Implication of shoreline and nearshore morphological changes on sediment budget of wave-dominated Chennai beach, India

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Received: 3 November 2021 / Accepted: 9 October 2022 / Published online: 21 October 2022
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Abstract
The study examines the shoreline (1990–2019) and nearshore morphological changes (seasonal) to understand the littoral drift and sediment budget variability. Shoreline change rate depicts erosion (−0.06 m/year) in the northern sector and accretion (+0.12 m/year) in the southern sector. Seasonal nearshore morphological changes from non-monsoon to monsoon period signifies net erosion (−1.8 × 10^4 m^3) in northern sector and net accretion (+2.5 × 10^4 m^3) in the southern sector. Although the lost sediment during monsoon is regained in non-monsoon period, the quantity of sediment gain is reduced in areas with human interventions. The results of the investigation depict the dominance of littoral drift towards north from February to October, when wave approach from east-southeast to south-southeast direction and southwards from November to January when the wave direction was from east-northeast to east-southeast. The net longshore sediment transport rate estimated during the study period was 2.6 × 10^5 m^3/year in the northern sector and 1.5 × 10^5 m^3/year in the southern sector with higher rate attributed to monsoon than the non-monsoon. Sediment budget results in deciphering the causes of erosion (−1.27 × 10^4 m^3/year) in northern sector and accretion (3.91 × 10^4 m^3/year) in southern sector in the wave-dominated Chennai beach.

Keywords Shoreline · Nearshore morphology · Longshore sediment transport · Sediment budget · Chennai

Introduction
Analysis of the satellite-derived shoreline change indicates about 24% of the world’s sandy beaches are eroding (≥ 0.5 m/year), 28% are accreting (> 0.5 m/year), and 48% are stable (−0.5 to 0.5 m/year) resulting for a profound knowledge about nearshore processes to mitigate coastal erosion (Luijendijk et al. 2018). Shorelines are highly dynamic due to complex hydrodynamic processes (wave, tide, and sea level rise), meteorological-geophysical events (cyclones, wind, rainfall, earthquake, tsunami), natural processes (littoral drift, sediment and water discharge), and anthropogenic activities (coastal protection structures and urbanization) (Mishra et al. 2019; Markose et al. 2016). Beach is the most dynamic zone due to the nearshore processes like reflection, refraction, bottom friction, shoaling, and breaking of waves (Jesbin et al. 2020). Sandy beaches are the main focus of the littoral morpho-dynamics investigation (Osborne 2005). The morphology of sandy beach is highly dynamic, rapid changes occur due to high wave energy conditions. In this context beach morphology and coastal processes involving sediment transport contributes to the better understanding of the spatio-temporal evolution of beaches. Cross-shore beach profiles and sediment grain size provides clues of transport and depositional conditions (Bui et al. 1989; Shetty and Jayappa 2021). Beach morphological change is an important tool in interpreting the coastal morphological trends (Udhaba Dora et al. 2012), which undergoes seasonal changes in response to the variation of waves and tides (Albert and Jorge 1998). The east coast of India experiences southwest (June–September) and northeast (October–December) monsoon seasons which induce northerly and southerly sediment transport resulting in erosion and accretion of beach (Sanil Kumar et al. 2006). The beach erosion and accretion processes are seasonal and over long-term the coastline is either prograding or receding (Jayappa et al. 2003). Coastal processes are responsible for the evolution of coastline due to the erosion, transportation, and deposition of sediments. The drastic increase in coastal population has become necessary to protect the coast...
Beach sediment volume, shoreline change, sediment grain size, and sediment transport rate are the essential parameters to depict the vulnerability of a beach and for planning the conservation measures (Arockiaraj et al. 2018). The direction of sediment transport is northwards when the wave direction is from south to southeast and southwards when the waves approach between east and southeast (Chandramohan et al. 1988; Usha Natesan et al. 2014). Accretion on the southern side and erosion on the northern side of breakwaters are prominent along the east coast of India due to the net northward littoral drift (Rao et al. 2009). The understanding of longshore sediment transport and sediment budget of a littoral cell is key for the effective design of coastal engineering structures. Sediment budgeting uses the application of primary conservation of mass equation with sediment sources and sinks on complex patterns of erosion and accretion in response to natural and engineering activities (Townend and Whitehead, 2003; Rosati, 2005). The primary sediment cell is classified as the large-scale offshore processes, secondary cells with regional-scale nearshore processes, and numerous tertiary cells comprising individual beaches (Short, 2020). We adopted the tertiary level classification within the boundaries of a secondary level compartment to analyze the sediment budget. In the present study, 3 decades of shoreline dynamics and seasonal nearshore morphological changes are investigated to understand the influence of littoral drift on sediment budget in the tropical beach.

**Materials and methods**

**Study site**

Chennai also known as Madras, is the capital of the Indian state of Tamil Nadu located on the Coromandel Coast of the Indian Peninsula. According to the 2011 Indian census (https://censusindia.gov.in) it is the sixth-most populous and fourth-most populous urban agglomeration in India. Chennai has hot and humid climate with maximum temperature around 35–40 °C from late May to early June, and with minimum temperature around 19–25 °C in January. The average annual rainfall is about 130 cm, gets most of its seasonal rainfall from the northeast monsoon winds from October to December (Kankara et al. 2013). Cyclones in the Bay of Bengal are the threat to this coastal city, leading to trail of destruction and devastation. The prevailing winds in Chennai are northerly from March to September and southerly from October to February (Ramana Murthy et al. 2008). The Chennai city depend on the annual rains of the monsoon season to replenish water reservoirs, as no major rivers flow through the area.
The study investigates an integral part of the Chennai coast, which extends from 80°16′13″E to 80°16′53″E longitude and 12°59′23″N to 13°2′24″N latitude (Fig. 1). The study site is sub-divided into the northern and southern sectors based on the presence of inlet. Srinivasapuram is a fishing village centered between Marina beach and Adyar creek, along the Chennai seashore. It has a large population of fishermen community who got affected by the 2004 Indian Ocean tsunami. Srinivasapuram experiences severe erosion, in spite of the widest Marina beach on the northern side with average beach width of 300 m. Adyar creek is a backwater estuary at the mouth of the Adyar River. Besant Nagar beach, popularly known as Elliot’s beach is located on the southern side of Adyar creek and it forms the end-point of the Marina beach shore. It is fairly a residential area with few pockets of fisherman boat landing places. To study the
seasonal changes in the coastline of Srinivasapuram fishing village (northern sector) and Besant Nagar (southern sector), the study site of about 5 km is selected. The northern and southern sectors are oriented in north–north–east direction with 7–13° and 12–21°, respectively. The local sea level is rising approximately 1.0 to 1.1 mm/year which is expected to increase (IPCC 2013). The study site experiences semi-diurnal tides having the average micro-tidal neap and spring tidal ranges of 0.1 and 1.4 m (Kankara et al. 2013). Erosion has affected the socio-economic activities of the Chennai coast due to the receding of shoreline.

Data collection and analysis

Shoreline change analysis is carried out from 1990 to 2019 using Landsat TM (30 m), Landsat ETM + (30 m), Cartosat-1 (2.5 m), and Resourcesat–II LISS IV (5.8 m) satellite images (Table 1). The satellite image processing and shoreline change analysis was carried out as per the methodology adopted in National Assessment of Shoreline Changes along Indian Coast (Kankara et al. 2018). In ERDAS Imagine version (v.)2013 software (https://www.hexagongeospatial.com), all the satellite images are rectified for image distortion and edge matching using ground control points (GCP) collected using Trimble GeoXH handheld Global Positioning System (GPS) with accuracy of < ±5 m. Second-order polynomial transformation method was applied for each image. Quality check for each data has to be done using GCP’s collected using GPS, which were not used in the rectification process.

Once rectified data have Root Mean Square Error (RMSE) of less than a pixel value, on screen digitization of shoreline (wet/dry line or high water line) is done manually with map scale of 1:2500 (Cartosat), 1:5000 (LISS IV) and 1:10000 (Landsat). By fixing the map scale, digitization error (linear-jagged edges) is minimized (smooth splines) in shoreline extracted from high and low resolution images. In the ArcGIS v.10.3 platform (https://www.esri.com), short-term and long-term shoreline geodatabase were created. The baseline layer was generated with buffer distance of 500 m landward from the oldest shoreline, and seaward transects (perpendicular lines) were generated at every 20 m interval along the coastline. Shoreline change statistics is evaluated using two approaches in Digital Shoreline Analysis System v.4.0 (Thieler et al. 2009): (1) long-term analysis (1990–2019) calculated using the weighted linear regression (WLR) method which takes into account the uncertainty field to calculate the long-term rates of shoreline change, and (2) short-term analysis (1990–2000, 2000–2006, 2006–2012, 2012–2019) calculated using the end-point rate (EPR) method by dividing the distance of shoreline movement by the time elapsed between the oldest and latest spatial difference over a defined transect. The position and measurement errors are considered (Eq. 1) to calculate the uncertainty field (U_i).

\[ U_i = \pm \sqrt{(E_p^2 + E_d^2 + E_{td}^2 + E_{r}^2 + E_{s}^2)} \]  

where seasonal error \((E_s = 4.5\text{ m})\) is quantified using seasonal beach profiles, tidal fluctuation error \((E_{td} = 0.1–1.4\text{ m})\) is calculated for each satellite image, digitizing error \((E_d = 1.25–15\text{ m})\) is the error associated with digitizing the shoreline, pixel error \((E_p = 2.5–30\text{ m})\) is the pixel size of the image, and rectification error \((E_r = 1.25–15\text{ m})\) is calculated from the ortho-rectification process.

Using Trimble-R10 Real Time Kinematic-Global Positioning System (RTK-GPS) base station was established by static method and observations were processed using Trimble Business Center v.4.10.1 (https://geospatial.trimble.com) to derive accurate position with reference to the International Terrestrial Reference Frame 2008 (Altamimi et al. 2011). Along the study site of ~5.5 km, at every 500 m transects (shore normal) were selected to measure the beach profiles. During the first survey conducted in April 2019 (non-monsoon), in each transect benchmark was fixed in the backshore and the same was considered

| Year     | Data (resolution) | Source                        | RMSE  | Natural calamities                                                                 |
|----------|-------------------|-------------------------------|-------|-----------------------------------------------------------------------------------|
| 1990 to 2000 | Landsat TM (30 m) | United States Geological Survey (USGS) Earth Explorer | 18 m  | Depression BOB 07 (1991), Cyclonic Storm BOB 08 (1991), Severe Cyclonic Storm BOB 03 (1994), Very Severe Cyclonic Storm BOB 06 (1996) |
| 2000 to 2006 | Landsat ETM + (30 m) |                        | 16.7 m | Extremely Severe Cyclonic Storm BOB 05 (2000), Cyclonic Storm BOB 02 (2001), Indian Ocean Earthquake and Tsunami (2004), Cyclonic Storm Fanoos (2005) |
| 2006 to 2012 | Cartosat-1 (2.5 m) | National Remote Sensing Centre (NRSC) Data Centre | 2 m   | Cyclonic Storm Nisha (2008), Severe Cyclonic Storm Jal (2010), Very Severe Cyclonic Storm Thane (2011) |
| 2012 to 2019 | Resourcesat–II LISS IV (5.8 m) |                        | 2.2 m | Cyclonic Storm Nilam (2012), Very Severe Cyclonic Storm Madi (2013), Deep Depression BOB 03 (2015), Very Severe Cyclonic Storm Vardah (2016) |
for the surveys carried out during September (southwest monsoon) and December 2019 (northeast monsoon). The horizontal and vertical accuracies of RTK-GPS is $\pm 5$ cm (Arockiaraj et al. 2018). The seasonal beach profile data (Eastings, Northings and Elevations) were plotted and computed using the Sands v8.1 software (http://www.sandsuser.com) for the changes in cross-sectional area (m$^2$) and volume (m$^3$) statistics. Foreshore sediment samples were collected from all the transects, and dried 100 g sample was sieved on Retsch AS200 sieve shaker using ASTM sieves with 0.50ɸ intervals from 2000 to 63 µm mesh sizes. The weight of each sieve corresponding to mesh-size were obtained and processed using EasySieve5.0 software (www.retsch.com) to derive the median sediment grain size ($d_{50}$) statistics.

Nearshore bathymetry along Chennai coast is determined from Landsat-8 (30 m) satellite imagery downloaded from the United States Geological Survey (USGS) Earth Explorer (https://earthexplorer.usgs.gov). For bathymetry estimation, blue (440–540 nm), green (500–600 nm), red (600–700 nm), and near-infrared (700–800 nm) bands were processed in ENVI v.4.7 image analysis software (https://harrisgeospatial.com) using the log-transformation algorithm and atmospheric correction of imagery is carried out by dark object subtraction method (Stumpf et al. 2003). Remote sensing reflectance ($R_{rs}$) in visible and near-infrared (NIR) bands was used for atmospheric correction, which significantly improves the quality by minimizing the noise (Pahlevan et al. 2017). The median 3 x 3 filter was used to remove the speckle noise from images. Vertical calibration procedure is carried out using 10–15 points collected from hydrographic chart (depths ranging from 5 to 15 m) defining stable points and avoiding areas that could have been modified. The model uses a ratio of log-transformed water reflectance of bands having different water absorptions, so the ratio of reflectance's will change with depth (Eq. 2). The relative/ pseudo depth (pSDB) was then scaled to satellite-derived bathymetry (SDB) with linear regression between the reference chart bathymetry by vertical calibration to transform the results to the actual depth (Eq. 3).

$$pSDB = \frac{\ln[nR_{rs}(\lambda_i)]}{\ln[nR_{rs}(\lambda_j)]}$$  \hspace{1cm} (2)

$$SDB = m_1pSDB - m_0$$  \hspace{1cm} (3)

In the above equation, $R_{rs}(\lambda_i)$ and $R_{rs}(\lambda_j)$ is the atmospherically corrected pixel value for blue and red bands, $n$ is a fixed constant ($n = 1000$) between the ratio and depth, and $m_1$ and $m_0$ (scale and offset, respectively) are constants to linearly transform the algorithm results to the chart depth. The $m_0$ coefficient (tide level) implicitly corrects the reference chart bathymetry.

Longshore sediment transport rate (LSTR) was estimated at all the ten transects using Kamphuis (2002) empirical formulae (Eq. 4) which is based on 3D model experiments with regular and irregular waves as a function of wave angle, wave steepness, beach slope, and $d_{50}$ of sediment. Input variables like significant wave height, average wave direction and wave period for 2019 was obtained from the Indian National Centre for Ocean Information Services (INCOIS) moored buoy (CB-06) deployed at 10 m (m) water depth in Chennai (https://incois.gov.in/portal/datainfo/mb.jsp). The wave characteristics in 10 m water depth is processed using the MS Excel program LITTORAL.xls (www.leovanrijn-sediment.com) to determine the significant wave height at the breaker line, peak wave period and angle between wave crest and coastline. Empirical coefficients like beach slope and shore normal angle were derived from beach profiles, and $d_{50}$
from sediment analysis data. The wave angle below shore normal is taken as positive with longshore current direction towards the north and above it is considered to be negative and southwards.

\[ Q = 7.3H_{sb}^{2} T_{p}^{1.5} m_{b}^{0.75} d_{50}^{-0.25} \sin^{0.6}(2\alpha) \]  

(4)

In the above equation, \( Q \) is the LSTR in m\(^3\) per unit time, \( H_{sb} \) is the significant wave height at breaker line, \( T_{p} \) is the peak wave period, \( m_{b} \) is the beach slope, \( d_{50} \) is the median sediment grain size, and \( \alpha \) is the angle between wave crest and coastline.

Longshore transport rates can be defined either through the pair of rates as left- and right-directed or as net and gross. The net LSTR is defined as the difference between

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**Fig. 3** Google earth images showing a before Tsunami, b after Tsunami, c beach recovery phase, d beach condition during the study, and e short- and long-term rate of shoreline change along the Chennai coast.
Fig. 4 The satellite-derived bathymetry during a non-monsoon (April 2019), b southwest monsoon (September), and c northeast monsoon (December 2019) seasons along the study site.
right-directed and left-directed littoral transport over a specified time interval. Whereas, gross LSTR is the sum of right-directed and left-directed littoral transport over a specified time interval. The sediment budget analysis framework helps in understanding erosion and accretion pattern in a littoral cell, which is an essential element in
evaluating the coastal processes. The concept of sediment budget estimation includes determining the boundaries of the littoral cell, quantifying sources and sinks, and the net gain or loss should correlate with the observed accretion and erosion of a beach (Rosati and Kraus 2003). Putro and Lee (2020) introduced the equation expressed in terms of input and output fluxes (Eq. 5) to formulate the sediment budget of a littoral cell.

\[
\frac{\Delta V}{\Delta t} = \sum Q_{in} - \sum Q_{out},
\]

where \(\Delta V/\Delta t\) is the rate of volume change during the monitoring period, \(Q_{in}\) and \(Q_{out}\) are the quantity of sediment transported in and out of littoral cells, respectively. The methodology and analysis workflow is presented in Fig. 2. The map layouts were prepared using ArcGIS v.10.3 (https://www.esri.com) and graphs/ charts/ plots were prepared using Sigma Plot v.11.0 software (http://www.sigmaplot.co.uk).

### Results

#### Shoreline change

The rate of shoreline change for the study site has been calculated in terms of EPR (short-term) and WLR (long-term) methods using digital shoreline analysis system (Thieler et al. 2009). Shoreline change rate are classified as erosion (≥ 0.5 m/year), stable (− 0.5 to + 0.5 m/year), and accretion (> + 0.5 m/year). Short-term shoreline change analysis is carried out between: 1990–2000, 2000–2006, 2006–2012, and 2012–2019. From 1990 to 2000, the coast was accreting (0.51 to 7.66 m/year) with a mean EPR of 3.64 m/year and eroding (− 0.51 to − 3.24 m/year) with mean EPR of − 0.98 m/year. Whereas from 2000–2006, the coast experienced erosion (− 0.56 to − 11.9 m/year) with mean EPR of − 4.67 m/year and accretion (0.58 to 2.61 m/year) with mean EPR of 1.56 m/year. The receding of coast during

### Table 2

| Sector | Transect | Cross-Sectional Area (m²) | CSA Difference (m²) | CSA Changes (%) |
|--------|----------|---------------------------|--------------------|-----------------|
|        |          | Apr-19 Sep-19 Dec-19 Apr-19 to Sep-19 Apr-19 to Dec-19 Sep-19 to Dec-19 Apr-19 to Sep-19 Apr-19 to Dec-19 Sep-19 to Dec-19 |
| Northern | P1       | 151 159 158 8 7 -1 | 5 5 -1 |
|         | P2       | 97 105 104 9 8 -1 | 9 8 -1 |
|         | P3       | 78 87 83 9 6 -4 | 12 7 -4 |
|         | P4       | 35 19 23 -17 -12 4 | -47 -34 24 |
|         | P5       | 45 16 30 -29 -15 14 | -65 -34 87 |
|         | P6       | 84 115 105 32 21 -10 | -38 25 -9 |
|         | P7       | 132 143 153 11 21 9 | 9 16 6 |
|         | P8       | 44 44 51 0 8 7 | 1 17 16 |
|         | P9       | 496 471 497 -25 1 26 | -5 0 6 |
|         | P10      | 57 57 61 0 5 5 | 0 8 8 |

% Change key
- **Accretion > 30%**
- **Accretion 15-30%**
- **Accretion 5-15%**
- **No Change < 5%**
- **Erosion 5-15%**
- **Erosion 15-30%**
- **Erosion > 30%**

### Table 3

| Sector | Volume Between Transect | Volume (m³) | Volume Difference (m³) | Volume Changes (%) |
|--------|-------------------------|-------------|-----------------------|--------------------|
|        | Apr-19 Sep-19 Dec-19 Apr-19 to Sep-19 Apr-19 to Dec-19 Sep-19 to Dec-19 Apr-19 to Sep-19 Apr-19 to Dec-19 Sep-19 to Dec-19 |
| Northern | P1 P2       | 68550 73230 72687 | 4680 4137 -544 | 7 6 -1 |
|         | P3 P4       | 41468 45660 44606 | 4192 3139 -1054 | 10 8 -2 |
|         | P5 P6       | 32262 30168 30436 | -2094 -1825 269 | -6 -6 1 |
|         | P7 P8       | 33573 14531 22208 | -19042 -11365 7677 | -57 -34 53 |
|         | P9 P10      | 43230 52040 51786 | 8811 8557 -254 | 20 20 0 |
|         |             | 48421 51734 56159 | 3313 7738 4425 | 7 16 9 |
| Southern | P6 P7       | 414571 135266 143923 | -6305 2352 8657 | -4 2 6 |
|         | P8 P9       | 227202 212739 225210 | -9963 2508 12471 | -4 1 6 |

% Change key
- **Accretion > 30%**
- **Accretion 15-30%**
- **Accretion 5-15%**
- **No Change < 5%**
- **Erosion 5-15%**
- **Erosion 15-30%**
- **Erosion > 30%**
2000–2006 is attributed to the impact of Indian Ocean Earthquake and Tsunami in December 2004 (Fig. 3a, b). However, from 2006–2012 period, the coast is observed to attain accretion (0.57 to 8.09 m/year) with a mean rate of 3.21 m/year. Thus, it is observed that the beach was re-built during the 2006–2012 period (Fig. 3c). From 2012 to 2019, the coast is observed to erode (−0.59 to −7.43 m/year) with mean EPR of −3.49 m/year and accrete (0.54 to 7.78 m/year) with mean EPR of 3.44 m/year (Fig. 3d).

Long-term shoreline change analysis (1990–2019) depicts accretion (0.51 to 2.75 m/year) with a mean WLR of 0.86 m/year and erosion (−0.52 to −1.12 m/year) with mean WLR of −0.71 m/year (Fig. 3e). The northern sector is eroding (−1.12 to 2.75 m/year) with mean WLR of −0.06 m/year, and southern sector is accreting (−0.36 to 1.43 m/year) with mean WLR of 0.12 m/year.

Nearshore morphology

The seasonal (non-monsoon, southwest and northeast monsoon) impact on nearshore morphology is deciphered from the cross-shore beach profiles and satellite-derived bathymetry (SDB). In understanding the seasonal and annual impact on the nearshore morphology, the present study on erosion/ accretion of the beach has been carried out. Seasonal SDB along the study site and nearshore profiles at selected ten transects are shown in Figs. 4 and 5, respectively. The in-situ and SDB shows a high correlation in shallow waters, while low in deep waters (Ehses and Rooney 2015; Pushparaj and Hegde 2017). Accuracy of bathymetry fluctuates significantly due to bad weather conditions, turbidity and waves. To retrieve the nearshore bathymetry seasonal satellite data were corrected for atmospheric, geometric, and tidal errors which significantly improves the accuracy. The computed depths were validated with the in-situ measurements, and the root mean square difference between in-situ and SDB was less than 0.5 m.

### Table 4: Seasonal changes in beach slope, median grain size, and sediment type in the study site

| Sector | Transect | April 2019 | September 2019 | December 2019 |
|--------|----------|------------|----------------|--------------|
|        | Beach slope | D₅₀ (µm) | Sediment type | Beach slope | D₅₀ (µm) | Sediment type | Beach slope | D₅₀ (µm) | Sediment type |
| Northern | P1        | 1:50       | 555.2 | Coarse Sand | 1:50       | 413.6 | Medium Sand | 1:33       | 532.7 | Coarse Sand |
|         | P2        | 1:50       | 528.6 | Coarse Sand | 1:50       | 392.8 | Medium Sand | 1:25       | 354.0 | Medium Sand |
|         | P3        | 1:20       | 588.9 | Coarse Sand | 1:20       | 375.1 | Medium Sand | 1:14       | 349.4 | Medium Sand |
|         | P4        | 1:10       | 580.5 | Coarse Sand | 1:7        | 437.7 | Medium Sand | 1:6        | 551.7 | Coarse Sand |
|         | P5        | 1:100      | 432.7 | Medium Sand | 1:50       | 458.8 | Medium Sand | 1:50       | 637.7 | Coarse Sand |
| Southern | P6        | 1:100      | 401.8 | Medium Sand | 1:100      | 432.8 | Medium Sand | 1:100      | 587.1 | Coarse Sand |
|         | P7        | 1:100      | 536.6 | Coarse Sand | 1:100      | 403.7 | Medium Sand | 1:50       | 589.2 | Coarse Sand |
|         | P8        | 1:20       | 609.5 | Coarse Sand | 1:20       | 383.0 | Medium Sand | 1:20       | 397.0 | Medium Sand |
|         | P9        | 1:50       | 352.9 | Medium Sand | 1:50       | 419.5 | Medium Sand | 1:50       | 468.1 | Medium Sand |
|         | P10       | 1:25       | 618.0 | Coarse Sand | 1:20       | 372.3 | Medium Sand | 1:17       | 700.5 | Coarse Sand |

Fig. 6 The bivariate plots of a significant wave height and average wave direction, and b significant wave height and average wave period in the study site.
square error (RMSE) and correlation coefficient ($r^2$) were calculated. High $r^2$ of 0.7 between estimated and hydrographic chart depths with RMSE of 0.6 m were estimated for April (non-monsoon), while moderate $r^2$ of 0.3 to 0.5 and RMSE of 1.1 to 0.9 m were estimated for September and December (SW and NE-monsoon). Remote sensing satellite images are constituted by the top-of-atmosphere reflectance during absorption and scattering radiation from the earth surface. In coastal environment the radiance in the blue band (450–515 nm) decreases rapidly with depth than radiance in the green band (525–600 nm). The nearshore bathymetry is estimated using the blue and green band pair. Light at wavelengths > 700 nm has a very low transmittance in sea water. Hence, land appears bright and water appears dark. Therefore, the NIR band (845–885 nm) is used to distinguish land from water. The depth soundings of hydrographic chart were used to reference the satellite-derived bathymetry with respect to the chart datum.

### Beach cross-section area and volume

Seasonal variation in the cross-section area (CSA) in m$^2$ and CSA changes in percentage at selected transects along the Chennai coast was estimated from April to December 2019 (Table 2). During April to September 2019 (non-monsoon to southwest monsoon), net erosion of −4 m$^2$ (−17%) on the northern sector and net accretion of 4 m$^2$ (8%) on the southern sector was estimated. The same trend was observed from April to December 2019 (non-monsoon to northeast monsoon) with net erosion of −1 m$^2$ (−10%) and net accretion of 11 m$^2$ (13%). Whereas, September to December 2019 (southwest to northeast monsoon) showed net accretion of 3 m$^2$ (21%) and 7 m$^2$ (5%) in the northern and southern sectors.

### Table 5 Monthly average of the significant wave height, wave direction, and wave period along the Chennai coast

| Months   | Significant wave height (m) | Wave direction (deg) | Wave period (s) |
|----------|-----------------------------|----------------------|-----------------|
| January  | 0.78                        | 92                   | 4.34            |
| February | 0.68                        | 108                  | 4.55            |
| March    | 0.68                        | 129                  | 4.46            |
| April    | 0.73                        | 131                  | 4.85            |
| May      | 1.03                        | 141                  | 4.74            |
| June     | 1.06                        | 149                  | 5.14            |
| July     | 1.01                        | 146                  | 5.19            |
| August   | 1.01                        | 146                  | 5.39            |
| September| 0.89                        | 135                  | 5.39            |
| October  | 0.75                        | 127                  | 5.00            |
| November | 0.96                        | 84                   | 4.70            |
| December | 1.21                        | 99                   | 4.74            |

### Table 6 Longshore sediment transport rate (m$^3$) estimated at selected transects along the northern and southern sectors

| Sector        | Transect | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---------------|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Northern      | P1       | 1485| 1788| 2351| 4540| 5902| 4434| 3844| 3484| 4268| -2717| 25690| 42630|
|               | P2       | -1179| 992 | 1887| 2462| 4554| 5419| 4434| 3844| 4268| -2717| 25690| 42630|
|               | P3       | -2614| 1653| 3585| 4696| 8780| 11228| 10985| 10132| 2409| -1817| 22990| 41740|
|               | P4       | -3851| 3241| 6164| 8042| 14874| 18774| 23372| 25372| 20091| 12764| 157742| 304072|
|               | P5       | -309 | 350 | 602 | 782 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 |
| Southern      | P6       | -1253| -354 | 989 | 1330| 2849| 3257| 3440| 3440| 3440| 3440| 3440| 3440|
|               | P7       | -1138| -265 | 944 | 1265| 2668| 3450| 3801| 3801| 3801| 3801| 3801| 3801|
|               | P8       | -3380| 439 | 3260| 4230| 8770| 11607| 11894| 11894| 11894| 11894| 11894| 11894|
|               | P9       | -1663| 768 | 2002| 2633| 5085| 5599| 5435| 5435| 5435| 5435| 5435| 5435|
|               | P10      | -2312| 1257| 2964| 3880| 7427| 11347| 11074| 11074| 11074| 11074| 11074| 11074|

**Net (m$^3$/year)**: Northwards (−) Southwards (+)

| Sector        | Transect | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---------------|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Northern      | P1       | 1485| 1788| 2351| 4540| 5902| 4434| 3844| 3484| 4268| -2717| 25690| 42630|
|               | P2       | -1179| 992 | 1887| 2462| 4554| 5419| 4434| 3844| 4268| -2717| 25690| 42630|
|               | P3       | -2614| 1653| 3585| 4696| 8780| 11228| 10985| 10132| 2409| -1817| 22990| 41740|
|               | P4       | -3851| 3241| 6164| 8042| 14874| 18774| 23372| 25372| 20091| 12764| 157742| 304072|
|               | P5       | -309 | 350 | 602 | 782 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 | 1418 |
| Southern      | P6       | -1253| -354 | 989 | 1330| 2849| 3257| 3440| 3440| 3440| 3440| 3440| 3440|
|               | P7       | -1138| -265 | 944 | 1265| 2668| 3450| 3801| 3801| 3801| 3801| 3801| 3801|
|               | P8       | -3380| 439 | 3260| 4230| 8770| 11607| 11894| 11894| 11894| 11894| 11894| 11894|
|               | P9       | -1663| 768 | 2002| 2633| 5085| 5599| 5435| 5435| 5435| 5435| 5435| 5435|
|               | P10      | -2312| 1257| 2964| 3880| 7427| 11347| 11074| 11074| 11074| 11074| 11074| 11074|
sectors, respectively. Seasonal variation in beach volume (m$^3$) between transects along the study site was deciphered using the beach profiles. Beach volume estimated during April to September 2019, showed net erosion of $-12264$ m$^3$ and $-4144$ m$^3$ ($-12\%$ and $5\%$) in the northern and southern sectors, respectively. Whereas, April to December 2019 showed net erosion of $-5915$ m$^3$ ($-6\%$) in the northern sector and net accretion of $21154$ m$^3$ ($10\%$) in the southern sector.
sector. However, from September to December 2019, in both the northern and southern sectors net accretion was deciphered with 6349 m$^3$ (13%) and 25298 m$^3$ (5%), respectively. Seasonal variation in volume between transects and changes (%) is given in Table 3.

**Beach slope and sediment characteristics**

Seasonal cross-shore profiles are used to determine the beach slope from the best-fit regression line and sediment characteristics are deciphered from the foreshore sediment samples. During April 2019 the beach slope in the northern and southern sectors ranged from 1:10 to 1:100 and 1:20 to 1:100 with medium to coarse sand (432.7–588.9 µm and 352.9–618 µm), respectively. Whereas, during September 2019 the beach slope ranged between 1:7 and 1:50 in the northern sector and 1:20 and 1:100 in the southern sector with medium sand (375.1–458.8 µm and 372.3–432.8 µm, respectively). The beach slope during December 2019 varied from 1:6 to 1:50 and 1:17 to 1:100 with medium to coarse sand (349.4–637.7 µm and 397–700.5 µm) in the northern and southern sectors, respectively. In the northern sector increase in beach slope during monsoon season indicates high energy waves causing erosion of beach sediment. Seasonal changes in the beach slope, median grain size ($d_{50}$) and sediment type in selected transects along the northern and southern sectors are given in Table 4.

**Wave characteristics**

Significant wave height during January to May ranged from 0.68 to 1.03 m, June to September was 0.89–1.06 m, and October to December was 0.75–1.21 m. Average wave direction was from 92° to 141° during January to May, 135° to 149° from June to September, and 84° to 127° during October to December. Average wave period was around 4.34 to 4.85, 5.14 to 5.39, and 4.70 to 5.00 s from January to May, June to September, and October to December, respectively. The seasonal wave characteristics in the study site are shown in Fig. 6. The monthly average of the significant wave height, wave direction and wave period during January to December are given in Table 5.

**Longshore sediment transport rate**

LSTR is estimated for all the transects in the northern and southern sectors for a period of 1 year (Table 6). The net LSTR estimated for each transect indicates that the predominant direction was northwards with highest estimated in the P4 transect ($1.24 \times 10^5$ m$^3$/year) and lowest in the P7 transect ($0.11 \times 10^5$ m$^3$/year). The gross LSTR was high in P4 transect ($1.57 \times 10^5$ m$^3$/year) whereas low in P6 transect ($0.25 \times 10^5$ m$^3$/year). LSTR from February to October ranged from 0.069 to $0.54 \times 10^5$ m$^3$/month and 0.018 to $0.36 \times 10^5$ m$^3$/month towards the north in the northern and southern sectors, respectively. Whereas, during November to January LSTR ranged from 0.015 to $0.33 \times 10^5$ m$^3$/month and 0.097 to $0.22 \times 10^5$ m$^3$/month towards the south in the northern and southern sectors, respectively. In the northern sector, LSTR of $3.08 \times 10^5$ m$^3$/annum was northwards and $0.49 \times 10^5$ m$^3$/annum was southwards. Similarly, in the southern sector, LSTR of $2.02 \times 10^5$ m$^3$/annum was northwards and $0.51 \times 10^5$ m$^3$/annum was southwards.

**Discussion**

Shoreline change studied in 5.5 km of Chennai coast depicts, from 1990 to 2000 period ~ 4.68 km of the coast is accreting, from 2000 to 2006 period ~ 3.74 km of the coast got eroded which is attributed to the impact of 2004 Tsunami, from 2006 to 2012 period ~ 5.32 km coast experiences accretion, from 2012 to 2019 period ~ 4.24 km was observed to erode with varying magnitudes due to severe cyclonic events (Fig. 7). Thus the coastal environment experiences erosion and heavy damages to livelihood due to natural calamities (Satheesh Kumar et al. 2008; Kannan et al. 2014; Gracy Margret Mary et al. 2020). The long-term analysis of shoreline depicts, the northern sector is eroding (P4), stable (P3 and P5), and accreting (P1 and P2), whereas the southern sector is stable (Fig. 8). The shifting of shorelines towards the land or sea in short- and long-term time frames occurs due to the interaction of a multitude of natural and anthropogenic forces.
Seasonal variation in the cross-section area and volume along the Chennai coast showed net erosion of $-7 \, \text{m}^2$ and $-5915 \, \text{m}^3$ in the northern sector and net accretion of $56 \, \text{m}^2$ and $21154 \, \text{m}^3$ in the southern sector (Fig. 9). The variation in the beach cross-sectional area is positively correlating with the sediment volume. The beach morphology is influenced by waves, currents, tides, and sediment characteristics (Bernabeu et al. 2003). In the northern sector, P4 and P5 transect eroded during the SW-monsoon season. The eroded sediment was transported northwards resulting in the accretion of P1 to P3 transects. Whereas, during NE-monsoon the sediments from P1 to P3 transects were transported southwards leading to accretion of the P4 and P5 transects. However, the northward transport was dominant which resulted in the net loss of sediment in P4 and P5 transects.

In the southern sector, the transect (P6) south of Adyar creek showed high accretion during SW-monsoon resulting in the closure of the creek outlet, which is artificially opened to maintain the tidal prism in the Adyar basin. The transects on the southern sector showed a net accretion trend during the study period. In both the sectors net sediment transport was towards north from non-monsoon to SW-monsoon and southwards from SW-monsoon to NE-monsoon period. The beach profile analysis helps in depicting the changes in cross-section area and volume along the profile transect (Deepika and Jayappa 2017). Understanding the physical processes in the nearshore region is very much essential to derive the causes of erosion/accretion. The morphological changes in sandy beaches are mainly due to the wave action and current pattern (Jesbin et al. 2020).

Fig. 9 Seasonal variation in the a beach cross-sectional area, and b sediment volume along Chennai coast during the study period.
The direction of sediment transport is found to be northwards from February to October, and southwards from November to January. The waves from 108 to 149° during February to October led to the transport of sediment northward, whereas from November to January the waves from 84 to 99° resulted in southward transport (Fig. 10a). The net LSTR towards northward direction was high during August and low during February. Whereas, towards southward direction net LSTR was high during November and low during January and December (Fig. 10b). The Chennai coast experiences seasonal changes in the coastal current patterns. The currents were northwards (18° to 45°) from March to October, southwards (196 to 227°) from November to February, and current speed varied from 0.5 to 41 cm/s with an average of 17 cm/s during the SW-monsoon, whereas 0.3 to 42 cm/s during the NE-monsoon with an average of 10 cm/s (Kankara et al. 2013). The high longshore sediment transport rate during monsoon is due to the increase in wave height, wave direction, wave period and current speed. The net sediment transport was predominantly northwards with $2.6 \times 10^5$ m$^3$/year and $1.5 \times 10^5$ m$^3$/year in the northern and southern sectors, respectively. The higher sediment transport in the northern sector is due to the sediment load from the Adyar river during monsoon and the transport of eroded sediment from highly eroding P4 transect in Srinivasapuram. The seasonal changes in beach width, sediment volume, sediment characteristics, and wave parameters attribute to the inter-annual variability of the coast (Arockiaraj et al. 2018; Shetty and Jayappa 2020). Seasonal changes in the beach are attributed to nearshore morphological characteristics and the degree of seasonality (Van Rijn 2011). The direction of sediment transport and LSTR estimated are in good correlation with the earlier studies (Ramana Murthy et al. 2008; Rao et al. 2009; Usha Natesan et al. 2014) along Chennai coast. Thus, our aim to relate seasonal beach morphological change and sediment transport rate in wave-dominated sandy beach improved the understanding of erosion, transportation and deposition processes.

To quantify the sediment loss or gain in each littoral cell, it is necessary to estimate a sediment budget which quantifies the volume of sediment entering, exiting and the surplus/deficit remaining by examining changes in the topography. It is necessary to evaluate the physical processes that transport sediment along the littoral zone. Waves and wave-induced current influence the beach sediment budget and are the dominant processes. Seasonal or annual changes that are of geomorphic or engineering significance are estimated for shoreline change, providing useful insights in the management of coast (Komar, 1996). Sediment budget is determined by analyzing sediment transport magnitudes and directions on a regional scale with the evolution of coastline. Sediment budget investigation depicts surplus sediment in littoral cells (LC) LC-1 to LC-3 ($4931$–$68950$ m$^3$/year) and deficit in LC-4 and LC-5 ($-11626$ to $-99172$ m$^3$/year) in the northern sector. Whereas in the southern sector, LC-6 and LC-8 depicts deficit of sediment ($-1116$ to $-205990$ m$^3$/year) and surplus sediment ($24669$ to $36759$ m$^3$/year) in LC-7 and LC-9 littoral cells (Fig. 11). The combination of satellite image analysis and field surveys can be a reliable approach for effective planning and management of the coast (Selvan et al. 2019). The importance of sediment budget for coastal planners and designers in the planning, construction and restoration to develop effective sediment management plan for coastal management is emphasized.
Conclusions

The shoreline dynamics and beach morphological changes are important in understanding erosion and accretion pattern for planning the coastal protection structures. Shoreline and nearshore morphological changes depict net accretion of 0.03 m/year and $1.5 \times 10^4$ m³/year, respectively. The longshore sediment transport estimated during the study period showed net northerly drift of about 0.15 to 0.26 million m³/annum along the Chennai coast. The high energy waves (>1 m) approaching the coast from east-southeast to southeast-southeast direction with a wave period of $>5$ s lead to higher sediment transport during monsoon than the non-monsoon. The study site is influenced by stronger coastal current during southwest and northeast monsoons. Seasonal morphological changes and direction of longshore sediment transport play a significant role in determining the temporal evolution of beaches. Accuracy of the LST rate estimation is

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improved using site-specific measured data inputs. Sediment budget analysis represent loss of sediment (− 1.27 × 10⁴ m³/year) in the northern sector and sediment gain (3.91 × 10⁴ m³/year) in the southern sector. The spatio-temporal variations of morpho-sedimentary processes are vital in the coastal zone management strategy.

Acknowledgements The authors are thankful to Ministry of Earth Sciences, Govt. of India, for implementing the Coastal Processes and Shoreline Management (CPSM) Project at National Centre for Coastal Research (NCCCR), Chennai. The authors are thankful to the Director, NCCR for the encouragement and CPSM Project team for the support during the field survey. Indian National Centre for Ocean Information Services is acknowledged for providing the necessary data to carry out this research work. We appreciate the Editor and Reviewers for all valuable comments and suggestions, which helped us to improve the quality of manuscript.

Funding There is no funding received.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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