Article

Cross-Shore Profile Evolution After An Extreme Erosion Event, Palanga, Lithuania

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Abstract: We report cross-shore profile evolution at Palanga, eastern Baltic Sea where short period waves dominate. Cross-shore profile studies began directly after a significant coastal erosion caused by storm "Anatoly" in December of 1999 and continued for a year. Further measurements were undertaken sixteen years later. Cross-shore profile $\Delta V(x)$ changes were described, and cross-shore transport rates $Q(x)$ were calculated. A K-means clustering technique was applied to determine sections of the profile with the same development tendencies. Profile evolution was strongly influenced by the depth of closure which is constrained by a moraine layer and the presence of a groyne. The method used divided the profile into four clusters: the 1st cluster in the deepest water represents profile evolution limited by the depth of closure, and the 2nd and 3rd mostly are affected by processes induced by wind, wave and sea-water level changes. The most intensive sediment volume changes were observed directly after the coastal erosion. The largest sand accumulation was in the 4th profile cluster, which includes the upper beach and dunes. Seaward extension of the dune system caused a narrowing of the visible beach which has led to an increased sand volume (accretion) being misinterpreted as erosion

Keywords: cross-shore profile; sediment transport rates; semi-enclosed sea; sandy coast; coastal erosion; dune development

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1. Introduction

Explaining changes to nearshore coastal profiles remains a challenge for coastal researchers, particularly where there is considerable alongshore sediment transport[1-3]. Changes to the underwater profile are frequently examined under controlled hydrodynamic conditions in wave flumes [4,5], with some studies incorporating the effects of structures [6]. There are numerous examples of beach profile datasets presented in the literature (e.g.[1-3,7-11]), which consider how beaches change in response to variability in wind and wave conditions, advancing understanding with the analysis of each new dataset collected under different conditions. This study examines beach changes at Palanga, Lithuania, a heavily modified beach on a tideless coast with significant longshore sediment transport.

The Baltic Sea's eastern coast is a relatively straight, high-energy (for the Baltic Sea), actively developing coast with fine, highly mobile sediments[12,13]. Sediment transport is generally counter-clockwise along the entire south-eastern coast of the Baltic Proper[14,15] from the Sambian Peninsula to Kolka Cape[16]. Minor variations in the physical nature of the coast and human activities (such as ports and other structures) add complexity to the system's evolution. For example, parts of the underwater slope along the Lithuanian and Latvian shores have boulders, pebbles, and coarse sand. At the same time, in other sections, such as along the Curonian spit, there are fine sands with well-developed bar systems. Only in a few places (the Curonian Spit and a short coastal section to the south-east of Kolka Cape) are there substantial quantities of fine sediment[17]. These coast sections are generally stable or accretionary.

In comparison, other parts of the SE Baltic proper coasts are generally erosive[12,18,19]. The most significant coastal retreat areas are near the Ports of Klaipeda, Liepaja, Ventspils, and in the vicinity of other structures[18-21]. Intensifying coastal erosion implies a sediment deficit on the eastern coast of the Baltic sea.

Coastal processes on beaches within semi-enclosed or enclosed seas can vary from those on open-ocean shores[22]. Swell waves are almost non-existent. Waves tend to be a short period, meaning that profile closure depths are limited, and wave refraction occurs close to the beach. Processes that generate significantly elevated water levels[23], such as storm surge[24] and wave set-up [25], which in turn are strongly related to coastal erosion, are highly variable in space and highly localised in their effect. A large proportion of the wave energy flux to the coast occurs on a very few days of the year[26], meaning that the wind direction at the time of major storms is a significant determinant of the coastal change outcomes. Changes in the wind regime, and therefore extreme water levels and wave characteristics[27], may radically alter coastal processes[28]. Few coastal beach profile studies address enclosed-sea environments, where the process-response regimes differ from open-ocean beaches.

Palanga (Figure 1) is the biggest eastern Baltic Sea seaside resort[29]. The first timber pier was built in 1889. It has a solid construction, interrupting the natural hydrodynamics and sediment transport. As a result, by 1892, sand accumulation next to the pier meant that ships were no longer able to moor. The design was adapted to repurpose the pier for recreation and Palanga was developed as a holiday resort. From construction until 1910, the seashore line moved seawards by '500 steps' (~400m), and through to 1947, it accreted another 100 metres[30]. At the end of the 19^{th} century, the coast nearby was relatively flat, but by the middle of the 20^{th} century, the shoreline comprised a dune field 80-100m wide with 6-8m high dunes, with a sand volume of about 400 m^3 per linear meter[31]. Over the course of a hundred years, the pier was reconstructed several times, without changing its basic structure. In 1990 a decision was made to build a new concrete pier, permeable to waves and sediments. The new pier was finished in 1995, and demolition of the old impermeable structure started. Coastal erosion was observed soon after the shore perpendicular groins, which were part of the old design, were removed in 1997[30,31]. Significant coastal erosion becomes evident after the storm "Anatoly" on 4 December 1999.

Storm "Anatoly" remains the most damaging storm recorded on the SE Baltic Sea coast [32,33] with predominant west and north-west wind directions, mean wind speed up to 22m/s, and maximum wind gusts reaching 40m/s[33]. During the storm, more than 3 million m^3 of sand were eroded from the Lithuanian Baltic Sea coast[32], which at Palanga caused a 35m reduction in beach width[30] and resulted in the dune base moving inland by 10m[10,30,31]. The pier was damaged at its landward end and detached from the shore, and the dune system was destroyed [30]. As a result of the changes, the groyne system (Figure 1 b)was rebuilt in May 2000[31].

In this paper, we analyse beach underwater profile recovery after the storm "Anatoly" and the groin reconstruction and later profile evolution. While processes associated with erosion of the upper beach and the deposition of sand in the nearshore are relatively well understood, cross-shore sediment transport variations under-recovery conditions have received less attention. The overall aim is to study cross-shore sediment transport variations under different accretive conditions, beginning with a significantly eroded underwater beach profile.

2. Materials and Methods

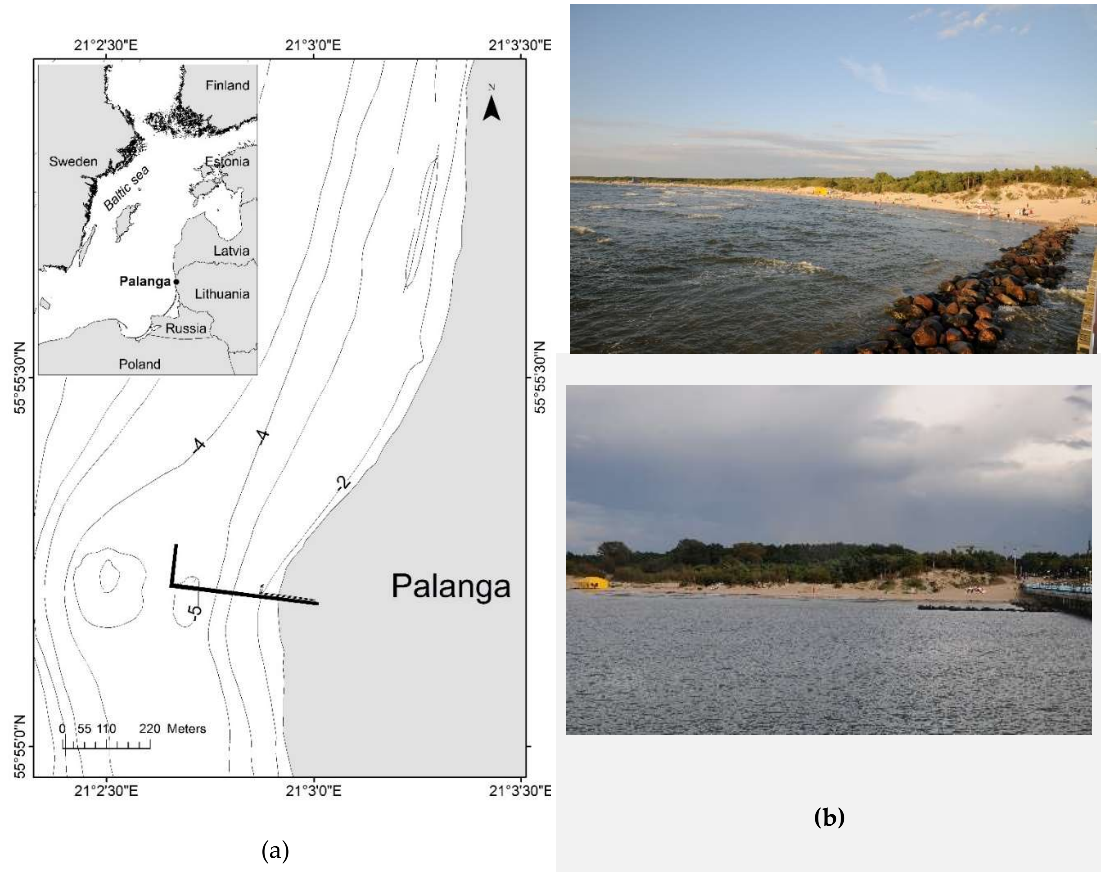


Figure 1. a) Study area and (b) the northern side of the pier, with the adjacent groin system (Photos: September 2018).

The cross-shore profile was surveyed at Palanga (Figure 1) adjacent to the Palanga pier over two time periods. The first set of measurements were undertaken in 1999 - 2000. Measurements began directly after the storm Anatoly on 7th of December 1999 and continued during the year 2000.

Initially, the field experiment was designed to monitor cross-shore profile changes under different hydrometeorological conditions[10]. Measurements with a weighted line (with rope vertically marked every 10 cm) were made along the southern side of the pier (400m length) every 2.5 m with zero distance being the pier's seaward-most handrail. Zero height was mean sea level, based on long term observations and set as 5.0 m below the handrail [10]. Measurements using the same methodology were undertaken in the stormy seasons of 2016 and 2017, with weekly measurements during the October - December periods until such time as there was ice along the coast.

The seaward limit of profile fluctuation over long-term (seasonal or multi-year) time scales is referred to as the "closure depth," denoted by h_c. Based on laboratory and field data, Hallermeier (1978, 1981) developed the first rational approach to determining closure depth [34]. Based on correlations with the Shields parameter, Hallermeier defined a condition for sediment motion resulting from relatively rare wave conditions. Effective significant wave height H_e and effective wave period T_e were based on conditions exceeded only 12 hr per year; i.e., 0.14 percent of the time. The resulting approximate equation for the depth of closure was determined to be:

$$h_c = 2.28H_e - 68.5(\frac{H_e^2}{gT_e^2}) \quad (1)$$

$$H_e = \overline{H} + 5.6\sigma_H \quad (2)$$

$$h_c = 2\overline{H} + 11\sigma_H \quad (3)$$

where g is gravity, and σ_H is the standard deviation of annual wave heights. Therefore good approximation to the data is given simply by h_c =1.57H_e [35]. In the case of the Lithuanian seacoast where H_e=4 m [36], the depth of closure is h_c=6.3±0.5 m [37,38]. However, the storm Anatoly revealed a layer of hard moraine sediments at ~-5 m depth, effectively constraining the profile at a level above calculated closure depth [10].

Comparative plots of beach profile evolution over time were constructed for the 1999-2000, 2016, and 2017-year cases. Average profiles for the periods were calculated. The cross-shore transport rates Q(x) were calculated using the methods in[4,5]. The total sediment transport rate (bedload and suspended load) per unit width between any two time periods (interval Δt) is determined from:

$$Q(x_n) = Q(x_{n-1}) - \int_{x_{n-1}}^{x_n} (1-p)\frac{\Delta z_b}{\Delta t}\,dx \quad (4)$$

where positive values of $Q(x_n)$ ($m^2/\Delta t$) represent onshore sediment transport at position n, Δz_b is the difference in the bed elevation between measurement intervals (m), Δt is the time difference between measurements (year), and p is the porosity of the sand, being 0,4 [2,5,6]. We assume no net sediment transport past the run-up limit x_{max} and beyond the depth of closure x_{min}, and sediment transport proceeds consistently over the beach profile.

The bulk cross-shore sediment transport Q across the whole profile between any two time periods is determined by integrating the local transported volume along the profile [5]:

$$Q = \Delta t \int_{x_{min}}^{x_{max}} Q(x)\,dx \quad (5)$$

between the same closure limits. Q represents the bulk cross-shore sediment transport (m^3 per linear meter) moved either shoreward (positive) or offshore (negative). This measure has been used to categorise the overall beach response as erosive ($Q < 0$), accretionary ($Q > 0$) or stable ($Q \approx 0$). Note that Q is a transport vector and can be either purely negative or positive, or a mixture, and therefore does not integrate to zero unless onshore and offshore transport magnitudes are equal or both identically zero.

We use K-means clustering to determine clusters of cross-shore profile segments with similar development trends [39]. The K-means algorithm is one of the most popular hierarchical algorithms and uses the minimum sum of squares to assign observations to groups. Such groups of data points are called clusters [40,41]. Observations allocated to the closest cluster, and the distance between an observation and a cluster is calculated from the Euclidean distance between the observation and the cluster centre. The objective function of K-means is given as:

$$\mathrm{E} = \sum ||X_i - m_i||^2 \quad (6)$$

where: E is the sum of square error for all objects in the data, X_i is the point in a cluster, and m_i the mean of cluster k_i. The goal of K-means is to minimise the sum of the squared error over all k clusters. The algorithm states that initially, k points are placed into space represented by objects that need to be clustered as initial group centroids. In the second step, each object is assigned to its closest cluster centre. Then, the mean of each cluster is calculated to have a new centroid. These steps are repeated until there is no change in centroids. The number of clusters was selected based on the elbow method [39], the main idea of which is to define clusters such that the total intra-cluster variation (or total within-cluster sum of square (wss)) is minimised. As seen in Figure 2, the elbow of the curve is formed when the number of clusters equal to 4.

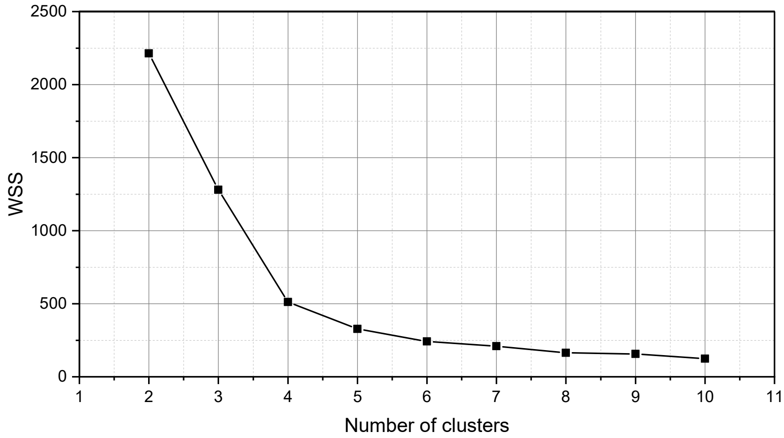


Figure 2. Within cluster sum of square dependence on the number of clusters.

3. Result

Westerly direction, >20 m/s winds during the storm "Anatoly" created an exceptional situation with the dune system destroyed and the newly built Palanga pier detached from the land (Figure 3a). The cross-shore profile measured directly after the storm was at its lowest at -5m (Figure 4).

(a) (b)

Figure 3. a) Palanga pier after the storm „Anatoly" December 1999 and (b) in September 2018.

Further erosion was observed in the month following the first survey on 7 December 1999, under relatively calm meteorological conditions with maximum 13 m/s predominant SW (22%) and W (23%) winds (Figure 5 b). A total of 66 m^3 of sand per linear meter of shoreline was lost (Figure 6a (i)) in one month. The sand was moved from the -1.7 to -3.6 m depths to deeper than - 4 m, covering the exposed moraine sediments. The position of MSL (0m), retreated landward by 20m (Figure 6a (i)). The cross-shore sediment transport rate Q shows a bidirectional sediment transport tendency: shoreward at 0-180m and seawards at 180-350m resulting in accumulation of sand on the lower part of the profile (Figure 6b (i)).

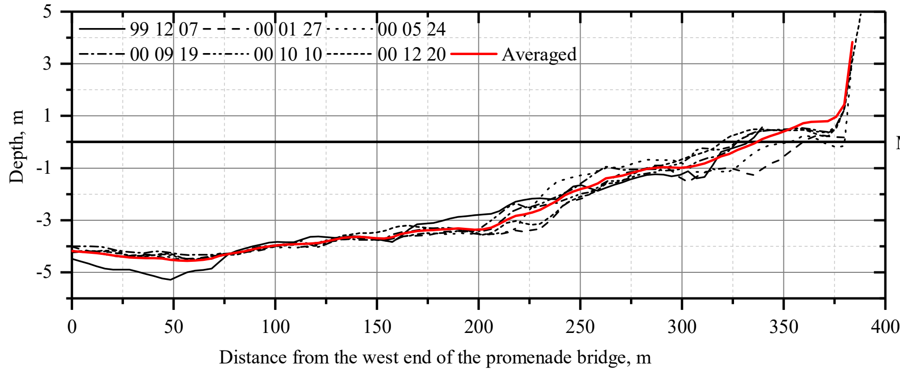


Figure 4. Changes in the beach profiles in 1999-2000
The measurement date is indicated in the legend (yy mm dd).

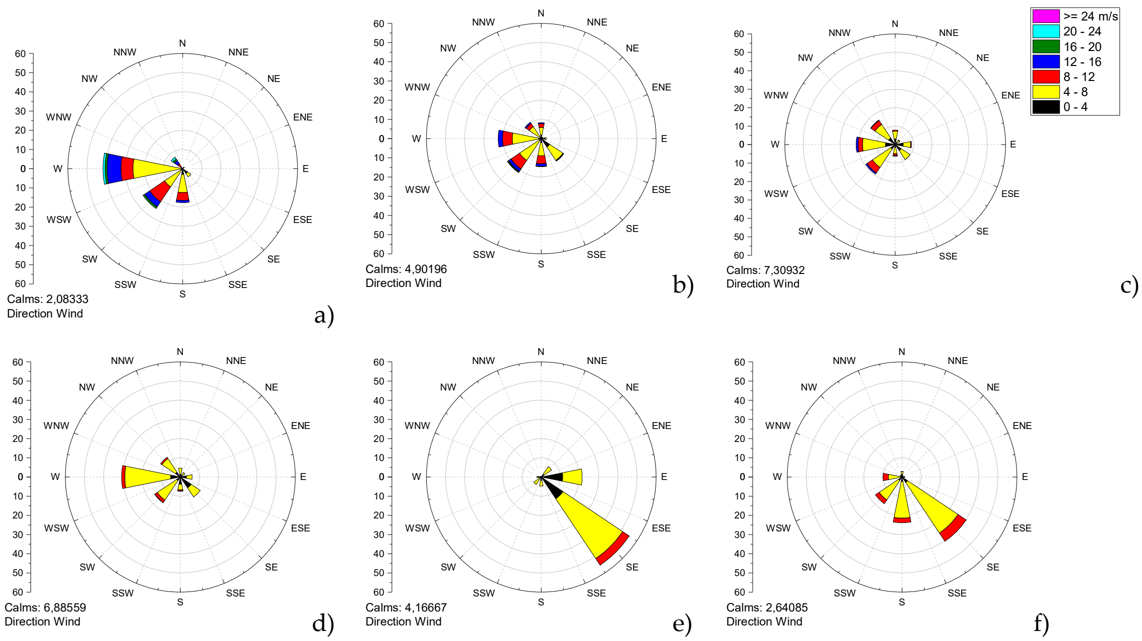


Figure 5. Wind roses for the study period: a) 25 11 1999- 06 12 1999; b) 07 12 1999 – 26 01 2000; c)27 01 2000 – 23 05 2000; d)24 05 2000 – 19 09 2000; e) 20 09 2000 – 09 10 2000; f)10 10 2000-19 12 2000.

From January to May 2000 there were several periods of strong wind with wind speeds up to 16m/s, with westerly winds prevailing: 21% from W and 19% from SW directions (*Figure 5* c). These meteorological conditions led to coastal erosion: as a result, the groin system (Figure 1 b) was rebuilt [10]. Measurements in May 2000 showed that after the rebuilding 69 m^3 of sand per linear meter was accumulated. The largest accumulation took place on the upper part of the profile between 215 – 325 m (Figure 6a (ii)). The cross-shore sediment transport volume across the whole profile from January to May was 5551m^2 with sand transport shoreward from the 218 m positions (Figure 6b (ii)).

In summer (May - September 2020) calm weather prevailed (Figure 5 d), and there was onshore transport. Almost the entire underwater profile shows positive Q transport, and as a result, there was accumulation on the upper part of the profile and the dune was partly replenished with sand (Figure 6 (iii)).

The presence of the newly rebuilt groin system, together with a calm autumn, extended a favourable condition for sand accumulation on the upper part of the cross-shore profile. September-December 2000 was calm with the average wind speeds up to 12m/s with a predominant SE direction (Figure 5 e,f). Profile changes showed sand movement from the shallow area to the offshore (Figure 6 iv, v), and in three months (October-December) only 7m^3 per linear meter of sand was lost on the underwater profile, with sand simply being relocated on the profile. It is noticeable that the cross-shore profile May-December was relatively stable and probably approximated the equilibrium profile shape for this location.

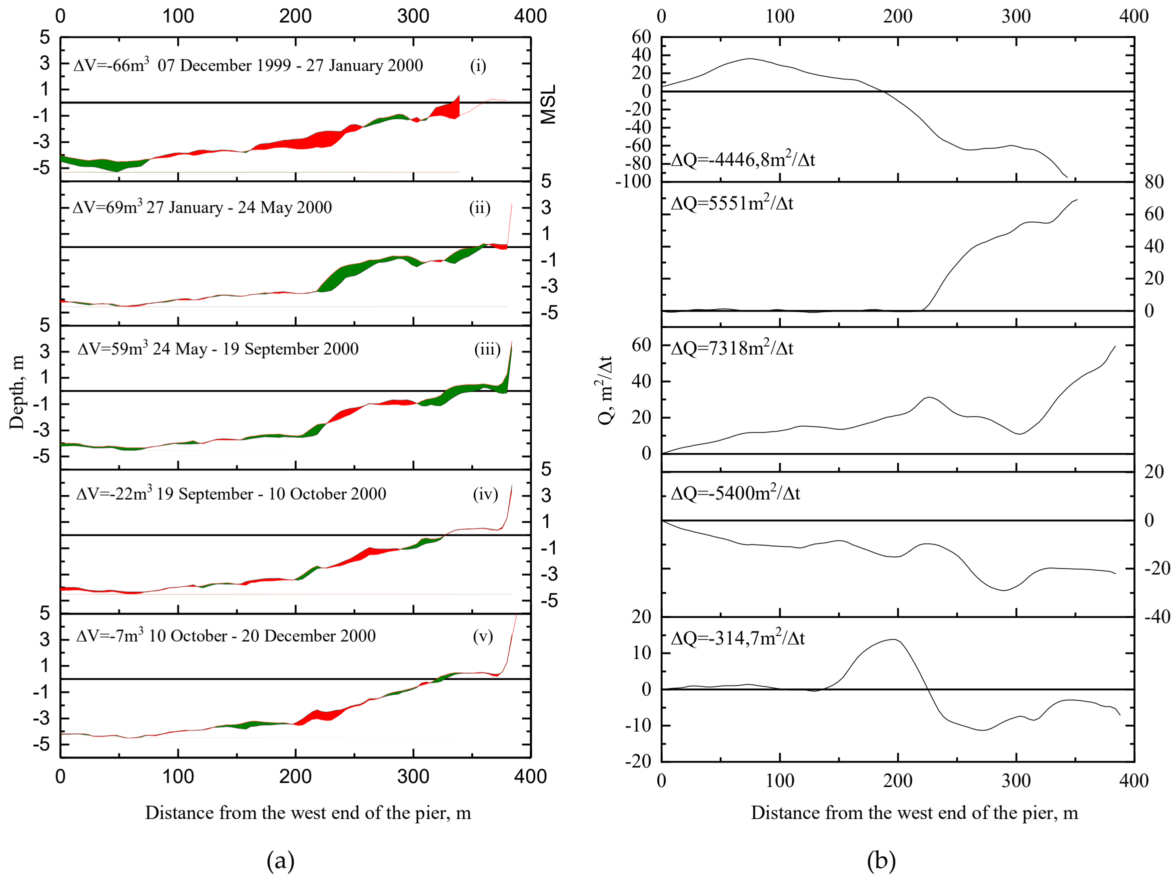
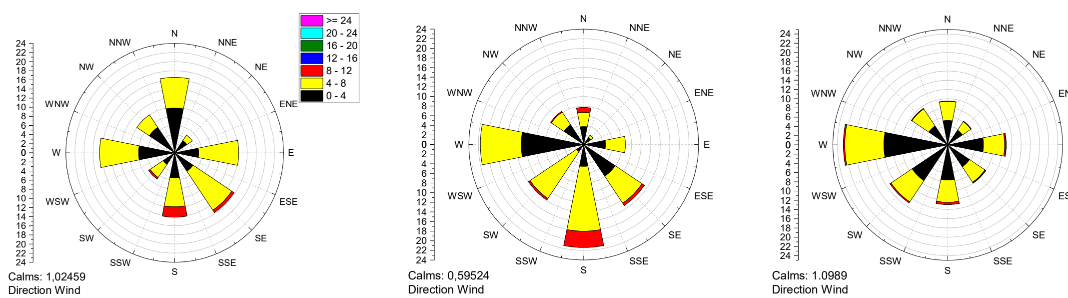


Figure 6. a) Cross-shore profile changes (green-sand accumulation, red-sand loss) and (b) sediment transport rate Q, December 1999-December 2000.

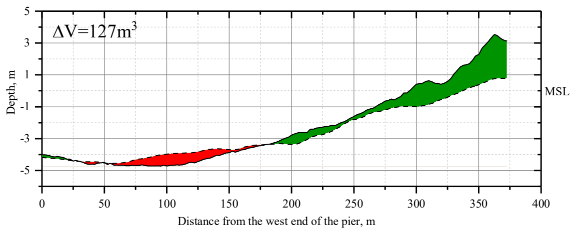
Profile measurements were repeated after 16 years with the expectation that perceptible erosion on Palanga beach [12,30,32,33,42,43] would be reflected in the underwater cross-shore profile. Also, we expected to observe short term changes in the cross-shore profile development during the stormy autumn season. Cross-shore profile measurements were repeated once per week in October-December 2016 and December 2017. Both measurements seasons were similar, with average wind speed not exceeding 12m/s. The significant difference between the two study seasons was in predominant wind direction: in 2016 N, E, and SE winds were prevalent, and in 2017 – S, SW and W wind directions prevailed (Figure 7).



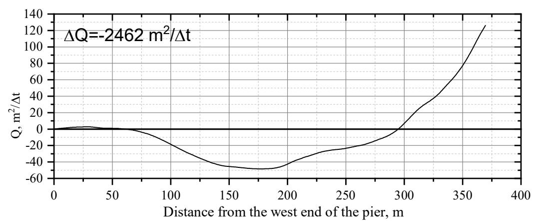
(a) **(b)** **(c)**

Figure 7. Wind roses for the October-December a) 2016 b)2017 and c)2016 December – 2017 October.

Over the sixteen years, 127m^3 per linear meter of sand accumulated on the cross-shore profile (Figure 8). Main changes were seen on the upper part of the profile, with the position of MSL moved seawards by 45m. Net sediment transport rates were positive and indicated net sediment transport direction onshore. Dune expansion often creates the impression of beach narrowing and coastal erosion, which demonstrates the value of the data. Minor profile changes were seen in the deeper parts of the profile (perhaps indicating the real closure depth). Sediment was lost between 75 and180m with accumulation landward. The cross-shore sediment transport rate at a 75-300m distance has negative values, showing a tendency for sand movement seawards. Sediment transport directed shoreward, Q, with positive values, is seen from 300m. The sand accumulation zone starts from the -4m depth.



(a)



(b)

Figure 8. Cross-shore profile changes (green-sand accumulation, red-sand loss) (a) and sediment transport rate Q (b) over the period 2000 to 2016.

In 2016 changes in the cross-shore profile do not exceed 40m^3 per linear meter over one week. The sediment transport rate Q, however, indicates considerable sand redistribution in the cross-shore profile without sand volume change (Figure 9). Noticeable changes in the profile shape were observed between 200-300m and to -3m depth. Small changes in weekly cross-shore profile volume show a quasi-stable state of the profile.

From December 2016 to October 2017, predominant wind directions were SW, NW, W (Figure 7(c)). Wind speed did not exceed 12 m/s with the strongest winds from an E direction. Previous work [10] reported that westerly winds create favourable conditions for sand to remain on the underwater profile[10], but we observed sand loss under these conditions. In the relative calm and favourable wind direction conditions for accumulation, 36m^3 per linear meter of sand was eroded from location 200-300 m, between 0.5 m and -3 m depth (Figure 11 (a)) and there was the retreat of the shoreline. In the dunes, some accumulation of sand occurred.

A bi-directional cross-shore sediment transport rate Q structure was seen at that time (Figure 10 b). Onshore sediment transport direction (Q positive) was observed from 0m to 245 m and offshore sediment transport (Q-negative) from 245 to 375 m. As a result, a bar was formed at -3 m depth.

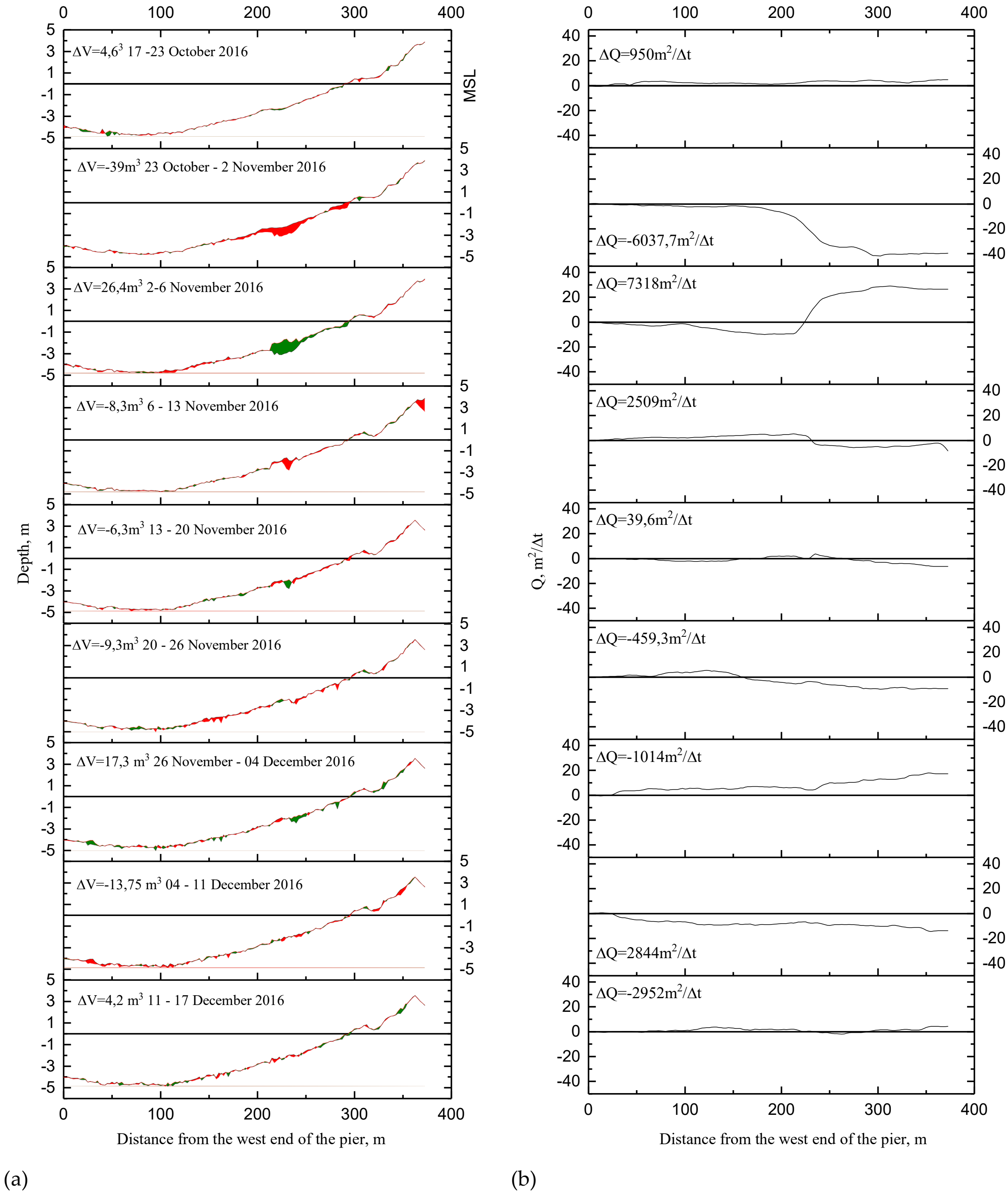
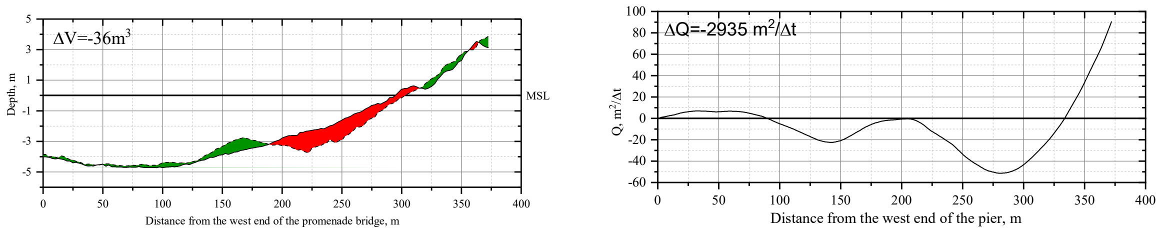


Figure 9. Cross-shore profile changes (green-sand accumulation, red-sand loss) and sediment transport rate Q in 2016.

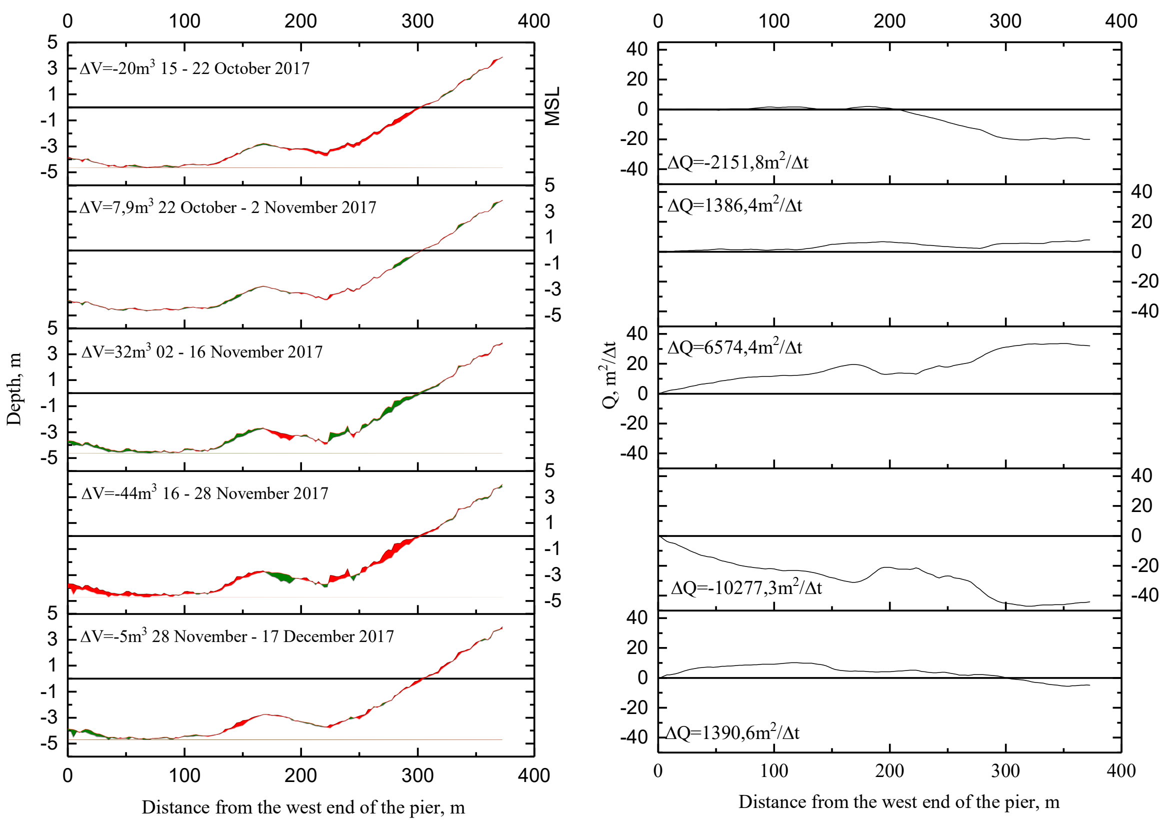


(a) (b)

Figure 10. Cross-shore profile changes (green-sand accumulation, red-sand loss) (a) and sediment transport rate Q (b) over the period 2016 to 2017.

Short-term profile changes and cross-shore sediment transport tendencies in 2017 were similar to those observed in autumn 2016. The sand bar formed at -3m remained stable during the observation period (Figure 11 a). We captured very small sand volume relocations on the profile. Sand movement on the cross-shore profile was mostly observed between the bar and mean sea level position; the largest sand relocations were observed close to the MSL position.

Total sand volume change during autumn 2017 was -30 m³ per linear meter, and the cross-shore sediment transport rate was ±4356,1 m² per week (Figure 11 b). This tendency indicates sand relocation on the cross-shore profile without significant changes to the profile volume.



(a) **(b)**

Figure 11. Cross-shore profile changes (green-sand accumulation, red-sand loss) and sediment transport rate Q in 2017.

Seabed elevation changes in comparison with the average overall measured profiles indicate two different states (Figure 12). The seaward 130 m of the studied profile, had minor changes in seabed elevation over 2016 and 2017. On more landward sectors, opposite trends were observed, being more active, with higher Δz values (up to ±1m). Only sectors greater than 300 m from the west end of the promenade bridge show positive Δz due to dune recovery after damage in December 1999.

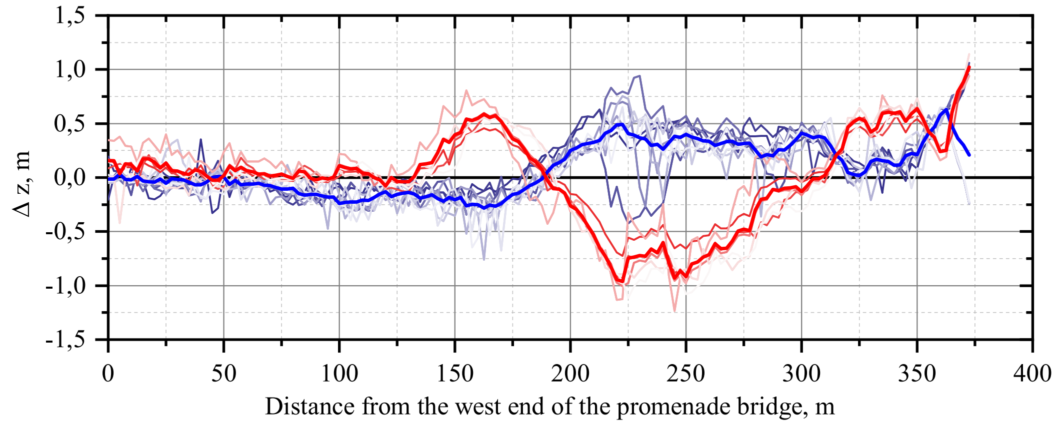


Figure 12. Spatial and temporal evolution of bottom elevation changes (Δz) showing the average of all measured profiles (blue - 2016, red - 2017).

To group cross-shore profile zones, K-means cluster analysis was performed. Cross-shore profile positions over the study period were grouped in 4 clusters, and all cross-shore profiles were also averaged. Standard deviations for the averaged curve were calculated.

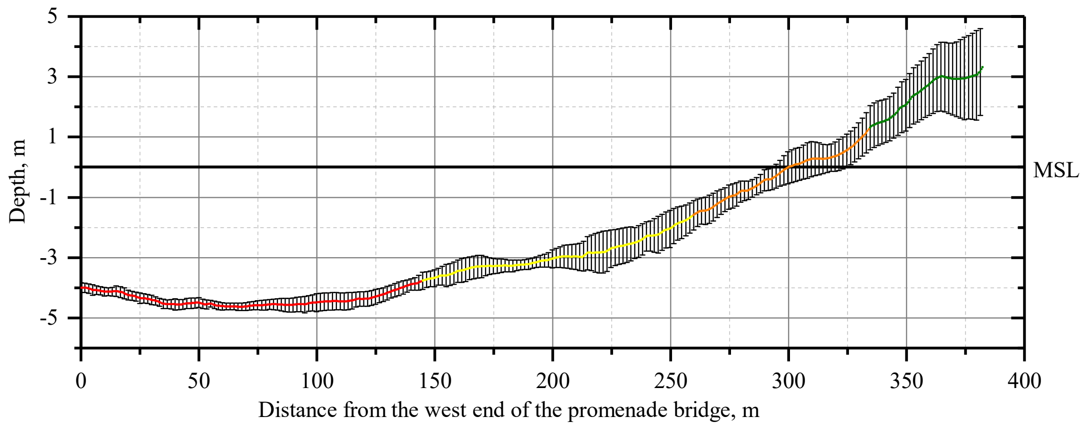


Figure 13. Average of all measured profiles (red 1st, yellow 2nd, orange 3rd and green 4rd clusters) with the standard deviation.

The four clusters represent sectors on the cross-shore profile that change due to different conditions. The first cluster is the lower part of the profile from -5 m to -3,5 m and includes 38% of the total profile length (146 m). The deepest part of the profile is constrained by a moraine layer which is exposed in intense storms. Small scale seabed features result in minor, (±0,1 to ±0,3 m) deviations from the average profile (Figure 14).

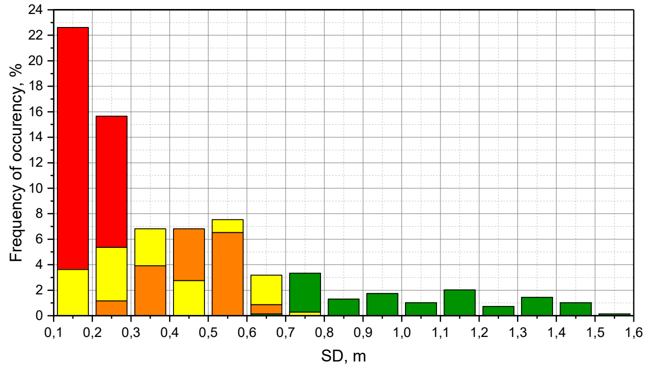


Figure 14. Distribution (%) of standard deviation (sd) per the clusters (red 1st, yellow 2nd, orange 3rd and green 4rd clusters).

The second cluster comprises 114 m of the cross-shore profile, 30% of the length. It includes the middle section of the underwater profile from -3.5 m to -1.6 m depth. This part of the profile is above the depth of closure and falls into a more active hydrodynamic zone with more soft-sediment than in deeper water. The standard deviation varies from ±0,1 m to ±0,8 m (Figure 14). The difference between the 2nd and 3rd clusters is likely the result of different hydrodynamic drivers. The 2nd cluster is where waves and alongshore currents dominate most of the time, with the 3rd cluster having similar process drivers, but affected by changes in the mean water level. This 73 m of the profile (19%) has a narrower distribution with standard deviation from ±0,2 m to ±0,7 m.The 4th cross-shore profile sector with the highest SD (from ±0,2 m to ±1,5m), is the dune system, with different processes operating. It is the shortest cluster, just 49 m, with a height from 1,8m up to 3,2 m. The highest dune point was measured at 4,8 m in 2017.

4. Discussion and Conclusions

Beach profile features and evolution are essential considerations for coastal engineering projects. In the eastern Baltic Sea, profile dynamics have received comparatively less attention than alongshore processes, and the available knowledge remains partly qualitative and empirical [1,9,35,44-46].

Cross-shore profile evolution is often studied in a controlled environment such as in wave tanks [2,4-6], and results may be difficult to apply to realistic situations [7]. Often, the emphasis has been placed on the equilibrium profile for a particular location and the closure depth [35,47] but local geomorphological conditions (such as, in this case, the presence of a hard layer at -5m) may be locally fundamental. Also, interaction with structures on the coast may drastically change underwater beach profile evolution [6].

At Palanga beach, a quasi-equilibrium state [35] was reached in the hundred years after the promenade bridge was built [30,48]. This fragile state was destroyed in 1999 when a new pier, with an open design, was built [48], and substantial damage to the coast done during storm "Anatoly" [30,48]. Disruption of the quasi-equilibrium state created conditions that led to a new profile shape.

One storm, together with the new sediment transport conditions, changed the cross-shore profile and coastal zone characteristics enormously. Loss of on at the lower profile part, deeper than -3m, continued for another sixteen years. This area is further from the shoreline than the newly built groyne, but shallower than the depth of closure.

It is common practice to try to stop coastal erosion, using both „soft"(e.g. beach nourishment) and „hard" (e.g. wave breakers, groins) coastal protection methods [49-52]. To stop further beach erosion, a groyne system was reconstructed in May 2000. First measurements after the groyne installation showed positive changes in the upper part of the cross-shore profile. In sixteen years, 172 m3 of sand per linear meter was accumulated, with full dune system recovery. A narrowing of the beach occurred along with a foredune recovery [53,54], and beach width is limited by the wave set up, maximum water level [55]. The foredune will likely be eroded by waves when water levels with around en year return period is reached, but it has had enough time to recover its long-term equilibrium shape [56]. Foredune recovery is a slow process that may take years to decades [57].

Part of the cross-shore profile corresponding to the dune sector falls into a separate 4th cluster, with the largest values of change and standard deviations. This section of the profile shows different development trends, dependent on the sediment characteristics rather than on the hydrometeorological conditions, which is intuitively predictable, but not statistically proven [54,56,57].

For the 1st cluster, at a depth close to the depth of closure, significant sediment relocation was observed after the storm "Anatoly". This area recovered fast, with insignificant (0,1-0,2m) changes during most of the study period. This section of the profile profile is influenced mainly by short period waves, predominant in the SE Baltic sea [36,58,59], and limited by the depth of closure [37].

The rest of the profile was further divided into two parts, the 2nd and 3rd clusters. These sectors of the profile had behaved similarly, and the distribution of standard deviations fall within the same limits. We believe that this profile sector was separated into two groups due to predominant external forces (wave breaker, wave set-up, wave run-up and sea-level fluctuations) influencing the cross-shore sediment transport [35,60,61]. There is a need for additional studies to determine further which driving mechanisms dominate on which profile segment.

Comparison of cross-shore profiles in 2016 and 2017 show the importance of the direction of the predominant wind for profile evolution. Moreover, even a small change in the predominant wind direction from the south to the west caused opposite seabed elevation changes. This supports previous observations concerning the importance of the wind (and therefore wave) direction to Baltic Sea coastal evolution[12,15,28,36,62].

Finally, the beach profile changes data collection is essential, and visual observations cannot be relied upon. It has been frequently stated that Palanga beach has been eroding in recent years, but apparently, erosion is caused by the upper beach narrowing due to dune advance. In this case, a significant increase in the volume of sand in the upper beach and dune system has been perceived as erosion.

Author Contributions: methodology, R.Ž.; formal analysis, V.K.; investigation, L.K.R., and V.K..; data curation, L.K.R., and V.K..; writing—original draft preparation, L.K.R; writing review and editing, K.P..; visualisation, V.K.. All authors have read and agreed to the published version of the manuscript.

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