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Integrating Remote Sensing and Field Survey to Map Shallow Water Benthic Habitat for the Kingdom of Bahrain

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Abstract: Identification and classification, as well as mapping of marine habitats, are of primary importance to plan management activities, especially in disturbed ecosystems like the ones in the marine areas of Bahrain. Remotely sensed Landsat-8 imagery coupled with field survey was used to identify, classify and map the benthic habitats in Bahrain marine area. The used geospatial techniques include advanced image processing procedures, which comprise of radiometric and atmospheric corrections, sun glint removal, water depth correction and image classification. Extensive ground-truthing analyses through in-situ field surveys by a team of scuba divers were conducted in October 2014 and June 2015 to inform and refine the classifications. The variables collected from this survey included physical and chemical characteristics of the water, habitat type, substrata, fauna and flora. A total of 176 field points were collected and utilized to perform an accurate assessment of the image classification. Initial habitat classification resulted in 20 habitat categories. However, due to the inability of the Landsat-8 sensors to accurately discriminate that level of classification, categories were merged into seven classes. The derived map shows that the benthic marine habitats of Bahrain consist of deep water (2,523 km^2), rock (1,738 km^2), sand (1,191 km^2), deep water/sand (1,006 km^2), algae (922 km^2), seagrass (591 km^2) and corals (275.50 km^2). Although limited by the spatial and spectral resolutions of Landsat 8, the used methods produced a suitable map of the benthic habitats within the marine area of Bahrain with an overall accuracy of 84.1%. The use of very high spatial resolution satellite imagery will most likely increase such accuracy significantly.

Key words: Landsat 8, marine, water column correction, scuba diving, GIS (Geographic Information System).

1. Introduction

1.1 Geological and Geomorphological Setting

Bahrain is composted of 40 low-lying islands that vary considerably in size and structure. The total area of the country is estimated at 767 km^2, including rocky coral atolls (Fasht). The total coastal length is more than 537 km while the marine area comprises of more than 9,200 km^2. The country is located in the southern part of the Arabian Gulf, between longitudes 50°16’ and 51°00’ easting and latitudes 25°33’ and 27°12’ northing (Fig. 1) [1].

The Arabian Gulf is a relatively shallow body of water with an average depth of 35 meters. Extreme temperatures and high salinity characterize its marine ecosystems [2]. Sea surface temperature averages 20 °C annually with temperatures range between 15.9 °C in the winter and 34.9 °C in the summer months [3]. Evaporation may rise to 3,000 mm per year.

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Hence, salinity may exceed 43 psu in the southern basin of the Gulf compared to an average oceanic salinity of 32-37 psu [4-6]. The relatively harsh conditions and the restricted exchange with the Indian Ocean as well as its 'young' age [7] have led to low species diversity [2]. Despite these limitations, the Gulf is considered rich in habitats and biota. Several ecosystems including seagrass beds, coral reefs, mangroves and mudflats contribute significantly to the productivity of marine resources in the Arabian Gulf [8, 9].

The marine ecosystem of Bahrain harbors the most valuable resources of the country, such as fish stocks, seagrass, algae, sand and seawater used in desalination plants [4, 10-12]. These ecosystems face continued deterioration and further declines in the quantity and quality of their habitats due in part to increase in natural and human pressures [13-17].

The intertidal zone along the shoreline of Bahrain consists of different habitats, including rocky substrates, sand, fine mud, salt marshes, mangroves and coral reefs [11]. These habitats harbor a wide variety of salt and desiccation resistance biota. Algae covers rocky shores and shallow subtidal zones of the coast, whereas seagrasses exist in sublittoral fringes (2-12 m depth) around Bahrain and Hawar Islands. Mangroves and lesser salt tolerant species are distributed along the Tubli Bay coastlines [11].

The current work is to identify, classify and map the extent and distribution of the benthic substrate of Bahrain marine area using geospatial techniques along with in-situ field measurements and bathymetric data.

1.2 Subtidal Habitat

Corals are one of the ecosystems in the marine area of Bahrain that provide a variety of services and hold social and cultural values [18]. They are adapted to high temperatures and salinity as well as sedimentation [19, 20]. However, extreme temperature, salinity and other physical factors restrict the growth and development of corals to patchy and fragmented habitats [7]. Four separate community types of corals, which are composed of 30 species, were reported to exist [21]. Dense coral cover (50-80%) typically occurred in shallow, well-flushed water, although such coral was also found in more saline areas to the southeast of Bahrain's main island where mono-specific stands of Porites exist [11]. The majority of coral habitats are shallow (< 2 m) with little coral coverage due to extreme temperatures associated with these shallow depths [11, 12].

Bahrain's reefs have undergone a significant decline in the last four decades as a result of large-scale coastal development and high sea surface temperature events. According to Sheppard, C., et al. [7], the coral reefs around Bahrain are currently unhealthy. Most reefs, which are located within 20-30 km of Bahrain Island, are in a state of ecological disorder as a result of beaching and marine related development activities. On the other hand, the most healthy and diverse coral reefs are located approximately 75 km to the north of the main island of Bahrain [22].

The beds of seagrass are one of the most productive ecosystems on earth with a considerable economic value of any marine ecosystem [23, 24]. Seagrass provides critical habitat for numerous species of fish and invertebrate and serves to stabilize sediments and protect shorelines [25, 26]. Seagrass beds only account for approximately 1% of primary production in the global ocean, yet they store about 12% of total oceanic carbon [27, 28]. Ecologically, seagrasses provide food sources and feeding grounds for several species in the Arabian Gulf [29, 30]. Economically, they serve as nursery grounds for some species important to the Arabian Gulf's commercial fisheries [31].

These seagrass species are tolerant of salinity and temperature extremes. According to Erftemeijer, P. L. and Shuail, D. A. [31], around 7,000 km^2 of seagrass habitats have been mapped in the Arabian Gulf to date. Dense growth of seagrass is usually associated with sandy and muddy substrates in near shore and shallow waters (less than 10 m).

In Bahrain, there are three species of seagrass: *Halodule uninervis*, *Halophila stipulacea* and *Halophila ovalis* [32, 33]. Vousden, D. H., et al. [21] and Basson, P. W., et al. [34] among others recorded more than 90 species of marine algae in the water around Bahrain, distributed among the main groups of algae, namely green, red and brown algae.

The status and boundaries of these habitats, especially the critical ones and their biota, are affected by natural and human pressures, which require periodic review and update. Hence, gaps exist in classifying and accurately defining these habitats. Furthermore, the status and trend of these creatures need to be assessed for better planning and management of marine biodiversity in Bahrain [35-37].

2. Benthic Habitats Mapping

2.1 General

Benthic habitats refer to anything associated with or occurring on the bottom of a body of deep water [38]. Habitat mapping can be considered as the spatial representation of described and classified habitat units [39]. Mapping the spatial characteristics and distribution of these habitats is of vital importance for environmental analysis and management of costal and marine environment [40-44]. Benthic habitat maps could be produced using different geospatial methods [40, 45-47]. Rapid development of remote sensing techniques has enhanced the capacity to characterize seafloor and associated habitats [44, 48-56].

However, the use of remote sensing in the marine environment presents challenges owing to a complex of physical interactions of absorption and scattering between water and light. Shorter wavelengths penetrate deepest into the water column and longer wavelengths are more rapidly absorbed and scattered. Therefore, the possible extent to use the remotely sensed imagery over the oceans relies more upon shorter wavelengths (e.g., blue and green bands). Optical remote sensing wavelengths typically penetrate clear waters to approximately 15-30 m. The extent of penetration of a spectral wavelength depends upon the optical properties of Mumby, P. J., et al. [57].

Remote sensing offers a useful supplement, both for selecting optimal sampling sites and mapping the distribution of seabed life [58, 59]. Since the late 1970s, scholars use Landsat satellite images to investigate conditions, spatial patterns and temporal changes of marine habitats around the world.

Many researchers investigated different aspects of the application of Landsat data in studies related to marine habitats. Satellite imagery was used to recognize benthic cover in the shallow water marine environment [60-63]. Some studies concentrated on seagrasses and coral reefs [63-69]. For that purpose, scholars utilized different approches and techniques using Landsat TM (Thematic Mapper) and ETM+ (The Enhanced Thematic Mapper Plus) [65, 67, 68, 70-73]. Others concentrated on coral reef ecosystem monitoring, change assessment and bleaching [71, 74-78].

Over the last few decades, significant, scale benthic habitat surveys based on remotely sensed Landsat imagery have been performed worldwide. In the tropical seas region, Call, K. A., et al. [66] tested the integration between in-situ spectral signatures, water column attenuation measurements, Landsat TM and GIS (Geographic Information System), to differentiate reef substrates in the area of Lee Stocking Island, Bahamas. Another study utilized an 18-year (1984-2002) time series of Landsats 5 and 7 to assess changes in eight coral reef sites in the Florida Keys National Marine [79]. Wabnitz, C. C., et al. [80] tested the feasibility of achieving Landsat-based large-scale seagrass mapping with limited ground-truth data in the wider Caribbean region. The resulting thematic maps were deemed adequate to regionally provide an adequate baseline for further large-scale conservation programs and research actions and enabled the reassessment of carrying capacity estimates for green turtles. Pu, R., et al. [81] evaluated the capabilities of

Landsat 5 imagery for assessing dynamics of seagrass abundance in response to multiple disturbances factors like a tropical storm along the central west Florida coast. Gullstrom, M., et al. [64] used Landsat data in Chwaka Bay, Zanzibar (Tanzania) to evaluate dynamicity of SAV (Submerged Aquatic Vegetation) dominated by seagrass. El-Askary, H., et al. [82] used Landsat satellite data in Hurghada at the Egyptian Red Sea coast to evaluate the state, distribution and change trends of coral reefs. Blakey, T., et al. [58] employed a supervised classification approach to investigate time-series mapping of seagrass in a subtropical lagoon, created from depth-invariant bands from Landsat 5 TM data.

Different remote sensing techniques have been used to monitor submerged habitats in inland lakes using Landsat data. For instance, Zhao, D., et al. [83] explored the habitats in Taihu Lake, China using the decision tree classification to study the distribution of aquatic vegetation. Luo, J., et al. [84] detected seasonal and interannual dynamics of aquatic plant types using HJ-CCD and Landsat data to assess eutrophication. In north America, Shuchman, R. A., et al. [85] verified SAVMA (Submerged Aquatic Vegetation Mapping Algorithm) to classify the bottom types of the Laurentian Great Lakes. In a later study, Brooks, C., et al. [86] used the same algorithm, i.e., SAVMA, with a series of multi-temporal Landsat data over the same site, to illustrate the prolific growth of submerged aquatic vegetation and evaluate related impacts of human, wildlife and economic conditions.

In the Indian Ocean, Hossain, M. S., et al. [87] mapped spatiotemporal changes in seagrass habitat and explored causes and processes of seagrass degradation using multi-date Landsat images in some estuaries and lagoons in Malaysia. In a similar study, Chen, P., et al. [88] used Landsat and SPOT (Satellite for Observation of Earth) satellite data for mapping the marine habitat in the Strait of Malacca. In the Mediterranean region, Bakran-Petricioli, T., et al. [89] reported the spatial distribution of the marine benthic habitats of the coasts of the Republic of Croatia. Villa, P., et al. [90] used in-situ data together with Landsat ETM+ to introduce two new vegetation indices for mapping aquatic plants: the NDAVI (Normalized Difference Aquatic Vegetation Index) and the WAVI (Water Adjusted Vegetation Index). The performance of these two indices in capturing information about aquatic vegetation features was assessed against pre-existing vegetation indices (e.g., NDVI and EVI). Benfield, S. L., et al. [91] showed how the integration between Landsat ETM+ and Quickbird was capable of distinguishing coarse and intermediate marine habitat classes.

Different studies have dealt with marine habitats in the Arabian Gulf using Landsat data. One of the earliest research in this region investigated Landsat data capabilities to explore the submerged Aeolian sand dunes of the intertidal area [92]. Another early study dealt with the monitoring of the effects of coastal development in Bahrain on the coastal marine habitats and resources using a visual interpretation of Landsat 5 TM data to map the intertidal and subtidal habitats [12]. The subtidal coastal habitats in the western Arabian Gulf were investigated using first and second bands data of Landsat TM to enhance the bottom type variations [73]. Some studies dealt mainly with the coral reefs habitat in the Arabian Gulf. Moradi, M. [93] studied the distribution of coral reefs around Khark and Kharkoo Islands, northwest of the Arabian Gulf. In 2006, the first map using Landsat data of coral habitats in the southeastern Arabian Gulf was produced. The map highlighted some of the most extensive and biologically significant corals in the marine areas of the United Arab Emirate of Abu Dhabi and Qatar [94].

Recent studies concentrated on using sensors with high spatial resolution such as IKONOS, Quickbird, and WorldView-2 in shallow water up to 30 m depth mainly to classify and map coral reef communities. This high spatial resolution helps to improve the ability to discriminate the benthos into broad habitat classes

[42, 95]. The combined use of multispectral imagery and bathymetry data also assisted in increasing the accuracy of benthic habitat mapping [57].

2.2 Bahrain Previous Habitat Mapping Studies

Several previous studies identified and mapped the benthic habitats of Bahrain. The first detailed study of the marine environment around Bahrain was achieved in 1983 [96], where six offshore and intertidal sites were surveyed three times on a seasonal basis during one year. Along with other results, the study confirmed the existence of the three seagrass species: *Halodule uninervis*, *Halophila ovalis* and *Halophila stipulacea*. Barratt, L. and Ormond, R. [97] evaluated the environmental impacts of the potential effects of a large-scale reclamation on "Fasht Al Adhm", the largest coral reef in the Bahrain marine area. It constituted a rapid but nonetheless very useful survey of the ecology and oceanography of the reef structure and surrounding habitats. Using Landsat 5 data, Vousden, D. H. P. [12] identified twelve habitat types and produced the first benthic habitats map for Bahrain's marine area. In 1995, Vousden, D. H. P. [12] conducted another advanced study for Bahrain marine habitats concentrated on some physical factors, which may affect the distribution of those habitat types. Remote sensing data is used to map the distribution of habitat types, in contrast to ground-truth data gathered by aerial photography and in-situ methods. The study surveyed over 250 intertidal and subtidal study sites and the final map demonstrated twelve habitat types with an accuracy of more than 87%. Furthermore, the study produced a set of sensitivity maps to identify areas of commercial and scientific importance, and to allocate areas, which need to conservation, protection and management. In 2006, the BCSR (Bahrain Center for Studies and Research) unleashed a comprehensive research project, called MARGIS II [98], after an early project MARGIS (Marine Geographic Information System) achieved in 1998-1999. The MARGIS II [98] project aimed to develop and operate an online marine environmental GIS to support decision-making management of the marine environment, awareness and for educational purposes. The project carried out a comprehensive field survey of over 735 sampling sites (294 subtidal and 441 intertidal). The team of investigators studied and documented habitats. They used ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) remote sensing data in that study due in part to their bandwidth and higher spatial resolution, which are optimized for coastal applications to produce a habitat oriented classification map that portrayed 16 intertidal and subtidal habitats' classes.

3. Data and Methodology

3.1 Data Sets

Landsat 8-OLI imagery, ground truth/survey data and ancillary information consisting of previous habitat maps and bathymetric data for Bahrain were used to produce an updated benthic habitat map for the Bahrain marine area.

3.1.1 Satellite Data

The newly available Landsat-8 data used were acquired in June 2015. The two sensors on board Landsat 8 provide 11 spectral bands with a spatial resolution of 30 m for the visible, NIR (Near Infrared) and SWIR (Shortwave Infrared) wavelengths, 100 m for the TIR (Thermal Infrared) bands, and 15 m for the panchromatic band. The first five spectral bands (coastal, blue, green, red and NIR) were used to carry out the image classification process and generate the benthic habitat map.

3.1.2 Survey: Ground Truthing Data

NOAA (National Oceanic and Atmospheric Administration) RAM (Rapid Assessment Method) was used to survey the investigated area, which was divided into a grid with 260 blocks of 5 × 5 km covering an area of 8,200 km^2. The four scuba divers took part in the survey followed the "stratified random sampling" protocol for observing and collecting the data. At each point/sample, the scuba divers surveyed a circular area with a diameter of 20 × 20 m. For each sample, a camera was used to capture photos and video. A total of 176 field points were collected and utilized to perform an accuracy assessment of the composite image classification (Fig. 1).

3.1.3 Bathymetric Data

The Bathymetric data used in this study composed of 24,691 depth points provided by HSD (Hydrographic Survey Directorate), Bahrain. HSD is the responsible directorate at the SLRB (Survey and Land Registration Bureau) in Bahrain to collect and update the bathymetry (depth) data every two years. They used multi and single beam devices to obtain the soundings (depth) data, taking into consideration the water levels,

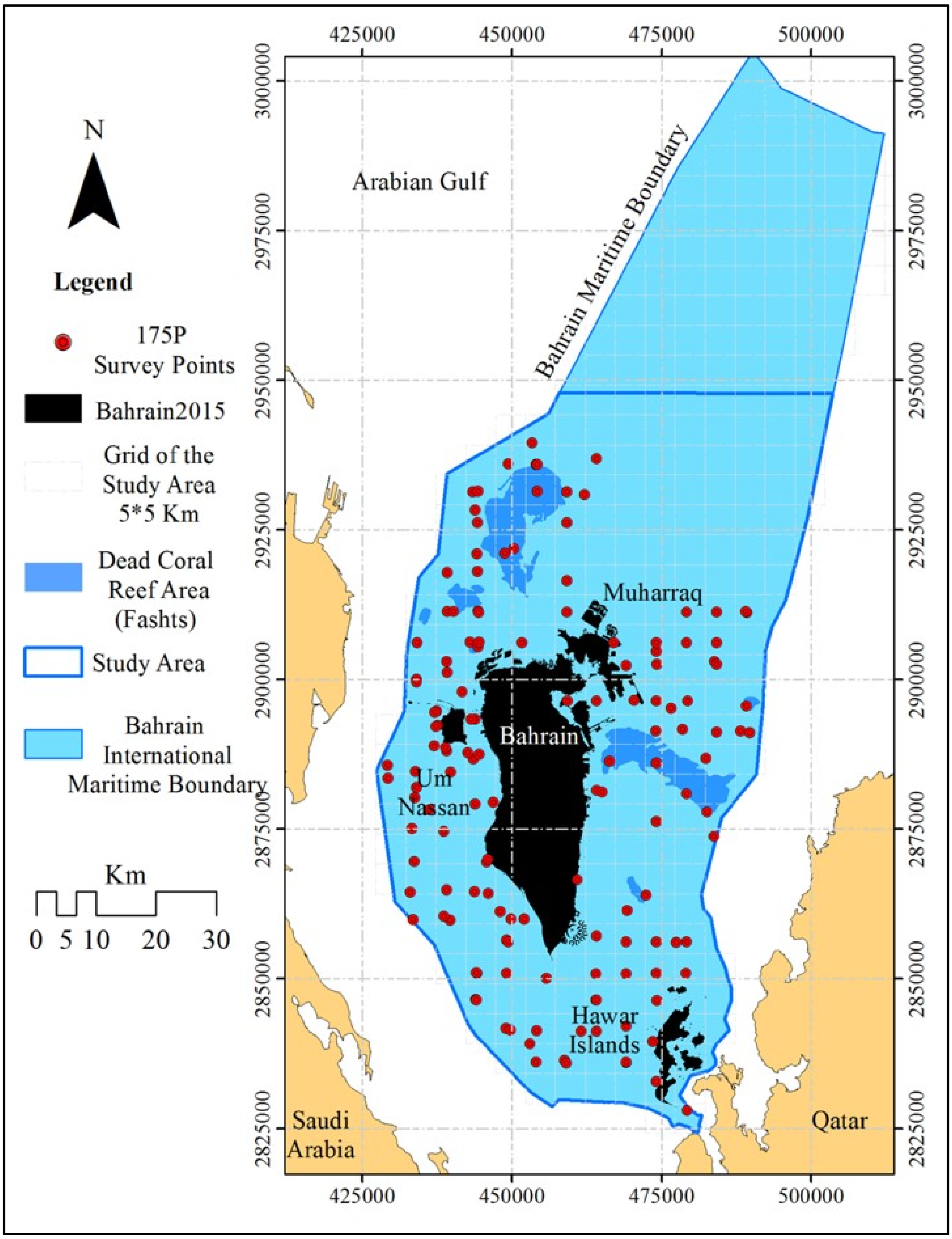

Fig. 1 Map showing the study area and locations of the survey points.

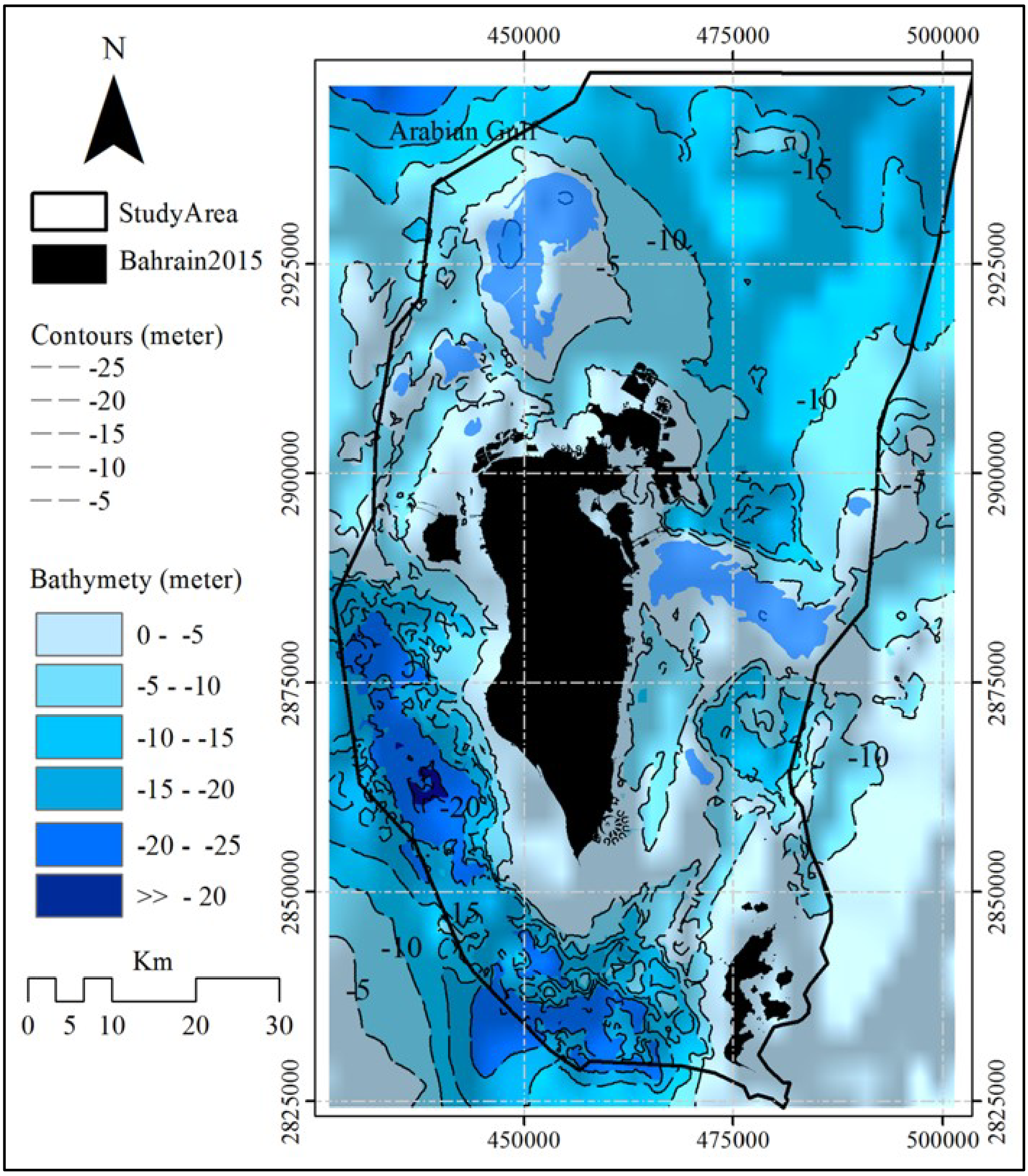

Fig. 2 The digital elevation model of the marine study area based on single beam data with a resolution of 30 m.

water temperature and salinity. They use HYPACK (Hydrographic Survey Software) to correct the soundings data and remove outliers. This study used the last produced bathymetric (depth/sound) as an XYZ data. These data converted to a GIS vector layer that consisted of a large set of points. These points were interpolated using kriging in ArcGIS to generate a continuous bathymetric map for Bahrain marine area (Fig. 2).

3.1.4 Marine Habitat Classification Scheme

The classification scheme adopted in this study was based on existing classification systems for coastal and marine ecosystems in Bahrain [11, 12, 98]. Furthermore, previous studies of coral reef and marine studies were reviewed [96, 97] and the photos and videos were collected from 176 fields surveyed points.

Habitats were defined using two attributes: geomorphological structure and benthic cover. These characteristics were chosen because they exert a combined influence on the spectra recorded by a remote sensing sensor [99] and can be interpreted realistically within a remotely sensed image. A habitat classification scheme allows for the grouping of habitat types based on common ecological or geomorphological characteristics [100]. The classification system was organized into three levels that merge the geomorphological and benthic classes to describe the habitat. Geomorphological categories were based on those used in Holthus, P. F. and Maragos, J. E. [101] and arranged into a two-tier hierarchy. The groups were included on a practical basis to avoid redundancy of terms. The natural habitat classes were initially derived from hierarchical cluster analysis of biological data obtained in the Turks and Caicos Islands in the Caribbean.

This study adapted hierarchical classification scheme to define and delineate habitats employing multispectral satellite imagery [100]. Considering the image used in the study was multispectral in nature (Landsat 8), the habitats were classified according to the first level benthic habitat classification scheme by Mumby, P. J. and Harborne, A. R. [100]. The first tier benthic habitats divide the marine habitats to four classes. However, in this study, considering the fundamental knowledge of the survey area, the previous studies results, the survey field work and the distinct characteristics in the image, five main classes were identified from the image. These five classes are coral, seagrass, algae, sand and rock. Finally, the deepwater and sand-deep water were added to these classes to create the final benthic habitats classification map.

3.2 Methodology

3 .2.1 Atmospheric Radiometric Correction

Atmospheric correction is a required step for the interpretation of satellite images so that biophysical parameters can be obtained from water bodies [102]. In this step, the DNs (Digital Numbers) stored in the original image are converted into biophysical variables of standard significance (reflectance). The algorithm for radiometric correction to TOA (Top of Atmosphere Reflectance) values was carried out for the Landsat 8, acquired in June 2015. The TOA spectral radiance is extracted using the band-specific multiplicative rescaling factor (M_L), the calibrated standard product pixel values (Q_{cal}) and the band-specific additive rescaling factor (A_L) as shown in Eq. (1).

$$L_\lambda = M_L * Q_{cal} + A_L \quad (1)$$

3.2.2 Sun Glint Removal

Sun glint, the specular reflection of light from water surfaces, is a serious confounding factor for remote sensing of water column properties and benthos [103, 104]. Sun glint, which is a function of sea surface state, sun position and viewing angle limit the accuracy of sensed data from water bodies and thus require correction [104, 105].

Various techniques of glint correction have been proposed [62, 104-109]. In these methods, the main concept is based on the subtraction the glint contribution to the radiance reaching the sensor from the received signal [104, 106]. One method proposed by Hochberg, E. J., et al. [62] relies on two assumptions: first, brightness in the NIR band is composed only of sun glint and a spatially constant ‘ambient’ NIR component; second, the amount of sun glint in the visible bands is linearly related to the brightness in the NIR band. This method assumes that the water absorbs the NIR. Therefore, any recorded NIR upward radiance above a water body should contain the reflected sun light as a function of geometry independent of wavelength. This method models a constant ‘ambient’ NIR brightness level that is removed from all pixels. This deglint method, however, has some limitations, as it is very sensitive to outlier pixels and it is presented in a mathematically complex manner [105]. Hedley, J. D., et al. [105] proposed a simpler method that addresses the concerns with the method of Hochberg, J. D., et al. [62] and made it more robust by using one or more samples of image pixels. This modified method establishes linear relationships between NIR and visible bands using linear regression based on the subsample of the image pixels. This approach is based on scaling the correlation between the NIR signal and sun glint on one or several areas of the image. These areas are chosen to include a range of pixel glint levels, but an assumed consistent underlying brightness and very shallow water-leaving radiance in the NIR (deep-water areas). For each band, a linear regression is made between the NIR radiance and the band radiance using all the pixels in the selected areas. The linear regression runs between the sample pixels of every visible band (y-axis) and the corresponding pixels of NIR band (x-axis).

The first four bands of LS-8 (coastal/aerosol, 0.433-0.453 µm; blue, 0.450-0.515 µm; green, 0.525-0.600 µm; and red, 0.630-0.680 µm), were used to identify and classify the benthic habitat in shallow water of the study area. Bands 1 and 2 can penetrate clear, sunlit water to about 30 meters and can identify features in shallow water, depending on the type and color of the features and the water depth [110]. Band 5 (NIR, 0.845-0.885 µm) is used to characterize the spatial distribution of relative glint intensity assuming that this band exhibits maximum absorption and minimal water leaving radiance over clear waters.

The sun glint removal was performed in the first five spectral bands of the corrected LS-8 scene using the formula developed by Hedley, J. D., et al. [105]. All pixels in the LS-8 image were deglinted in a single band (R_i') (Fig. 3), as illustrated in Eq. (2).

$$R_i' = R_i - b_i(R_{NIR} - Min_{NIR}) \quad (2)$$

3.2.3 Water Depth Correction

When deriving quantitative information about bottom habitats, water depth significantly affects the remotely sensed measurement. When light penetrates water, its intensity declines exponentially as depth increases. This process, also known also as attenuation, exerts a profound effect on remotely sensed data of

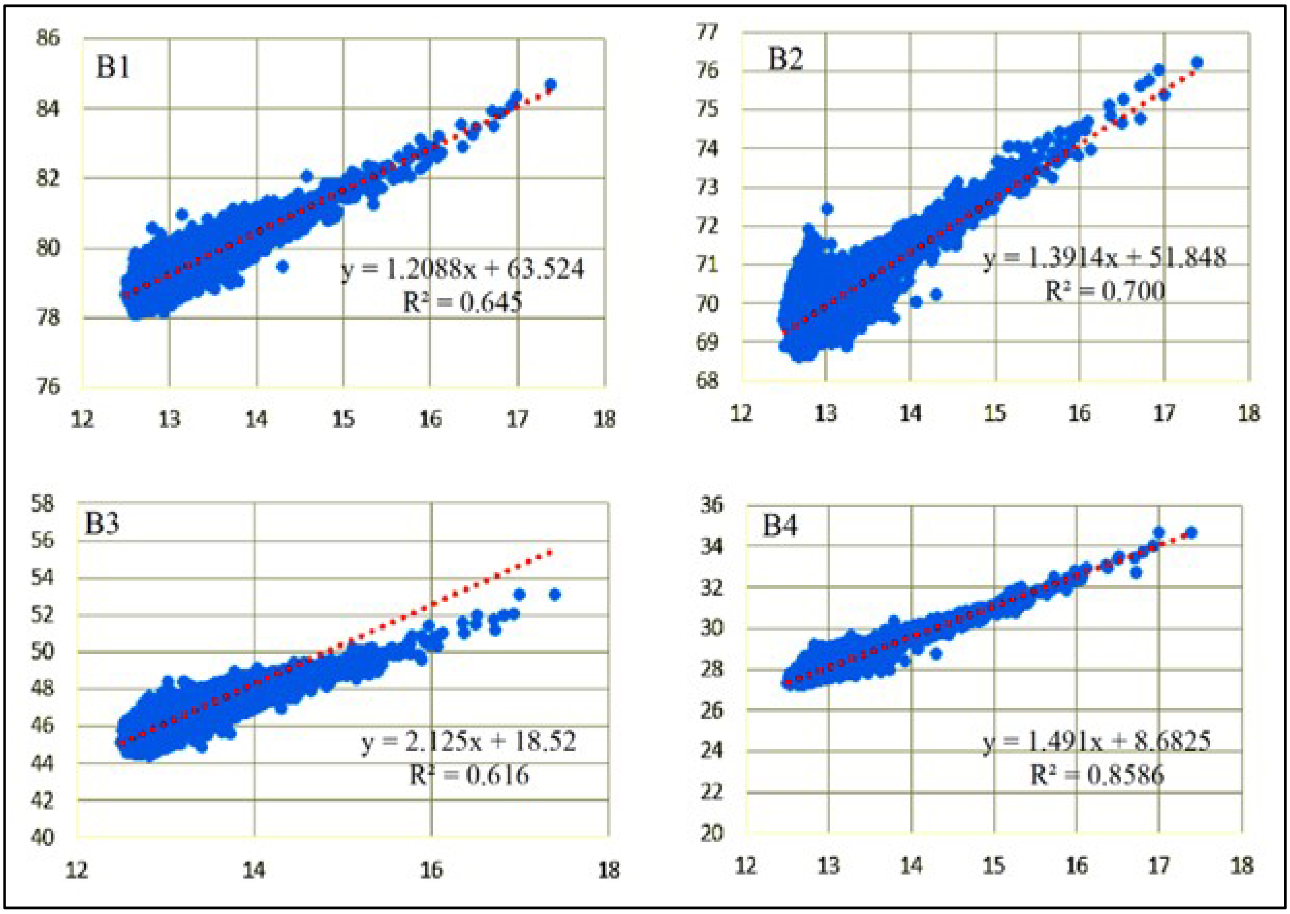

Fig. 3 4 bi-plots of pixels with different sunglint intensity between visible bands and NIR band.

aquatic environments. Lyzenga, D. R. [107, 109] proposed a widely used approach, which is a simple image-based approach to correct for the water depth effect and enable the mapping of bottom features accurately. Rather than predicting the reflectance of the seabed, which can be difficult, Lyzenga, D. R.'s method produces a "depth-invariant bottom index" from each pair of spectral bands to compensate for the effect of variable depth when mapping underwater features. Recently Kanno, A., et al. [111] offered a modification of the Lyzenga, D. R.'s approach to correct for depth in a shallow-water reflectance. This method includes the up-welling (L) and downwelling radiance (E) of the water surface to measure the water depth (h) from the bottom reflectance values (R_b) using an attenuation coefficient (k) as illustrated in Eqs. (3), (4) and (5).

$$R = R_\infty + (R_b - R_\infty) * e^{-k*h} \quad (3)$$

$$R \equiv \pi * L/E \quad (4)$$

$$\log[R - R_\infty] = \log[R_b - R_\infty] - k * h \quad (5)$$

Here the $\log[R - R_\infty]$ can be derived by using the average R of the deep-water pixels as a substitute for R_∞ and $\log[R_b - R_\infty]$ depends on R_b but not on h [111].

3.2.4 Benthic Habitat Classification

The number of classes that remote sensing distinguishes often depends on many factors, including the platform (satellite, airborne), type of sensor (spectral, spatial and temporal resolution), atmospheric clarity, surface roughness, water clarity and water depth [57]. Landsat series images can be utilized to perform underwater [58, 112-114]. The multispectral LS-8 images have the ability to map benthic habitat up to the second level of detail at benthic habitat classification scheme [100]. The main aim of the image classification was to separate different feature types of the sea bottom into sets of spectral classes that represent the main benthic habitat of the study area. Seven main habitat categories were identified and labeled as: algae (a), seagrass (b), coral area (c), sand (d), rock (e), deep water (> 10 m) and deep water/sand (Fig. 4).

The k-means unsupervised classification method was used in the present analysis to group all pixels in LS-8 based on their spectral similarities. Pixels having similar spectral characteristics were grouped together in a distinct cluster. Before classification, a binary mask layer was created and applied to the NIR channel (band-5) to segregate sea from land. The selection of infrared band depends mainly on the high absorption of water in this wavelength window. It is considered to be the most useful spectral region for the discrimination between land and water. All the land area and coastal habitat such as mangroves that stand above seawater were excluded from the classification process. The availability of the ancillary data (single beam data) of the bathymetry of the study area used to categorize the sand in the study area into two classes: the deep water (0-10 m) and the deep water/sand (> 10 m) (Fig. 5).

The accuracy of the classification map was assessed by comparing the derived benthic habitats classes to the 176 ground truth points collected in the field. The field control points distributed between benthic habitat classes were 37 for algae, 25 for seagrass, 6 for corals, 48 for sand, 21 for rock, 8 for deep water/sand and 31 for deep water. The overall accuracy in ENVI (Environment for Visualizing Images) was determined by dividing the total correctly classified classes in the error matrix by the total number of samples on the ground.

4. Results and Discussion

The derived classification map of the benthic habitats (Fig. 6) provided a satisfactory result with an overall accuracy of 84.1% and a Kappa coefficient of 0.81. The classification map revealed that there are seven dominant benthic habitat types in the area under investigation. The presence of these benthic habitats is confirmed by field survey (including GPS, photos and video data collected during the study time, as well as through knowledge that local experts and scuba divers provided).

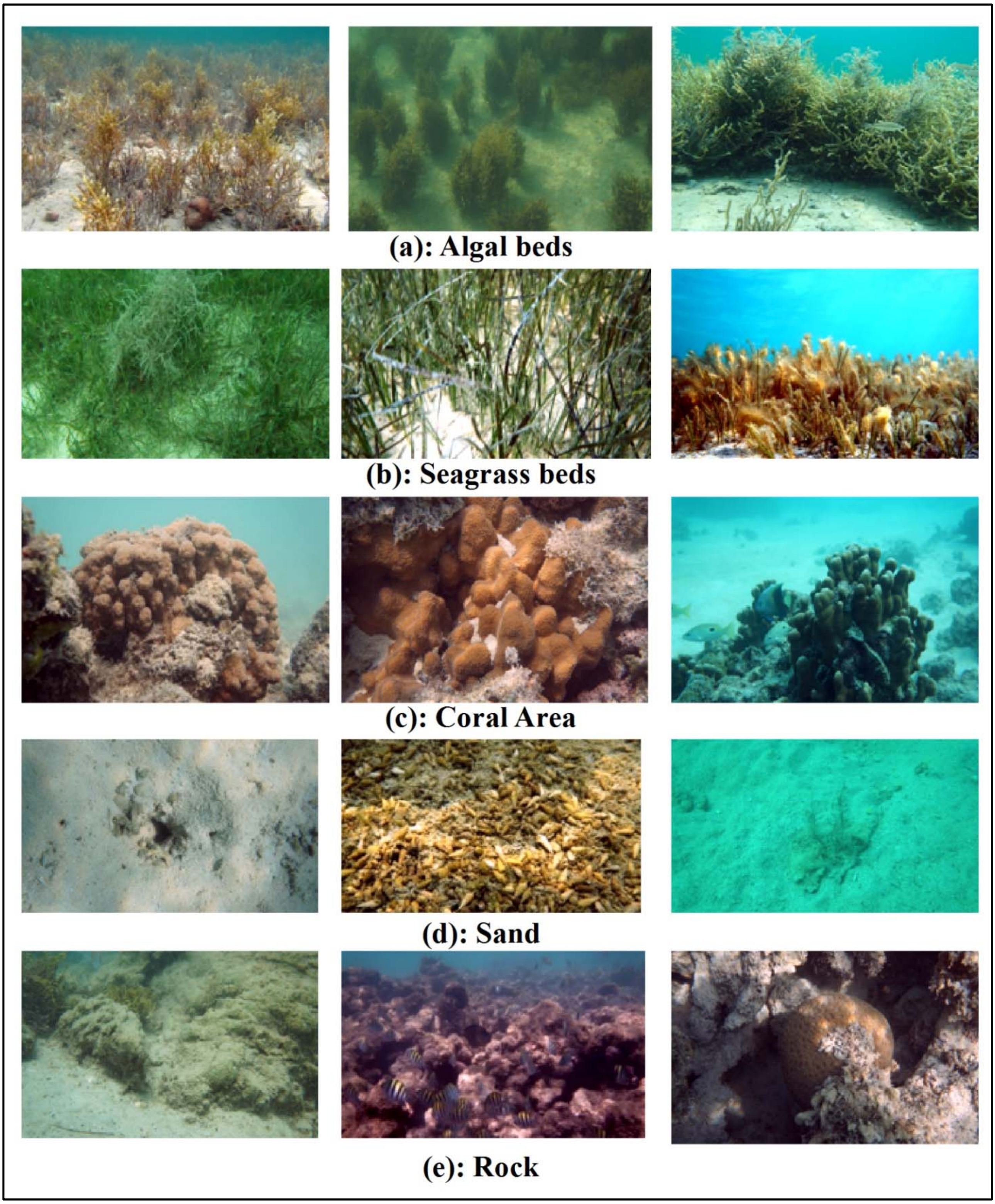

Fig. 4 Classes defined for benthic habitat classification in the marine study area prepared for the Landsat 8-OLI 4 first bands combination: (a) algal beds, (b) seagrass beds, (c) coral reef area, (d) sand and (e) rock.

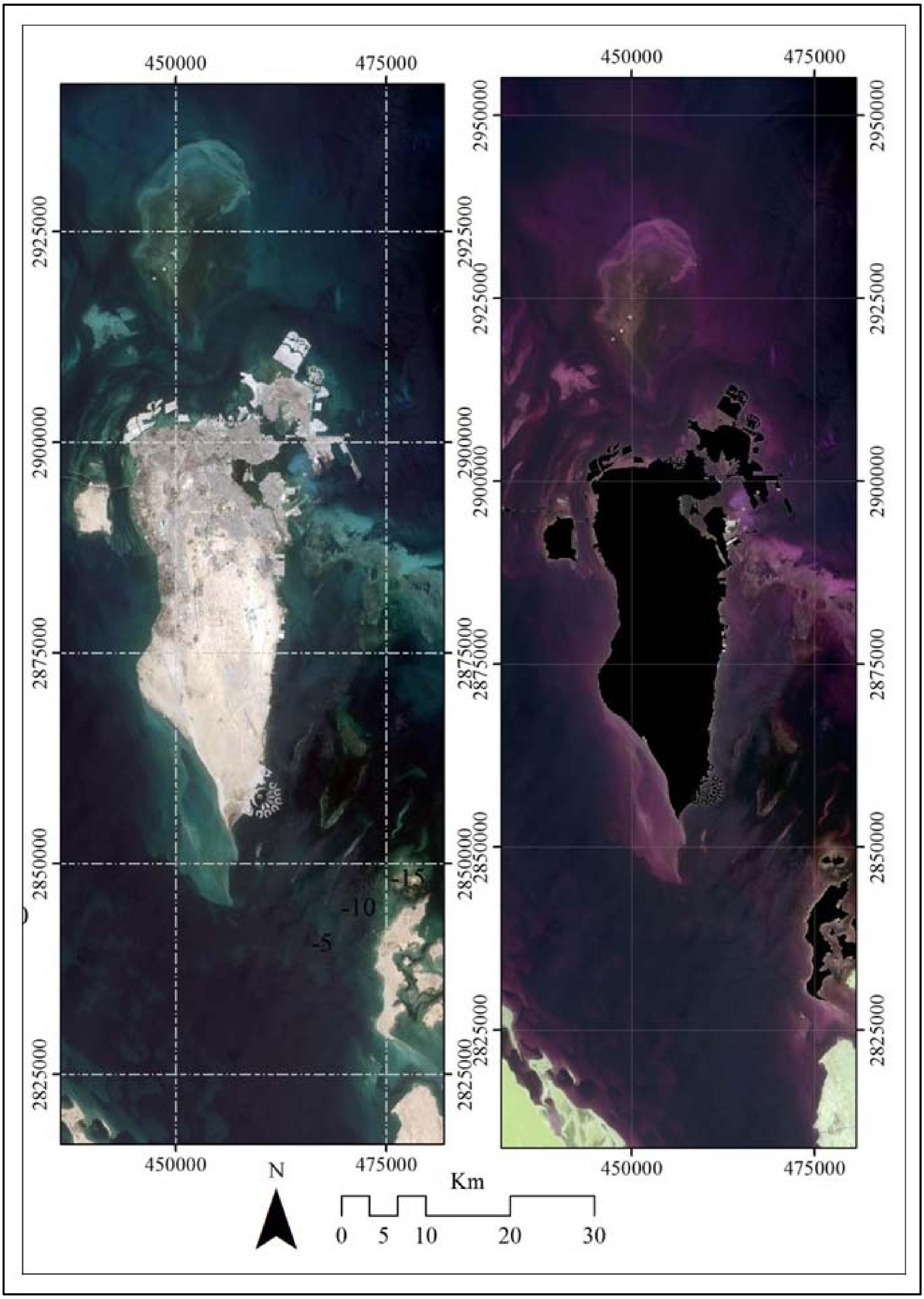

Fig. 5 Landsat 8-OLI image before sun glint removal (left) and after sun glint removal (right).

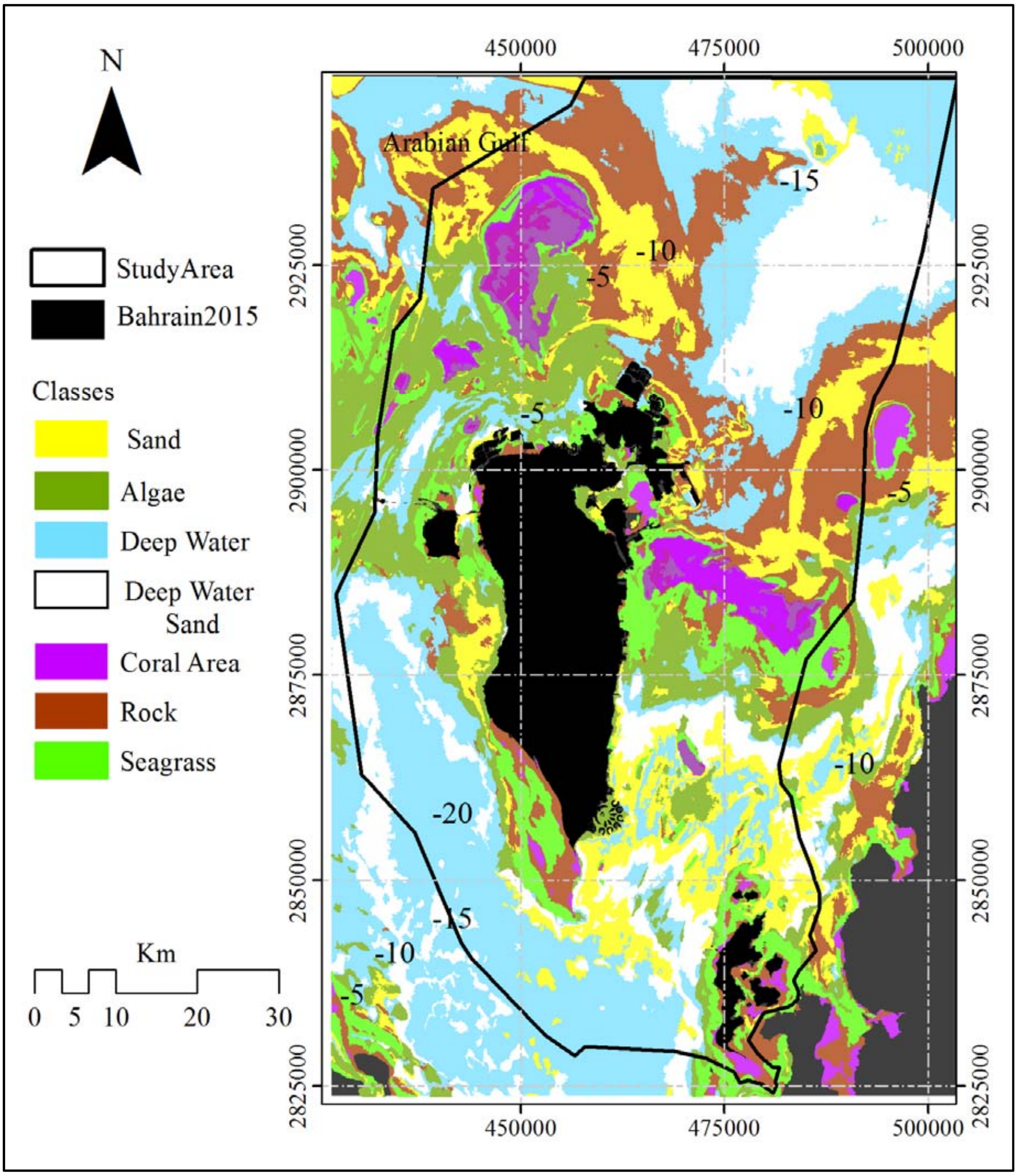

Fig. 6 Benthic habitat classification map of Bahrain marine area derived from Landsat-8 imagery.

The final map revealed that the benthic marine habitats of the Kingdom of Bahrain consist of deep water (2,523 km^2), rock (1,738 km^2), sand (1,191 km^2), deep water/sand (1,006 km^2), algae (922 km^2), seagrass (591 km^2) and coral (275.50 km^2) (Fig. 6). The analysis shows that algae and seagrass habitats, which are found in shallow water (1-5 m), accumulate on sandy and rocky substrata. Algal beds spread over 9.6% of the study area, while the seagrass beds spread over nearly 6.2% of the survey area. The coral reef area covers 2% of the total study area, sand spreads over 12.4%, deep water/sand found on approximately 10.5% and rock area spreads over 18.3% and the deep water (> 10 m) covers about 26.33% of the total study area.

Algae habitat was found in the eastern and western subtidal areas around Bahrain's main island and Hawar islands. Different types of algae species were found during the fieldwork survey. Among them are: *Hormophyssa*, *Avrenvillia*, small filamentous algae attached to *pebbles*, *Caulerpa*, *Cladophra*, *Dictyota*, Brown filamentous algae, *Sargassum-hermophyssa-Padina*, *Hormophyssa* and other types of filamentous algae. Most of the surveyed locations revealed low to medium (10%-50%) algae accumulation over rock or sand surfaces, whereas few sites exhibit an intense concentration of algae (Fig. 4-a shows green algae colony). Since it is tough to distinguish between different types of algae using satellite remote sensing, all algae species were grouped into one major algae class in this study (Fig. 7).

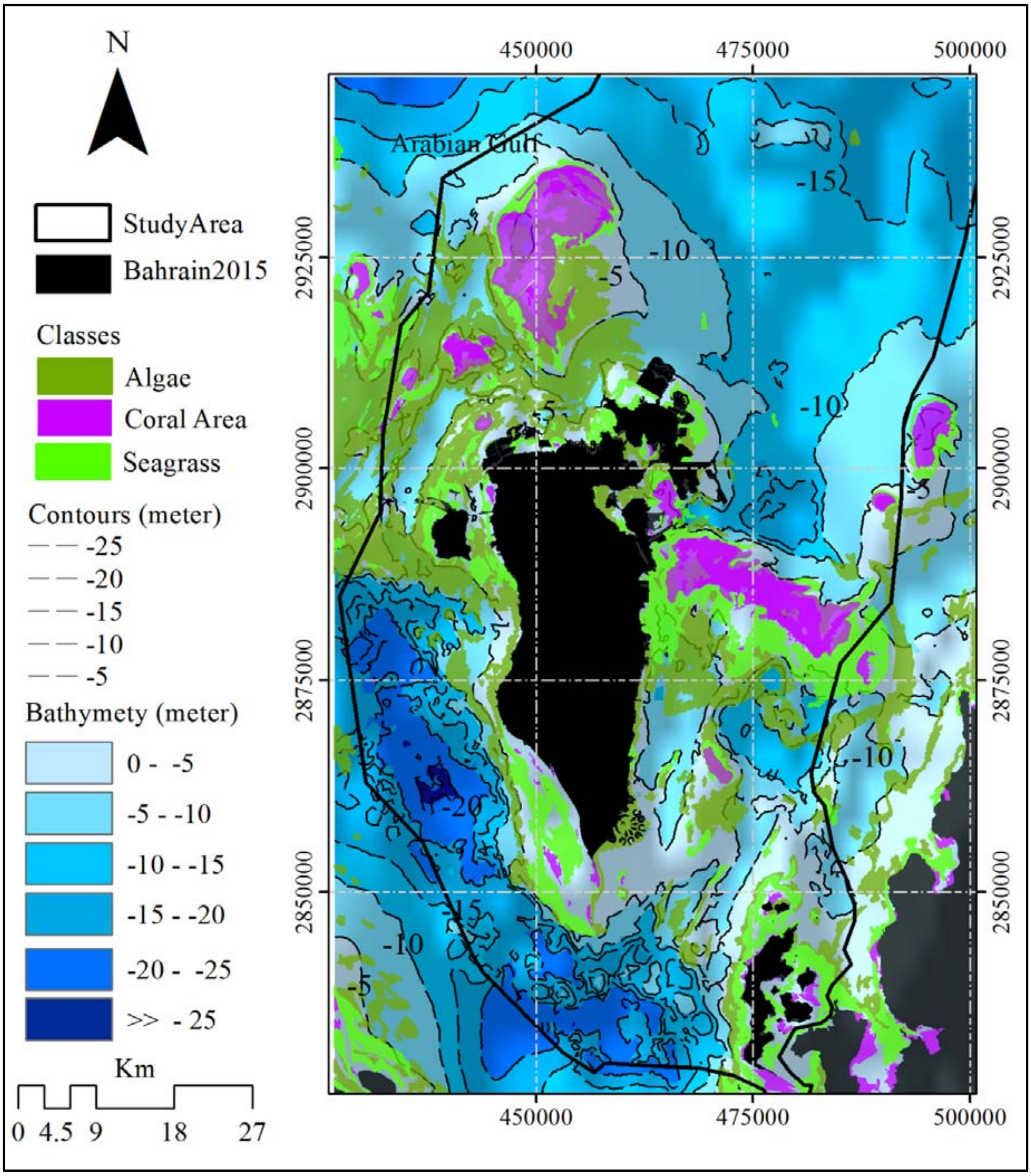

Fig. 7 Seagrass and algae habitat locations surrounding Bahrain Islands.

Seagrass beds of Bahrain cover a large area of the sea bottom and provide a suitable habitat for many important marine species. Based on the field survey, there are three common types of seagrass species (including *Halodule uninervis* (Forsskal) Ascherson, *Halophila ovalis* (R. Brown) Hooker and *Halophila stipulacea* (Forsskal) Ascherson) are found in the study area. As illustrated in the derived benthic habitat map, seagrass beds cover a large area of about 591 km^2 of the sea bottom, mainly in the eastern and western shallower subtidal areas around Bahrain's main island and Hawar Islands. The densest locations of seagrass were found surrounding the dead coral areas and towards the southwestern part of Bahrain's main island. Most of these habitats are covered with cyanobacteria (Fig. 7). No seagrass was detected in the deep water at the northern east of the study area.

The corals in Bahrain support more than 71 fish species [115] and serve as nursery habitats for shrimp, crabs and other sea creatures. Most of the coral reef areas are located in the offshore shallow marine water surrounding the islands of Bahrain. Most of these reefs are dead corals. Some parts are composed of rocky surfaces with many types of living corals attached to them. In all locations, sands deposit around the structures of old dead coral reefs. Here, a solid substrate covered with sand-veneer surround patches of old corals and rocks. In addition, coarse-grained sand and sparse seagrass and algae frame some parts of these ancient reefs (Fig. 7). The sand class represents different grain sizes including fine, medium, coarse, gravel and mixed grains sand. Sand habitat is mainly found around parts of the main island of Bahrain particularly to the east covering all the marine area from Muharraq Island to the north to the Hawar Islands to the south.

Sand deposits are found partially to the west coast of the main island of Bahrain. Based on the bathymetric data, sands are mainly in shallow areas where water depth ranges between 1-5 m below sea level (Fig. 8). Rock habitat/substrata represents the rocks occurring in the subtidal areas and part of the dead coral rock reefs. It is mainly in the north of the study area and partially to the west coast. In some locations, different algae species partially cover rocks (Fig. 8). The sand class in the deep water represents the underwater sand dunes located between Bahrain and Saudi Arabia and the sand habitat far north of Bahrain's marine area. This habitat is at a water depth of more than 10 m. Bathymetric data of the study area were used to verify the accuracy of the seabed elevation under seawater (Fig. 9). The deep-water class represents clear water areas where the bathymetry is deeper than 10 m below sea level. One or more types of the habitat cover this area (Fig. 10).

The classification of the water depth corrected image resulted in seven benthic habitats map for the study area. Comparable to the map that Vousden, D. H. P. developed in 1988 [12], which classified Bahrain's marine area to eleven classes using Landsast-5 and more than 250 field survey points, the new benthic habitats map seems to be presentable. The rapid assessment methods, employed in this study, show that the use of remote sensing data is a cost-effective tool in mapping shallow water benthic habitat. However, a full investigation of the marine area using high-resolution remote sensing data will improve the mapping accuracy and provide more detailed ecologically meaningful information across large geographic regions.

5. Conclusion

Remote sensing provides a rapid and cost-effective method of distinguishing shallow water marine habitats across the Kingdom of Bahrain. This study showed that using NIR band to remove the sun glint in moderate spatial resolution Landsat 8-OLI image improved the quality of the image for further underwater image analysis. Moreover, sun deglinting considerably enhanced the differentiation of benthic habitats in the study area. The newly available LS-8 data are promising for an automated benthic habitat mapping in the Kingdom of Bahrain. An informative habitat map was produced with an acceptable overall accuracy of 84.1%. The relatively coarse spatial resolution of LS-8 is, however, still problematic in mapping small patches. The problem can be mitigated by utilizing higher spatial resolution multispectral images such as Quickbird and Worldview-3. The derived LS-8 classification map, supported by field survey data, revealed that algae and sand are the most abundant benthic habitat in Bahrain, whereas seagrass and coral reefs are the least dominant. Benthic habitat mapping of Bahrain is imperative since it provides an inventory of habitat types, the location of environmentally sensitive areas and the hot spots of habitat diversity. These maps can guide planners and decision makers in Bahrain to plan the networks of protected areas and enable the monitoring of benthic habitat fragmentation over defined temporal and spatial scales. The benthic habitat map, produced in this work, could be used in future studies that would focus on detecting large-scale changes and potential damage to the benthic cover of the Kingdom of Bahrain.

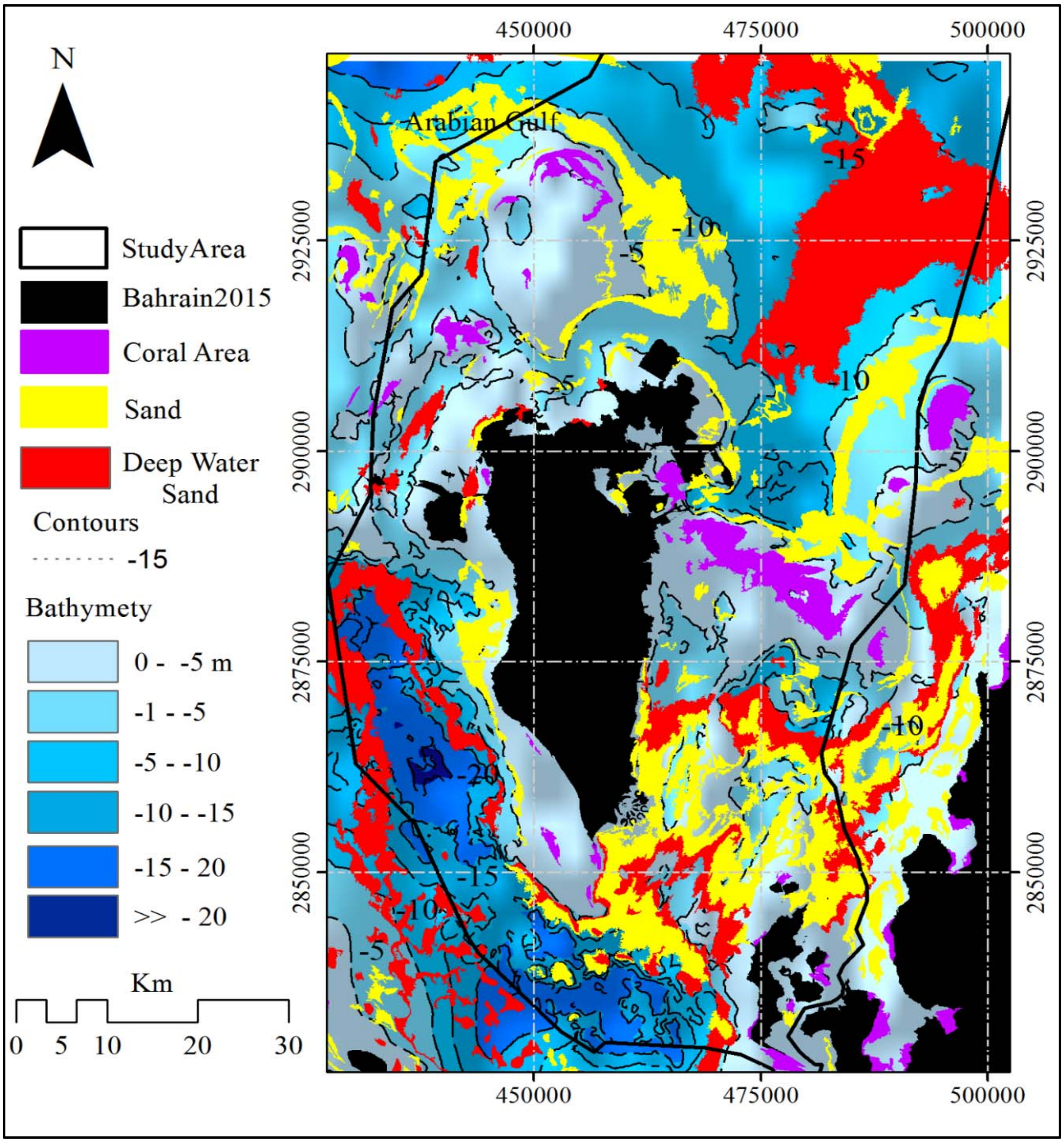

Fig. 8 **Sand and deep water/sand habitat locations surrounding Bahrain Islands.**

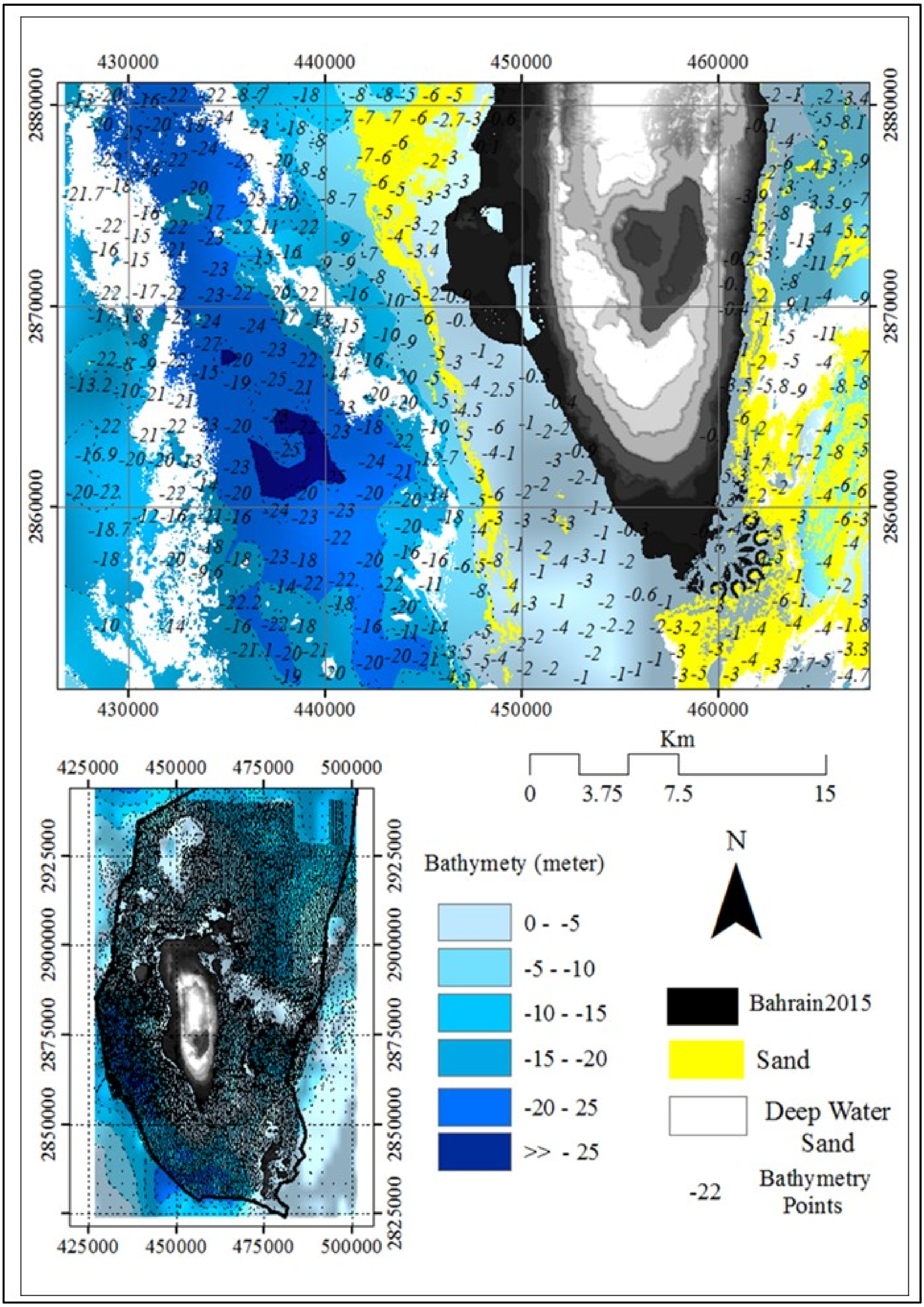

Fig. 9 Deep water/sand habitat class and single beam data (ground truthing).

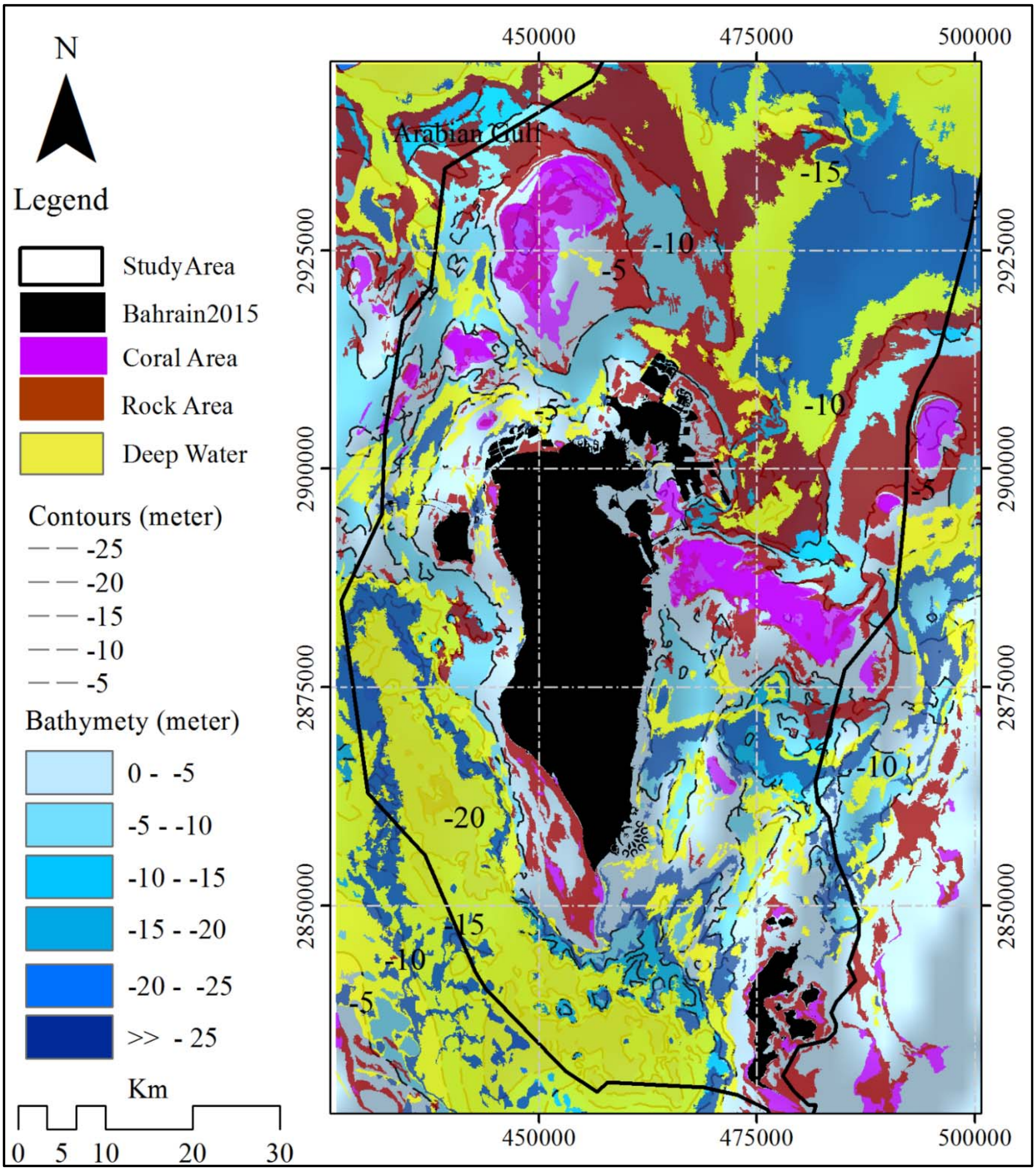

Fig. 10 Rock and deep water locations surrounding Bahrain Islands.

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