[1]NDVI-Based Vegetation Dynamics on Coastal Sand Dunes Responses to Climatic Change in Western Kachchh, India

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Abstract

The present research aims to examine the vegetation dynamics of selected eight dune sites on the Kachchh coast from Jakhau to the east of Kori Creek by utilizing remote sensing methods to assess the stability of dunes and the extent of the inland dunes. Normalized Difference Vegetation Index (NDVI) analysis has been performed to address this issue, and dune stability maps were produced from the downloaded Sentinel-2A (S2) data. The NDVI was computed with the help of Arc GIS's spatial analyzer and the NDVI of coastal dunes was automatically extracted. The prime points of this method are: 1) Vegetation dynamics of dunes in terms of their extent inside the mainland 2) Normalized Difference Vegetation Index (NDVI) approach to the coastal dune's stability and its extent from the near coast to the inland 3) Defining the relationship between vegetation dynamics among climatic variability of coastal dunes system. Results based on NDVI analysis show that many of the coastal dunes close to the sea are stable while some inland ones are active. Hence, the present work could provide significant information on the dune's stability and climatic variability.

Keywords: **Sand Dunes · Remote Sensing and GIS · Normalized Difference Vegetation Index · Sea level rise · Kachchh coast**

1. Introduction

The coastal dune system is generally found opposed to the beach backshore zone [20] and is inhabited in a wide region across the Kachchh coast. Since the early 19th century, sand dunes have been a topic of investigation [4]. The sediments of the beach intertidal region acquire frequent and periodic exposures to the onshore winds and are adapted as coastal dunes. Sand transportation towards the beach is responsible for the formation of sand dunes along the coast. The source of sand is fluvial until that occupies the offshore, which is eroded from cliffs by waves and carried along the shoreline by ocean currents. Coastal sand dunes grow best on low-angle coasts with dissipative wave domains (spills), where the beach dries out when the sea is shallow, or where splash shields are welded on the higher beach on a regular basis [12][89]. The coastal dunes are

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essential components of the coastline's landform associated with sea level changes. The formation of coastal dunes is governed by changes in terms of wind regime, tectonic and hydraulic factors, and sediment supply [7][26][70]. The importance of vegetation in trapping, fixing, and accumulating the sediments as well as the involvement of the waves in the development of beach morphology, reloading the sediment sources and reworking the foredunes are useful in distinguishing the coastal dunes from most active dunes in arid regions. Dunes of different sizes and morphologies are generated depending on the features and availability of the sediment supply, prevailing wind velocity and direction, moisture and vegetation present, and the geomorphology of the nearshore and beach face [89]. A widespread landward migration and the disappearance of sedimentary beaches are the results of the rise in sea level and global climate variability [35][64][74][82]. Low-lying places become permanently submerged by rising sea levels, and/or their vulnerability to sporadic overflow of water from storm heaves, tsunamis, and extremely high astronomical tides [46][100]. The vegetation better stabilizes and holds the dune sediment, captured the loose wind-blown sand, increases the dune-fringed beaches' physical resilience to wave erosion episodes and overall increases the dune height and volume [38]. Increased dune volume results in more inertia and reduces the rate at which barrier shorelines are retreating, although dune crest elevation is a crucial factor in determining overwash vulnerability [41]. The morphology and behaviour of coastal dunes change according to shifting environmental factors. The dynamic sand blow causes dunes to break apart and drift and is generally used to study these changes from stable, vegetated situations. During the Last Glacial Termination (22 - 11.5 ka) and succeeding climatic eras of the Holocene, actively drifting (unvegetated) coastal dunes were common [23]. For instance, the episode of the active coastal dunes (detected by sand-blow) across Europe between 1300 AD and 1850 AD during the LIA, led to remarkable human intervention (deliberate afforestation) to stop the progression of inland dunes [22][43]. The area of dune vegetation and stability both increased at the termination of the LIA, which was also accompanied by a general drop-in dune activity.

Numerous local and regional investigations during the last few decades have shown a decline in the mobility of coastal dune activity. For instance, over a 34-year period, variations in rainfall and wind speed were correlated with the increasing vegetation cover and drifting potential of dunes in southern Brazil [24]. Gao [37] made an attempt to understand the global trends and the main drivers for the shifting of coastal dune mobility by studying 176 individual dunes for the period 1870 – 2018 and the study reveals that dune stabilization can be seen worldwide due to the rapid growth in urbanization and vegetation. The study also reported that the stabilization of dune is due to various factors including anthropogenic activities have played a major role in shifting the dunes during the last century while the main drivers for the dune sites without anthropogenic activity was governed by storms and changes in climatic condition. Kar [49] describe that in the Thar desert, the sand control measure of the dune-covered area is dependent on vegetation propagation; no mechanical and chemical control methods are applied. In the Thar Desert, he identified two groups of dunes - new dunes and old dunes based on dune types, morphology, mobility of dunes, vegetation condition and land use practices etc., where the new dunes are mobile, and mobilization is due to mechanical processes; old dunes are naturally stabilized and reactivated in recent times due to the increasing population in the area. He suggested that the dune fields are the natural laboratory where one can find enough clues of possible parameters of sand movement as well as the controlling measures of such deposits. He also concluded that for any type of sand control measures study, it is important to understand the geomorphic characteristics as well as the interactions between the geomorphic processes and the morphology of the sand dune.

Dunes along the coastal region are an important geomorphic feature of both India's western and eastern coasts [1][65]. Few researchers have tried to rebuild sea level changes on the western coast of India [83]. Studies related to sea level change along the Kachchh coast of western India are just initiated by a few researchers wherein they have established the sea level fluctuation in Holocene and late Holocene period [25][61]. There is a huge concurrence with the researchers that during the Last Glacial Maximum (LGM), the mean sea level was 120m down than the present day [14][47][63]. Also, very few research has been attempted on the geomorphology of the Kachchh coast and the sediment texture [48][63][79][90]. Limited papers were published related to the Kachchh coast's current dynamics, sediment type and sediment supply of sea surface or other sediment provenance in this macro-tidal regime [3][17][52][66]. Due to the offshore dynamics of the coastline, many researchers are interested to study on the Kachchh coast. Overall, after seeing attempts to research the Kachchh coastline, it has been recommended as 'terra Incognita'. It is also established that the provenance of the sediment of the Kachchh coastline is mostly from the Indus River [79][80][78]. Some other workers are also having similar work at the Kachchh coastline using satellite imageries and the Suspended Sediment Concentration (SSC) [52]. The Holocene epoch has seen climatic shifts and ancient civilisations' corresponding growth/decline [55] [76][77][94]. Numerous studies have identified the occurrence of aridity both worldwide and regionally, including the 4.2 ka drought spell that corresponds to the Meghalayan Era [8][50]. Ancient human civilizations and coastal villages both benefited due to the increase in sea level during the Holocene [93][27][28][54]. The geomorphology, ecology, coastal communities, and settlements can all be significantly impacted by minor sea level changes along the coastlines. To comprehend the existing and projected climate change estimates, the paleo-record of the climate and its nature must be reviewed.

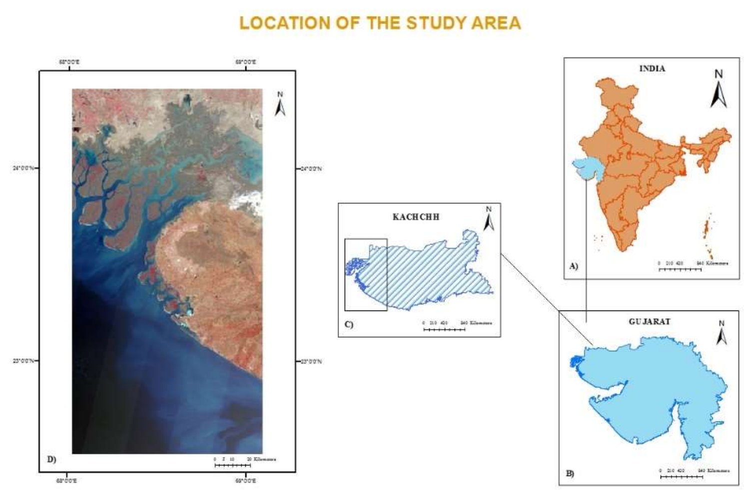

Figure 1. Study area map showing the far western coast of Kachchh.

Both India's western and eastern coasts contain distinct geomorphic structures known as coastal dunes [1][65]. The current study focuses on the expansion of coastal dunes along the western coast of Kachchh Mainland, situated at the westward edge of Gujarat (Fig.1). When dunes are close to settlements or agricultural fields and begin to advance toward them, it is crucial to have a substantial understanding of dune dynamics. Numerous research has been conducted, utilizing both conventional field survey methods and remote sensing techniques to better understand how wind-blown sand builds up in sand dunes. Our study aims with the following objectives - 1) Vegetation dynamics of dunes in terms of their extent inside the mainland. 2) NDVI approach to the coastal dune's stability and its extent from the near coast to the inland. 3) To characterize how vegetation patterns in the coastal dune system correlate with the climatic variability of the region. 4) To acquire the spatial pattern of the vegetation dynamics at the regional and pixel scale in the Kachchh coastal region. In the present study, coastal dunes located at the western coast of Kachchh between Jakhau port and Kori Creek have been taken into consideration to analyze the change in vegetation pattern (Fig.1). To find out the stability of the dunes system based on the amount of vegetation, NDVI analysis were obtained from the Sentinel-2A data from eight sites along the western Kachchh coast (Fig.1 and 2). The outcomes of this study may offer a thorough understanding of vegetation dynamics and theoretical direction for dunes stability and climatic changes in the Kachchh coastal region. Remote Sensing and GIS techniques are frequently used for mapping and evaluation of coastal dunes. A wide variety of spatial scales, objectivity, repeating coverage, the multispectral dataset from several satellite platforms, economy, and effectiveness are only a few of the many advantages of RS data analysis for coastal dunes [72][67].

2. Study Area

The area of present interest lies between Jakhau port and Kori Creek in the west on the western Kachchh coast (22°15´N to 23°40´N latitude & 68°20´E to 70°40´E longitude) (Fig.1 and 2). Kachchh is known for its long-lasting aridity in western India; it also has various ecological habitats and ecosystems. Kachchh coastline is one of the most rapidly industrializing coastlines in western India [96]. The Kachchh coastline covers an area of 406 sq. km and it consists of the villages like Lakhpat, Jakhau, Mandvi, Mundra, Kandla etc. The Narayan Sarovar-Jakhau, Jakhau-Khuada, Khuada-Bhada, Bhada-Mundra, and Mundra-Surajbari segments are the five morphologically dissimilar geomorphological segments that divide the west-to-east coastline of Kachchh [48][63]. Variability in the intertidal zone width, formation of landforms like bars, beaches, and spits, width of the mobile and stabilized coastal dunes, raised mudflats and beaches, uplifted estuarine tidal terraces, and the expansion of coastal alluvial plain in the Jakhau-Khuada and Bhada-Mundra segments are the main geomorphic features of interest [48][63]. It developed a transition zone between the water body and the land where the terrestrial environment affects marine [12]. The Kachchh coast is classified as a submerging (estuarine) coast [1]. Kachchh Coastal Plain is a primarily low-lying and flat area with sparse but wide-open vegetation as well as immense mangrove formations. The continental shelf here is about 164,000 sq km which enables fishing grounds [5]. The geology of the Kachchh coastline consists of Tertiary and Quaternary sediments. Mandvi and Pingleshwar coast of Kachchh is sandy and happens to be a favourable breeding or nesting ground for sea turtles [5]. The geomorphological system of the Kachchh coast is susceptible to the environment, always in equilibrium with the deposition and erosion of sediments as well as continuously forming the landscape [11]. In the coastal area of Kachchh, the Tertiary rocks are well exposed in the western part while in the eastern part, the mudflats are covering all the rocks and also massive port development in the eastern segment. Tertiary rocks are found to be deposited on the weathered and eroded rocks of the Deccan Trap and sedimentary rock platforms of the Mesozoic period. Since the study area lies in the zone of tropics of cancer, it belongs to the sub-tropical climatic zone.

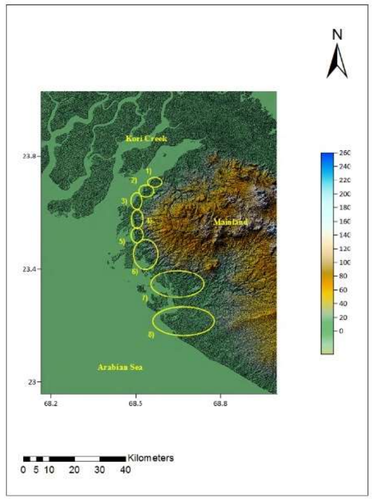

Figure 2. DEM map of the western Kachchh coastal area showing prime villages/ locations in the yellow eclipses indicate the marked dune sites – the windows.

3.Materials and Methods

3.1. Method

The selection of dune sites was based on a variety of requirements or criteria, including the presence of a large transgressive dune field that was sufficiently expansive in space (in kilometers) to be sufficiently imaged by Sentinel Data and that showed clear signs of inland migration. So, the following criteria were used to choose the site: (1) be situated in non-polar, non-arid areas; (2) have little to no human influence; (3) have a major interior expansion and a vast coastal dune field (more than 5 km^2). Figure 2 shows the methodology flow chart and gives an overview of all the processing and analysis done to accomplish the aim of the present study.

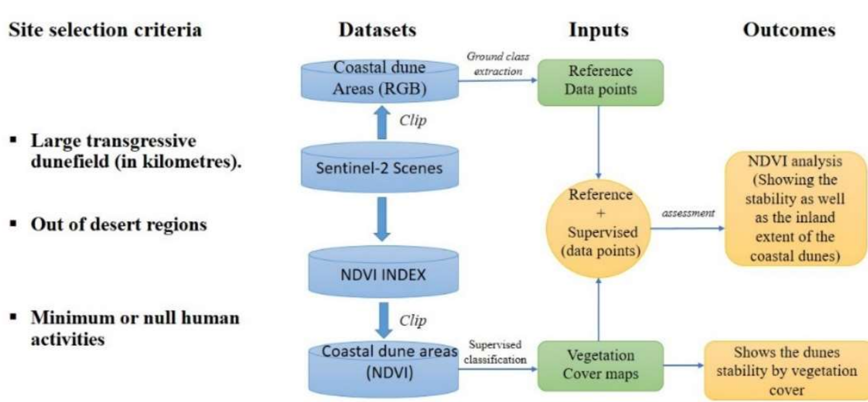

Figure 3. Flowchart showing the methodology used in the present work

3.2. Data Source

Remote sensing is a special technique for keeping an eye on deltaic and coastal habitats which can provide important preliminary estimations of change [18]. Compared to conventional methods, remote sensing data have shown to be more useful for change detection assessment in coastal zones [85]. The present study used the Sentinel-2 data to perform the NDVI analysis of the coastal dunes of western Kachchh. Multi-temporal satellite data downloaded on 13 April 2022 was selected as it was freely available from the USGS data archive *(http://www.eros.usgs.gov)*.

Table 1. Details of Sentinel Data used for classification.

Satellite	Sensor_ID	Dataset Provider	Date of acquisition	Spatial Resolution (m)
Sentinel-2 L2A	MSI	Copernicus	13 April 2022	10m to 60m

3.2.1. NDVI data set

The visible band (red) and near-infrared band (NIR) of the Sentinel-2 data are transformed nonlinearly to get the NDVI. It is the difference between these two bands (visible and near-infrared), over their sum. It is also an alternate method to measure the extent of vegetation cover and the condition associated with the vegetation canopy features such as biomass, leaf area index and percentage of vegetation cover. Vegetation indices (VI) have been employed in remote sensing for a long time to monitor the temporal change in vegetation patterns [59]. The NDVI has been used by many as an accurate indicator of vegetation health [10] which can be obtained using the below equation:

$$NDVI = (NIR - Red)/(NIR + Red) \quad (1)$$

where the terms Red and NIR stand for measurements of spectral reflectance made in the red (visible) and near-infrared bands, respectively [81]. This data is collected on 13 April, 2022 from the USGS website *(http://www.eros.usgs.gov)*.
NDVI value ranges between -1 to +1 while the good vegetation is having high NDVI values of 0.1 - 1. However, water bodies are non-vegetated surfaces having great reflectivity in both the Red and NIR bands and hence showing negative values that are close to “0” [57]. For change detection monitoring, a variety of techniques using NDVI categorization are used [35]. RGB-NDVI classification is the quickest and simplest way to evaluate how vegetation has changed. For the present study, satellite images of the eight dune sites were stacked and RGB-NDVI is produced. Due to chlorophyll absorption, healthy vegetation often exhibits significant reflectance in the near-infrared area but low in the red visible range. In both bands, transitional zones and portions of water have proportionately darker tones. It is anticipated that the value of the vegetation-covered land mass will be significantly greater than that of the ocean/sea. Based on the above reasoning, NDVI was used to segregate the coastline and demarcated the water and land in LISS-III and ETM+ using threshold values of 0.33 and 0.20 respectively. The thematic layer resulted was then divided into land and water up to the seashore. But each form of land cover lacks a clear border. When the NDVI value is nearby to 0, the region will be having degraded or deserted land and when the value is close to +1, there will be green leaves or vegetation cover while the negative values indicate water bodies.
For the current study, four signatures such as water body, vegetation land, degraded land

(severely affected) and deserted land (very severely affected) are considered using ArcGIS software.

Supervised classification

In supervised classification, unknown identity pixels were classified using samples of known identities. The coastal and inland vegetation of selected dune sites in the study area is mapped using a supervised digital classification method which is assumed to be the most adequate method of classification for remote sensing data. The characteristic spectral information of the classes such as agricultural land, mixed mangrove, salt marsh, dune and other vegetation are then produced for the selected dune sites in the satellite imageries. After selecting the dunes, ArcGIS software was used to run the classification on the image.

3.2.2. Climate data set

The southwest monsoon season governs the wave regime in the present study area. The sea is calm when the monsoon retreat, but on prevailing southwest monsoon, powerful waves are frequent for shorter periods. The wave height (Hs) can be seen between 4.2 - 4.4 meters [68]. The prevailing wind system is seasonal, with occasional cyclonic disruptions. From June to September, the region has west-southwesterly winds, while from December to March, it experiences north-northeasterly winds. The windiest months are June through September. The alongshore current, which travels from the Indus Delta in the west to the Gulf of Kachchh in the east is accountable for the dispersal of the suspended particles in the Gulf of Kachchh [88]. The area receives 310 mm of precipitation each year, and the typical summer temperature ranges from 48 to 50 ^{0}C [6].

4. Results

4.1. NDVI Approach to the Coastal Dunes

The NDVI of each of the satellite images for the selected dune sites regarding the present study has been generated. A total of eight NDVI images of the western Kachchh coastal area between Jakhau and Kori Creek are identified (Fig. 5). RGB-NDVI combination shows dune vegetation as green spots which suggests an increase in the accumulation of healthy vegetation over the dune and thus the stability of the dunes. Eight major dune sites were selected as some of them are stable and fixed with the vegetation and the others are showing their inland movements, which means they are active and movable; defined by dune vegetation, mudflats, soil, and saltwater identified using satellite data (Fig. 5). The encircled sites are named (a) Akri Moti Sand Dunes (b) Khirsara Sand Dunes (c) Narayansarovar Sand Dunes (d) Lakki Sand Dunes (e) Gugariyana Sand Dunes (f) Guharmoti Sand Dunes (g) Jakhau Sand Dunes (h) Dhunay Sand Dunes.

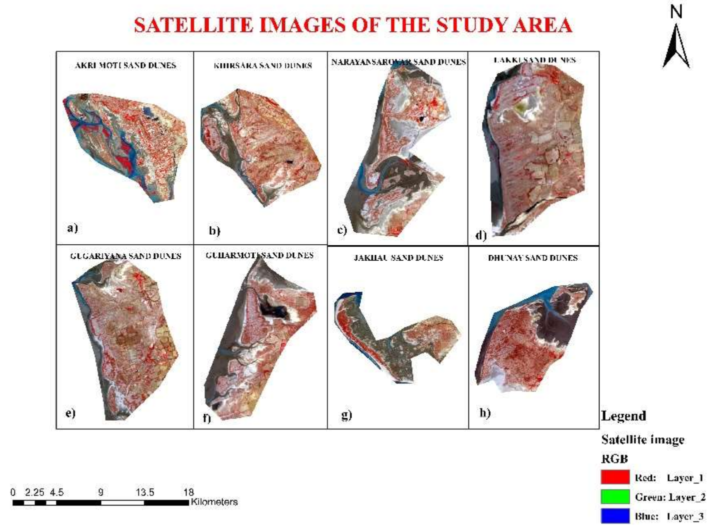

Figure 4. RGB Satellite images of the study area from windows (a)-(h), Window-(a) stands for Akri Moti Sand Dunes, Window-(b) stands for Khirsara Sand Dunes, Window-(c) stands for Narayansarovar Sand Dunes, Window-(d) stands for Lakki Sand Dunes, Window-(e) stands for Gugariyana Sand Dune, Window-(f) stands for Guhar Moti Sand Dunes, Window- (g) stands for Jakhau Sand Dunes and Window-(h) stands for Dhunay Sand Dunes.

4.2. Geomorphic characterization

Based on the RGB satellite imageries and Google image observations, the geomorphic features are identified for all the study windows (a-h) shown in (Fig. 4). The entire system from Lakhpat to Jakhau is almost 100km long where dunes are frequently found along the coast and are either sitting on the Tertiary hard rocks or the raised mudflats. These dunes are stabilized at places while at many places they are active.

(a) Akri Moti coastal dunes (23°21'06.69"N - 68°38'52.76"E)

The linear and longitudinal dune ridges are overlying the upper Tertiary sequence (Miocene) on the surface. This section has largely two geomorphic domains; first the active mudflat system with mangroves and dunes overlying the mudflats in the west, and the second is the NE-SW trending dunes sitting on the Tertiary hard rocks (limestone and sandstone) and also on the alluvial deposits in the hinterland area to the east (Fig.4(a)). These hinterland dunes are sparsely vegetated. On both sides, the dunes are partly covering the earlier erosional landscape.

(b) Khirsara coastal dunes (23º29'10"N – 68º31'21"E)

In Khirsara coastal dune system, a small patch of longitudinal dunes is observed to the west of the area, mostly covered by the active mudflats that are overlain by the dunes with a good amount of vegetation, while the hinterland area has majorly Tertiary limestone and sandstone or Recent alluvium which is sparsely covered by the thin veneer of dunes (Fig.4(b)). The flat and westward sloping erosional rocky landscape is distinguished by the yellow to brown color while the erosional depressions are accommodated by the alluvium depicted by the farmlands in FCC (Fig.4(b). The white and light-colored patches are the areas covered during the extremely high tides and storm surges making it more saline; they are probably the paleo-mudflats. In the far west, on a detached island, the dunes seem to be stabilized as they are covered by vegetation (Fig.4(b). This island is surrounded by active mudflats.

(c) Narayansarovar coastal dunes (23°40'39.73"N - 68°31'43.86"E)

These dunes are also stretching along the eastern bank of Kori Creek, trending 50° to 60° north, and are located above the Tertiary Oyster beds (Fig.4(C). The series of longitudinal dunes are mostly arranged in a straight and linear fashion from Koteshwar to the south, beyond the BSF camp of Narayan Sarovar. These dunes cover a large area of possibly raised mudflats that during the high storms only filled up by the water, while during most parts of the year remain flat saline wasteland. The long axes of the dunes are mostly SW, i.e. the direction of the SW monsoon winds. Geologically, Narayan Sarovar pilgrim place is sitting on the Tertiary/ Miocene sandstone with anticlinal and synclinal structures. The dunes to the west and southwest of it are also overlying the Tertiary beveled rocks. There are mudflats capping on the same beveled hard rocks, out of which some are slightly raised than the active mudflats. This conspicuous dune system continues to the south for about 20 km with some intermittent breaks (Fig.4(c).

(d) Lakki coastal dunes (23°35'36.67"N - 68°29'45.20"E)

This refers to the active transverse dunes in the main dune field as well as portions of the seaward fringe. Near the BSF outpost of Lakki–Rodasar, large numbers of stabilized linear dunes are found with conspicuous interdune depressions. The width of the dune field is not exceeding 1.5 km from the coast to the hinterland which is projected by the pixels and colors in the RGB, Google Earth, and processed images. Most of the dunes found near Lakki-Rodasar are dotted with much vegetation, confirming them to be stabilized ones (Fig.4(d). The upper veneer of the dune sand is active at places while most inter-dune depressions are mixed with the alluviums and are stabilized. A river passing from the south of the Lakki dune system supplies the sediments and deposits them in the mouth region making a dynamic fluvial system for a short distance along the coast (Fig.4(d).

(e) Gugariyana coastal dunes (23°34'08.01"N - 68°29'41.69"E)

The sequence of dunes lies between Khirsara and Gugariyana in a straight line and also in the form of discrete islands all along the coast (Fig.4(e). In fact, this is the area where large numbers of mangroves are found with low islets and intermittent creeks to the west of the dune system towards the sea. It is a straight aeolian sequence that runs parallel to the coast where most of the dune’s patches are stable and are extended inland for about 400m to 1.1km (Fig.4(e). The westernmost tip of India falls at this section, where the Tertiary rocks are exposed. Large exposures of Tertiary sandstones and limestones are covered with the thin veneer of the sand dune system.

(f) Guhar moti coastal dunes (23°37'29.56"N - 68°30'39.17"E)

Here, also like the other adjoining segments, thick aeolian deposits are resting over the Tertiary/ Miocene hard rocks and mudflats. This segment is just a few meters north of the Lakki-Rodasar segment and has almost similar geographic and geological setup. The dunes cover most of the seaward extensions of the bedrock bevels as well as raised or paleo-mudflats.

(g) Jakhau port coastal dunes (23°13'35.85"N - 68°35'17.28"E)

A straight line of stable longitudinal dune profile is exposed along the coast near Jakhau port (Fig.4(g). On average, 100 to 500m wide and 5 to 10m high dune field covering the port from the open sea, securing it from the high sea storms. In fact, the dunes are sitting on the raised mudflats and collectively making the entire zone almost 2 km wide. The strip of dunes when goes down southeast, it becomes thinner to about 50m wide only and forms the backwater for several (~14) kilometres. This narrow strip shields large salt pans of Jakhau. Between these salt pans and Jakhau port, there occurs another hinterland/ inland dune complex spanning 3 km (length) and 2 km (width) (Fig.4(g). These dunes seem to be highly stabilized with immense vegetation on them; however, looking at their discontinuity in length, they may be the relics of the older dune system (Fig.4(g). The inter-dune depressions are mostly covered by thick vegetation. They were also found to be overlying the mudflats and partly on the Tertiary hard rocks.

(h) Dhunay coastal dunes (23°42'40.59"N - 68°33'40.93"E)

These dunes stretch along the eastern bank of Kori Creek, trending 50° to 60° north, and are located above the Tertiary Oyster beds. These are mostly stable and densely vegetated throughout the length (Fig.4(h). There is a large gap of raised mudflats between the Narayan Sarovar dune complex and the Dhunay dune complex. They make initially straight coastline trending NNE and from a certain point it runs parallel to the trend of the dune's longitudinal direction i.e., N 50^0. A line of discontinuous dunes sitting on the mudflats runs to the east where the dunes are overlying the Tertiary (Eocene and Miocene) beds.

5. Discussion

Figure 4 cover all eight studied segments of the western Kachchh coast dune system that depicts the marked regions across a series of satellite photos to show how vegetation cover has grown and bare sand parts have disappeared. There is evidence of rapid vegetation that spread throughout the entire dune field. This refers to the mobile or active transverse dunes in the main dune field body as well as portions of the seaward fringes. The primary dune field's initial vast expanses of bare movable sand are divided into isolated basins and separated from one another by vegetation. The size of these basins then progressively decreases as the margins are colonized by vegetation, resulting in a mostly stable dune landscape. Modifications to vegetation succession and structure can affect or alter dune morphology [104][84]. In all the segments, the quantity of vegetation cover is considered rather than its type which is excluded from the observations. Further, the species distinction cannot be studied due to the examined pixel size.

5.1. Dune Dynamics and Stability

Dune dynamics along the coast are known to be affected by various environmental factors that include: (i) air temperature, which affects the growing time span of dune plants each year (typically, the sum of all days with temperatures >/= to 5 °C); (ii) concentrations of greenhouse gas and CO2 affecting the growth rate of plants; (iii) rate of precipitation, which affects the fluctuation of water level and, in turn, the availability of water and moisture; (iv) wind patterns that control the ability to move sand and, eventually, control the substrate and circumstances for plant life and (v) declined in the supply of beach sediment to dunes due to which a quarter of the world's sandy beaches have become deficient in recent years [58] can significantly reduce the volume of coastal dunes that are mostly stabilized by vegetation (so static) and so lower possibility for lodging space to store any new beach sand attempting to obtain inland access. This causes the sand to "back up" at the back beach area, and depending on the situation (i.e., if the tidal reach permits more wind deposition), the sand may also collect in the supratidal zones under this stabilized main dune state. Greater foredune (vertical) development is projected to produce a better buffering effect, giving coasts a better-protected dune line for potential future dune trimming events that could occur as a result of either rising sea levels or increased storm activity. The likelihood of new beach sand trying to move landward and finding a place to stay is substantially lower in coastal dunes that are mostly stabilized by vegetation (static dunes) (Fig.4 and Fig.5). Due to the fact that sand dunes change from a stable condition to an active state over relatively short periods of time (often several years to decades), provide a chance to evaluate the relationships between environment, land use, and geomorphologic processes [56][103]. The dunes found all along the western coast of Kachchh (all eight windows under study) are stabilized on the supratidal flats and those occurring inland are partly stabilized and partly dynamic in nature (Fig. 5). The reasons for their stability could be one of the five mentioned above or they may be more than one out of them, owing to the variable nature of climate in Kachchh in the last few thousand years.

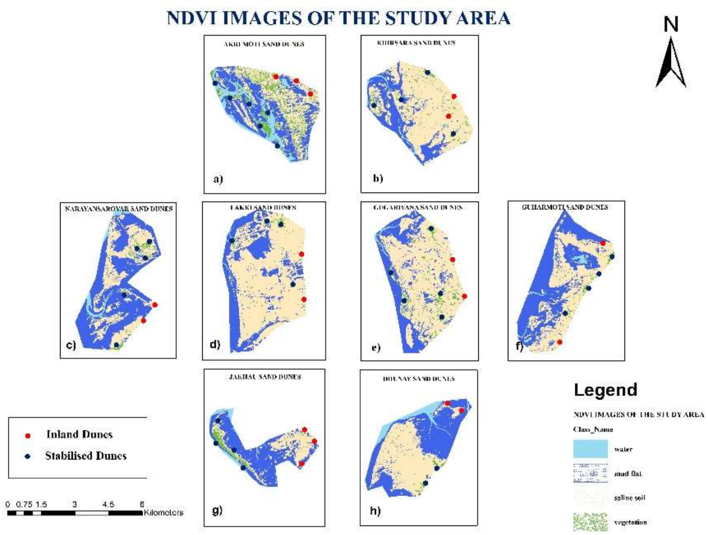

Figure 5 -NDVI images for windows (a)-(h), where FCC images are further processed to generate NDVI image to get the clear picture of vegetation cover in each segment. Window-(a) stands for Akri Moti Sand Dunes, Window-(b) stands for Khirsara Sand Dunes, Window-(c) stands for Narayansarovar Sand Dunes, Window-(d) stands for Lakki Sand Dunes, Window-(e) stands for Gugariyana Sand Dune, Window-(f) stands for Guhar Moti Sand Dunes, Window- (g) stands for Jakhau Sand Dunes and Window-(h) stands for Dhunay Sand Dunes.

5.2. Climate variability and Dune stability

Aerial photographs and climatic time series from the past can be used to analyze variations in dune activity since dunes (both inland and coastal) respond quickly to changes in climatic conditions [56[62][42]. Climatic factors like precipitation, temperature, evapotranspiration, and wind speed are the criteria to assess dune mobility [102]. The amount of water available for plants in some desert dunes is what limits plant development and aeolian activity [53]. Coastal dune stability in response to climate change has a significant consequence on dune management and the effects of storms.

Increased vegetation cover increases the possibility of sediment holding capacity at the shore because silt is stored while dunes grow laterally and vertically (seaward). Increases in flora may help delay the retreat of the coastline along dunes because strongly vegetated coastal dunes are found to be 30 per cent more resistant to erosion from marine storms [2][33][91]. Several studies assert that tropical cyclones (hurricanes or typhoons) would occur more frequently, would be stronger, and cause greater destruction [32][51][101]. However, some studies claim decreased in their frequency [69][75]. According to Wolman & Miller (1960), tropical cyclones having moderately sized phenomena are frequent and have a profound impact on the world's tropical and subtropical coastal morphology and environments [13][19][40][41][71]. In the western Kachchh coast, the intertidal and supratidal zone is exceptionally wide (13 to 10 km), especially near Narayansarovar, Lakki, and Gugariyana coasts, while going to the south this zone is decreased to about 3-4 km only and tapers to extreme southwest to about 100 to 200m wide. The reasons for dune stability here could be anything out of humidity, precipitation, silt deposition, algal activities, or mangrove forest. The high-energy storms, cyclones, and strong southwest monsoon wind may be responsible for the stability of the dune field.
The capacity of a dune field to withstand flooding is directly increased by any increase in dune height [99], and the shoreline's resistance to storm wave erosion is raised due to an increase in the quantity of sediment held back in the dune system. Large amounts of silt in the littoral zone also aid in reducing the rate of land retreat while the sea level is rising [105]. This will increase the susceptibility of low-lying coastal regions in the face of rapidly accelerated worldwide environmental changes, including an abrupt rise in sea level [29][45], surges in storm intensity and frequency [31] and other changes [73]. It might be a formerly undetected geomorphic response in the system that, by improving the physical buffering capacity could control the shoreline response and predict a secular rise in sea level. These enhanced dune vegetation growth patterns are observed in response to climate causes and are somewhat paradoxical. Because vegetation better binds and stabilizes the dune sediment and firms extra windblown sand, the mechanical resistance of dune-fringed beaches to the process of wave erosion is increased. As a result, dune height and volume generally rise [39]. Increased dune volume results in more inertia and reduces the speed of withdrawal of barrier shorelines, although dune crest elevation is a crucial factor in determining overwash vulnerability [41]. The shapes and behaviors of coastal dunes changed in response to shifting environmental factors. Changes from a vegetated, stable state to times when dunes are blown by an active sandstorm to break up and migrate are frequently used to track these. The Last Glacial Termination (22 to 11.5 ka) [23] and the following climatic eras of the Holocene were characterized by actively drifting (unvegetated) coastal dunes. For instance, in an episode of active coastal dune (detected by sand-blow) across Europe between 1300 and 1850 during the LIA, extensive human intervention was required (deliberate afforestation) to stop the dune's advance inland [22][44]. The area of dune vegetation and stability both increased at the conclusion of the LIA, which was also accompanied by a general drop-in dune activity.

5.3. Concern of vegetation restoration at Kachchh coast

Continuous vegetation growth in arid regions has led to increased evapotranspiration, decreased discharge from the surface, and reduced regulated groundwater levels [60]. In dry and semiarid regions, regional water conflicts have grown as a result of vegetation, increasing the amount of soil water scarcity that has grown during the recovery years. Climate change is uncontrollable, and it is unlikely to be able to check if future climate circumstances will be able to facilitate the direction of growth in vegetation [95]. It's also crucial to keep in mind that, for re-vegetation to succeed over the long term, the optimal planting density must be reached in order to identify the environmental carrying capacity on the basis of the regional water resources balance, the extent of the anthropogenic activity, and the significance of plant’s responses to the available water to the increased in future temperature.

5.4. NDVI based study for dune stability

The present Remote Sensing based research using NDVI on western Kachchh advances our understanding of the spatiotemporal properties of vegetation along the Kachchh shoreline as well as the forces that shape its dynamics (Fig.5 and Fig.6). Through this study, only the stability of the coastal dunes of western Kachchh has been understood, and other influences on the growth of vegetation, such as topographical and geographic elements, along with wind speed, radiation, and relative humidity are not considered. Most of the dunes covering the supratidal regions in western Kachchh are found to be more stable and highly vegetated, no matter how far they are sitting from the mainland and tidal channels. The vegetation types are not identified but based on the Google images, it is apparently distinguished between the mangroves and other inland vegetation. The mangroves within the dune complex are more common in the Akri Moti dune complex out of eight studied sectors, while the Jakhau port dune complex is found to be more stable though is 3-4km away from the actual mainland of Kachchh (Fig.5 and Fig.6). Most of the inland dunes are partly stabilized and partly active. The Dhunay dune complex in the mouth of Kori Creek is active but partly stabilized (Fig.5 and Fig.6).

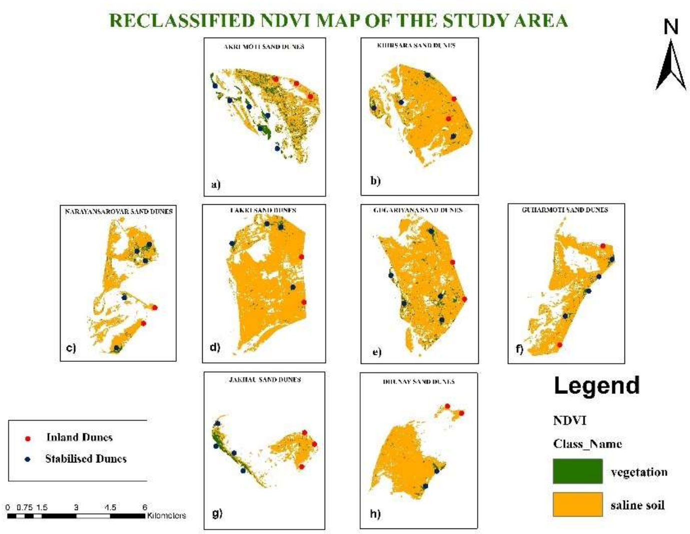

Figure 6. Reclassified NDVI maps of each dune site of the study area of the western Kachchh.

6. Conclusions

The present study's objective was to delineate the stability of coastal sand dunes by performing the Normalized Difference Vegetation Index (NDVI) using the remote sensing data. Different Arc GIS steps were used in this study to detect the dune’s stability. Another key concern is the increase in the eustatic sea level brought on by global warming. The present work has been done to show how remote sensing and GIS techniques can be used for assessing the stability of the coastal dune system of the Kachchh coast due to the increase of predicted vegetation cover. NDVI analysis has been computed for the Kachchh coast in a total of 8 dune sites for the Kachchh coast with NDVI results indicating that most of the dunes are stable and immovable.

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