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Characteristics of Tidal Zone in Kalubhar Island, Gulf of Kachchh, Gujarat and Its Geomorphological Implications

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Abstract

Tidal networks, tidal flats and mangroves are some of the important features of tidal areas in the Gulf of Kachchh. Insight on the patterns of tidal networks, vegetation and sedimentation is useful in understanding geomorphological processes active on the region. In the present study features of tidal zone of Kalubhar island, located in the south-central part of the Gulf have been studied with emphasis on tidal networks using Sentinel-2 Multispectral Imager (MSI) data having spatial resolution of 10m. Typology of tidal network is described for the first time. The typology of tidal network pattern, their density, presence of mangroves and beaches indicate low energy depositional setting in eastern, south-eastern and southern parts. This coupled with continued sedimentation and long sub-aerial exposure during low tides may not be ideal environmentin future for live corals present in the intertidal zones.

Keywords: Tidal Network Pattern, Sentinel-2 MSI, Kalubhar Island, Gulf of Kachchh

Introduction

Indian subcontinent is characterised by diverse landforms, *viz.* Himalayas and Indo-Gangetic plains in the north and north west, Peninsular plateaus in the south and coastlines that have formed through geological time and process. Coastline of India is approximately 7500 km long and is characterised by a variety of landforms such as tidal networks, tidal flats and marshes, rocky shores, sandy beaches and muddy shores (SAC, 2003). Features such as tidal flats, channel networks and marshes are developed due to tidal actions, sedimentation and subsequent colonisation of plants and they are influenced by current dynamics and the local geomorphology (Kunte *et al.*, 2003). Gulf of Khambhat, Sundarbans and Gulf of Kachchh are the most prominent macrotidal sites in India (SAC, 2003).

Tidal flats form in gently sloping coasts of enough sediment supply and comparatively low wave action (Reineck and Singh, 2012). In a tide-dominated coastal landscape such as the Gulf of Kachchh, tidal channels are the primary conduit for tide propagation into land, sediment transportation, and the evolution of tidal flats and salt marshes (Mason and Scott, 2004). Characteristics of tidal flats change with changing tidal network patterns leading to change in surface sedimentary facies too (Eom *et al.*, 2012), hence understanding morphology of tidal channels is crucial to understanding the dynamics involved.

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Monitoring of tidal networks is important to understand the evolution of a tidal ecosystem, and that can be either achieved by on site observations or with the help of satellite imageries. On site observations have limitation in terms of accessibility and spatial coverage besides requirement of field survey to be synchronised with tidal conditions. Due to their synoptic coverage, high spatial and spectral resolutions satellite remote sensing data have potential in studying the highly dynamic coastal environment, hence are extensively utilised for monitoring and mapping (Nayak, 2017; Deshmukh *et al.*, 2005). However, availability of suitable remote sensing data is constrained by cloud cover and tidal stage.

This study is based on the Kalubhar island located in the southern Gulf of Kachchh. The study concerning upper intertidal zone features has been carried out with an aim to understand geomorphological processes active in the Kalubhar island with emphasis on tidal networks. The extent and geological setting of the study area is briefly described in section 2. Description of data used and the methodology adopted is presented in section 3.In section 4, we present our findings along with relevant discussions, the conclusion of which is drawn and presented in section 5.

Study Area

The study area *i.e.*, Kalubhar Island is located between the 22º23'19" N to 22º29'02" N latitudes and 69º33'56" E to 69º39'27"E longitudes in the Gulf of Kachchh (Fig. 1). The Kalubhar Island falls under Khambhalia Tehsil of Jamnagar District and has an area

of ~67km^2. The Kalubhar Island has been classified as platform type of coral reef (Kumar *et al.*, 2017).

The Gulf of Kachchh, a semi-enclosed water body bounded by Kachchh and Saurashtra peninsulas varies in depth from ~60m at the mouth to less than 20m at the head (Kunte *et al.*, 2003). Depth of central part of the Gulf ranges between 30 and 35m and is stretched for about 100km in the east-west direction and about 20km in the north-south direction (Unnikrishnan *et al.*, 1999). The topography at the mouth is very irregular and the central portion of the gulf consists of pinnacles and scarps with heights ranging from 6 to 32m (Kunte *et al.*, 2003). This region experiences mixed semi-diurnal type of tides having tidal range of 4m at the mouth to ~7m at the head (Deshmukh *et al.*, 2005). Southern coast of the Gulf is characterised by numerous coral reefs, mangrove forests, islands and vast expanse of mudflats. These mudflats become exposed during low tides. On the other hand, the northern coast is largely characterised by the presence of mangroves and tidal flats (Nayak *et al.*, 2012).

The gulf's water is highly turbid because water carrying a significant amount of sediment enters the gulf from the north-western side (Deshmukh *et al.*, 2005), whereas low turbid water entering from the south goes north along the south-eastern coast before turning north-east and east to reach the Gulf of Kachchh (Kunte *et al.*, 2003). Major source of sediment in the Gulf of Kachchh region is mighty River Indus (Deshmukh *et al.*, 2005). Tides regulate the sediment dispersal pattern in the gulf. The presence of numerous coral reefs in the southwestern region of the southern gulf has a significant impact on these tidal currents (Deshmukh *et al.*, 2005).

Several seasonal rivers drain into the gulf from the Kachchh mainland. These rivers primarily drain Juro-Cretaceous and Tertiary sedimentary rocks, as well as Late Cretaceous basalt; in coastal areas, they flow through unconsolidated Quaternary deposits (Prizomwala *et al.*, 2010). The Mesozoic, Paleogene-Neogene, and Quaternary sedimentary assemblages can all be found in the Kachchh Rift Basin, which is on the northern side of the Gulf of Kachchh (Kumari, 2022; Biswas *et al.*, 2021; Chauhan *et al.*, 2021; Solanki *et al.*, 2016; Fig.1F). Sandstone, shale, limestone, and basalt are the most prevalent lithologies in Kachchh mainland (Prizomwala *et al.*, 2010). Deccan traps lay disconformably over Mesozoic sediments to the south of the Gulf, which are then overlain by disconformable Palaeocene volcanoclastic sediments (Michael *et al.*, 2009; Fig. 1F). The peninsula of Saurashtra is mostly composed of Tertiary shale and limestone, with Late Cretaceous basalt and laterite rocks forming outcroppings along the coast (Prizomwala *et al.*, 2010). Geologically, the Kalubhar Island comprises calcareous clay and silty marl (https://bhukosh.gsi.gov.in/Bhukosh/MapViewer.aspx).

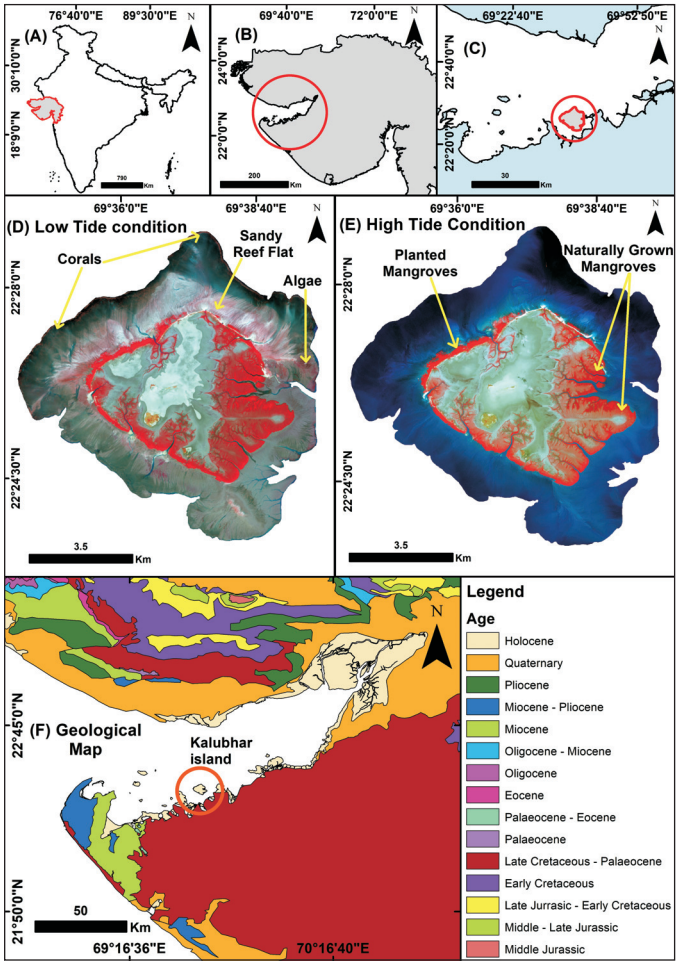

Fig.1. Map showing location of Gujarat in India (A), Gulf of Kachchh, Gujarat encircled in red colour (B), Kalubhar Island in the south-central part of gulf (C). D and E showing FCC of Kalubhar Island generated using Sentinel-2 imageries of 06 December 2020 and 11 March 2021 at low tide condition and high tide condition, respectively. Geological map showing the Gulf of Kachchh and environs, Gujarat. The study area *i.e.*, Kalubhar Island is represented in red circle (F).

Material and Methods

Sentinel-2A MSI satellite imagery of 06 December 2020 (Fig. 1D) and 11 March 2021 (Fig. 1E) at low tide and high tide condition, respectively, having 10m spatial resolution has been downloaded from the USGS Earth Explorer data portal from which the area of interest was extracted using QGIS 3.18. Out of its 12 bands, Green (Band-3), Red (Band-4) and NIR (Band-8) bands were used for generation of false colour composite (RGB 843) to extract different features employing visual image interpretation based on spectral signature, context and moisture content. Tidal networks present on the island were extracted from satellite image of high tide condition as they have better contrast for delineation of land water boundary. To understand geomorphology of the area and its relationship with tidal networks, mangrove areas and beaches were also digitised from satellite images of high tide condition. Data of low tide condition was selected to identify the live coral, sandy reef flats and algal area (Fig. 1D). Different types of tidal networks were identified and interpreted with emphasis on understanding geomorphology of the study area. To corroborate the changes observed in the extent of beaches, Landsat 8 (OLI) data of 09 March 2020 and Landsat 7 (ETM+) data of 05 November 2000 were used. Methodology adopted in this study is presented in the flow chart (Fig. 2). The observation from visual interpretation of the image has been corroborated with the available field information.

Results and Discussion

The Kalubhar Island comprises some major tidal creeks and many minor ones, mangroves, sandy reef flats, mudflats, live corals and algae. Results obtained on the nature of various geomorphic elements have been discussed in the following three subsections:

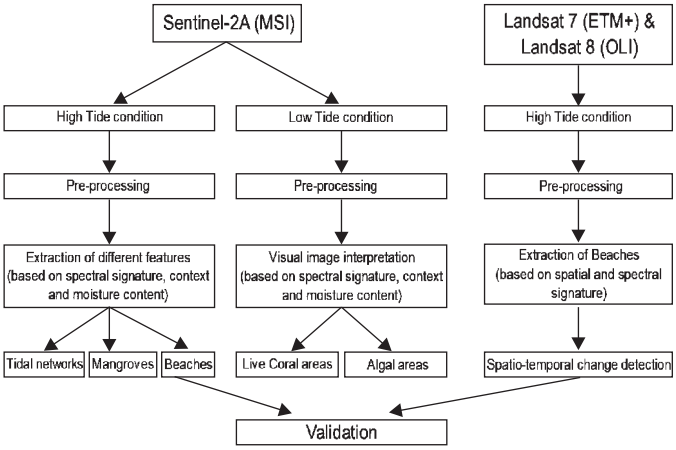

Fig.2. Flow chart of the methodology used in the study.

Tidal Network Patterns

The western and southern parts of the island contain major creeks that can be easily identified. However, tidal networks linked with these major creeks are not easy to identify due to their narrow width. Those tidal networks were visually delineated within the dense mangrove patches based on presence of water and moisture content as mangroves along such channels show darker tone in image of high tide condition. Some tidal networks were found having no discernible connection with any of the major creeks due to their initial stage of development. It is observed that eastern part of the island is having higher drainage density compared to the rest of the island. It was observed that the density of the higher order channels also remains higher in the eastern part of the island (Fig.3A).

Based on the extraction of tidal networks, six different types of tidal network patterns are found to be present in the Kalubhar Island namely dendritic, reticulate, linear, sinuous, meandering and meandering-dendritic (Fig. 3A) following the standard classification (Pye and French, 1993; Eisma, 1998). Geomorphological significance of different types of tidal network patterns has been identified in the Kalubhar Island (Table 1). It is observed that dendritic network systems are the most dominating type of tidal network pattern present on the island. This type of pattern is shown by channel number 1, 3, 4, 5, 6, 8 and 13 (Fig. 3A; Table 1). These channels are connected by large and wide channel which is well developed in intertidal area (Fig. 1D). Reticulate channel systems exhibited by channels 2, 9 and 10 are comparatively less in number than the dendritic type. These channels have many minor creeks joining major creeks at approximately right angle and are developed in moderately vegetated areas mostly dominated by mud and relatively low energy environment (Fig. 3A).

Mangrove Areas and Beaches

Mangroves, also known as the land builder comprises majority of the flora of the study area. In the study area, mangroves are growing naturally as well as due to plantation. Both can be identified in the satellite images on the basis of their tone and texture, and differentiated based on their location as mangroves plantation is taking place seawards (Fig. 1E). Larger patches of mangroves are observed in the eastern and south-eastern parts of the island while

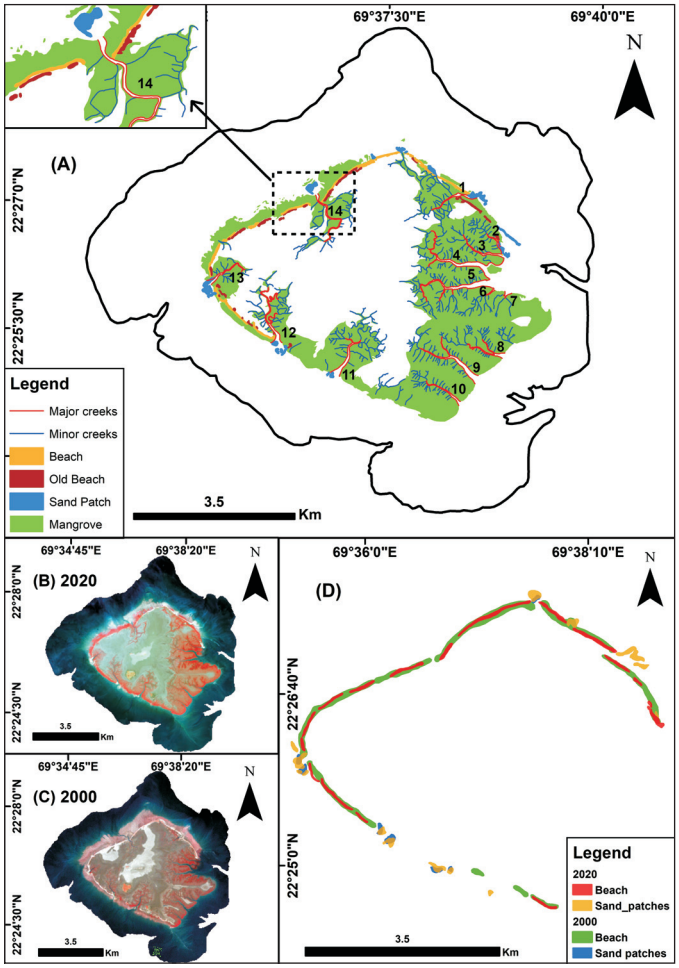

Fig.3. Map of Kalubhar Island showing distribution of major and minor creeks, extent of mangroves, old and current beaches, and Sand patches in Kalubhar Island (A), FCC of Kalubhar Island generated by using Landsat 7 (ETM+) of year 2000 and Landsat 8 (OLI) of year 2020 (B and C, respectively), Data showing beaches and nearby sandy patches during the years 2020 and 2000 (D).

relatively smaller patches are observed in the western and northern parts of the island. Larger patches of mangroves are present in the eastern part of the island due to presence of higher density of tidal channels and these mangroves are grown naturally while planted mangroves on the western, north-western and north-eastern parts of the island appear to be expanding seaward of beaches. The mangroves are thriving in those areas due to the plantation activities and the protection provided to them for their growth, which otherwise are not the ideal geomorphic location for their habitation and growth (Fig. 1D). Live coral areas are largely restricted to the outer intertidal regions (Deshmukh, 2003). Seaward expansion of the planted mangrove patches coupled with long subaerial exposure of the tidal flats during low tides and sediment deposition may further reduce areas of live corals in future (Deshmukh, 2003).

Beaches are absent in the south and south-eastern parts of the island as the energy there rather facilitates mud deposition which through the course of time are being habitated by the mangroves naturally (Fig. 3). In the areas of plantation, it was observed that the mangrove cover is increasing seawards beyond beaches as a result of which the beaches are also shifting. In Sentinel imageries of 2021 old beaches were identified and differentiated from current beaches on the basis of spectral signatures as current beaches appear brighter

Table 1: Various types of tidal network patterns as identified in Kalubhar Island and categorised based on the typology (*After,* Pye and French, 1993; Eisma, 1998)

Type of network patterns	Channel number	Geomorphological significance
Linear	7	More likely develops on easily eroded, non-cohesive and unvegetated substrates
Sinuous	14	Sinuosity increases as channels extend into vegetated regions such as salt marsh (Pestrong, 1965; Garofalo,1980; Eisma, 1998)
Meandering	12	Highly sinuous channels having sinuosity ratio >1.5 are termed as meandering channels. In the smaller creeks, the meandering is more intense.
Dendritic	1, 3, 4, 5, 6, 8 and 13	The smallest, or first-order, channels abruptly cease on the marsh platform or tidal flat, and are fed by sheet flow over the inter-channel zones. Two of these smaller channels connect to produce a larger (second-order) channel in a conventional dendritic system, and so on, until the system's highest-order channel is attained.
Meandering-dendritic	11	Grow across the line separating the vegetated salt marsh from the sandy tidal flats
Reticulate	2, 9 and 10	Reticulate channels are a kind of dendritic channel that differs from others in that the low-order channels meet the higher-order channels at a 90° angle. First-order tidal creeks usually end at a right angle to the higher-order, whereas higher-order channels usually meet at a lower angle (Zeff, 1988; Eisma, 1998; Ginsberg and Perillo, 2004).

in satellite imageries than the old beaches. Presence of dust and sparse vegetation give a comparatively darker tone to the old beaches. Changes in beaches were further validated from the extent of beaches identified in the Landsat satellite imageries of the years 2020 and 2000 (Fig. 3B-D). It was observed that in such places, finer sediments are also being entrapped and deposited in the areas seaward. Further, it is observed that sand deposition at the mouth of channels have also increased in last two decades (Fig. 3D). From the temporal data it was observed that beaches have become narrower and shifted seawards in northern, north-western and south-western parts of the island. These changes could have taken place due to plantation of mangroves which reduced energy and acted as barrier for sediments carried by tides.

Intertidal Areas and Sedimentation

Width of the intertidal region of the island varies in different parts of the island (Fig. 1D). Intertidal flats in eastern and south-eastern parts of the island are comparatively narrower than other parts. Flora other than mangroves includes the algae which forms large mats in the eastern part (Fig. 1D). Live coral colonies have been observed mostly in the northern and north-western parts in seaward areas of the intertidal zone.

Sediments deposited around the island vary in size as finer sediments are deposited in the eastern, southern and south-eastern parts while relatively coarser sediments are deposited on the northern, western, north-eastern and north-western parts of the island. Presence of shoals at the mouth of the Gulf of Kachchh reduces the energy of the water (Kunte *et al.*, 2003). Due to reduction in the energy, coarser sediments get mostly deposited at the mouth of gulf and finer sediments in the form of suspended load are carried forward. In the study area, coarser sediments are observed to be mostly restricted to the region from north-east to north-west, while the finer sediments get carried away further into the gulf as suspension (Deshmukh, 2003; Kunte *et al.*, 2003). Presence of the live coral colonies in the outer western and northern parts of island also affects the sediment deposition. The southern and south-eastern regions of the island face the least current energy, creating an ideal environment for suspension load deposition as evident by the presence of large muddy areas. Deposition of mud particles and marshy condition provides favourable condition for the growth of mangroves hence mangroves are best grown naturally in this region (Fig. 4).

Sediments deposited at the mouth of channels in north-western region show sediment transportation towards the north-eastern direction while the north-east and south-western regions show shifting of sediments towards north-western direction. This shifting can be associated with the lower energy ebb tide current. When the water escapes from the entire gulf, it sweeps along the island as a clockwise current on the entire western coastline and as an anticlockwise current on the entire eastern coastline (Fig. 4). This explains why the sediments have been reworked in contrasting manners on either side of the island. Due to this same effect the northernmost tip of the island is believed to be acting as a pressure shadow region. This is the conjuncture of two currents with contrasting directions, as a result of which the net energy here anomalously drops, hence creating an ideal environment for coarser sediment deposition. This is seen evidently as the northernmost tip

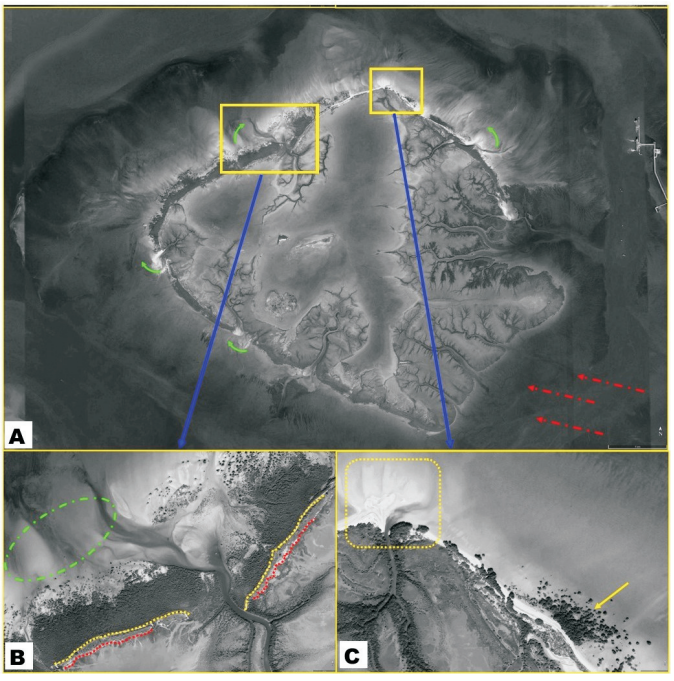

Fig.4. (A) Dotted red arrows show net direction of ebb current while green arrow represents sweeping of current in clockwise direction in western part and anticlockwise in eastern part of the island. (B) Green dotted circle showing deposition of mud particles due to growth of mangroves. Red dotted line represents old beaches while yellow dotted line represents shifting of beaches seawards. (C) Solid yellow arrow showing mangrove plantation and yellow box showing sand deposition at the northern tip of the island.

shows maximum amount of sand deposition in the intertidal area (Fig. 4).

Conclusions

This study has been carried out to understand geomorphic characteristics prevailing on the upper intertidal region with the help of tidal networks, mangroves and beaches. Result of the study lead to the following conclusions and recommendation: Use of high spatial resolution image such as Sentinel-2A (MSI) is helpful in extraction of tidal channels which otherwise may not be easily identified in images of coarser spatial resolution. Of the six types of tidal networks identified in the study area, dendritic networks are the most dominating network type. Other five types are sinuous, reticulate, linear, meandering and meandering-dendritic networks. Density of the tidal networks is observed to be higher in the eastern part of the island. Presence of relatively larger mangrove patches and mud deposition in the eastern region suggests that eastern, south-eastern and southern parts are experiencing comparatively low energy environment. Mangrove plantation in western, north-western and north-eastern parts has resulted in their seaward expansion which coupled with long subaerial exposure during low tides and sediment deposition may further restrict the areas of live corals. To better understand the geomorphic process active in the region study of characteristics of tidal networks present in lower intertidal areas are required.

Authors' Contributions

Rohitash Kumar: Conceptualisation, Methodology, Data Acquisition, Processing and Analysis, Writing-Original Draft. **Sourish Chatterjee:** Interpretation, Editing. **Rohit Kumar:** Data Processing, Editing. **Benidhar Deshmukh:** Conceptualisation, Methodology, Data Analysis and Interpretation, Reviewing and Editing, Supervision.

Conflict of Interest

Authors declare no conflict of Interest.

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