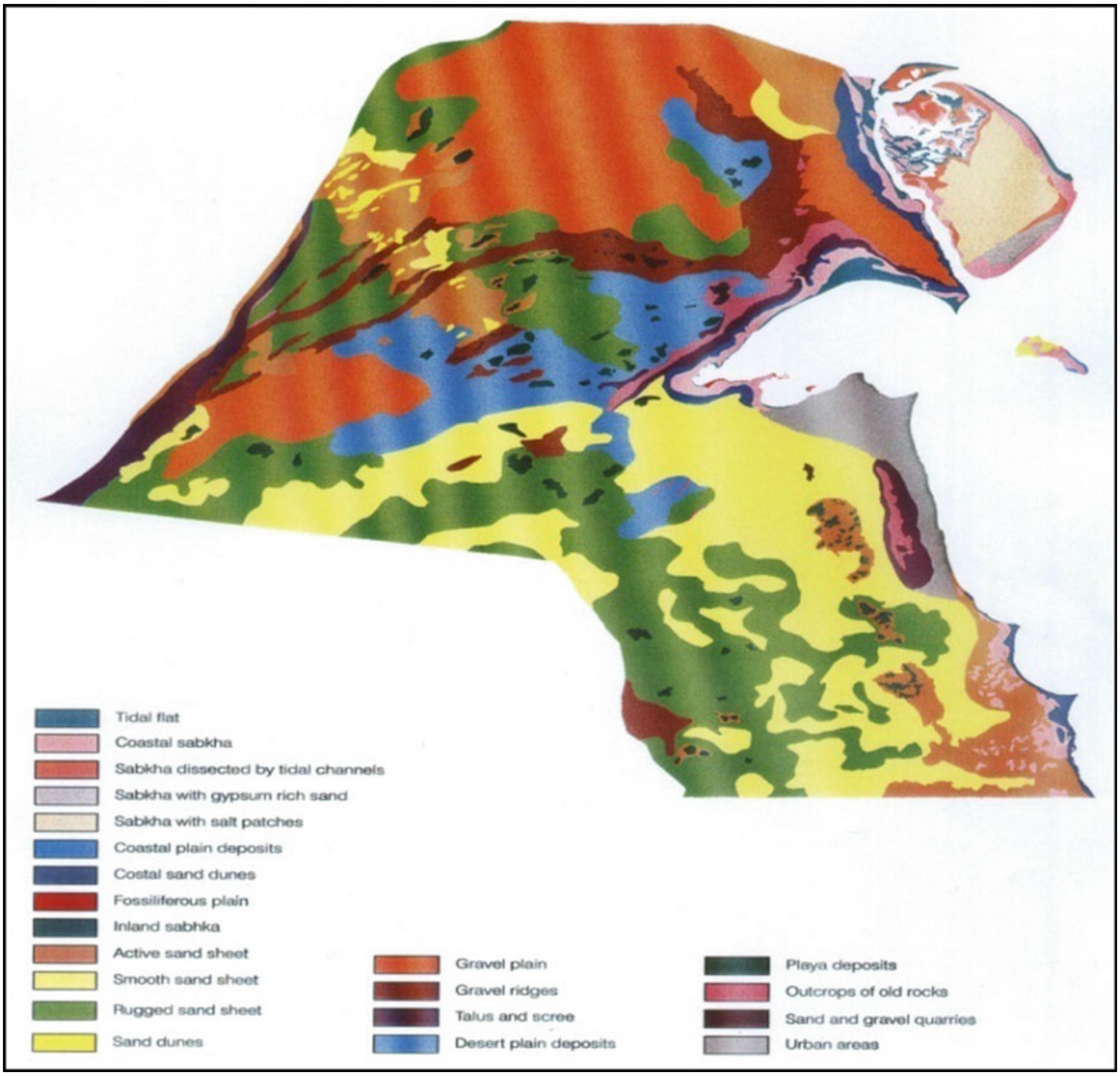


**Fig. 8.14** Surface sediment map of Kuwait (modified after Khalaf & Al-Ajmi, 1993)

extensive knowledge of the area, to quantify and rank the control factors (Al-Hellal & Al-Awadhi, 2006). An AHP-based sand encroachment susceptibility workflow chart to develop an AHP model to determine the sand encroachment susceptibility index is shown in Fig. 8.18.

Al-Awadhi (2008) integrated a March 2001 Landsat image and seven other Kuwait maps of physical attributes to compose a Geographic Information System (GIS) composite sand encroachment susceptibility index map. The nine maps are ($X_1$) sand drift potential, wind energy, ($X_2$) surface sediment type, ($X_3$) vegetation density cover, ($X_4$) land use type, ($X_5$) drainage type, ($X_6$) topography change, and ($X_7$) vegetation type. The relative weight factor values were entered in Eq. 8.4 to compute the Sand Encroachment Index (SEI).

$$\begin{aligned} SEI = {} & 0.37X_1 + 0.26X_2 + 0.12X_3 + 0.11X_4 + 0.07X_5 \\ & + 0.05X_6 + 0.02X_7 \end{aligned} \tag{8.4}$$

where

$X_1$: Sand drift potential (Wind energy);
$X_2$: Surface sediment type;
$X_3$: Vegetation density cover;
$X_4$: Land use type;
$X_5$: Drainage density;
$X_6$: Topography change;
$X_7$: Vegetation type.

Sand Encroachment Susceptibility (SES) zones were computed by solving Eq. 8.4 using Raster Calculator spatial

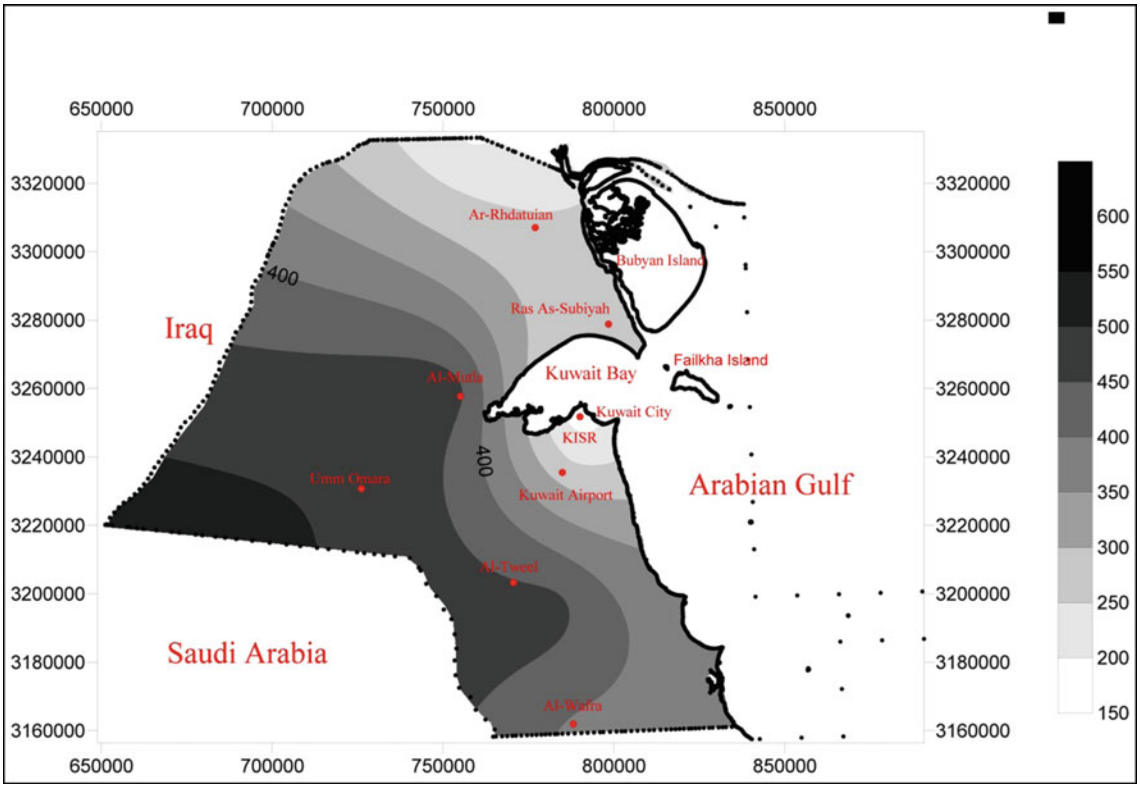


**Fig. 8.15** Annual sand drifts potential by wind (after Al-Awadhi et al., 2005b)

analyst function tool in ArcView8 software, which is capable of weighting and combining reclassified raster layers.

Table 8.7 shows the percentages of sand encroachment classes indicated in the SES map of Kuwait (Fig. 8.19).

## 8.5 Destructive Flash Floods

In Kuwait, flash floods occur in several areas including urban and desert areas. These floods have negative socio-economic, economic, and environmental consequences. Generally, floods usually occur when the rainfall amount reaches 30–40 mm in one event, e.g., February 1993 flash flood (40 mm) with duration 6–8 h, November 1997 flash flood (105 mm) with duration 3–4 h), and November 2018 flash flood (60 mm). Losses of the destructive floods of November 2018 reached KD 180,000,000. These include losses of the oil refineries, stock market, and suspension of work of governmental organizations for three days. Historical flood events in Kuwait took place on December 27, 1934 and November 30, 1954. The following hilly terrain areas (80–220 m above sea level) are considered the main watershed areas in Kuwait: Jal Az Zour hills, Al Rukham hills, Jal Al Liyah Ridge, Ahmadi Ridge, Hills of Wadi Al-Batin and Ritqa-Abdaly. Ahmadi Ridge is the sole watershed in the urban area of Kuwait. It is about 40 km length and 5 km width (area 200 km$^2$). This ridge is affected by a water divide. Two different drainage systems are developed on both sides of the water divide. Hydrographic basins in Kuwait are distinguished into exterior and interior units. The flash floods cause intensive damage to several residential areas and infrastructures including roads, bridges and tunnels. Death cases were reported on November 11, 1997 and November 9, 2018.

The geomorphologic, hydromorphologic features, and ground elevation are among the factors controlling the conditions of flash floods in Kuwait. Hill shade image (Fig. 8.20a) and the Digital Elevation Model (Fig. 8.20b) show at least 7 hydromorphologic features. These are Wadi Al Batin, Dibdiba ridges and wadis, Raudtain Depression, Jal Az Zour Hilly Terrain, Ahmadi Ridge, Rugged terrain and Shaqiah Playas. Digital Elevation Model offers important information about the ground elevation of the wadis and watersheds. For example, the ground elevation of Wadi Al Batin main channel is close to 280 m above sea level, while that of the main channel of Wadi Al Ahmadi is close to 40 m above sea level.

Hill shade value ranges between 0 and 247, Jal Az Zour Hilly Terrain has the lowest value while Wadi Al Batin has the highest value (Fig. 8.21a) shows hill shade map, while (Fig. 8.21b) shows Digital Elevation Model for Kuwait.

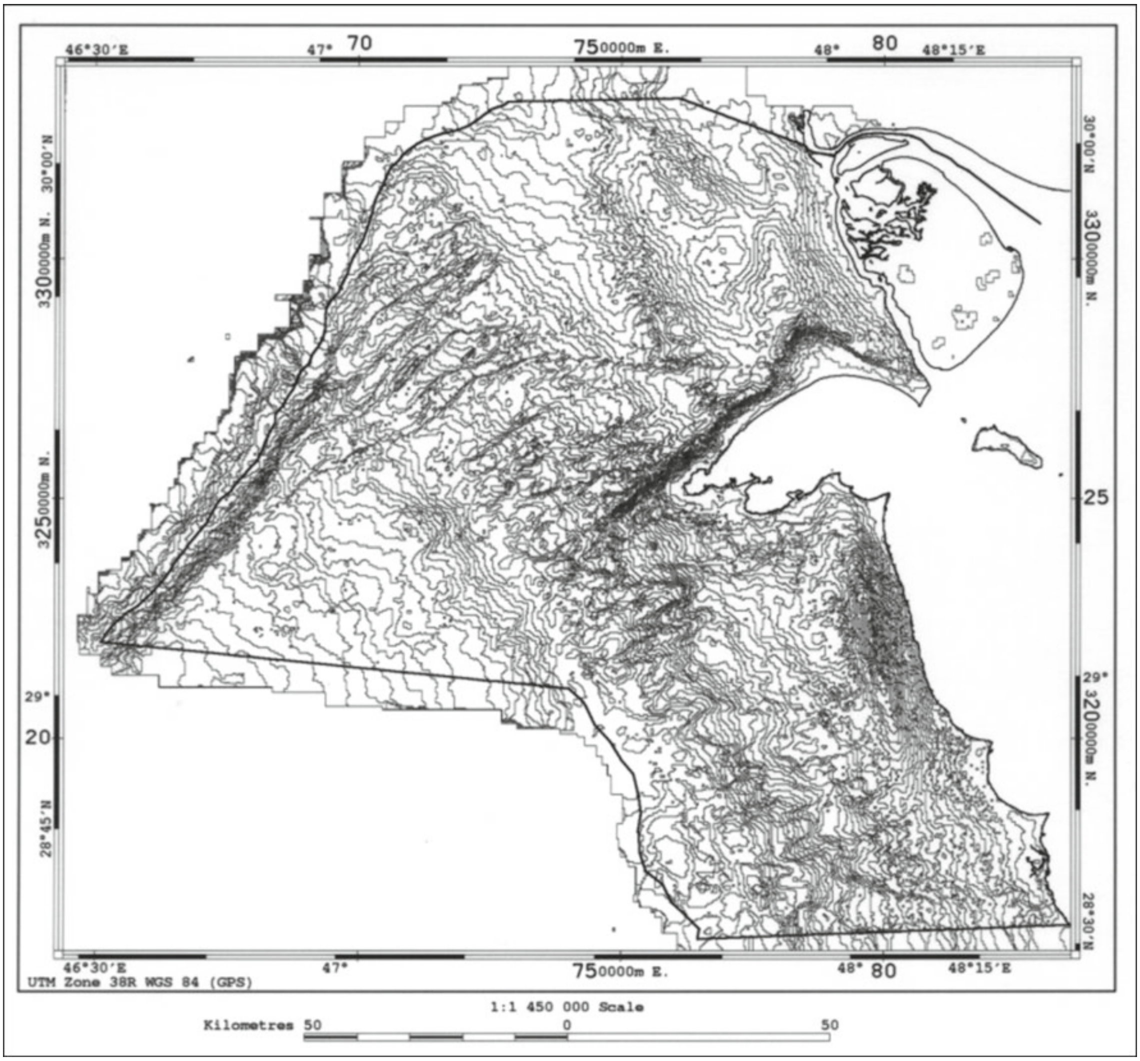


**Fig. 8.16** Topographic map of Kuwait; contour interval 5 m (after Misak et al., 2000)

### 8.5.1 Impact of Flash Floods

Flash floods in Kuwait have several types of damages. These are

- **Socio-economic**
  - Great threats to human life.
  - Physical damage to buildings and infrastructures (roads, power lines, drainage systems, and other utilities)
  - Traffic problems, ground collapse, and death cases (floods of 11 November 1997 & November 2018
- **Economic**
  - Delay and disruption of different human activities.
  - Inundation of large areas resulting in transportation delay.
  - High cost for maintaining the damage of flash floods.
  - Loss of millions of cubic meters of fresh water (rainwater).
- **Environmental**
  - Severe water erosion (removal of soil materials by runoff water).
  - Uprooting trees and tear out natural vegetation (grasses and shrubs).
  - Disruption and wearing away of desert surface.
  - Damaging of wildlife habitats.

### 8.5.2 Lessons Learned from the Floods of Nov. 2018

Floods of November 2018 were the worst during the last fifty years. Floods were caused by heavy rain storms close to


**Fig. 8.17** Paleodrainage map of Kuwait (after Misak et al., 2000)

300 mm. It caused severe damage to the existing infrastructures and development plans. Highways, bridges, tunnels, fences, houses, dams, dykes, water wells, storm water drainage systems, and oil facilities were damaged by the runoff water. Figure 8.22 shows damages of November 2018 flash floods in several areas.

Economic losses of the destructive floods reached KD 180,000,000 (Al Hemoud, 2018). These include losses of the oil refineries, stock market, and suspension of work for the governmental organization for three days. In addition, huge number of water ponds were resulted from the rainstorms of November 2018. These ponds were distributed in several areas in south part of Kuwait. The total area of these ponds reached 6.79 km$^2$, while the size and the depth varied between 0.0176 and 2.2 Km$^2$ and 0.5 m to 5 m ( about 2 m in average), respectively. The total volume of water in these water ponds attained about 13 million m$^3$.

The following are the most significant lessons which are learned from the 2018 November floods.

– Watershed management should start at the upper reaches of drainage basins (secondary channels).
– Big risk (unsafe) to construct check dams to the east of King Fahd Road.
– Rainwater storage pits are safe and cost-effective measures for flash floods management.
– Combination between well-established check dams and large-size rainwater storage pits (2000 m$^3$) is appreciated under specific conditions.
– Establishing an Early Warning System (EWS) for flash floods is the most effective tool for risk reduction.
– Maintaining soil crusts and soil compaction enhances infiltration of rainwater into the soil (measure of runoff management).

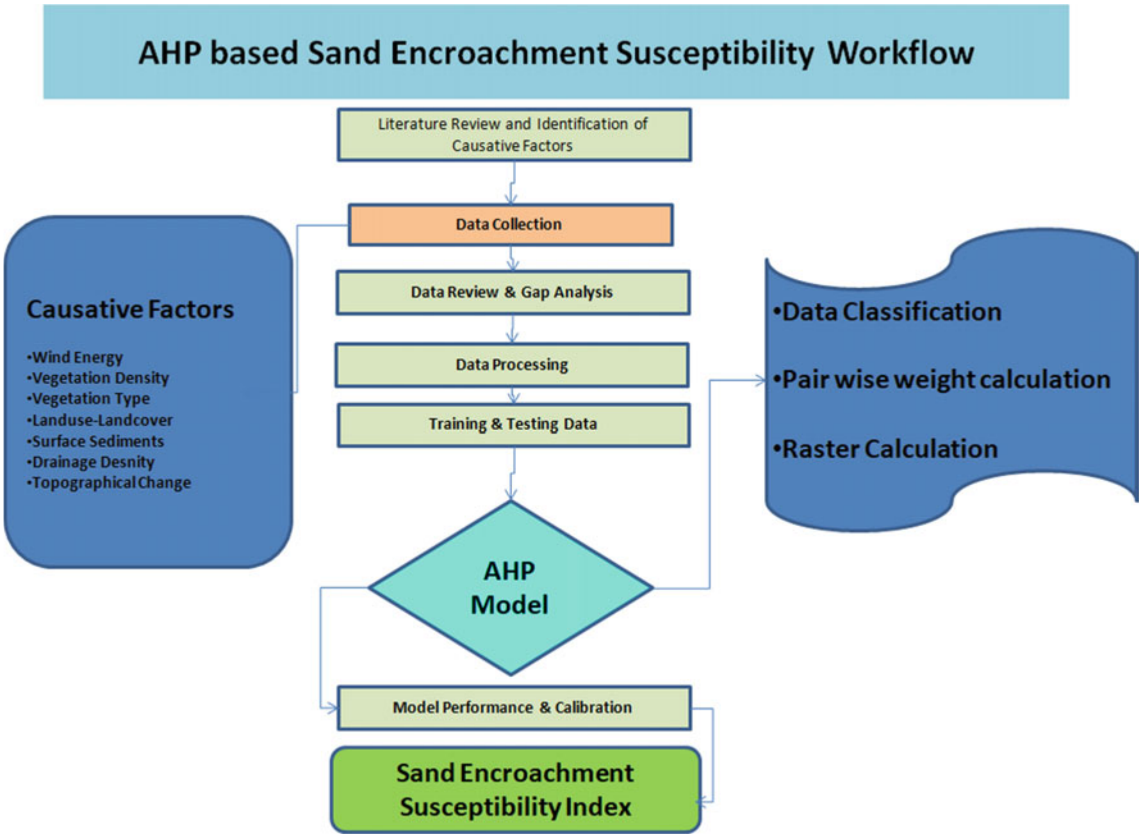


**Fig. 8.18** Generalized process flowchart to produce sand encroachment hazard map

**Table 8.7** Sand Encroachment Classes (SEC) and Sand Encroachment Index (SEI)

| Sand Encroachment Classes (SEC) | Sand Encroachment Index (SEI) | % | Area ($km^2$) |
|---|---|---|---|
| Very low | 0–48 | 5 | 782 |
| Low | 48–59 | 14 | 2,343 |
| Moderate | 59–69 | 24 | 4,190 |
| High | 69–79 | 22 | 3,841 |
| Very high | 79–100 | 35 | 6,060 |

– The surface runoff created on the slopes and embankments of highways is a significant source of flooding.

### 8.5.3 Surface Hydrologic Maps

A surface hydrologic map was produced by Misak et al. (2013). Accordingly, hydrographic basins (wadis) in Kuwait are divided into two main categories as follows:

- **Exterior** set of basins where the discharge happens around water bodies, i.e., such type of basins are formed in Khor As Sabiyah, Kuwait Bay, and Arabian Gulf.
- **Interior** set of basins where the discharge happens in inland hollows (playas) and plains. Such types of basins are differentiated into several units, exhibiting wide ranges in size and landforms, e.g., Ritqa, Abdaly, Raudtain-Umm El Eish collectors (locally called khabari), Al Liyah-Umm Al Rimmam, Umm Ruwaysat, Wadi Al Batin, Dibidibah, and Kabd-wafra areas.

Figure 8.23 shows three maps of drainage basins of Kuwait.

In Kuwait, runoff water has different directions including east, north, and west (Fig. 8.24).

Based on the analyses of data and information of flood events, the geography and morphology of drainage basins,

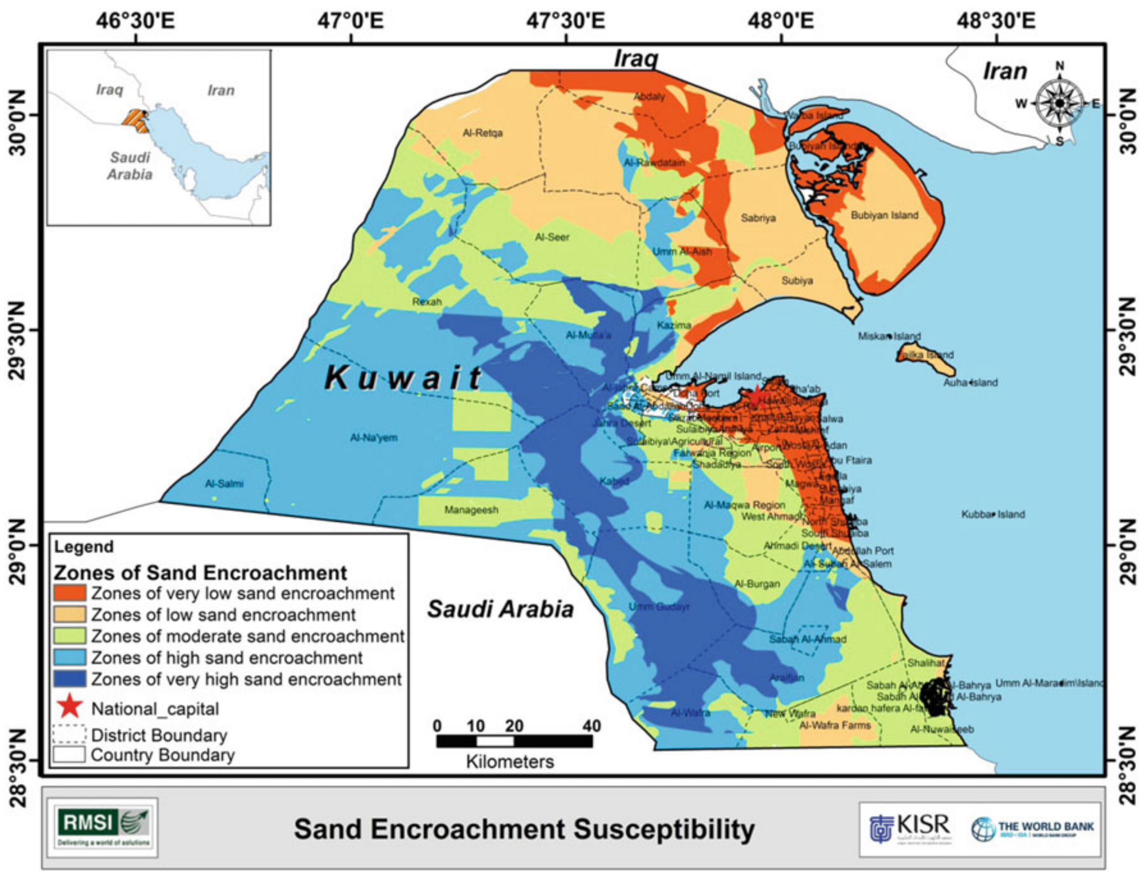


**Fig. 8.19** Sand Encroachment Susceptibility (SES) map of Kuwait

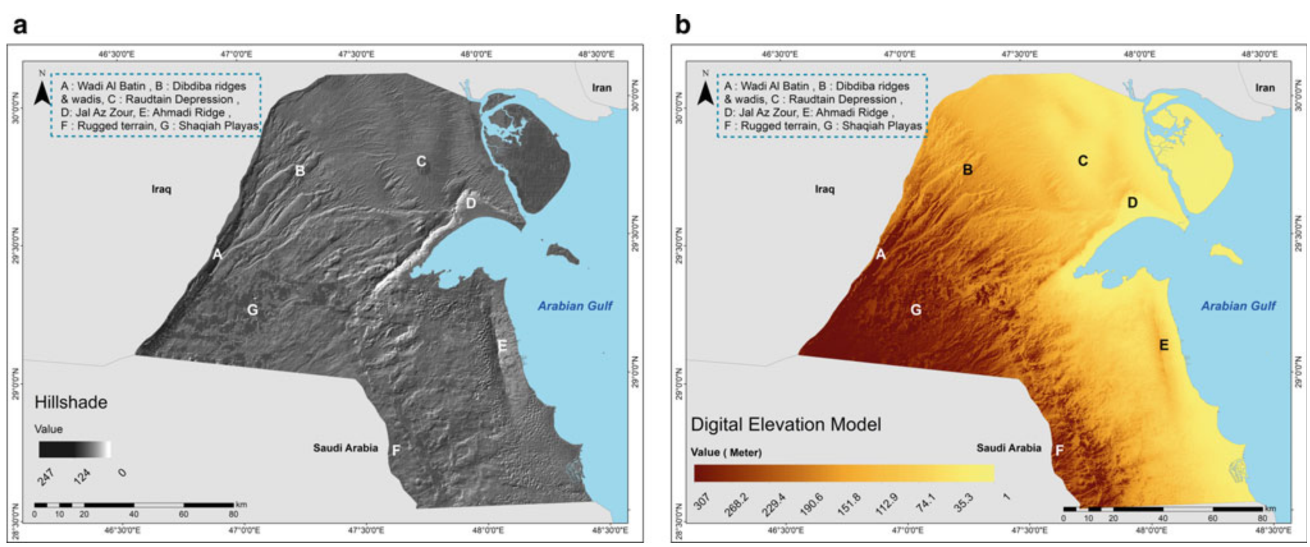


**Fig. 8.20** Hillshade map showing significant hydromorphologic features (**a**) and Digital Elevation Model (**b**) showing significant features

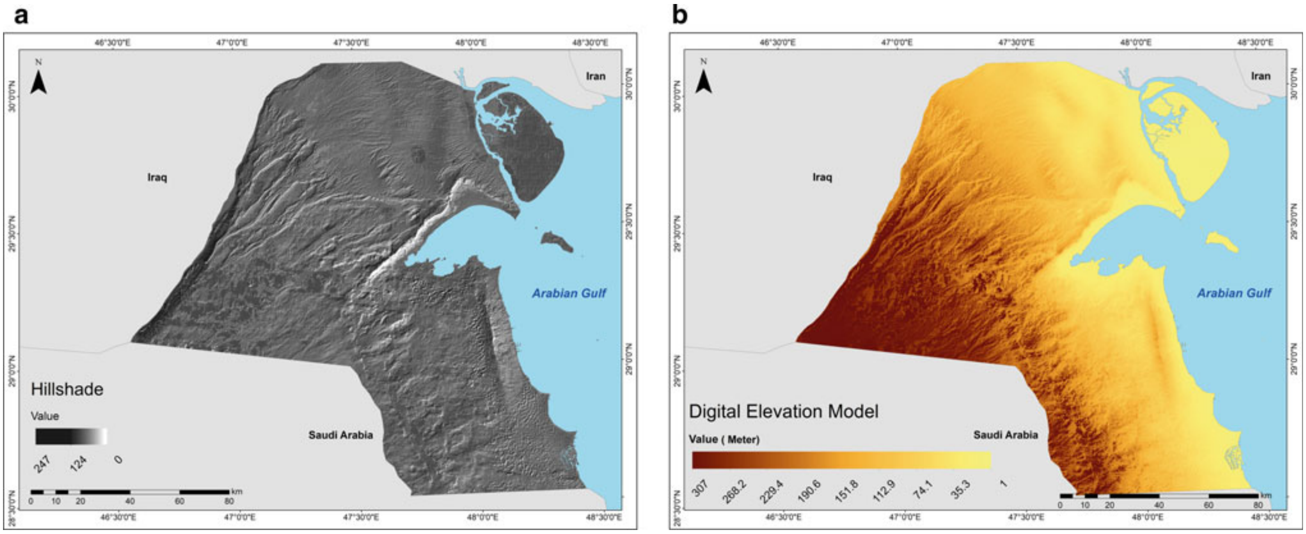


**Fig. 8.21** Hill shade map (**a**) and Digital Elevation Model (**b**) of Kuwait

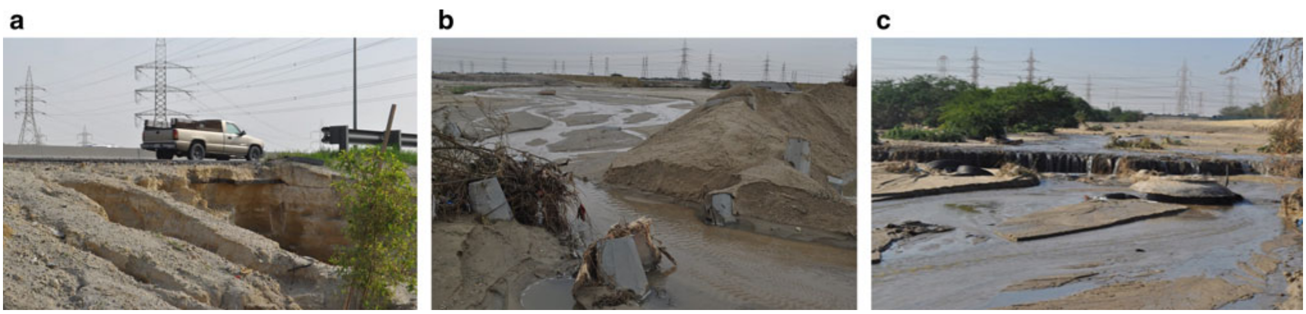


**Fig. 8.22** Soil erosion in Fahaheel area (**a**), Destruction of dykes and dams of Wadi Al Ahmadi (**b**), Destruction of storm water drainage system of Wadi Al Ahmadi (**c**)

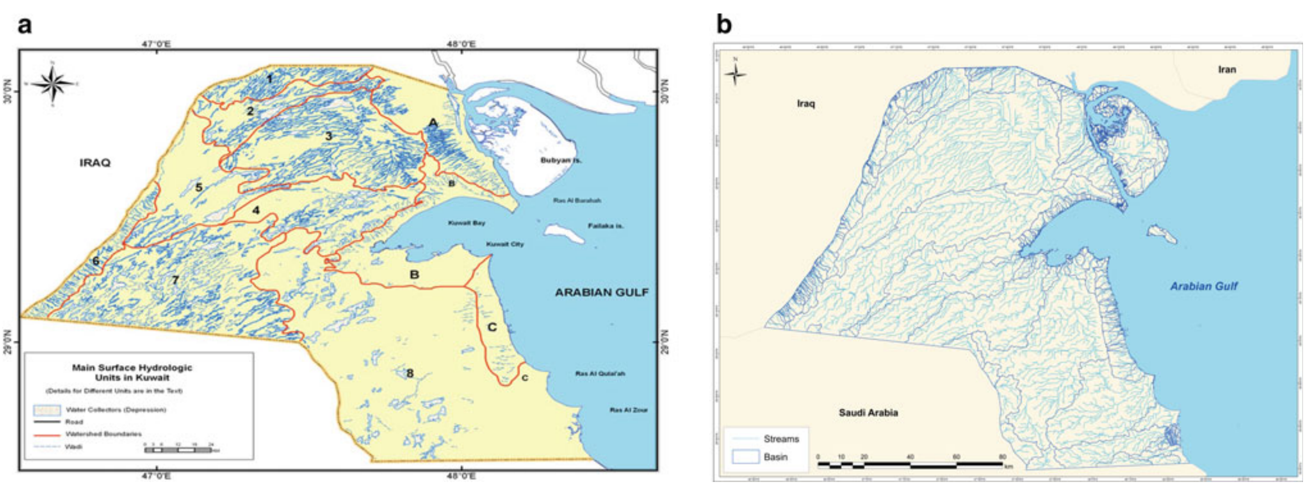


**Fig. 8.23** Drainage basins in Kuwait (**a**) (after Misak et al., 2013) and Drainage basins in Kuwait as 2018 (**b**) (modified of Misak et al., 2013)


**Fig. 8.24** Maps showing the drainage basins and the runoff directions (2018), and arrows indicate the runoff direction

the drainage wadis are classified, on hazard bases into three categories. These are as follows:

1. Extremely dangerous
   Extremely dangerous basins include the following:
   – Eastern basins of Ahmadi Ridge (8 basins including Wadi Al Ahmadi which covers about 17 $km^2$).
   – Western basins of Ahmadi Ridge (Burgan playa).
   – Wadi Arifjan (affects Sabah Al Ahmad Residential City).
   – Wadi Al Batin.
2. Dangerous
   Dangerous basins include the following:
   – Kabd-Wafra basins.
   – Ritqa-Abdali basins.
   – Several basins cutting Jal Az Zour Hilly Terrain, e.g., Wadi Al Auga.
3. Moderately dangerous
   Moderately dangerous basins include the following:
   – Liyah basins.
   – Al Rukham basins.
   – Dibdiba plain basins.
   – Raudtain basin.

### 8.5.4 Proposed Risk Mitigation Plan (RMP) for Flash Floods in Kuwait

In Kuwait, several land use types increase the risks of flash floods. Examples of these land use types are off-road vehicles and rangelands grazing. Both land uses result in soil compaction and degradation of vegetation. As mentioned in relevant literature, the amount of infiltrating rate of rainwater in compacted soils may reduce by 40–100% of its natural rate if the soil is not compared. Consequently, the runoff water and the associated soil erosion increase. So, management of rangeland and off road traffic is one of the key approaches for risk reduction of flash floods.

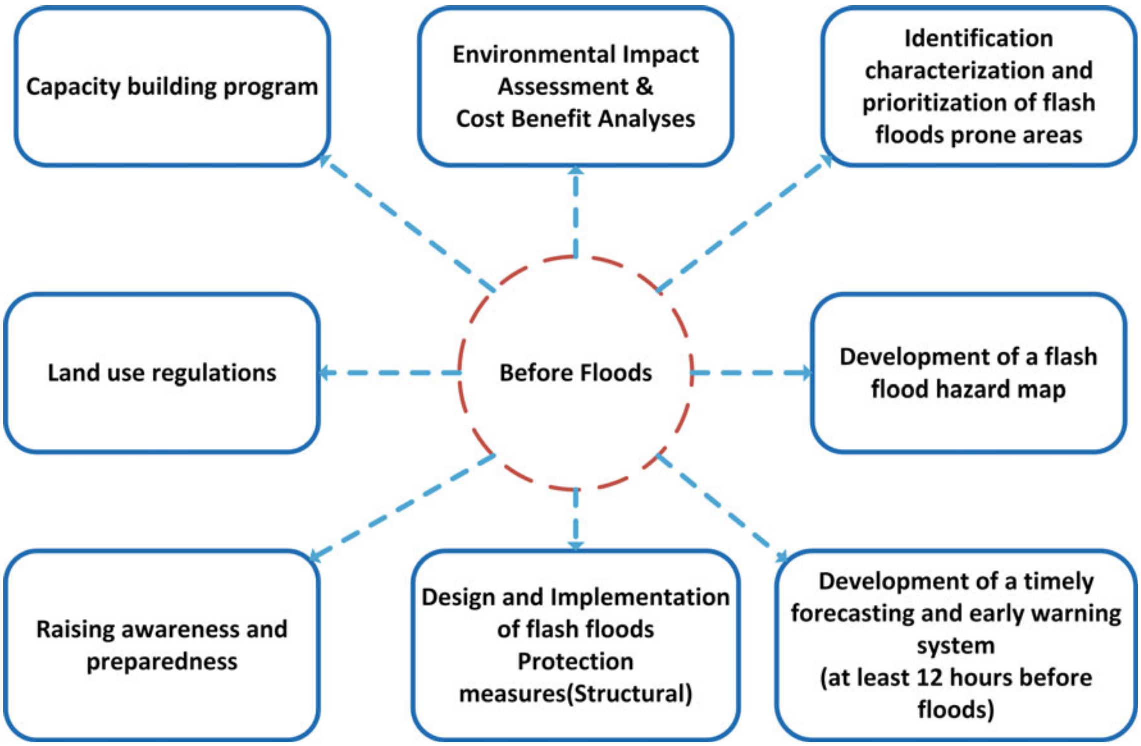


**Fig. 8.25** Main approaches of the Proposed Risk Mitigation Plan (PRMP) for flash floods in Kuwait

The proposed Risk Mitigation Plan consists of number of strategic approaches. These approaches are shown in Fig. 8.25.

Before floods, a set of 8 strategic approaches and measures are proposed. These include 1—Identification, characterization, and prioritization of flash floods prone areas, 2—Development of a flash flood hazard map, 3—Development of a timely forecasting and early warning system (at least 12 h), 4—Design and implementation of flash floods structural measures ( dams, dykes, and reservoirs), 5—Raising awareness and preparedness, **6**—Land use regulations, 7—Capacity building program, and 8—Environmental Impact assessment and cost–benefit analyses.

During floods phase, approaches include 1—Follow up media for update weather conditions and emergency activities, 2—Evacuation activities, 3—Monitoring the conditions of floods (magnitude, rainfall, depth, and velocity of water), and 3-Follow up water harvesting activities. After floods phase, approaches include Damage Assessment and losses estimation as well as restoration program.

## 8.6 Conclusion

This chapter deals with meticulously and carefully all the natural hazards facing the State of Kuwait, as well as the technical techniques of mitigating their effects. The chapter reviewed and accounted the earthquake hazard and the modern geophysical methods used to calculate the seismic hazard values for the State of Kuwait. The risks of dust falling on Kuwait were studied with a high efficiency, and the results were reviewed. Land degradation in Kuwait were also studied and referred to in this chapter, and a review of the most important results published in this regard. The Aeolian sand movement and destructive flash Floods were also studied in this chapter and their most important topics and results are presented.

## References

Abd el-aal, A. K., Al-Jeri, F., Al-Enezi, A., & Parol, J. A. (2020). Seismological aspects of the 15 November 2019 earthquakes sequence, Kuwait. *Arabian Journal Geosciencem 13*, 941. https://doi.org/10.1007/s12517-020-05919-1.

Abd el-aal, A. K., Parol, J. A., Al-Jeri, F., & Al-Enezi, A. (2021a). Modeling and simulating ground motion from potential seismic sources to Kuwait: Local and regional scenarios. *Geotectonics, 55*. https://doi.org/10.1134/S001685212103002X.

Abd el-aal, A. K., Al-Enezi, A., Sadalla, H., & Al-Jeri, F. (2021b). Tectonic and anthropogenic characteristics of the 15 November 2019 micro earthquakes sequence, Kuwait. *Geotectonics, 55*, 137–152. https://doi.org/10.1134/S0016852121010039.

Abd el-aal, A. K. A., Al-Enezi, A., Al-Jeri, F., & Mostafa, S. I. (2021c). Earthquake deterministic hazard and sensitivity analysis for residential Cities in Kuwait. *Journal of Volcanology and Seismology, 15*(6), 445–462. https://doi.org/10.1134/S0742046321060051.

Abd el-aal, A. K., Al-Enezi, A., Al-Jeri, F., Naser, O., Alenezi, & Mostafa, S. I. (2022). Probabilistic and deaggregation seismic hazard scenarios for Kuwait. *Submitted to Arabian Journal Geoscience*.

Abd el-aal, A. K., Kamal, H., Abdelhay, M., & Elzahaby, K. (2015). Probabilistic and stochastic seismic hazard assessment for wind turbine tower sites in Zafarana Wind Farm, Gulf of Suez, Egypt. *Bulletin of Engineering Geology Environment, 74*(4), 1225–1241.

Al-Ajmi, D., Misak, R., Al-Dousari, A., & Al-Enezi, A. (1994). Impact of the Iraqi war machinery and ground fortifications on the surface sediments and aeolian processes in Kuwait. In *Proceedings International Conference on the Effect of the Iraqi Aggression on the State of Kuwait*, Kuwait, 2–6 April, 3, 229–248.

Al-Awadhi, J. (2005). Dust fallout and characteristics in Kuwait: A case study. *Kuwait Journal of Science and Engineering, 32*, 135–152.

Al-Awadhi, J. M., & AlShuaibi, A. A. (2013). Dust fallout in Kuwait city: Deposition and characterization. *Science of the Total Environment, 461–462*, 139–148.

Al-Awadhi, J., & Al-Awadhi, A. (2009). Modeling the aeolian sand transport for the desert of Kuwait-Constraints by field observations. *Journal of Arid Environments, 73*, 987–995.

Al-Awadhi, J. (2008). Mapping land degradation hazard in Kuwait: Using Delphi and AHP methods. *Kuwait Journal of Science and Engineering, 35*(1A), 71–91.

Al-Awadhi, J. M. (2001). Impact of gravel quarrying on the desert environment of Kuwait. *Environmental Geology, 41*(3–4), 365–371.

Al-Awadhi, J. M., & Misak, R. (2000). Field assessment of aeolian sand processes and sand control measures in Kuwait. *Kuwait Journal of Science and Engineering, 27*(1), 159–176.

Al-Awadhi, J. M., Al-Dousari, A., & Al-Enezi, A. (2001). Barchan dunes in northern Kuwait. *Arab Gulf Journal of Scientific Research, 18*(1), 32–40.

Al-Awadhi, J. M., Omar, S. A., & Misak, R. F. (2005a). Land degradation indicators in Kuwait. *Land Degradation and Development, 16*(2), 163–176.

Al-Awadhi, J. M., Al-Hellal, A., & Al-Enezi, A. (2005b). Sand drift potential in the desert of Kuwait. *Journal of Arid Environments, 63*, 425–438.

Al-Besharah, J. (1992). The Kuwait oil fires and oil lakes—facts and numbers. *Proc* (pp. 12–15). University of Birmingham.

Al-Dousari, A. M., & Al-Awadhi, J. M. (2012). Dust fallout in northern Kuwait, major sources and characteristics. *Kuwait Journal of Science and Engineering, 39*(2A), 171–187.

Al-Dousari, A. M., Misak, R., & Shahid, S. A. (2000). Soil compaction and sealing in AL-Salmi area, Western Kuwait. *Land Degradation and Development, 11*, 401–418.

Al-Enzi, A., Sadeq, A., & Abdel-Fattah, R. (2007). Assessment of the Seismic Hazard for the state of Kuwait. Int rep EC011C, submitted to KFAS 2007.

Al-Hellal, A., & Al-Awadhi, J. M. (2006). Assessment of sand encroachment in Kuwait Using GIS. *Environmental Geology, 49*, 960–967.

Al-Sudairawi, M., & Misak, R. (1999). Challenges and problems confronting the sustainable development in the desert of Kuwait. In *Proceedings. 9th International Conference Environmental Protection Is a Must*, Alexandria, Egypt.

Bath, M. (1979). Introduction to Seismology (Second, Revised ed.). Basel: Birkhäuser Basel. ISBN: 9783034852838.

Bormann, P. (Ed.) (2012). New manual of seismological observatory practice (NMSOP-2), IASPEI, GFZ German Research Centre for Geosciences, Potsdam; nmsop.gfz-potsdam.de. https://doi.org/10.2312/GFZ.NMSOP-2.

Brown, G., & Porembski, S. (1997). The maintenance of species diversity by miniature dunes in a sand-depleted Haloxylon salicornicum community in Kuwait. *Journal of Arid Environments, 37*, 461–473.

Cornell, C. A. (1968). Engineering seismic risk analysis. *Bulletin of the Seismological Society of America, 18*, 1583–1606.

Gu, C., Al-Jeri, F., Al-Enezi, A., Büyüköztürk, O., & Toksöz, M. N. (2017). Source mechanism study of local earthquakes in Kuwait. *Seismological Research Letters, 88*(6), 1465–1471.

Gu, C., Prieto, G. A., Al-Enezi, A., Al-Jeri, F., Al-Qazweeni, J., Kamal, K., Kuleli, S., Mordret, A., Büyüköztürk, O., & Toksöz, M. N. (2018). Ground motion in Kuwait from regional and local earthquakes: Potential effects on tall buildings. *Pure Application Geophysics, 175*, 4183.

Hamoud, N. (2018). Al-Alati Int. *Journal of Engineering Research and Application, 8*(4) www.ijera.com ISSN: 2248-9622, (Part—III) April 2018, pp. 06–17.

Holden, C. (1991). Kuwait's unjust deserts: Damage to its desert. *Science, 251*, 1175–1181.

Howle, S. (1998). *The long term environmental consequences of the Gulf War in northeastern Kuwait*. M.Sc. Thesis, University of Massachusetts, Boston, Massachusetts, USA.

Karrar, G., Batanouny, K. H., & Mian, M. A. (1991). A rapid assessment of the impact of the Iraqi-Kuwait conflict on terrestrial ecosystem, part II. The State of Kuwait. Report prepared for International Fund for Agricultural Development, Rome, Italy.

Khalaf, F. I. (1989). Desertification and aeolian processes in the Kuwait desert. *Journal of Arid Environments, 16*, 125–145.

Khalaf, F. I., Al-Kadi, A., & Al-Saleh, S. (1980). Dust fallout in Kuwait. Kuwait Institute for Scientific Research, Final report No. KISR/PPI 108/EES-RF-8016, Kuwait.

Khalaf, F. I., & Al-Ajmi, D. (1993). Aeolian processes and sand encroachment problems in Kuwait. *Geomorphology, 6*, 111–134.

Khalaf, F. I., Gharib, I. M., & Al-Hashash, M. (1984). Types and characteristics of the recent surface deposits of Kuwait. *Arabian Gulf Journal of Arid Environments, 7*, 9–33.

Kuwait Institute for Scientific Research. (1999). Soil survey for the state of Kuwait, vol 1. Executive summary. AACM International, Adelaide, Australia, CD-ROM.

Loska, K., & Wiechula, D. (2003). Application of principle component analysis for the estimation of source of heavy metal contamination in surface sediments from the Rybnik Reservoir. *Chemosphere, 51*, 723–733.

Misak, R., Khalaf, F., & Omar, S. (2013). Managing the hazards of drought and shifting sands in drylands (the case of Kuwait), Developments in Soil Classification, land use planning and Policy Implications, pp. 703–729 editors Shabbir A. Shahid, Faisal Taha, Mahmoud Adbulftatah.

Misak, R., Al-Awadhi, J. M., & Al-Sudairawi, M. (1999). Assessment and controlling land degradation in Kuwaiti desert ecosystem. In *Proceeding Conference on the Impact of Environmental Pollution on the Development in the Gulf Region*, Kuwait, 15–17 March.

Misak, R., Kwarteng, A., Al-Sudairawi, M., Omar, S., Al-Awadhi, J., Al-Obaid, E., Shahid, S., & Kerdi, Z. (2000). *Controlling land degradation in severalareas of Kuwait, Phase 1: mapping and assessment*. Kuwait Institute For Scientific Research, Report No. KISR 6005, Kuwait.

Mostafa, S. I., Abd el-aal, A. K., & El-Eraki, M. A. (2018). Multi scenario seismic hazard assessment for Egypt. *Journal Seismology*. https://doi.org/10.1007/s10950-018-9728-y.

Omar, S. A., Shahid, S. A., & Misak, R. (1999). *Assessing damage magnitude and recovery of the terrestrial eco-system*. Follow up of natural and induced desert recovery. Kuwait Institute for Scientific Research, Kuwait.

Omar, S. A. (1991). Dynamics of range plants following 10 years of protection in arid rangelands of Kuwait. *Journal of Arid Environments, 21*, 99–111.

Omar, S. A. S., Bhat, N. R., Shahid, S. A., & Assem, A. (2005). Land and vegetation degradation in war-affected areas in the Sabah Al-Ahmad Nature Reserve of Kuwait: A case study of Umm. *Ar. Rimam. Journal of Arid Environments, 62*, 475–490.

Omar, S. A. S., Misak, R., King, P., Shahid, S. A., Abo-Rizq, H., Grealish, G., & Roy, W. (2001). Mapping the vegetation of Kuwait through reconnaissance soil survey. *Journal of Arid Environments, 48*, 341–355.

Reiter, L. (1990). *Earthquake hazard analysis*. Columbia University Press, 254 pp.

Shahid, S. A., Omar, S. A. S., & Al-Ghawas, S. (1999). Indicators of desertification in Kuwait and their possible management. *Desertification Control Bulletin, 34*, 61–66.

Shahid, S. A., Omar, S. A. S., Grealish, G., King, P., El-Gawad, M., & Al-Mesabahi, A. (1998). Salinization as an early warning of land degradation in Kuwait. *Problems of Desert Development, 5*, 8–12.

Shahid, S. A., Omar, S. A. S., Misak, R., & Abo-Rizq, H. (2003). Land resource stresses and degradation in the arid environment of Kuwait: An overview. In A. S. Alsharhan, W. W. Wood, A. S. Goudie, A. Fowler, & E. M. Abdellatif (Eds.), *Desertification in the third Millennium*. Swets and Zeitlinger Publisher, Lisse, The Netherlands, pp. 351–360.

Sutherland, R. A. (2000). Bed sediment associated trace metals in an urban st ream, Oahu. *Hawaii. Environmental Geology, 39*(6), 611–627.

Zaman, S. (1997). Effects of rainfall and grazing on vegetation yield and cover of two arid rangelands in Kuwait. *Environmental Conservation, 24*, 344–350.