Geomorphological Analysis of Coastal Erosion Patterns

Vishal
Assistant Professor in Dyal Singh College Karnal, Haryana (India)
Corresponding author Email: vishalsharma15052000@gmail.com

Abstract: The shoreline is one of the important dynamic coastal features where the land, air and sea meet. In any open coast, when manmade structures such as harbor or breakwaters interfere with the littoral current shoreline changes drastically. In India, Chauhan and Nayak (1995) have studied the shoreline changes using the satellite data along the Indian coast. During the low tide condition, maximum land is exposed and even low water line/land water boundary and high water line are distinctly visible. This enables better mapping of the shoreline. Coastal zones are facing intensied natural and anthropogenic disturbances including sea level rise, coastal erosion, over exploitation of resources among others. Over 70% of the world's beaches are experiencing coastal erosion and this presents a serious hazard to many coastal regions (Appeaning Addo et al., 2008).

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Introduction:

Regional patterns show how representative observation locations can be of the dynamics surrounding them. Regarding this, Bracs et al. [1] proposed the concept of “regionally representative” coastal monitoring sites, obtaining a great intensity of measurements by which the patterns and trends observed at these sites in the long term can be representative of other beaches.

The coasts of Colombia, together totaling more than 6000 km, can offer good examples of these spatial differences, since they interact with two seas, the Pacific Ocean and the Caribbean Sea. The two coasts present complexities, which are related to the type of coastal zone (sandy, muddy and rocky) and the marked climatic and oceanographic differences [2], as well as the presence of different marine–coastal ecosystems and socio-cultural diversity [3]. Therefore, it is necessary to develop methodologies to represent such diversity and differences on coasts, which can facilitate decision making and adequate planning in relation to the country’s coastal areas.

Coastal erosion or sedimentation processes also cause damages and losses for society and human activities; in turn, this modifies the coastline and coastal geomorphology [4], and so coastal erosion is currently considered a major problem for states [5]. However, it should also be mentioned that coastal erosion or sedimentation is also a natural process necessary to many ecosystem functions. The causes of this phenomenon are diverse and are related to geomorphological, climatic, oceanographic, anthropic, and geological factors [2].

In Colombia, different studies on coastal erosion have been undertaken, starting with the descriptive analyses carried out by Posada and Henao Pineda [6] and Posada et al. [7,8], which generated the first coastal erosion maps of the country from observations of coastal geomorphological features. These studies were later complemented with quantitative analyses through the calculation of changes in coastlines and the use of GIS tools [9,10,11]. Likewise, semi-quantitative information has been generated with relevance to risk management by conceptually adapting the CVI (Coastal Vulnerability Index) methodology of the USGS [3], which facilitated the generation of maps of the hazard and vulnerability caused by coastal erosion in Colombia [2]. Finally, as part of the Third National Communication on Climate Change, a vulnerability and risk analysis related to climate change was carried out for Colombia, which included shoreline changes and their future projection in relation to SLR (Sea Level Rise) [12].

The aim of this article is to employ spatial autocorrelation statistics to identify and interpret statistically significant changes in the shorelines (erosion and coastal sedimentation), and the results obtained from the DSAS (Digital Shoreline Analysis System), on the two coasts of Colombia (Pacific and Caribbean). Thus, satellite imagery and shoreline detection have been widely developed and used for a long time, and range from the manual digitization of the coastline to proven automated processes [13,14,15,16]. In the same way, the quantitative evaluation of changes that occur on coasts using tools such as DSAS [17,18,19] has been very popular, and there are countless publications on this [9,11,18,20,21]. The use of this metric requires multiple corrections and rules [22] in order to obtain values close to reality, but before defining which method and tools to use, the objective must be defined; that is, one must define the purpose of this metric, and from that, choose appropriate elements.

The concept of spatial autocorrelation [23] is defined as the concentration or dispersion of the values of a variable in space; in other words, it reflects the degree to which objects or activities within a geographic unit are similar to other objects or activities within nearby geographic units [24]. This starts from the first law of geography, or the principle of spatial autocorrelation, proposed by Tobler [25], which states that everything is related to everything else, but close things are more related than distant things.

Spatial statistical analyses, such as the Moran Index, have been used to evaluate the distribution of physical phenomena such as soil erosion [26], rainfall [27], and ecological features [28], generating clustered results similar to those of this study. On the other hand, this process has mostly been applied in human and social studies, in order to evaluate distribution, segregation, and transformations, among other social phenomena [29,30], while other studies have focused on distribution phenomena or spatial autocorrelation theory [31,32,33].

Shoreline and its definitions

Coastal scientists and other coastal agencies have been quantifying the shoreline change rates for many decades. There are various definition of shoreline identified and some of them are summarized here. The line of contact between land and water is defined as shoreline. In other term shoreline is defined as the intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach). However, the shoreline approximates the mean high-water line on coast and Geodetic Survey nautical charts and surveys. In Coast Survey usage, the term is considered synonymous with coastline (Shalowitz, 1962).The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line (USACE, 1984). Apparent shoreline is the line drawn on a map or chart in lieu of a mean high-water line or the mean water level line in areas where either may be obscured by marsh, mangrove, cypress, or other type of marine vegetation. This line represents the intersection of the appropriate datum on the outer limits of vegetation and appears to the navigator as the shoreline (Ellis, 1978). High-Water Line Mark: A line or mark left upon tide flats, beach, or alongshore objects indicating the elevation of the intrusion of high water. The mark may be a line of oil or scum along shore objects, or a more or less continuous deposit of fine shell or debris on the foreshore or berm. This mark is physical evidence of the general height reached by wave run-up at recent high waters. It should not be confused with the mean high water line or mean higher high water line (Hicks, 1984).

Review of Literature:

About 34% of the Earth's coasts are affected by permafrost; 35% of these coasts in the Arctic are lithified, while 65% are unlithified (Lantuit et al., 2012) and particularly vulnerable to coastal erosion. Where excess ground ice is present, coastal erosion is especially efficient because of the thermal impact of sea water and the loss of volume upon thaw. Permafrost coastal erosion is limited to the ice-free summer season and is during this period comparable to rates of rapidly eroding non-Arctic coasts (Are, 1988). An average Arctic coastal erosion rate is 0.5 m a^{-1} ; 3% of the Arctic coastline is retreating faster than 3 m a^{-1} . (Lantuit et al., 2012). Jones et al. (2009) reported an extreme 25 m erosion event that occurred during one year at Drew Point, a particularly ice-rich site on the Alaskan Beaufort Sea coast. Permafrost coastal erosion has attracted much scientific attention because of the large amounts of sediment released to the Arctic Ocean (Rachold et al., 2000), the mobilisation of old organic carbon (Vonk et al., 2012), and the release of nutrients which affects elemental budgets and biogeochemical cycles in the coastal zones of the Arctic Ocean (Ping et al., 2011). High erosion rates can occur within a short time period at specific locations (Dallimore et al., 1996; Barnhart et al., 2014a), while average erosion rates for longer coastal segments or long observation periods are generally much lower (Solomon, 2005). This spatial and temporal variability is caused by a wide spectrum of factors acting at different spatio-temporal scales. Regional factors acting on a larger scale are storminess, waves and storm surges, ice-free season duration, sea level, and summertime sea surface temperature. Local factors controlling erosion are sediment properties (cohesiveness and grain size), cryostratigraphy (amount, type, and distribution of ground ice), and geomorphology (cliff height and slope, exposure, underwater shore slope, presence of barrier islands and spits, littoral sediment supply, and coastal hinterland topography) (Héquette and Barnes, 1990; Solomon, 2005; Jones et al., 2009). Dallimore et al. (1996) emphasised the importance of storm events in connection with ground ice contents in the onshore sediments for coastal erosion in the Canadian Beaufort Sea. Barnhart et al. (2014a) indicated the importance of the seaicefree season, wave exposure, and sea water temperature in the Alaskan Beaufort Sea, while Günther et al. (2015) demonstrated the importance of the temporal concurrence of open water with warm summer air temperatures in the southern Laptev Sea. Arctic coastal erosion studies commonly use historic and current satellite imagery or aerial photographs to define coastlines position based on ocean-land interface. This approach provides horizontal measures of coastal retreat. Timespans between different datasets using this method usually ranged from 50 to 10 years, the shortest being 5 years in Jones et al. (2009). Studies that attempted to quantify volumetric change used digital elevation models (DEMs) derived from tacheometric surveys (on shorter timespans) and stereophotogrammetry (on longer timespans) (Lantuit and Pollard, 2005; Leibman et al., 2008; Günther et al., 2012, 2015). In contrast to the methods used in these studies, airborne Light Detection And Ranging (LiDAR) scanning enables short term mapping of small objects and surfaces with very little texture and contrast and offers new applications for coastal erosion studies. White and Wang (2003) and Young and Ashford (2006) used repeat airborne LiDAR data to estimate volumetric erosion and sediment pathways of non-permafrost coasts. Jones et al. (2013) demonstrated suitability of airborne LIDAR data for landscape changes of arctic coastal lowlands, including volumetric changes due to coastal erosion. Most existing studies on permafrost coastal erosion estimate the erosion rates over time periods from a few years to decades. Many of the factors influencing coastal erosion are discrete events in time and space and can significantly vary between years. Examples are different mass-wasting processes such as retrogressive thaw slumping, activelayer detachments and block failures, which are typical for ice-rich and unconsolidated coasts. Retrogressive thaw slumping is a very rapid mass wasting formed by thaw of ice-rich ground (Lantz and Kokelj, 2008). Retreat of exposed massive ice on sloping terrain leads to the formation of C-shaped depressions surrounded by a headwall (Burn and Lewkowicz, 1990; Lantuit and Pollard, 2008). Retrogressive thaw slumps (RTSs) can transport considerable amounts of sediments in form of earth falls and mudflows (Lantuit and Pollard, 2005). Active-layer detachment (ALD) is a translational landslide with a shallow failure plane that occurs on very gentle to moderate slopes in summer-thawed material overlying permafrost (Lewkowicz and Harris, 2005). Block failure is a very rapid form of mass wasting along permafrost coasts, which involves the collapse of large blocks that detach from cliffs under the influence of gravity. The collapsed blocks have to be first removed before coastal erosion can proceed (Hoque and Pollard, 2009).

Major causes for shoreline change

Shoreline is subject to change due to natural and manmade activities (P. Bruun and B. U. Nayak, 1980). Some of the changes are summarized below:

Natural Causes

1. Action of Waves: Waves are generated by offshore and nearshore winds, which blow over the sea surface and transfer their energy to the water surface. As waves move towards the shore, waves break, and the turbulent energy is released to the water column. This energy stirs up and moves the sediments deposited on the seabed.
2. Winds: Wind act not just as a generator of waves, but also aids in the landward movement of dunes (Aeolian erosion).
3. Tides: Tides are rise and fall in water elevation due to the attraction of water masses by the moon and the sun. During high tides, the energy of the breaking waves is released higher on the foreshore.
4. Nearshore currents: Sediments scoured from the seabed are transported away from their original location by currents. The transport of (coarse) sediments defines the boundary of coastal sediment cells, i.e. relatively self-contained system within which (coarse) sediments stay. Currents are generated by winds, tides (ebb and flood currents), wave breaking at an oblique angle with the shore (longshore currents), and the backwash of waves on the foreshore (rip currents). All these currents contribute for shoreline changes.
5. Storms: Storms generate storm surges and high energy waves. Combined with high tides, storms may result in catastrophic damages. Besides damages to coastal infrastructure, storms cause beaches and dunes to retreat tens of meters in a few hours.
6. Sea Level Rise: Sea level has risen about 40 cm in the past century and is projected to rise another 60 cm in the next century. Sea level has risen nearly 110 meters since the last ice age. Due to global warming, average rise of sea level is of the order of 1.5 to 10 mm per year. It has been observed that sea level rise of 1 mm per year could cause an inundation of the order of about 0.5 m per year (IPCC report).

Anthropogenic Causes

Human influence, particularly urbanization and economic activities, in the coastal zone has turned coastal erosion into a problem of growing intensity. Anthropological effects that trigger shoreline changes are: construction of coastal structures, mining of beach sand, offshore dredging and damming of rivers. Human intervention can alter the natural processes through the following actions:

dredging of tidal entrances and navigational channels, construction of harbours and coastal structures such as groins and jetties, River water regulation works such as damming hardening of shorelines with seawalls beach nourishment, Destruction of mangroves and other natural buffers and Beach sand mining.

Indian coast and its Geomorphology in general

Indian mainland coast includes 9 coastal states and 2 union territories having 66 coastal districts. Morphology of the coast consists of 43% sandy beach, 11% rocky coast, 36% of muddy flats 10% of marshy coast, 97 major estuaries and 34 lagoons (CPDAC Report). There are 13 major ports, 46fishing harbours and 187 minor ports.

Table 1: Coastal geomorphic features of India

Sl. No	State	Landforms and features
		East coast of India
1	Tamil Nadu	Deltas, long narrow beaches, spits, tidal flats, mangroves, coral reefs, sand dunes, Ridge swale complex etc.
2	Andhra Pradesh	Deltas, long narrow beaches, spits, mangroves, cliffs, long sand dunes, Ridge swale complex etc.
3	Odisha	Deltas, long beaches, spits, tidal flats, long sand dunes, ridges etc.
4	West Bengal	Large delta, very thick mangroves, tidal channels, islands, dunes, tidal flat, beaches etc
		West Coast of India
5	Kerala	Estuaries, lagoons, barriers, spits, dunes, tombolo, cliff, beaches etc
6	Karnataka & Goa	Estuaries, spits, sand dunes, tombolo, cliff, wave cut platforms, beaches etc
7	Maharashtra	Estuaries, cliffs, small sand dunes, tombolo, cliff, wave cut platforms, pocket beaches etc
8	Gujarat	Marshy land, tidal flats, estuaries, cliffs, mud flats, mangroves wave cut platforms, beaches etc.

Coastal geomorphology deals with the shaping of coastal features (landforms), the processes at work on them and the changes taking place. The shore is the zone between the water's edge at low tide and the upper limit of effective wave action, usually extending to the cliff base. It includes the foreshore exposed at low tide and submerged at high tide and the backshore extending landward from the normal high tide limit, but inundated by exceptionally high tides or by large waves during storms. Coastal geomorphology is susceptible to coastal changes and plays an important role in determining the impact of sea-level rise. Every landform offers certain degree of resistance to erosion. For example, rocky coast and wave-cut benches offers maximum resistance. On the other hand, sandy beaches, sand dunes, mudflats, mangroves, etc, show least resistance to sea-level rise. East coast is mostly dominated by coastal plains and is wider with many large deltas, lagoons, mangroves, long and wide stretches of sand dunes, ridges and beaches are the common features observed along the coast. Along the west coast, most common geomorphic features are rocky coast, headlands, cliffs, estuaries and bays, etc.

Shoreline proxies adopted Shoreline mapping at ESSO-NCCR

In 2013 ICMAM has conducted a R&D study on shoreline changes using different proxies and varying datasets and prepared a report on methodology for shoreline change mapping. In this report, ICMAM proposedhigh Water line (HWL) mark as shoreline position considering the varying coastal features, other variability and limitations of RS data along Indian coast.In August 2014, a committee of experts from ICMAM, INCOIS and NCESS evaluated the results and recommended that, In sandy shore,"wet/dry line" which is clearly identifiable from all images was considered as shoreline proxy. This wet/dry lineis equivalent to high water line (HWL) mark from all satellite images. The identification of the feature "wet/dry line" from the images is as follows: on a rising tide, it is equal to maximum run up line, and on falling tide, it is equal to part of beach which is still wet, but it may be beyond the instantaneous run up limit. Vegetative line is considered as shoreline proxy, where there is no sandy beach. The waves directly interact with the vegetations along the coast. Seashore facing direction of vegetative limits is demarcated as shoreline proxy and it can be clearly interpreted with the satellite images. In case of artificial structures (seawalls), the sea shore facing direction of seawall is considered as shoreline position.In rocky coast, cliff base or sea shore edge is considered as shoreline position.

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