Coastal Coral Reef in Arabian Gulf between Ras Al Khafji and Ras Tannurah Biogeography and Marine Environment Protection Study

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Abstract. This research concerned the coastal reefs in the Arabian Gulf between Ras Al Khafji and Ras Tannurah, to identify the current status of the coral colonies, their geographic distribution, their most important forms and the impacts that affected them. The research is based on the descriptive approach by studying the environment of the coral reefs in the Arabian Gulf, knowledge of the coral species, and it was also based on the spatial analytical approach when studying the geographical distribution of coral reefs by analysis of the images of Landsat 8 OLI using ArcGIS 10.2.2 and Erdas Imagine 2014. Different processing techniques were carried out over the six images, such as: rectification, masking, water column correction, classification, and coral areas survey. The statistics of coral reef obtained from supervised classifications of 2016 in the study area was 78.3 km², which are scattered spots close to the coast except the area between Ras Al Khair to Abu Ali Island, which it is one of the richest areas in coral reefs. The most important coral species that resisted the environmental changes are *Favia* spp. and *Porites compressa*. It was also found that oil pollution and the climate change are the most important environmental pressures that have affected the species composition and reduced the area of coral reefs.

1. Introduction

Coral reefs of the Arabian Gulf are distributed along its western and southern coasts, and in offshore around the atolls. These reefs are able to adapt, grow and reproduce despite the harsh climatic factors; like water temperature, which between 14 and 34 °C, or the salinity rate, may reach more than 60 parts per thousand in some shallow coastal areas (Aramco Saudi Arabia, 2012).

Coral reef colonies are a fertile natural environment and source of marine biodiversity in the Gulf, where many species of marine organisms live in a complex and balanced ecosystem of invertebrates, algae, worms, shellfishes, fish, turtles, mammals and other

organisms that depend on coral reefs for their stability author year. Besides, they contribute in protecting the coasts from water erosion, forming atolls, and an important economic factor; as coral reef fish represent about 40% of the total Gulf fisheries. (Saudi Geological Survey Committee, 2007). It is also a marine tourism source and a destination for swimming and diving enthusiasts.

Coral reefs in the Arabian Gulf face many challenges. They are subject to a large variation in temperature and salinity levels, increased sedimentation and oil pollution, expansion of residential and industrial communities on the coasts, overfishing and uprooting of mangrove forests. Therefore, the

phenomenon of coral bleaching and the mass mortality of corals in recent years has become one of the most important environmental problems in the Arabian Gulf. For example, the mass mortality of coral communities around Abu Ali, Jana and Karan Islands reached about 99% in 1999 (Saudi Geological Survey Committee, 2007). This decline in the coral reefs' area in the Gulf represents a major threat to the natural heritage and biodiversity, as well as to economic activity associated with the fisheries sector.

The previous years, there was an interest in studying coral reefs on the Saudi side as an attempt to uncover the causes of their death and decline. Coles and Fadlallah (1991) examined the impact of cold fronts in the coral reefs of Tarut Bay and the coast of Munifah from December 1988 to March 1989 and determined the coral species that have gone extinct, namely *Platygyra daedalea* and *Acropora pharaonis*. In addition, the study revealed that some coral species like *Porites compressa*, were able to regain their vitality after 6 months.

Moreover, Vogt (1994) conducted a comprehensive survey of marine and coastal reefs in six regions around the Jana, Karan and Abu Ali Islands between 1992 and 1994. It was found that the coral reefs have survived the 1991 Second Gulf War, about three and a half years after the incident of oil spills in the Gulf water, which means that coral reefs in the Arabian Gulf survived the largest oil spills in the world. Fadlallah *et al.*, (1995) reported the effect of the temperature decline in winter 1991 and 1992 in the coral reefs of Tarut Bay. The study indicated that this decline coincided with the decreasing in the level of seawater during the phenomenon of spring floods. The result was the death of *Acropora* and *Stylophora* colonies after being exposed to air, and consequently the damage of the upper surface of the colonies. Fadlallah *et al.*, (*op.*

cit) also showed that low temperatures and winds affected coral reefs in shallow coastal areas more than the incident of the oil spill in the Gulf in 1991. This was confirmed by Richmond (1996), who sampled shells of marine organisms in February from 1992 to 1994, from a tidal region in Al Jubayl Marine Protected Area (MPA). He demonstrated that the diversity of marine environments in the tidal region is similar to that found in the northern regions of the Gulf. He also demonstrated that the living organisms in the region were not affected by oil pollution. In fact, it is revealed a rich diversity of species and a remarkable increase in their abundance during the years of study. Vogt (1996) also revealed the changes that occurred as a result of the oil spills incident during the Gulf War by identifying 10 coral reef sectors in two areas close to the coast of Al Jubayl and monitoring them using underwater video shooting between 1992 and 1993. The results indicated that the coral reef was stable and there were no cases of deterioration in coral reefs, except for some reefs around the Jana, Al Jurayd, Kurayn and Karan Islands, which were severely damaged by the anchoring of fishing boats. In fact, a considerable number of nets and other fishing tools were found scattered in coral reefs. The comparison of the nearshore reefs with those that are far from the shore, showed a significant difference; the nearshore coral reefs are weak living coral composed of porous species of *Porites* and covered with seaweed for several months of the year. It showed also that the coral moss *Lithophyllum kotschyannum* is one of the most important components of the coral reefs that are far from the coast, up to 2 meters deep. The deeper water shows that *Acropora* coral is the predominant species. In general, the coral was weak to average at a depth of 2 to 6 meters, scattered at a depth of more than 10 meters and rarely at the depth of 20 to 25 meters.

Because there is a need for more studies on the coral reefs in the Saudi Arabian Gulf, this study is conducted to determine their current geographical distribution in the coastal area and the main species that are currently growing to define the current status of coral reefs in the region, the most important natural and anthropogenic pressures negatively affecting their development and prosperity, and the suggested solutions that can be taken to protect them and classify them as MPA in accordance with the Council of Ministers' decision No. 12375 of 13 Rabii II of 1423HJ that all coral reefs in Saudi Arabia will be treated as protected areas (Aramco Saudi Arabia, 2012) and so this will be taken into consideration when making any coastal expansion in the region. This study is based on the use of remote sensing technology to establish a map of the current geographical distribution of the coral reefs in the northern coast of Saudi Arabia.

2. Study Area

The study area extends on the west coast of the Arabian Gulf basin in the eastern region of Saudi Arabia between Ras Al Khafji in the north and Ras Tannurah in the south, between latitudes $48^{\circ} 51' 08''$ and $50^{\circ} 52' 51''$ North extending for about 254 km (Fig. 1).

The coastal area is characterized by the presence a large group of small bays and capes such as Ras Al Khafji, Ras Mishab, Ras Tanaqib, Ras Al Ghar, Ras Tannurah and a number of islands near the coast, namely, Al Musallamiyah, Qunnah, Ath Thumayri, Ad Duayyinah, Al Haylamiyah, Al Qarmah, Al Batinah and Abu Ali. The seashore is characterized by its shallowness, with an average depth of 10–15 meters, and it is also covered with mud, lime and sand deposits (Saudi Geological Survey Committee, 2007). However, the study area may extend to a depth of 25 meters below sea level in some reef sites, as shown in Fig. 2.

In the study area, there are urban centers such as Al Jubayl, Al Khafji, Ras Tannurah, Ras Al Khair, in addition to oil fields and commercial fishing areas.

3. Data and Methodology

To achieve the objectives of the present study, natural environments, climatic boundaries and biodiversity of the coral reefs were discussed by the aid of the remotely sensed data.

3.1 Data Used

Landsat 8 OLI one of the most suitable images for mapping suitable for mapping marine habitats and the bottom cover of coral reefs for large depths (more than 60 m) (Contreras-Silva *et al.*, 2012; Mumby *et al.*, 1997 and 2004).

The study area enclosed six images of the satellite Landsat 8 from Ras Al Khafji to Ras Tannurah (Table 1), and they were analyzed and processed using ArcGIS 10.2.2 and Erdas Imagine 2014 programs. A free cloud satellite images which acquired in August are chosen for image processing.

3.2 Preprocessing of Satellite Images

Before starting analysis of the preliminary images, some correction are necessary to correct the radiometric distortions to make sure that the images correspond to reality and to obtain accurate results. However, the atmospheric correction did not apply to the images because there were no climatic effects that needed to be removed as the images were taken on days when there was no large cloud cover or air barriers in the study area and the geometric correction was adjusted from the source.

Because the purpose of the work is to determine the geographical distribution of coral reefs and biological diversity in the water, it was necessary to make a water

column correction in each image because the radiation changes its reflection whenever it hits the surface of the water and it also varies according to depth. In fact, radiation may be reflected from different living organisms or benthic rock components and give the same values, which gives inaccurate results. However, when applying the water column correction, these reflections are corrected, giving more reliable and realistic data that show the spatial characteristics and components of the study area at the time of the image acquire (Contreras-Silva *et al.*, 2012). These corrections were made using the Erdas Imagine 2014 program and the procedures are shown in flow chart (Fig. 3).

3.2.1 Radiometric Correction

The radiometric correction is applied to improve the radiations reflected from different phenomena and which are affected by several factors, including altitude and weather (GSP 216, 2015) and it has been applied as follows: (Komatsu, 2015)

$$L_i = M_{Li} \times D_i + A_{Li},$$

where:

D_i Digital Number Value (Recorded and obtained from the sensor)

L_i radiance at sensor aperture

A_{Li} band-specific additive rescaling factor (from Metadata)

M_{Li} band-specific multiplicative rescaling factor (from Metadata)

i Refers to the Band Number

Fig. 1. Study area.

Table 1. Characteristics of the Landsat 8 OLI image used.

Characteristics of the Landsat image used	Image 1	Image 2	Image 3	Image 4	Image 5	Image 6
Date	2016-08-16	2016-08-7	2016-08-30	2016-08-30	2016-08-7	2016-08-16
Path/Row	163/42	163/41	165/41	165/40	164/42	163/43
Spatial resolution (m)	30 & 100 fpr TIR	30 & 100 fpr TIR	30 & 100 fpr TIR	30 & 100 fpr TIR	30 & 100 fpr TIR	30 & 100 fpr TIR
Spectral bands used	2,3,4 and 10, 11	2,3,4 and 10, 11	2,3,4 and 10, 11	2,3,4 and 10, 11	2,3,4 and 10, 11	2,3,4 and 10, 11
Spectral range (μm)	0.452-0.673	0.452-0.673	0.452-0.673	0.452-0.673	0.452-0.673	0.452-0.673
Sun_Azimuth	114.38	111.65	126.66	129.12	108.42	111.30
Sun_Elevation	64.37	61.60	60.90	65.39	64.72	65.12
Earth_Sun_Distance	1.01	1.01	1.01	1.01	1.01	1.01

Fig. 2. A contour map showing the depth gradation at the study area.

Fig. 3. Steps of processing the original satellite images.

The reflection correction is also applied to make sure that there are no distortions in the images, by applying the following equation (Komatsu, 2015):

$$\rho\lambda_i = \frac{M_{\rho i}D_i + A_{\rho i}}{\cos(\theta_{sz})} = \frac{M_{\rho i}D_i + A_{\rho i}}{\sin(\theta_{se})},$$

where:

$\rho_{\lambda i}$ Reflectance (Top of Atmosphere)

$M_{\rho i}$ band-specific multiplicative rescaling factor (from Metadata)

$A_{\rho i}$ band-specific additive rescaling factor (from Metadata)

D_i Digital Number Value (Recorded and obtained from the sensor)

θ_{se} Local sun elevation angle of the scene center in degrees (from Metadata)

θ_{sz} local solar zenith angle ($\theta_{sz} = 90^\circ - \theta_{se}$)

3.2.2 Water Column Correction

The water column correction is essential when studying habitats in water. When the light penetrates the water column, its intensity decreases proportionately as the water depth or the wavelength increases. This process is known as attenuation, and it has an important impact on the data obtained by remote sensing devices in aquatic environments (Green *et al.*, 2000). This phenomenon is produced when the living organisms such as algae absorb these radiations and transform them into thermal or chemical energy, and when these radiations spread and reflect after a collision with living organisms in the water and reflect again, which give false data. This phenomenon increases as the radiation's depth increases because it causes a spectral confusion, and thus significantly affects the measurements of submerged habitats, by giving the same spectrum value to several habitats in the sea, which causes an error in the classification. This means as wavelength increases, there will be more confusion between the habitats. To eliminate this effect, water column correction equations were applied, and

hence the results allow us to distinguish categories of benthic ecosystems occurring at different depths. The water column correction is, therefore, an indispensable method of preprocessing in mapping water-submerged aquatic ecosystems (Contreras-Silva *et al.*, 2012; El-Askary *et al.*, 2014), and it is the most appropriate correction for ETM+ images that penetrate water with multiple spectral bands, (El-Askary *et al.*, 2014).

To eliminate this confusion, it was necessary to use a model to compensate the water column effect, and this was to determine the Depth-Invariant Index by applying the following equation (Contreras-Silva *et al.*, 2012; Mumby *et al.*, 1997):

$$a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}}$$

where:

DII_{ij} Depth-Invariant Index for bands i and j,

K_i Attenuation coefficient in band i,

σ_{ii} Variance in band i,

σ_{ij} Covariance between bands i and j.

After applying the Depth-Invariant Index to all images, the water body was separated from the coral reef ecosystem by using the Water Mask in the different band ratios (2/3 – 3/4), because the water body and coral reefs have a similar spectral reflection in shallow waters and coastal areas, which causes a bad classification (El-Askary *et al.*, 2014). Moreover, shallow coastal areas (less than 2 m) were separated from the sea surface because the data were distorted (Mumby *et al.*, 2004) as in Fig. 4.

3.2.3 Unsupervised Classification

The study area was subset after processing and loading into the ArcMap 10.2.2 program to determine coral reef locations

using the Iterative Self Organizing Data Analysis (ISODATA) method to identify coral colonies and map their current geographical distribution in the study area and delimit the area they cover. This step can only be accomplished after the water column correction and the application of the Depth-Invariant Index to avoid the interference of the biotic and rock environments at different depths (Contreras-Silva *et al.*, 2012). As shown in Fig. 5, the change of the classification in the satellite image is subject to the water column index on band 3/4 that was selected for the classification.

Fig. 4. Water column corrections and masking of band ratios of 2/3 and 3/4 of land sat 8 OLI.

Following the application of the unsupervised classification on the Water Masks images in Fig. 6; it shows spectral classes based on very precise natural differences of images values in various incorrect categories, as these categories reflect the high spectral difference between the subcategories of the same coral community, as shown in Fig. 7, which causes difficulties in using unsupervised classification as a tool for coral reef positioning (Contreras-Silva *et al.*,

2012). But it was used as guidelines to supervisor classification later on.

Fig. 5. Unsupervised classification with a normal satellite image and a satellite image in which water column was corrected.

3.2.4 Supervised Classification

We applied supervised classification of the corrected image. Coral reefs' locations were determined through the region's historical maps issued by the Geological Survey Committee (Saudi Geological Survey Committee, 2007) and Aramco Saudi Arabia Company (Aramco Saudi Arabia, 2012) in addition to the area's frequent visitors, like divers and fishermen. We excluded the distortions that have appeared in the classification in some areas near the shore at a depth of less than 2 m above sea level because most reefs near the shore are almost dead skeleton rather than live corals.

All training areas and samples that were selected during supervised classification and hence for identification of classes, then was used supervised classification for further definition of these classes. By define spectral signatures for key categories of features, evaluate the spectral signatures, use the

signatures to create a maximum likelihood supervised classification, and conduct a qualitative evaluation of the accuracy of our classification.

A map of the coral reef locations was created in the study area, because the study area is a large region and confirming the benthic biodiversity is difficult, thus, a coral colony located in the north of Abu Ali Island was selected to determine the habitats according to the different beams within the polygons that were observed from the images. Finally, three categories were classified as coral reefs communities' habitats, and they are 1) coral, 2) seaweed and algae and 3) sand.

4. Classification of coral reefs in the Arabian Gulf

In the Arabian Gulf, there are about 110 species¹ of coral reefs belong to 45 genera and 16 families. As shown in Table 2, few species belong to genus and families, with a genus equivalent of about 2.5, which is a low rate due to the small number of coral species that have adapted to the harsh environment of the Arabian Gulf basin.

The most dominant families in the Arabian Gulf in terms of the number of species are *Acroporidae*, *Faviidae*, *Poritidae* and *Agariciidae*.

Their numbers have been less in the past, but now, they have benefited from the space available after the death of other species of corals during the past years (Aramco Saudi Arabia, 2012).

The few number of coral species that were able to resist the environmental

conditions of the Arabian Gulf basin is reflected in the number of endemic species. There are only three coral endemic species: Two species from the *Acropora* genus (*Acropora downingi*, *Acropora arabensis*) and one species from the *Porites* genus, compared with 18 endemic species in the Red Sea (Riegl, *et al.*, 2012).

These corals build colonies of varying size that are locally called Shib, Fashts, Qitat and Qassar, depending on their size, area and structure.

Coral reefs generally grow in all shallow sites in the Arabian Gulf basin (Fig. 8). They usually grow at depths up to 10 meters. In some cases, individual colonies may be found at depths of 20-25 cm and they rarely grow in the deep depths (Vogt, 1996). Therefore, they are distributed along the western coast of the Arabian Gulf basin and around the islands, and very few are on the Iranian coast.

Because salinity rises southwards along the west coast of the Gulf, the number of reefs decreases gradually on the western side from North to South, and is significantly reduced from Ras Tannurah toward the south-east up to the west coast of the Kingdom of Bahrain and Qatar, where coral reefs disappear in Salwa Gulf due to the increasing salinity in it (Aramco Saudi Arabia, 2012). The coral reappears again on the Emirati and Omani coasts and the islands up to the Strait of Hormuz.

Coral reefs in the Saudi islands of the Arabian Gulf are typical reefs because they are the most diverse and prosperous species, with nearly 50 coral species recorded (Rieg and Purkis, 2012; Riegel *et al.* 2012), followed by the coral reefs region located near the Emirati coasts with 34 species, and it is expected that the coral reefs are also rich in the Strait of Hormuz because environmental conditions there are better than other locations in the

¹ There is confusion and disagreement about the exact number of coral reef species in the Arabian Gulf, and we believe that the species actually present in the Gulf are less than the stated number with at least 40 species (Riegl, *et al.*, 2012).

Arabian Gulf in terms of low temperature, salinity and depth (Riegel *et al.* 2012). In general, the diversity of coral reefs in the Gulf

is very similar to the diversity in the Indian Ocean and the Arabian Gulf of Oman (Riegl and Purkis, 2012).

Fig. 6. Unsupervised Classification of Water Mask Images.

Fig. 7. Multiple spectra of the coral reef community.

Table 2. Taxonomic classification of the Arabian Gulf corals.

SPECIES	GENUS	FAMILY	SPECIES	GENUS	FAMILY
<i>Echinophyllia aspera</i>	<i>Echinophyllia</i>	<i>Pectiniidae</i>	<i>Pocillopora damicornis</i>	<i>Pocillopora</i>	<i>Pocilloporid</i>
<i>Oxypora lacera</i>	<i>Oxypora</i>		<i>Stylophora pistillata</i>	<i>Stylophora</i>	<i>ae</i>
<i>Blastomussa merleti</i>	<i>Blastomussa</i>	<i>Mussidae</i>	<i>Seriatopora subseriata</i>	<i>Seriatopora</i>	
<i>Acanthastrea maxima</i>	<i>Acanthastrea</i>		<i>Seriatopora caliendrum</i>		
<i>Acanthastrea hillae</i>			<i>Madracis kirbyi</i>	<i>Madracis</i>	<i>Astrocoeniid</i>
<i>Acanthastrea echinata</i>			<i>Stylocoeniella guentheri</i>	<i>Stylocoeniella</i>	<i>ae</i>
<i>Symphyllia radians</i>	<i>Symphyllia</i>		<i>Montipora circumvallata</i>	<i>Montipora</i>	<i>Acroporidae</i>
<i>Symphyllia agaricia</i>			<i>Montipora venosa</i>		
<i>Hydnophora exesa</i>	<i>Hydnophora</i>	<i>Merulinidae</i>	<i>Montipora tuberculosa</i>		
<i>Hydnophora microconos</i>			<i>Montipora monasteriata</i>		
<i>Favia favius</i>	<i>Favia</i>	<i>Faviidae</i>	<i>Montipora floliosa</i>		
<i>Favia maxima</i>			<i>Montipora aequituberculata</i>		
<i>Favia pallida</i>			<i>Montipora efflorescens</i>		
<i>Favia rotumana</i>			<i>Montipora mollis</i>		
<i>Favia speciosa</i>			<i>Montipora verrucosa</i>		

<i>Favites chinensis</i>			<i>Montipora spumosa</i>		
<i>Favites pentagona</i>			<i>Acropora clathrata</i>	<i>Acropora</i>	
<i>Favites abdita</i>			<i>Acropora arabensis</i>		
<i>Favites complanate</i>			<i>Acropora pharaonis</i>		
<i>Platygyra daedalea</i>	<i>Platygyra</i>		<i>Acropora valenciennesi</i>		
<i>Platygyra lamellina</i>			<i>Acropora valida</i>		
<i>Platygyra sinensis</i>			<i>Acropora muricate</i>		
<i>Plesiastrea versipora</i>	<i>Plesiastrea</i>		<i>Acropora divaricate</i>		
<i>Leptastrea purpurea</i>	<i>Leptastrea</i>		<i>Acropora nasuta</i>		
<i>Leptastrea transversa</i>			<i>Acropora horrida</i>		
<i>Cyphastrea</i>	<i>Cyphastrea</i>		<i>Acropora downingi</i>		
<i>microphthalma</i>					
<i>Cyphastrea serailia</i>			<i>Astreopora</i>	<i>Astreopora</i>	
			<i>myriophthalma</i>		
<i>Leptoria Phrygia</i>	<i>Leptoria</i>		<i>Astreopora</i>		
			<i>myriophthalma</i>		
<i>Echinopora lamellose</i>	<i>Echinopora</i>		<i>Astreopora expansa</i>		
<i>Echinopora gemmacea</i>			<i>Porites compressa</i>	<i>Porites</i>	<i>Poritidae</i>
<i>Culicia rubeola</i>	<i>Culicia</i>	<i>Rhizangiidae</i>	<i>Porites lutea</i>		
<i>Paracyathus sp</i>	<i>Paracyathus</i>	<i>Caryophylliidae</i>	<i>Porites murrayensis</i>		
<i>Heterocyathus</i>	<i>Heterocyathus</i>		<i>Porites lobate</i>		
<i>aequicostatus</i>					
<i>Euphyllia glabrescens</i>	<i>Euphyllia</i>		<i>Porites solida</i>		
<i>Tubastraea urea</i>	<i>Tubastraea</i>	<i>Dendrophylliida</i>	<i>Porites nodifera</i>		
<i>Turbinaria mesenterina</i>	<i>Turbinaria</i>	<i>e</i>	<i>Porites harrisoni</i>		
<i>Turbinaria reniformis</i>			<i>Goniopora lobate</i>	<i>Goniopora</i>	
<i>Turbinaria peltata</i>			<i>Goniopora somaliensis</i>		
<i>Psammoseris sp</i>	<i>Psammoseris</i>		<i>Alveopora tizardi</i>	<i>Alveopora</i>	
<i>Pocillopora verrucosa</i>	<i>Pocillopora</i>		<i>Goniopora djiboutiensis</i>	<i>Goniopora</i>	
<i>Pocillopora damicornis</i>			<i>Goniopora lobate</i>		
<i>Heteropsammia cochlea</i>	<i>Heteropsammia</i>		<i>Goniopora columna</i>		
<i>Pavona cactus</i>	<i>Pavona</i>	<i>Agariciidae</i>	<i>Goniopora somaliensis</i>		
<i>Pavona diffluens</i>			<i>Goniopora tenuidens</i>		
<i>Pavona explanulata</i>			<i>Siderastrea savignyana</i>	<i>Siderastrea</i>	<i>Siderastreida</i>
<i>Pavona duerdeni</i>		<i>Agariciidae</i>	<i>Pseudosiderastrea</i>	<i>Pseudosiderastrea</i>	<i>e</i>
			<i>tayami</i>		
<i>Pavona decussate</i>			<i>Anomastrea irregularis</i>	<i>Anomastrea</i>	
<i>Pavona venosa</i>			<i>Psammocora haimeana</i>	<i>Psammocora</i>	
<i>Pavona frondifera</i>			<i>Psammocora</i>		
			<i>superficialis</i>		
<i>Pavona varians</i>			<i>Psammocora albopicta</i>		
<i>Leptoseris solida</i>	<i>Leptoseris</i>		<i>Psammocora contigua</i>		
<i>Leptoseris</i>			<i>Coscinaraea monile</i>	<i>Coscinaraea</i>	
<i>mycetoseroides</i>					
<i>Leptoseris foliosa</i>			<i>Coscinaraea columna</i>		
<i>Gardineroseris</i>	<i>Gardineroseris</i>		<i>Galaxea fascicularis</i>	<i>Galaxea</i>	<i>Oculinidae</i>
<i>planulata</i>					
<i>Physogyra lichtensteini</i>	<i>Physogyra</i>	<i>Euphyllidae</i>	<i>Fungia curvata</i>	<i>Fungia</i>	<i>Fungiidae</i>

Fig. 8. The most important coral reef distribution sites in the Arabian Gulf.

Coral reefs of the Arabian Gulf are classified according to their shapes into the following types:

- **Fringing reefs:** They are reefs that have evolved into islands; they are one of the best types of coral reefs in the Arabian Gulf in terms of diversity and growth. It can be seen from the coast when the waves hit it. The water may also recede from its upper parts during the ebb phenomenon, such as the islands of Karan and Jana.

- **Stringer reefs:** They consist of parallel coastal longitudinal coral structures that span several hundred meters, and may extend to several kilometers, such as the reefs in north Abu Ali Island.

- **Patch reefs:** They are small round reefs that grow in shallow coastal areas and observe sometimes outside water. Their upper part may appear during the ebb. Their size is between 1

and 10 meters, examples include the Qitat Sufan and Abo Usayyah.

- **Bioherms:** They are thin clusters of reefs that do not reach the water surface, i.e., they do not develop to become coral reefs because of either topography or disturbances during coral growth.

As for non-framework-building, they are dispersed clusters of a small number of small size coral reefs separated by spaces so they do not intertwine with each other and therefore do not form clear forms, and their biological diversity is low compared with Biostromes and coral reefs. This is the most common pattern in the Arabian Gulf in the appropriate habitats from 2 to 20 meters (Riegl and Purkis, 2011), as in Dawhat Deffi, Al Musallamiyah and Ras Mishab.

Several species of brown algae accompany coral growth, especially in winter, such as *Padina* sp., *Sargassum boveanum*,

Colpomenia sinuosa and several other species of red algae, such as *Lithophyllum kotschyannum* (Vogt, 1996).

5. Results and Discussion

5.1 Geographical Distribution of Coastal Coral Reefs between Ras Al Khaffi and Ras Tannurah

The study area is dominated by sporadic and intermittent coral reefs as clusters or colonies that are fairly abundant in some places and are all located at a depth of 1 to 20 meters and in some cases at 25 meters below sea level. Figure 9 showed that coral reefs cover around 78.3 km², distributed in the following locations from north to south:

- From Ras Al Khaffi to Ras Mishab, which are scattered spots close to the coast, the most important of which are Shib Umm Ash Shayahin, Shib Umm Al Ghirban, Qitat Al Baldani, Qitat Qamra, Arid Yusif, Qassar Umm As Sihal, at depths of 5 to 20 meters below sea level.

- From Ras Mishab to Ras As Saffaniyah, they are sparse and scattered near and far from the coast, the most important of which are Shib Ubu Usyyah, Qassar Al Maytamah, Qitat Khalaluh, Qitat Sufan and Qitat Muwayqilah growing in the sloping seabed at 5 to 20 meters below sea level.

- From Ras As Saffaniyah to Ras Tanaqib, they extend in a continuous line in the south of As Saffaniyah. They grow in shallow waters no more than 5 meters below sea level.

- From Ras Tanaqib to Ras Al Khair, in the shallow water area of Dawhat Bilbul and they scatter and become fewer in the direction of Ras Al Khair, in an area no deeper than 10 meters below sea level.

- From Ras Al Khair to Abu Ali Island, it is considered one of the richest areas in coral

reefs, as they are located on the northern coast of Abu Ali Island, at the cape in the eastern side and also in the tidal area in Dawhat Deffi and Dawhat Al Musallamiyah, the most important of which is Fasht Al Kash. They grow on the bottom at a depth of 15 meters below sea level maximum.

Because this area is one of the rare costal areas where there is a flourishing growth of reefs, a specific map is prepared, showing the bio diversity of the coral community as shown in Fig. 10. In the colony, there is sand at the bottom, algae and sea grasses that are usually associated with coral reefs, especially near the coast.

- Coral reefs are almost nonexistent on the southern side of the study area between Abu Ali Island and Ras Tannurah, as they are located only near Ras Al Ghar and south of Ras Tannurah, the most important of which are Fasht Umm Al Jimal, Fasht Ghuraybah and Fasht Abu Safah, they grow near the shore in shallow areas not more than 10 meters depth.

- Through fieldwork and interviewing the usual visitors to the study area, like amateurs and fishermen; we learned that the most important marine organisms living near coral communities are *Epinephelus*, *Siganus*, *Ostracion*, *Amphiprion*, *Chlorurus*, *Chelonia mydas* and *Eretmochelys imbricate*.

5.2 Qualitative Changes of Coastal Coral Reefs between Ras Al Khaffi and Ras Tannurah

The coral species that are currently growing in the study area are species that have survived the severe environmental conditions that the region has experienced over several years; in terms of water temperature change, changing salinity rates and the increasing volume of pollutants and sediments. In fact, the study area was subject to a significant biological change that started in the 1980s, and

the species that are sensitive to climatic and physical changes of the sea have declined, like the species belonging to the Genus *Acropora* such as *Acropora tenuis*, which was extinct from the Gulf in 1996, and have not been recorded since that year. Moreover, other species in the south have died in Ras Tannurah, the most important of which are *Acropora pharaonis* and *Platygyra daedalea* (Coles and Fadlallah, 1991).

At the beginning of the 1990s, there was also a mass mortality of two species: *Acropora clathrata* and *Stylophora pistillata*, which gave other organisms an opportunity to expand, such as brown algae that covered the dead parts of coral reefs (Fadlallah *et al.*, 1995). They were replaced by *Porites compressa* and *Favia* sp. So, the main component of the region's reefs become *Porites* species, specifically *Porites compressa*, which is the most common, especially between As Saffaniyah and Abu Ali Island (Aramco Saudi Arabia, 2012).

5.3 The Most Important Stresses Facing Coral Reefs between Ras Al Khafji and Ras Tannurah

The Arabian Gulf has generally suffered significant losses in its living organisms and their appropriate habitats. The International Union for Conservation of Nature (IUCN) and the World Wildlife Fund (WWF) have classified organisms in the Arabian Sea-including the Arabian Gulf-as "at risk of extinction" (Riegl and Purkis, 2011). In fact, nearly 84% of coral species in the Gulf are threatened with extinction according to the IUCN Red List (The IUCN Red List of Threatened Species, 2016) (IUCN Red List).

Coral species can be divided into two categories: Species that are flexible and resistant to changes in their environment, which are still present and can be rehabilitated in suitable areas such as species of Genus

Porites, and other species sensitive to any incident or changes, such as species of the family Acroporidae.

Marine coral reef habitats in the study area have been exposed to negative change more than the habitats located far from the coast because the water in the study area is shallow and close to urban centers. In fact, the species belonging to the Genus *Acropora* are the important species covering most of the coral colonies in the study area in particular and the Gulf in general, and losing them will cause damage to biodiversity in the region (Riegl and Purkis, 2011).

Among the most important challenges of the coral reefs that are currently located in the study area are:

- *Natural stress*

Most of the scientific research has shown that coral reefs around the world are more affected by low water temperature than high water temperature. The death of coral reefs and the distribution of their species in areas like Florida, Panama, Hawaii and the Arabian Gulf have been associated with low, rather than high, heat stress (Fadlallah *et al.*, 1995). Therefore, lower water temperatures are the greatest threat to coral reefs in the Arabian Gulf, especially the coastal reefs, as they are more likely to be exposed to extreme climatic changes than those in deep water. The annual temperature range of coastal waters and small bays in the western side of the Gulf reaches approximately 30 °C (Aramco Saudi Arabia, 2012). Coral reefs are affected when the water temperature falls below 13 °C for days or weeks (Fadlallah, *et al.*, 1995), which occurs in the winter often, repeatedly, irregularly and unexpectedly. In fact, the water temperatures drop rapidly as the winter begins (approximately 10 °C), coinciding with the north-west cold winds.

In the winter of 1988–1989, coral in the study area endured a series of cold fronts. The temperature of coastal waters dropped to less than 11.5 °C during four consecutive days and to 13 °C for more than a month resulting in the death of *Acropora pharaonis* and *Platygyra daedalea* sequentially in the area of Munifah; so, they lost their beautiful colors and changed into calcareous stones that were covered later by brown algae *Colpomenia sinuosa* and green algae *Enteromorpha*, to a depth of 6 meters.

It is worth mentioning that coral response to heat stress varies from one species to another. The species that resist thermal fluctuations most are the species belonging to genera *Acropora* and *Platygyra* (Fig. 11). Other species show stress signs but still a life; this is why the numbers of the species belonging to the two aforementioned genera increases as we go southwards where they are less exposed to cold fronts. So, we notice that these species grow in the State of Kuwait 50% less than the species growing in the Kingdom of Saudi Arabia (Coles and Fadlallah, 1991).

The situation gets worse if the temperature decline coincides with the spring tide, low sea water level and the exposure of coral reefs to the air, which is one of the main causes of coral bleaching and death. This is because coral becomes directly exposed to cold winds and solar radiation, and this also exposes it to direct contact with oil contaminants leaking on the surface of the water. Coral mortality is usually associated with repeated exposure to air during the winter (Fadlallah, *et al.*, 1995).

Low water temperature causes the death of coral in the study area during the years 1983, 1985, 1989 and 1992 (Fadlallah *et al.*, 1995); on the other hand high water temperature has also caused the death of coral species in the years 1996, 1998 and 2002. Salinity plays also an important role in coral mortality in the study

area due to high rates of evaporation during summer. Salinity increases towards the south and reaches up to 41.2‰, especially with dry winds (Riegl and Purkis, 2011). The oxygen solubility in the seawater decreases with the increase of salinity, leading to the formation of environments with low available oxygen (Aramco Saudi Arabia, 2012).

Finally, we can say that the lowest and highest temperature limit for the growth of coral reefs in the Arabian Gulf is unknown, as it depends on the type of species and several other natural factors.

• Human stress

Human activities play a main role in the change in coral reef habitats and their exposure to the risk of death. The greatest threat to the biosphere in the Arabian Gulf is oil pollution. The Gulf is considered as one of the world's most important commercial seas and is undergoing heavy maritime transport.

Moreover, the most important oil fields in the Kingdom, as well as the most important industrial cities and several ports for the industrial and economic activities are located in the study area. This has made the region vulnerable to oil and industrial pollution that has become over time the most dangerous pollutants to the natural environment and living organisms. Figure 12 shows that the study area is rich in oil and gas fields that are located in the areas where coral reefs grow. This exposes them to direct pollution, especially during operations of oil exploration and digging at the bottom of the Gulf, the pollution may also occur directly because of oil leakage from petroleum and gas transmission pipelines or from oil platforms.

By looking at Fig. 13, we notice that more than 140 commercial vessels per day cross the region, this large number make the region highly exposed to accidents of ships

and oil tankers. Usually, coral reefs are not affected by oil pollution as long as it stays on the surface and does not contact the coral. This is the reason why the impact of the large oil spill that occurred in 1991 in the Saudi coasts had a slight effect on the reef, as the reefs did not contact the oil slick (Fadlallah, *et al.*, 1995). The damage that the reefs suffered later, such as *Acropora*'s bleaching was actually due to the weather (Vogt, 1994).

The coastal cities, especially Al Khafji and Al Jubayl also have a role in coastal pollution, with the liquid and solid industrial pollutants from oil refineries or civil pollutants from sewage pipelines that they discharge in the water. In addition, the desalination stations on Al Jubayl and Al Khafji expose the area water to thermal pollution. Very high temperatures up to 40 °C were recorded in the discharge areas of the power generation and desalination stations, which expose the coastal waters to a decrease in the total concentration of oxygen (Aramco Saudi Arabia, 2012).

Overfishing is one of the most influential activities in the region. The development of fishing methods and the lack of sustainable fishing solutions have reduced the biodiversity of the sea. This has negative impacts on benthic ecosystems. Moreover, fishing practices may expose parts of the reefs to damages by fishermen throwing anchors or even amateur ships (Fig. 14).

Among the things that have negative impacts on coral reefs are urbanization and coastal erosion, which destroys coastal ecosystems. Some man-made marine structures such as Abu Ali bridge may stop the water flow and reduce its regeneration, increasing the salinity of water in inland bays and changing its natural properties (Aramco Saudi Arabia, 2012). Postconstruction negative effects such as the release of thermal and chemical wastewater, oxygen and nutrient depletion, increased

sedimentation and turbidity are still long-term problems that reduce the ability of marine organisms to adapt (Riegl and Purkis, 2011).

6. Conclusion

In the present study, the possibility of detecting coral reefs in the coastal region of the Arabian Gulf by remote sensing has been verified, using a geographical information system that leads to a map distribution of the most important sites of the coral colonies in the study area, which was assisted by six images from Landsat 8 OLI analyzed and processed using the ArcGIS 10.2.2, Erdas Imagine 2014 software. The data extracted from the satellite images helped reach the coral reef area in a cost and time-effective manner. This work was preceded by studies of images without need for field trips and ground measurements, Only on a small scale during field verification.

The processes on it to correct all the distortions, most importantly the water column, were performed and then the ISODATA method was used to identify the coral colonies and current geographic distribution in the study area and identify the area covered by using the supervised classification for coral reef sites with its confirmation using the historical map of the area, divers' and fishermen's statements. We excluded the distortions that have appeared in the classification in some areas near the shore at a depth of less than 2 m above sea level, and then the coral reef area of 78.3 km² has been extracted.

There are about 110 species of coral reefs derived from 45 genera and 16 families, and these numbers need more studies. Looking at current threats that lead to a great drop in coral reefs' habitat, the most important are the escalation of human risks and the threats that are related to global climate change that put the coral reefs in the Arabian Gulf at a high risk of collapsing.

Fig. 9. Distribution of coastal coral reefs between Ras Al khafji and Ras Tannurah.

Fig. 10. Benthic biodiversity in the colony of coral reefs north of Abu Ali Island.

Fig. 11. The phenomenon of coral bleaching in the study area.

Fig. 12. Oil and gas fields in the study area.

Ministry of Energy, Industry and Mineral Resources, General Authority for Surveying, Topographic Maps of Al khafji and Qaysumah City, No. 5, Eastern Region No. 6, and Riyadh and Samman Region No. 7, scale 1: 1000000, Riyadh.

Fig. 13. Density of ships cruising per day (ship / km²) in the Arabian Gulf in 2015-2016.

Marine Traffic, 2017, Retrieved on: 19/5/2017 from:
<https://www.marinetraffic.com/ar/ais/home/centerx:55.3/centery:32.7/zoom:6>

Fig. 14. Fishing nets wrapped on the *Acropora* coral.

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الشعاب المرجانية الساحلية في الخليج العربي بين رأس الخفجي ورأس تنورة دراسة في جغرافية الأحياء وحماية البيئة البحرية

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المستخلص. تناول البحث الشعاب المرجانية الساحلية في الخليج العربي بين رأس الخفجي ورأس تنورة في المملكة العربية السعودية، بهدف التعرف على الوضع الراهن للمستعمرات المرجانية وتوزيعها الجغرافي ومساحتها، وأهم تكويناتها النوعية والضغطات الطبيعية والبشرية التي أثرت فيها. واعتمد البحث لتحقيق هذه الأهداف على المنهج الوصفي من خلال دراسة البيئة الطبيعية للشعاب المرجانية في الخليج، ووصف أنواعها، وعلى المنهج التحليلي المكاني عند دراسة التوزيع الجغرافي للمرجان أثناء تحليل مرئيات القمر الصناعي الأمريكي Land Sat 8 OLI بالاستعانة ببرامج حاسوبية أهمها: ArcGIS 10.2.2, Erdas imagine 2011. تم خلالها تنفيذ تقنيات معالجة مختلفة من خلال الصور التي غطت المنطقة والبالغ عددها ست صور، مثل: التصحيح الهندسي، والطبقات (masking)، وتصحيح عمود الماء، والتصنيفات، ومن ثم مسح المناطق المرجانية. قدرت مساحة الشعاب المرجانية التي تم الحصول عليها من التصنيفات الخاضعة للمراقبة لعام ٢٠١٦م بنحو ٧٨,٣ كم^٢، وكانت عبارة عن بقع متناثرة بالقرب من الساحل، باستثناء المنطقة الواقعة بين رأس الخير وجزيرة أبو علي، التي تعد واحدة من أغنى الشعاب المرجانية في منطقة الدراسة. كما توصل البحث إلى أن أهم الأنواع المرجانية التي قاومت التغيرات البيئية هي: Favia spp. و Porites compressa، حيث كان التلوث النفطي والتطرف المناخي من أهم الضغوط البيئية التي أثرت في التكوين النوعي وقلصت من مساحة الشعاب المرجانية.

كلمات مفتاحية: الشعاب المرجانية، الخليج العربي، البيئة البحرية، جغرافية الأحياء، المملكة العربية السعودية.