ISSN 2354-9114 (online), ISSN 0024-9521 (print)
Indonesian Journal of Geography Vol 55, No 3 (2023): 408-420
DOI: 10.22146/ijg.82508 website: https://jurnal.ugm.ac.id/ijg

INDONESIAN JOURNAL OF GEOGRAPHY

REVIEW ARTICLE

Spatio-temporal Evolution of Coastal Sabkhas in Arid Rapid Urban Development Area of Kuwait

Adeeba Al-Hurban[1] and Jasem Albanai[2 & 3]
[1] Earth & Environmental Sciences Dept., Faculty of Science, Kuwait University, Kuwait
[2] Marine Monitoring Section, Water Quality Monitoring Department, Environmental Public Authority, Kuwait
[3] Department of Mathematics and Geosciences, University of Trieste, Italy,

Submit : 2023-02-22
Received: 2023-08-06
Accepted: 2023-10-19

Keywords: Quaternary Deposits; Desert Geomorphology; GIS; Remote Sensing; Sabkhas

Correspondent email: Adeeba.alhurban@ku.edu.kw

Abstract. Sabkha is the Arabic term meaning "salt flat". It is usually used to describe coastal flat areas extending above the high tide level and which are evaporate-rich clastic sediments. In Kuwait, sabkhas exist along the southern and northern coastal areas. Previous studies did not discuss the chronological changes of the coastal sabkhas in Kuwait, especially the northern sabkhas, where the Government of the State of Kuwait plans urban expansion to the North to achieve Kuwait Vision 2035. This current study aims to detect the geomorphological, spatial, and temporal evolution of coastal sabkhas in Kuwait using remote sensing data and Geographic Information System (GIS) methods. Landsat satellite images were used to study the distribution and evolution of the sabkhas across Kuwait's coasts. The selected images from Landsat MSS 1985 (before the gulf war), Landsat ETM+ 2002 (after the war), and Landsat OLI 2022 (current form) have been classified using the IsoData unsupervised classification method that takes into account near and short infrared radiation. The classification accuracy was validated for 2022 images using the Kappa coefficient, where the value was 0.81. The results showed that sabkhas in Kuwait have changed geomorphologically; anthropogenic activities and urban expansion have certainly influenced this change to cope with socioeconomic demands. The area of the sabkhas shrank from 1,267 to 1,019 (-17%). The results also showed that the southern sabkhas of Kuwait are declining significantly, from 207 in 1985 to 52 in 2022. The current study presents a methodology to study the spatio-temporal evolution of sabkhas in dry areas around the world, using spatial analysis and in the context of the rapid urban development that the world is witnessing.

1. Introduction

"Sabkha" is the Arabic term meaning "salt flat"; it is usually used to describe coastal flat areas that extend above the high tide level and are evaporate-rich clastic sediments (Khalaf et al., 1984a; Al-Hurban, 2004). Various scientists in different ways have defined Sabkhas. Kinsman (1969) defines a sabkha as a deflation surface down to the groundwater level or the capillary evaporation zone. Neal (1975) terms it a geomorphic surface whose level is dictated by the water table. A sabkha was described by Warren (1989) and Briere (2000) as an equilibrium of geomorphic surface whose level is indicated by the local water table. They also described it as a marginal marine and continental mudflat where evaporite minerals occur in the capillary zone above the saline water table. An important fact is that a stream or runoff does not feed a true sabkha. Sabkhas are defined as low coastal and inland areas dissecting the underlying shallow groundwater table. Variously sized quartz sand is the major component of the sabkha deposits, mixed with carbonate mud and scattered gypsum crystals, all encrusted with a thin veneer of salts left after the evaporation of collected water after a rainy season (Al-Hurban, 2004).

Traditionally, geomorphologists have studied the distribution and morphology of sabkhas through field surveys. These field studies are very practical for identifying surface features but are also costly to conduct (Albugami et al., 2018; Baird et al., 2019; Chavez Jr. et al., 2002; Livingstone et al., 2007)the Co-Registration of Optically Sensed Images and Correlation, was first used to produce a raster map of sand dune movement, however, no studies have yet applied it to the full Landsat archive. The orthorectified and geolocated Landsat Level-1 Precision Terrain (L1TP. The development of space-based measurements and geographic information systems (GIS) has increased our ability to understand more about the land surface through spatial data, with the ability to analyze this data in a specific spatial and temporal period, whereby it is possible to study and detect many geomorphological features through the electromagnetic relationship of radiations and surface features (Albanai, 2021a).

Previous literature has studied sabkhas and their temporal and spatial evolution, whether from a geomorphological perspective (Omar et al., 2002; Al-Ajmi, 2008; Al-Dalama and Al-Hurban, 2019). The first attempt at the beginning of the twenty-first century was a map published in the National Atlas of Kuwait (2001), which showed the geographical distribution of surface sediments in the State of Kuwait and included sabkhas. The total area of sabkhas in this study was about 722 . Two years later, based on previous studies, Omar et al. (2002)

drew the first map showing the geographical distribution of sabkhas in the State of Kuwait. The total area of sabkhas in the mentioned study amounted to about 1,800 .

Al-Ajmi's study (2008) was one of the first studies that relied on remote sensing sources and the capabilities of geographic information systems in studying the distribution of sabkhas. The study showed the properties and distribution of the northern sabkhas in the State of Kuwait, based on satellite images taken by Landsat 5 in 2003 and the topographic map of the State of Kuwait in 1995, at a scale of 1:50000, and field study. The study showed that the geographical distribution of the total area of sabkhas reached about 770 . In a recent study, Al-Dalama and Al-Hurban (2019) dealt with the changes that occurred in the sabkhas of the southern coast of Kuwait as a result of the urban expansion in the south and the filling and dredging operations that took place depending in geographic information systems and remote sensing. The study found that the total area of sabkhas on the southern coast of the State of Kuwait has declined by about 6.5 over thirty years as a result of human activities.

Previous studies show a large discrepancy in estimating the total area of sabkhas in Kuwait. Studies at the beginning of the second millennium relied on estimates based on field surveys in estimating the total area of sabkhas and their geographical extent, which gave some generalization in the results. Also, recent studies based on spatial techniques in mapping sabkhas lacked comprehensiveness, as they dealt with either the northern part without the southern one or vice versa, which limits the spatial comparison between the two sites. In addition, there has been no study so far dealing with the chronological development of the northern sabkhas in the country. However, the Kuwaiti government has laid the northern region as a basis for urban expansion to implement the State of Kuwait 2035 vision and the major changes that occurred in the sabkhas after the 1990 Gulf War. The current study aims to fill the gaps in previous studies by monitoring the spatial distribution and temporal development of the northern and southern sabkhas in the State of Kuwait, particularly focusing on how they were changed to satisfy the demand for recreational purposes or any socioeconomic developments, based on Landsat program satellite images over three time periods (1985 before the Gulf War, 2002 after the Gulf War and at the beginning of the current century, in 2022 to define sabkhas in their current form). It also aims to present an open-access methodology using the latest available resources and the most accurate (spatially) to study the spatial and temporal changes of coastal sabkhas in dry areas around the world in the context of the rapid urban development that the world is witnessing.

Kuwait is situated in the northwestern corner of the Arabian Gulf in a transitional zone between the stable Arabian Foreland on the southwest and the vast compound delta of the Mesopotamian Plain in the North and northwest (Purser, 1973). It is located between longitudes 46°30′ and 48°30′ East and latitudes 28°30′ and 30°08′ North. Climatologically, Kuwait is classified as an arid region, and the climate throughout the country is arid to semi-arid, distinguished by hot, dry, and dusty summers and relatively cool winters with scarce and irregular rainfall, in addition to rapidly infiltrating precipitation, which does not leave permanent surface water, except for some temporal wadi fills of winter rains (Safar, 1985). The Arabian Gulf is regarded as a hypersaline basin as it is located within an arid climatic zone bordering a desert region with high evaporation rates that go far beyond the freshwater influx (Albanai, 2021, 2021c, 2021d, 2021e). The Holocene transgression-regression episode results in major sea level changes, of which major transgression was recorded as 1.3 to 1.6m higher than the present sea level at approximately 4570 years BP; a major regression followed this during the period 3040-2320 years BP (Al-Asfour, 1978 and Al-Zamel, 1983). In Kuwait, the evaporation rate is much more than the average precipitation rate.

Surficial deposits of Kuwait are primarily of Quaternary sediments, including Al-Dibdibbah Pleistocene gravel deposits and Holocene sediments (Khalaf *et al.*, 1984b). Kuwait was subjected to tectonic movements and geomorphic processes (weathering, aeolian and coastal) during the late Pliocene-Pleistocene age, which in turn resulted in the formation of multiple geomorphological features of interest along the coastal area (Kassler, 1973; Al-Sarawi *et al.*, 1993; Al-Sulaimi & El-Rabaa, 1994; Picha, 1978; Al-Zamel & Al-Sarawi, 1998). Sabkhas exist along Kuwait's southern and northern coastal areas (Figure 1).

Two main types of sabkha deposits are identified: coastal, near the shoreline and surrounding areas, and inland sabkhas, which occur landward from the coastal sabkhas. According to their nature, geographic settings and mode of occurrence, they are classified accordingly as either inland or coastal sabkhas. The former occurs in the western side of the country, whereas the latter extends along the southern coastal line (Al-Hurban & Gharib, 2003 & 2004). The coastal sabkhas are further classified into old sabkhas and young sabkhas where the old ones are developed at the western end of the elongated coastal ridge belt, which runs parallel to the coastline, whereas the young ones occur in the inter-ridge areas (Al-Hurban, 1996; Fig. 2). The inland sabkhas occur in the irregularly sloped desert land west of the coastal area, more than 10 km from the coastline. Due to the action of the prevailing northwesterly wind, both types of sabkhas are invaded by mobile sand. Therefore, their wet floors act as aerodynamic traps for drifting sand; they form thin sheets or sand drifts on the sabkhas' surfaces (Kleo et al., 2003; Misak et al., 2003; Al-Hurban, 2014; Albanai, 2021a).

Coastal sabkhas in Kuwait are either of two kinds of sabkha, located roughly 125 km apart. These are the southern carbonated sabkhas along the southern coastline of Kuwait—distributed 80km long and 50km wide and bounded by longitudes 47°45′80″ and 48°5′50″ East and latitudes 28°30′59″ and 29°15′00″ North—and the clastic coastal sabkhas, along both the northern coast of Kuwait and in Kuwait Bay. These two kinds differ in their physiography, hydrology, and deposit composition properties, all of which can be attributed to the differences in the geomorphology and source of sediments of each area. The deltaic sedimentation of the Shatt-Al-Arab (Tigris-Euphrates rivers) influences the northern clastic sabkhas, whereas it does not have such an influence on the southern carbonate sabkhas. These are more akin to the other sabkhas along the southern coastal line of the Arabian Gulf, e.g., in Abu Dhabi and Qatar (Evans et al., 1969; Purser, 1973; Butler et al., 1982). Other inland sabkhas are in the northern areas, but now, these are covered with some aeolian sediments (Al-Hurban, 2014).

The sabkhas in the country's south are one of the existing geomorphological features. These were formed relative to the pre-existing morphological features, such as depressions and gentle slopes, as a part of a land system starting from the shoreline and passing through barrier islands, dunes and

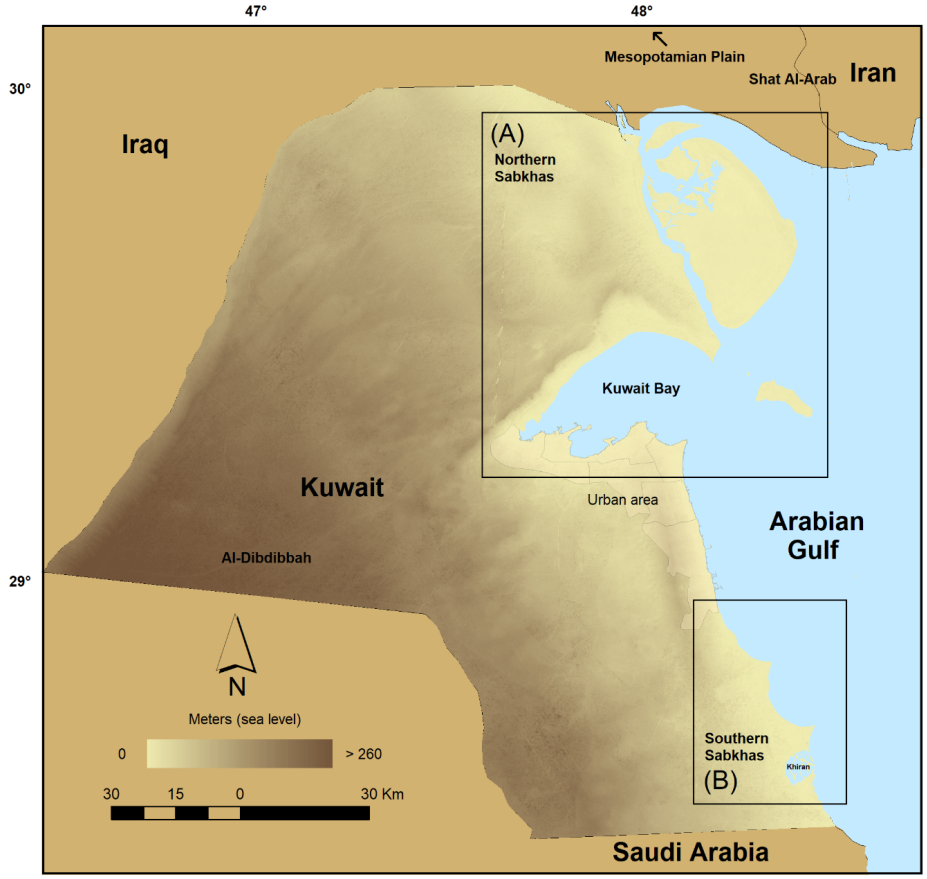

Figure 1. Study area. Sabkhas in Kuwait can be found in two areas: (A) Northern area and (B) Southern area

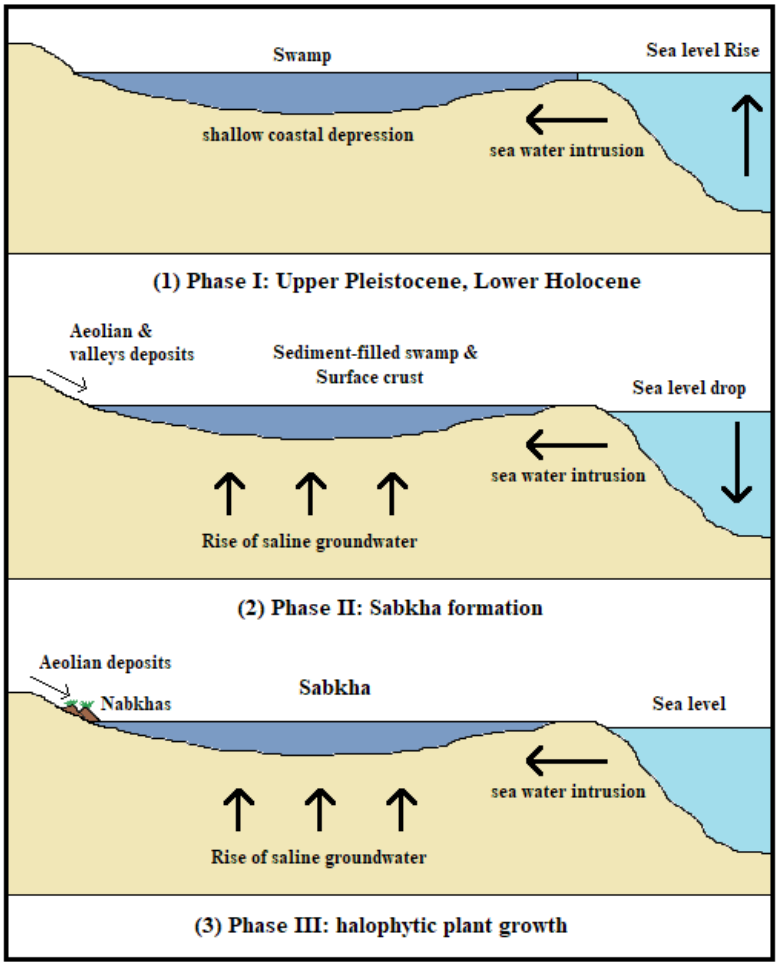

Figure 2. Sketch profiles showing stages of the development of sabkhas from the Upper Pleistocene and Lower Holocene to the current form (Al-Hurban, 1996 and Kleo, 2006)

lagoons up the truly terrestrial land systems, with extremely flat surfaces extending from 15-20km. They are among the different types of Quaternary surficial deposits covering a considerable portion of Kuwait's surface land. Some of the southern sabkhas are vegetated, while some lack vegetation. The prevailing northwesterly winds play a major role in subjecting the sabkhas to the encroachment of mobile sand, as the inland sabkhas are partially covered by active sand sheets of different thicknesses (Al-Hurban, 2014).

Sabkhas in the northern part of Kuwait are obviously different from the southern coastal sabkhas, as they are predominantly composed of clastic sediments; they have abundant siliciclastic and carbonate host sediments. The northern sabkhas are considered among the recognized coastal sedimentary facies. Northern sabkhas are geographically distributed along a narrow line aligned to the coastline of Kuwait, and often, they are adjoined to the high tide line. The distance between the coastline and the northern sabkhas varies from 0km (i.e., the sabkha is bordered directly by the coastline and parts of it are flooded by the high tide water, to about 6km along the northern coastline of Kuwait. Sabkhas of the northern coast cover an area of 75.3km^2 of the coast's land, i.e., almost 9.8% of the total sabkha areas in Kuwait; these are distributed over 52 recognized sabkhas, which vary in their size, shape, area, elevation, and distance from the coastline (Kleo, 2006; Al-Ajmi, 2008; Kleo & Al-Otibi, 2011).

2. Methods

Landsat satellite images have been used to study the sabkha distribution in Kuwait. Images of Landsat MSS 1985, ETM+ 2002, and Landsat Oli 2022 (Table 1) have been downloaded from the USGS open portal EarthExplorer (earthexplorer.usgs.gov). The periods were chosen before the Gulf War in 1990 and after the Gulf War at the beginning of the current century 2002, and at present. Four images from each year in the high tide time have been downloaded to cover the state of Kuwait, making a total of 12 images. The images' ROWs are 39 and 40 and the PATH are 165 and 166. All of the images have the following characteristics: Projection: UTM Zone 38N, Spheroid: WGS 84, Datum: WGS 84 (see Table 1). ENVI 5.3 software was used to preprocess and analyze the satellite images, using the following process: 1) Radiometric correction, in which the stored digital number (DN) in the image pixel is converted to brightness values (BV) to have one scale allows to compare pixels' values from different images (Albanai, 2019; Albanai, 2021b, 2022); 2) Atmospheric correction, which should be done to be able to compare satellite images of different dates and avoid atmosphere obstacles. The atmospheric correction is executed using the Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) tool, which is computed using the following algorithm:

$$L = \left(\frac{A\rho}{1-p_e s}\right) + \left(\frac{Bp_e}{1-p_e s}\right) + L_a \quad (1)$$

Where ρ is the pixel surface reflectance, ρe is an average surface reflectance for the pixel and a surrounding region, S is the spherical albedo of the atmosphere, La is the radiance backscattered by the atmosphere, A and B are coefficients that depend on atmospheric and geometric conditions, but not on surface conditions.

After the preprocessing, the images were classified using the IsoData classification method (depending on near and short infrared radiation); this is one of the unsupervised classification methods provided by ENVI 5.3 software. Using ground truthing points (GTPs), the classification of coastal features was evaluated for accuracy. The ground truthing points (n = 45) for the coastal southern and northern sabkhas were randomly picked from the field survey. The identified sabkhas and GTPs were matched using Cohen's Kappa coefficient in ArcGIS Pro. The projected shapefile of the ground truthing sites was imported into the software and superimposed on the secure map. For matching, the points were transferred to a raster. The spatial resolution used in this investigation called for the cell size for the categorized map and GTPs to be equivalent to 30 . Both were then over-layered to extract values and determine Cohen's Kappa coefficient. The model's outcome demonstrated acceptable accuracy with a Kappa coefficient of 0.81. Then, the raster layers extracted from the classification were transferred to ArcGIS Pro, where they were transferred to vectors to spatially analyze (extracting measurements) and export the final maps. The following equation is used to determine the kappa coefficient:

$$K = \frac{N\sum n_{ij} - N\sum n_{i+}n_{+j}}{N^2 - \sum n_{i-}n_{-j}} \quad (2)$$

Where is the value of the ground truthing point and is the value from the categorized map for the same place.

3. Results and Discussion

Sabkhas are considered as one of the major geomorphological features in the state of Kuwait. Geographically, they are located in either the northern or southern parts of the state of Kuwait's area. The current study finds that the sabkhas area is concentrated in the eastern part of the state of Kuwait alongside the Arabian Gulf. Table 1 shows that the estimated area of sabkhas has fallen from about 1,267 in 1985, to 1,231 in 2002, and around 1,019 in 2022. The findings display a decrease in the area covered by sabkhas—this equates to around 3% of the total area of 1985 in 2002, and 17% of the total area of 2002 decreased in 2022. In general, 20% of the total area of sabkhas decreased between 1985 and 2022. Table 2 shows the descriptive statistics of northern and southern sabkhas over Kuwait in 1985, 2002, and 2022. The table shows that the sabkhas area average over Kuwait is around 0.39 . The results show that the northern sabkhas of Kuwait cover a much larger area than the southern sabkhas in

Table 1. Satellite data description

Spatial resolution ()	Satellite (sensor)	Path & row	Acquisition date	No. of images
60	Landsat (MSS)	165,166/39,40	May 21st & 28th 1985	4
30	Landsat (ETM+)	165,166/39,40	January 20th & 27th 2002	4
30	Landsat8 (OLI)	165,166/39,40	March 31st&April 1st 2022	4

all of the years of study. The total area of northern sabkhas was 1,060, 1,106, and 967 in 1985, 2002, and 2022, respectively, the southern equivalent amounted to only 207, 124, and 52 at the same points in time. The results show that the rate of contraction in the southern sabkhas is much higher than that in the North. The rate of the southern sabkhas reached only 5% of the total sabkhas in Kuwait, while the northern sabkhas represented the remaining percentage (95%, Fig. 3).

Table 3. The descriptive statistics of northern (A) and southern (B) sabkhas over Kuwait in 1985, 2002, and 2022). The table shows that the northern and southern coastal sabkhas gradually receded in the three time periods, especially the southern coastal sabkhas in the recent period when backfilling and dredging operations were carried out to establish the marine city of Khairan.

The sabkhas of Bubyan Island occupy the largest percentage of the sabkhas of the northern coast of the State of Kuwait. In 1985, the sabkhas covered the entire surface of the island without a noticeable change in 2002, while in 2022, the sabkhas of the southern region of the island shrank significantly. As for the other northern sabkhas, they extend along the northern coast of the State of Kuwait and the northern and southwestern coasts of Kuwait Bay. It is noticeable that the sabkhas of the southwestern coast of Kuwait City shrank during the study years until they disappeared in 2022. As for the middle portion of the northern coast of the State of Kuwait, adjacent to Khor Al-Subiya, its sabkhas have significantly decreased. Figure 4 shows the geographical distribution of the northern coastal sabkhas in the State of Kuwait in 1985, 2002, and 2022.

As for the sabkhas of the southern coast, it is noticeable that they have shrunk significantly during the study years. The southern sabkhas were geographically distributed in the regions of Ras Al-Zour and Ras Julai'a in the year 1985. The southern sabkhas began to shrink significantly in 2002. In 2022, after the Al-Khairan project, the southern sabkhas shrunk to their minimum extent in the study period, reaching about 5% of Kuwait's marshes. Figure 5 depicts the geographical distribution of sabkhas on the southern coast of the State of Kuwait. Figure 6 also shows the monitoring of changes in the geographical distribution of sabkhas over the years of the study. It highlights some areas that have undergone a wide change, such as the northern coast next to Khor al-Subiya, the northern coast of Kuwait Bay, Doha Bay, Failaka Island, and the southern coast. Figure 7 shows sabkhas classes/areas over Kuwait in 2022, while Figure 8 shows an exemplary model of the morphology of coastal sabkhas in the State of Kuwait.

Table 2. The difference and change percentage of sabkhas in Kuwait in 1985, 2002, and 2022

Year	Area ()	difference	Change percentage
1985	1267.12	-	-
2002	1230.81	- 36.31	- 3%
2022	1018.67	-212.14	- 17%

	1985		2002		2022	
	A	B	A	B	A	B
Count	2716	281	2179	734	1232	430
Minimum	0.000001	0.013756	0.000001	0.000002	0.000008	0.002664
Maximum	117.8323	37.4148	447.7285	28.28029	339.5777	17.08017
Sum	1059.977	206.9985	1106.159	124.3795	966.8813	51.67167
Mean	0.390271	0.736649	0.507645	0.169454	0.784806	0.120167
SD	3.710869	3.677749	9.86905	1.242691	11.95777	0.853387

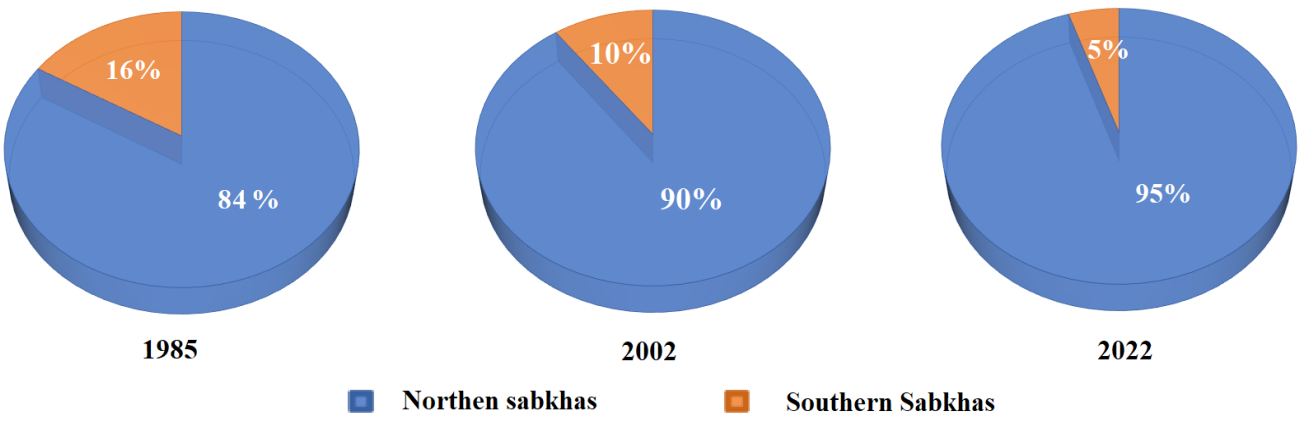

Figure 3. Comparison between northern and southern sabkhas over Kuwait in 1985, 2002 and 2022

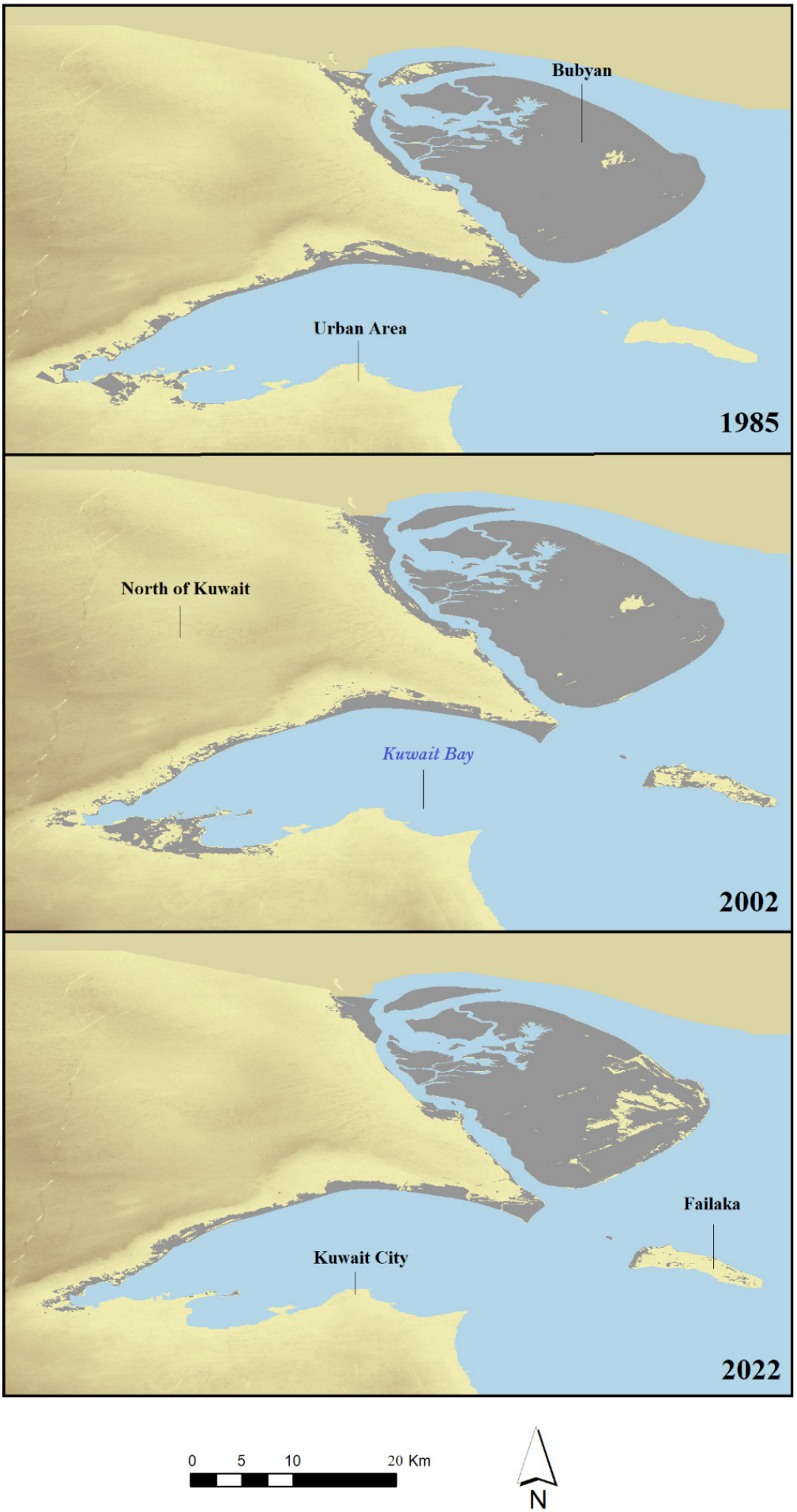

Figure 4. Geographical distribution of northern sabkhas over Kuwait in 1985, 2002 and 2022

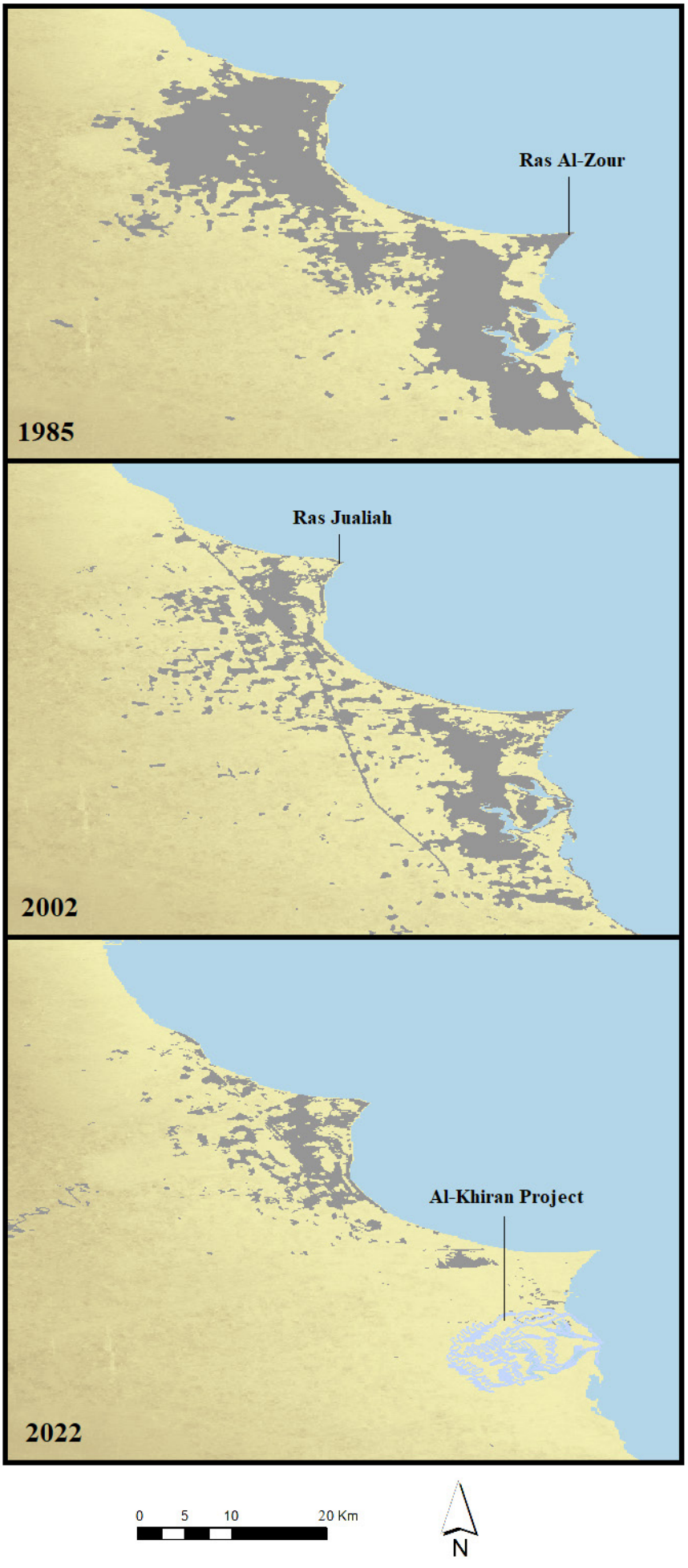

Figure 5. Geographical distribution of southern sabkhas over Kuwait in 1985, 2002 and 2022

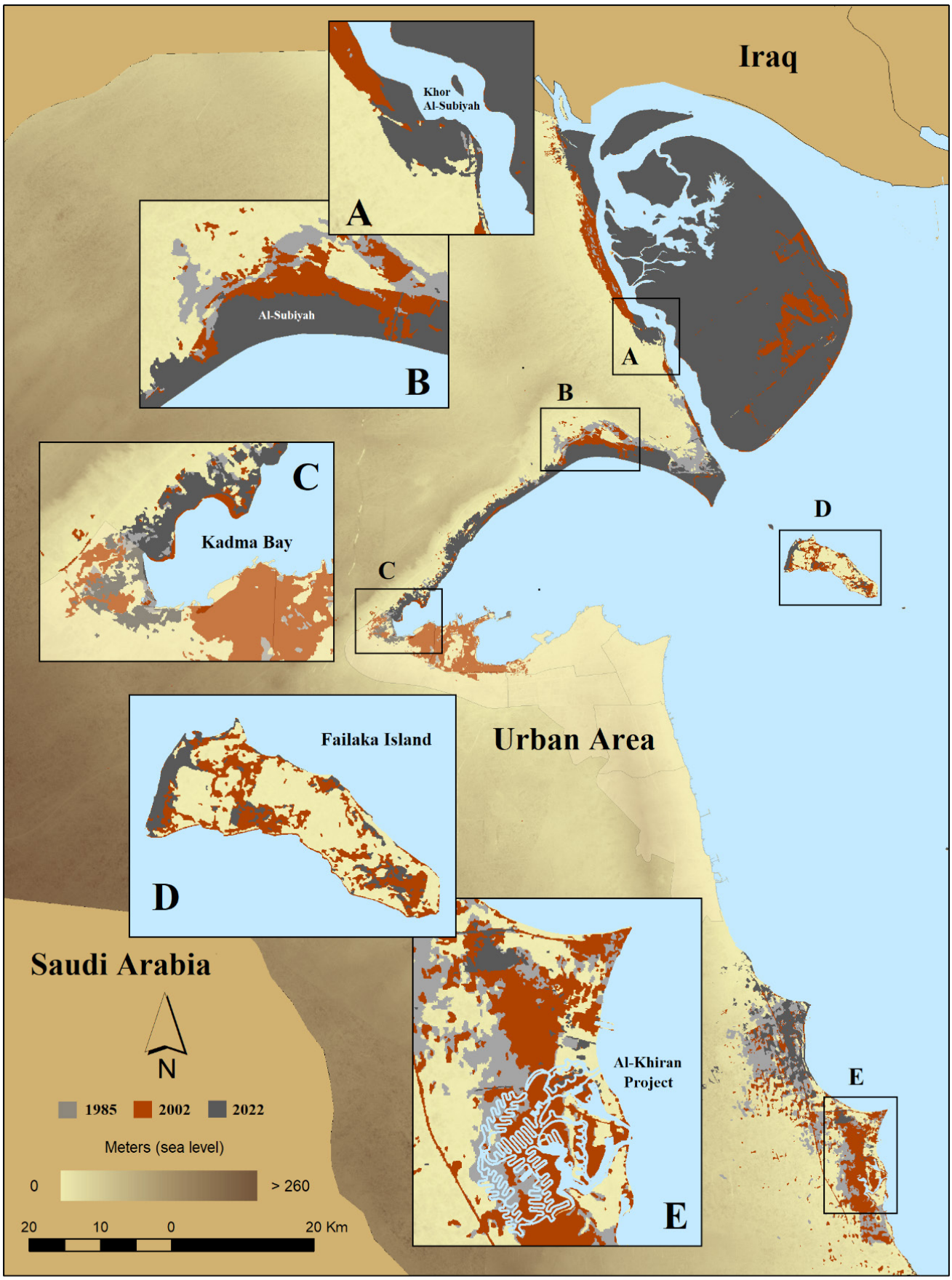

Figure 6. Change detection of northern and southern sabkhas over Kuwait in 1985, 2002 and 2022

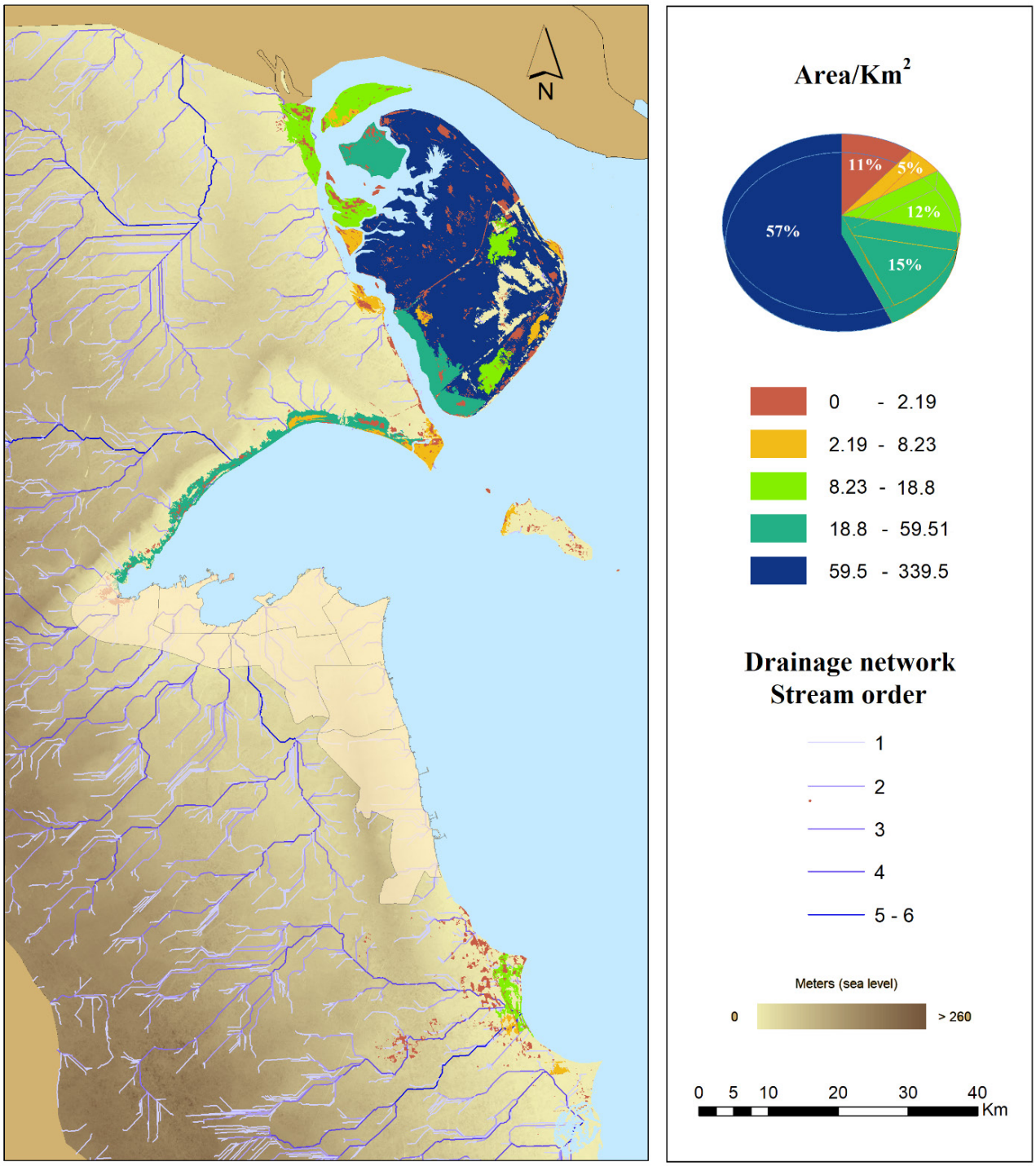

Figure 7. Sabkhas classes/area over Kuwait in 2022 and the stream order of the drainage network

The study found that the main reason for the decrease in the sabkha area is the expansion of urbanization. Figure 9 shows the urban growth in Kuwait City from the 1980s until the second decade of this century. The sabkhas located southwest of Kuwait Bay (at Doha Bay) have largely receded due to land reclamation and the construction of new areas such as Jaber Al-Ahmad City. Accordingly, the sabkhas in this region are almost entirely gone. These results are consistent with the results of Albanai (2021a, 2021d), where the study clarified the geographical distribution of the sabkhas in 2020 using a spectral index applied to satellite images; the sabkhas were found to be receding in the southwestern side of Kuwait Bay.

The results indicate that the sabkhas area in the southern part of the country is more affected than the northern part since the urban area expansion is more prevalent in the south than the North. Figure 10 shows the development of the construction works of the Al-Khairan project, which contributed significantly to the decline of the southern sabkhas of the State of Kuwait, where sandy soil was moved to reclaim the land for the implementation of the project.

The results are similar to Al-Delamah and Al-Hurban's (2019) study. The study used GIS and remote sensing to reveal the effect of anthropogenic activities, particularly urbanization and expansion, either for recreational or residential purposes, on the southern coastal sabkhas from over 30 years until 2016. They found that such activities resulted in the shrinkage of the sabkha area and subjected the area to sand drift and encroachment, leading to adverse impacts on the sabkhas' geomorphological and structural characteristics. However,

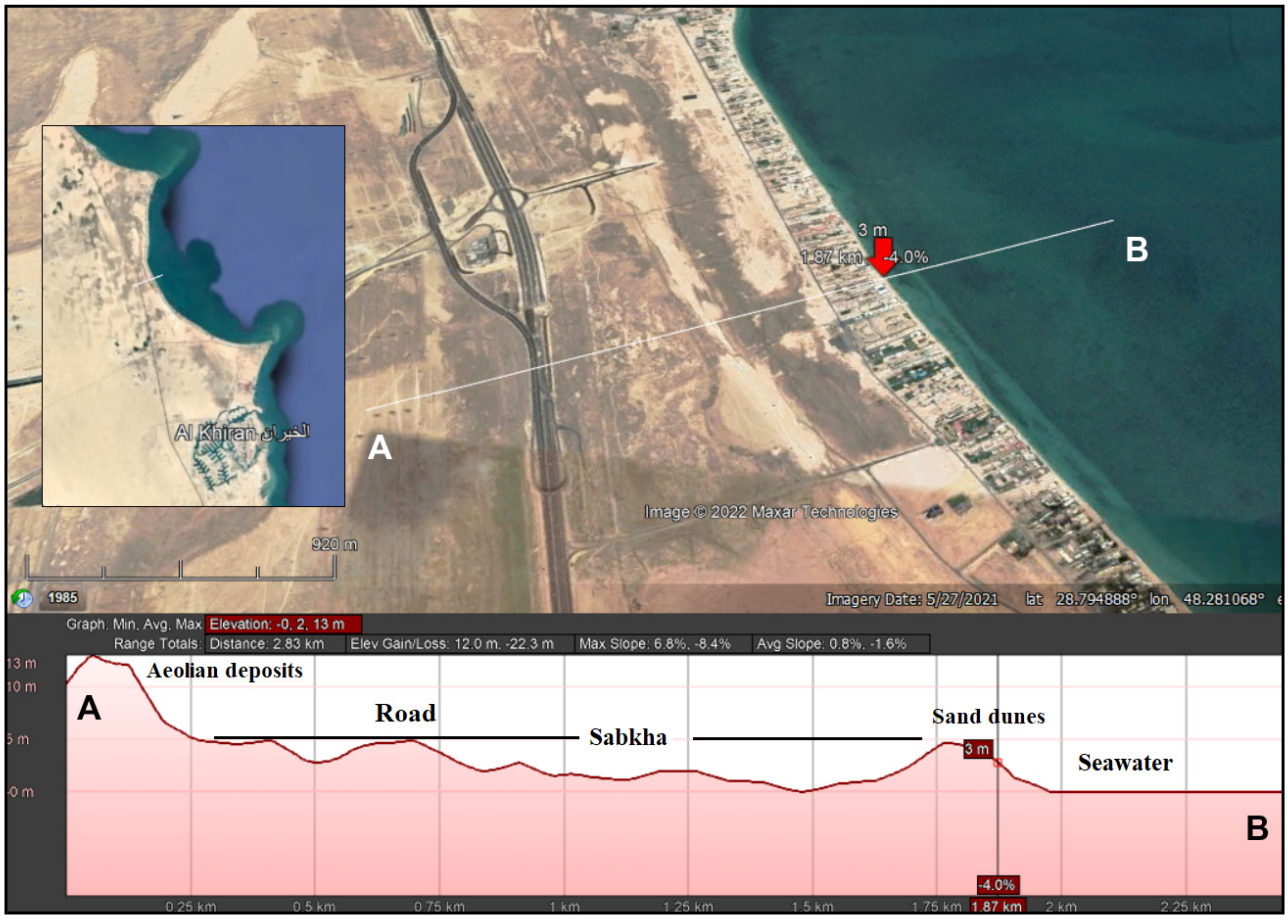

Figure 8. Elevation profile of one of the southern sabkhas in Kuwait 2022 shows its morphology and formation.

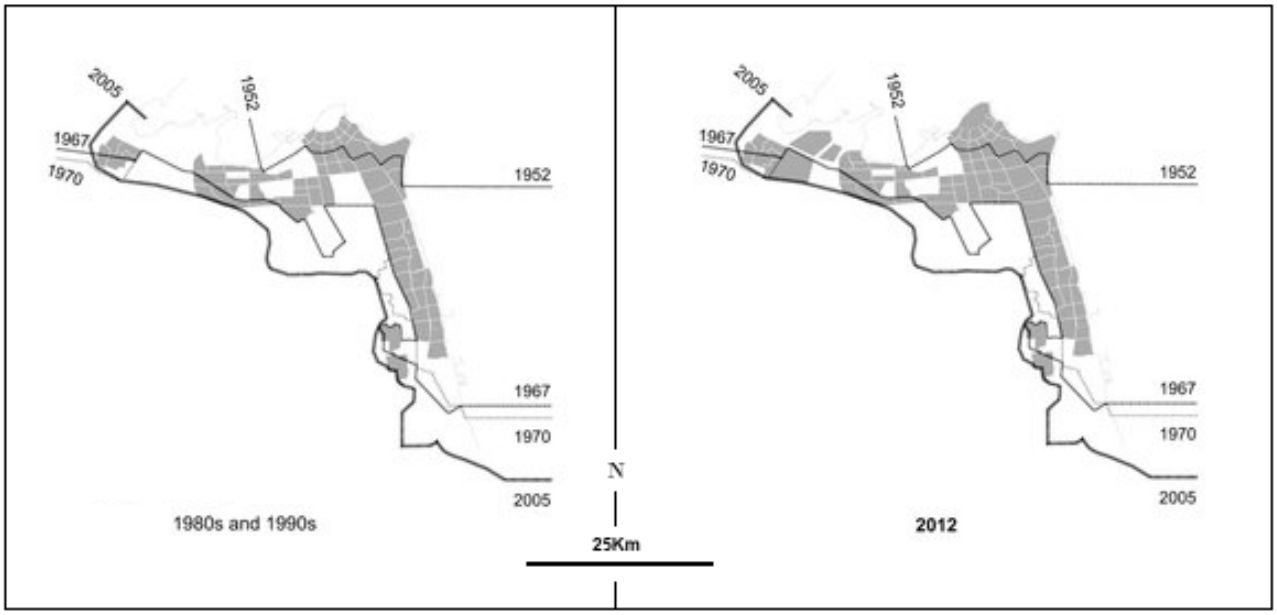

Figure 9. Urban growth in Kuwait from the 1980s to the second decade of this century. The impact of urban expansion on the shrinkage of the marshes in the west of Kuwait Bay is significant (After Al-Haroun, 2019)

the results of the geographical distribution of the southern and northern sabkhas in Kuwait in 2002 are different from the map published in the Kuwait National Atlas for 2001, whereas the study exaggerated and generalized the results, as the total area of marshes in the State of Kuwait was about 570 more than the current study. As for the study of Omar et al., (2002) and Al-Ajmi (2008), there are apparent differences in the total area of marshes. They estimated the total area of marshes with a smaller area of 460-510 than the current study. The results differed from other results about whether all the lands of Bubyan Island were considered sabkhas. Since information about the island, whether from the field or space, was much less than it is today about the uninhabited island.

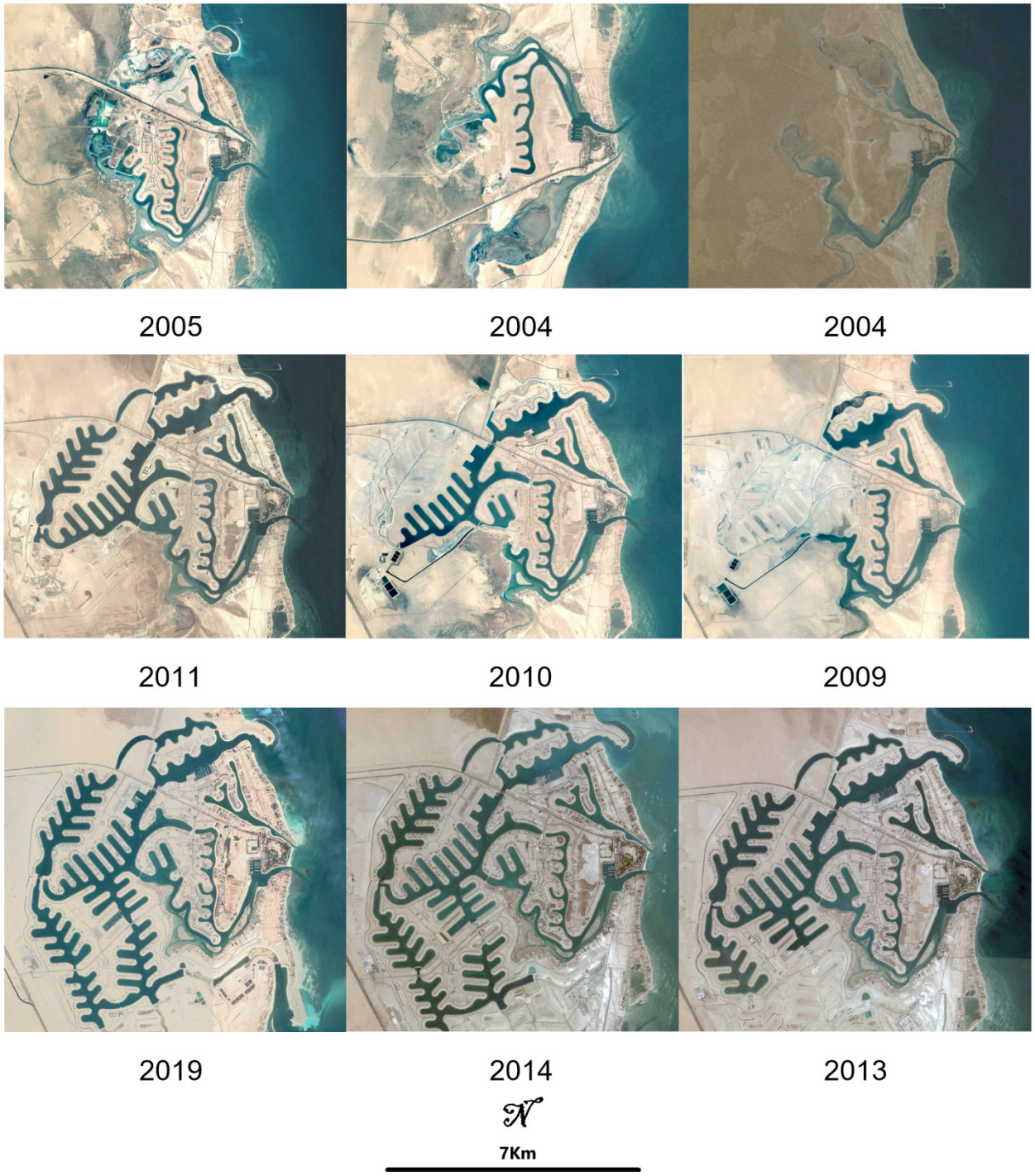

Figure 10. The development of the construction works of the Al-Khairan project from 2005 to 2019 (After Albanai, 2021a, 2021d)

The differences in the spatial resolution between the Landsat image taken in 1985 (60) and 2002 and 2022 (30) is one of the limitations of the approach used in this study. The standardization of the spatial resolution of the satellite images used in the study increases the accuracy of monitoring the temporal evolution of the sabkhas, and this was not available in this study, as the spatial resolution equal to 60 is the best that we found from the satellite images in the period preceding the Gulf War. The Kappa coefficient showed good accuracy for the applied classification of the northern and southern coastal sabkhas of the State of Kuwait, based on 45 monitored field points with equal and random locations from the south and North. Although the coefficient showed good monitoring accuracy, there were difficulties in accessing some of the interior areas in the islands of Warba and Bubiyan, for example, so monitoring more points will give better accuracy in future studies.

4. Conclusion

Using GIS and remote sensing data, this study detected the change in the geomorphological evolution of sabkhas. Landsat satellite images have been used to study the sabkha distribution and evolution over Kuwait's area. Selected images from Landsat MSS 1985 (before the Gulf War), Landsat ETM+ 2002 (after the Gulf War), and Landsat OLI 2022 (currently) have been classified using an IsoData unsupervised classification method that uses near and short infrared radiation. The classification has been validated using the Kappa coefficient where the value was 0.81. The results showed that the total sabkha area is facing degradation, mainly in the southern part

due to anthropogenic activities and expansion of the urban area, where they have changed geomorphologically to cope with socioeconomic demands. The area of the sabkhas shrank from 1,267 to 1,019 , representing a change of up to -17%. The results also showed that the southern sabkhas of Kuwait are declining significantly, from 207 in 1985 to as little as 52 in 2022. The current study presented a methodology to study the spatio-temporal evolution of sabkhas in dry areas around the world using spatial analysis, particularly in the context of the rapid urban development that the world is witnessing.

Acknowledgment

The authors would like to thank the USGS for providing Landsat images and Mr. Abdelaziz Adoum Mahamat for participating in satellite image processing.

References

Al-Ajmi, J. A. S. (2008). Sabkhas of the Northern Coast of Kuwait "A Geomorphological Study." Center For Research and Studies on Kuwait.

Al-Asfour, T. A., (1978). The marine terraces of the Bay of Kuwait. In: Brice, W.C. (Ed.), The environmental history of the near and middle east since the last ice age, pp. 249-260. Academic Press, Inc: London Ltd.

Albanai, J. A. (2019). A GIS Science Simulation for the Expected Sea Level Rise Scenarios on Failka Island in The State of Kuwait (1st ed.). Center For Research and Studies on Kuwait.

Albanai, J. A. (2021). Seawater quality atlas of the state of Kuwait (1st ed.). Center For Research and Studies on Kuwait.

Albanai, J. A.(2021a). Coastal Atlas of The State of Kuwait: Geomorphology from Space and Atmosphere. Kuwait Foundation For The Advancement Of Science.

Albanai, J. A. (2021b). Mapping Kuwait bathymetry using passive multispectral remote sensing. Kuwait Journal of Science, 48(4), 1–10. https://doi.org/10.48129/kjs.v48i4.8978

Albanai, J. A. (2021c). Seasonal Spatial and Temporal Distribution of Chlorophyll-a Concentration over Kuwait and the Arabian Gulf using Satellite and In-Situ data. https://doi.org/0.20944/preprints202107.0232.v1

Albanai, J. A. (2021d). Spatial Distribution of Kuwait Coastal Geomorphological Features using Remote Sensing Methods and GIS Solutions. Journal of Social Sciences, 49(3).

Albanai, J. A. (2021e). Trend and dynamic of the chlorophyll-a concentration over the Arabian Gulf A long-term study using MODIS data (2004-2019). Journal of Engineering Research.

Albanai, J. A. (2022). Accuracy assessment for Landsat 8 thermal bands in measuring sea surface temperature over Kuwait and North West Arabian Gulf. Kuwait Journal of Science, 49(1). https://doi.org/https://doi.org/10.48129/kjs.v49i1.9549

Albugami, S., Palmer, S., Meersmans, J., & Waine, T. (2018). Evaluating MODIS dust-detection indices over the Arabian Peninsula. Remote Sensing, 10(12). https://doi.org/10.3390/rs10121993

Al-Dalama, A. and Al-Hurban, A., (2019). The impact of urbanization expansion on the geomorphology of the southern coastal sabkhas from Ras Al-Jailiaha to Al-Khiran, South Kuwait. Journal of Geographic Information Systems, Vol. 11, No. 5: 609-632, Scientific Research Publishing, DOI: 10.4236/jgis.2019.115038

Al-Haroun, Y. A. M. (2019). The phenomenon of apartments in the Kuwaiti house. Journal of Engineering Research (Kuwait), 7(2), 1–24.

Al-Hurban, A., (1996). Recent surface sediments and landforms of the southern area of Kuwait. Ph.D. thesis, University of Birmingham, 317pp.

Al-Hurban, A. & Gharib, I., (2003). Morphological, sedimentological, and hydrogeochemical studies of sabkhas in southern Kuwait. Suppl. Geografia Fisica e. Dinamica Quaternaria Journal, VI, 13-18.

Al-Hurban, A., & Gharib, I., (2004). Geomorphological and Sedimentological characteristics of coastal & inland sabkhas, southern Kuwait. Journal of Arid Environment, Vol. 58, Issue 1, 59-85.

Al-Hurban, A., (2004). Sabkha. In Encyclopedia of Geomorphology. Ed. Goudie, A., Routledge Taylor & Francis Group, pp. 1156.

Al-Hurban, A., (2014). Effects of recent anthropogenic activities on the surface deposits of Kuwait. Arab J Geosci, 7, 665–691. https://doi.org/10.1007/s12517-013-0866-9

Al-Sarawi, M. A., Al-Zamel, A., and Al-Rifaiy, I., (1993). Late Pleistocene and Holocene sediments of the Khiran area (South Kuwait). Journal of University of Kuwait (Science) 20, 145-156.

Al-Sulaimi, J. S. and El-Rabaa, S. M., (1994). Morphological and morphostructural features of Kuwait. Geomorphology, 11, 151-167.

Al-Zamel, A. Z., (1983). Geology and oceanography of recent sediments of Jazirat Bubiyan ad Ras As-Sabiyah, Kuwait, Arabian Gulf. Unpublished Ph.D. Thesis. University of Sheffield, Sheffield, pp 273-274.

Al-Zamel, A. Z., and Al-Sarawi, M., (1998). Late quaternary sabkha sedimentation along Kathma Bay coast, Kuwait, Arabian Gulf. Arab Gulf Journal for Scientific Research, 16 (3), pp. 471-495.

Baird, T., Bristow, C. S., & Vermeesch, P. (2019). Measuring sand dune migration rates with COSI-Corr and Landsat: Opportunities and challenges. Remote Sensing, 11(20). https://doi.org/10.3390/rs11202423

Biere, P. R., (2000). Playa, playa lake, sabkha: Proposed definitions for old terms, Journal of Arid Environments 45: 1-7.

Butler, G. P., Harris, P. P., and Kendall, C. G. St. C., (1982). Recent evaprites from the Abu Dhabi coastal flats, in Depositional and diagenetic spectra of evaporites. A core workshop: SEPM Core Workshop 3, Calgary, p. 33-64.

Chavez Jr., P. S., MacKinnon, D., Reynolds, R. L., & Velasco, M. G. (2002). Monitoring dust storms and mapping landscape vulnerability to wind erosion using satellite and ground-based digital images. Arid Lands Newsletter. http://pubs.er.usgs.gov/publication/70209719

Evans, G., Schmidt, V., Bush, P. and Nelson, H., (1969). Stratigraphy and geologic history of the sabkha, Abu Dhabi, Persian Gulf. Sedimentology, 12: 145-149.

Folk, R. L., (1974). Petrology of Sedimentary Rocks. Hemphills Publishing Co., Austin, TX, USA, 92pp.

Folk, R. L. and Ward, W., (1957). Brazos river bar, a study in the significance of grain size parameters. Journal of Sedimantary Petrology 27, 3-27

Kassler, P., (1973). The structural and geomorphic evolution of the Persian Gulf. In: Purser, B. H. (Ed.), The Persian Gulf. Springer, New York, pp. 11-32.

Khalaf, F. I., Gahrib, I. M., And Al-Hashash, M. Z., (1984b). Types and characteristics of the recent surface deposits of Kuwait, Arabian Gulf. Journal of Arid Environments 7, 9-33.

Kinsman, D. J. J., (1969). Modes f formation, sedimentary association, and diagenetic features of shallow-water and supratidal evaporites. American Association of Petroleum Geologists Bulletin 53 (4), 830-840.

Kleo, A., Abu-Alaennen, H., Alhusaini, A., & Alasfour, T. (2003). Selected Studies in Geomorphology of Kuwait Lands. Center For Research and Studies on Kuwait.

Kleo, A., (2006). Sabkhas of the northern coast of Kuwait: Distribution, origin, classification, and properties. Kuwait Geographical Society, 318.

Kleo, A. and Al-Otibi, O., (2011). The Sustainable Development of Kuwaiti Sabkha. Digest of Middle East Studies, 20, 27-49. https://doi.org/10.1111/j.1949-3606.2011.00064.x

Livingstone, I., Wiggs, G. F. S., & Weaver, C. M. (2007). Geomorphology of desert sand dunes: A review of recent progress. Earth-Science Reviews, 80(3), 239–257. https://doi.org/https://doi.org/10.1016/j.earscirev.2006.09.004

Misak, R., Mahfoz, S., & Alasfour, T. (2003). Desert Environment in The State of Kuwait. Center For Research and Studies on Kuwait.

Neal, J. T., (1975). Playa surface features as indicators of environment. In Neal, J. T. (Ed.), Playa and Dried Lakes. pp. 363-380. Benchmark Papers in Geology, Halsted Press.

Omar, S., Missak, R. & Shahid, S. (2002). Sabkhat and Halophytes in Kuwait, Barth and Boer (eds.) Sabkhas Ecosystems. Kluwer Academy pub. Netherlands, pp. 71.81.

Picha, F., (197)8. Depositional and diagenetic history of Pleistocene and Holocene oolitic sediments and sabkhas in Kuwait, Persian Gulf. Sedimentology, 25: 427-450.

Purser, B. H., (1973). The Persian Gulf, Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea. Springer, Berlin, pp. V-VI.

Reda, A. A., (1986). A Reconnaissance study of a clastic coastal sabkha, Babrab area, northern Kuwait, Arabian Gulf. M. Sc. Thesis in geology, Kuwait University.

Safar M. I., (1985). Dust and duststorms in Kuwait, 1st edn. Directory of General of Civil Aviation Meteorology Department, Kuwait, p 212.

Saleh, A., Al-Ruwaih F., Reda, A., and Gunatilaka, A., (1999). A Reconnaissance study of a clastic coastal sabkha in northern Kuwait, Arabian Gulf. Journal of Arid Environments, 43, 1-19.

Warren, J. K., (1989). Evaporite Sedimentology. New Jersey: Prentice-Hall Inc. 285 pp.