Observation and analysis of coastal changes in the West Estonian Archipelago caused by storm Ulli (Emil) in January 2012

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ABSTRACT

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The study analyzes the meteorological parameters, hydrodynamic conditions and coastal changes at three practically tideless locations on Saaremaa Island caused by storm Ulli (sustained wind speed 20 m/s, gusts 28 m/s) which struck the Estonian coast on 4 January 2012. It was the last and the most influential storm of a series of storms which began on November 2011. Wind and sea-level data from nearby meteorological and hydrological stations were used to provide the forcing data for hydrodynamic study. Wave hindcast was performed using a semi-empirical SMB-type wave model. Shorelines, scarp positions and beach profiles were measured in August 2011, and again during each of storm Berit (in November) and storm Ulli (in January). Local storm surge height reached 1 m, significant wave height (Hs) was up to 2.8 m, the combined sea level and Hs reached 3.65 m, and local wave run-up reached 3.2 m during Ulli. At Cape Kiipsaare, recession of the sandy scarp reached 9 m (at the rate of nearly 1m per hour). The loss of sand was approximately 4-5 m^3 per 1 m of shoreline. Erosion occurred on the shores exposed to the prevailing wind direction while accumulation was recorded on the leeward side of the spit. Erosion mostly occurred at the elevations between 1-3 m. Although the winter 2011/12 included a series of influential storms, nearly two-thirds of coastal erosion during the winter 2011/2012 was caused by storm Ulli, which featured the highest sea levels.

ADDITIONAL INDEX WORDS: *Extreme storm, coastal processes, Baltic Sea, sediment transport, nearshore hydrodynamics, overwash, storm surge.*

INTRODUCTION

Estonia is a relatively small country (45,000 km^2), but it is rich in its diversity of shore types formed under distinct geomorphic conditions. This is due to its location at moderate latitudes in a transitional area between major geological structures (Fennoscandian Shield and East European Platform) and climatic (maritime and continental) regions. The shoreline is relatively long (approximately 4,000 km) due to numerous peninsulas, bays and islands. The coast is geologically diverse and is characterized by its embayed nature with a variety of beach types experiencing land uplift ranging from 0.5 to 2.8 mm/y (Vallner *et al.*, 1988). Accumulative coastal landforms, such as spits, beach ridges and tombolos, develop by a variety of means at different locations.

The effects of global climate change over the last decades have been particularly evident in northern Europe. The Baltic Sea region has seen a statistically significant increase in mean air temperature from 0.5 to 0.9 °C over the past century (Jaagus, 2006; Wang *et al.*, 2006; Langenberg *et al.*, 1999). A statistically significant increase in monthly mean temperature is present only during the period from January to May.

A significant change in winter cyclonic activity over the North Atlantic and the Baltic Sea region has been observed during the second half of the 20th century (Zhang *et al.*, 2004; Jaagus, 2006). A northward shift of the cyclone trajectories in recent decades has been recorded (Sepp *et al.*, 2005; Wang *et al.*, 2006). As a result, storminess has increased and trends towards higher storm surge levels have recently been reported at various locations, including along the eastern coast of the Baltic Sea (Langenberg *et al.*, 1999; Orviku *et al.*, 2003; Lowe and Gregory, 2005; Suursaar *et al.*, 2006; Kont *et al.*, 2008; Furmanczyk, and Dudzinska-Nowak, 2009; Lehmann *et al.*, 2011). The combined effects of warmer winters, an absence of sea ice, increased cyclonic activity, more frequent extreme storms, and higher storm surge levels vitalizes shore processes and causes abrupt changes in the geological structure and evolution of seashores.

The energy of strong storms and their impact on shore dynamics is exponentially larger than that of moderate storms (Orviku *et al.*, 2009). Strong storms may leave a lasting mark on the geomorphology of the shore or may change the trend of development of existing shore formations (Tõnisson *et al.*, 2007; 2008). There is, consequently, a crucial need to understand and better quantify the relationships between extreme storms and shore processes and their effects on the coastal zone.

The study analyzes the meteorological parameters, hydrodynamic conditions and coastal changes caused by an extreme storm known as Ulli (Emil), which seriously affected the British Isles, the Netherlands, Denmark and Sweden. It travelled across the Baltic Sea from 3 to 5 January 2012.

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Figure 1. Location of the study areas.

It was the last and the most influential storm of a series of storms that began on 22 November 2011 with Berit and was followed by Yoda, Friedhelm and Patrick. Upon reaching the Estonian coast the storm was somewhat weakened. According to meteorological stations in West Estonia, one hour sustained wind speed exceeded 20 m/s and gusts were up to 28 m/s during storm Ulli. However, within the preceding month, average sea level gradually rose from -30 cm to +50 cm and peaked at 126 cm near the Harilaid geomorphic study sites and 161 cm in Pärnu (Table 1). The objectives of this study are: (1) to present a meteorological and hydrodynamic analysis of Ulli; (2) to analyze coastal changes caused by the storm in two study areas; and, (3) to analyze the relationships between coastal changes, meteorological parameters and hydrodynamic conditions during the storm.

Study Area

The study was carried out in three different locations of Saaremaa Island: Harilaid Peninsula, Cape Sõrve and Küdema Spit (Figure 1). All sites lie in an active region in terms of both geomorphic and hydrodynamic processes, where historical changes in shoreline position and contour reflect past changes in wind and wave climate. Tidal motions are negligible (less than 10 cm) in this region, and the major hydrodynamic agents acting on seashores are waves, and relatively infrequent storm surges.

Saaremaa is the largest island in the West Estonian Archipelago. Its NW coast is exposed to the strongest winds and highest waves in the archipelago. The most detailed studies were carried out in Harilaid. It is a small (approximately 4 km^2) peninsula in Saaremaa, which is connected to the larger Tagamõisa Peninsula by a tombolo (Figure 1). The primary landform of the peninsula is a glaciofluvial ridge. The most rapid coastal changes take place on Cape Kiipsaare, the north-westernmost tip of Harilaid where a sandy scarp borders a 50 m wide beach. The scarp is the highest (3 m a.s.l.) in the NW part of the cape where shore processes are the strongest. Shore processes during the last century have caused the north-westernmost point of the cape to migrate to the northeast (Tõnisson *et al.*, 2007).

Gravel-pebble shores characterize the southern part of Harilaid Peninsula where a series of beach ridges and increments of different ages form an over 1 km long spit known as the Kelba spit. It consists of well-rounded crystalline gravel, pebble, cobble and boulders. The crests of the beach ridges are approximately 2.5 m high. Accumulations of new beach ridges gradually elongate the spit. Lagoons and small lakes lie behind the spit. The study site is well exposed to a relatively narrow area between 260 and 310 compass degrees where fetches, according to the model calibration procedure, are 100 to 200 km. Owing to the embayed location of the Kelba Spit, the fetches are restricted by shoals and islets down to 5–20 km in northerly and southerly directions. And finally, there is no significant wave action coming from the landward side during easterly winds, where the fetches are just 1–2 km.

Table 1. Key meteorological and hydrodynamical values during storm Ulli compared to the values from other storm events in 2011 (see Figure 2). One-hour sustained wind speeds (SWS) and maximum gust wind speeds (GWS), maximum sea levels (SL) at tide gauges, modelled significant wave height at Kelba (Hs), and Ristna SL – Kelba wave height combined (SL+Hs).

Station	**3-4 January 2012 Ulli**	**Max Nov.-Dec. 2011**
Vilsandi SWS (m/s)	19.5	19.8
Vilsandi GWS (m/s)	28.0	28.8
Kihnu SWS (m/s)	16.4	17.9
Sõrve SWS (m/s)	20.0	19.6
Ristna SL (cm)	117	93
Pärnu SL (cm)	161	145
Kelba Hs (m)	2.80	2.73
Ristna SL+Hs (m)	3.65	3.28

The Sõrve study site is located in the southernmost point of the Sõrve Peninsula, SW Saaremaa (Figure 1). The area consists of gravel and pebble beach ridges continuing to the south and southwest in the form of islets of similar composition and origin. The islets change their shape from time to time based upon the direction of the storm wave activity. The material deposited onto the beach ridges has eroded from an extensive meridional submarine ridge and has been transported from south to north. The site is one of the most exposed to the open sea in Estonia where wind velocities are the highest. The shore dynamics are much different from the other study sites due to its exposure to both the Baltic Sea proper and the Gulf of Livonia (Riga). The shores in Sõrve are shaped by storm wave activity from west, southwest, south, southeast and east (Tõnisson *et al*., 2008).

The Küdema study site is situated on the eastern coast of Küdema Bay, on the northern part of Saaremaa (Figure 1). A complex accumulative coastal formation with a spit (nearly 3 km long, 0.5 km wide and up to 3.5 m high) is the principal evolving relief structure the formation and development of which strongly depend on the erosion of the Panga cliff to the north. The 2.5 km long cliff (up to 21 m a.s.l) consists of Silurian limestone. Küdema Bay is relatively deep reaching 22 m about 1 km west of the study site. About 100 m from the eastern coast, the basin becomes abruptly shallower forming a 2-3 m deep erosion surface in the Silurian limestone. Similar to Cape Kelba, the study site is exposed only to waves coming from the W–NW.

METHODS

Meteorological and Hydrodynamic Factors

Wind data from nearby Vilsandi meteorological station (7 km south of Harilaid Peninsula) and sea level data from Ristna tide gauge (50 km north of the study site) were used to assess the meteorological conditions and to provide the forcing data for hydrodynamic study. The Ristna tide gauge station on Hiiumaa Island is the nearest to the study site.

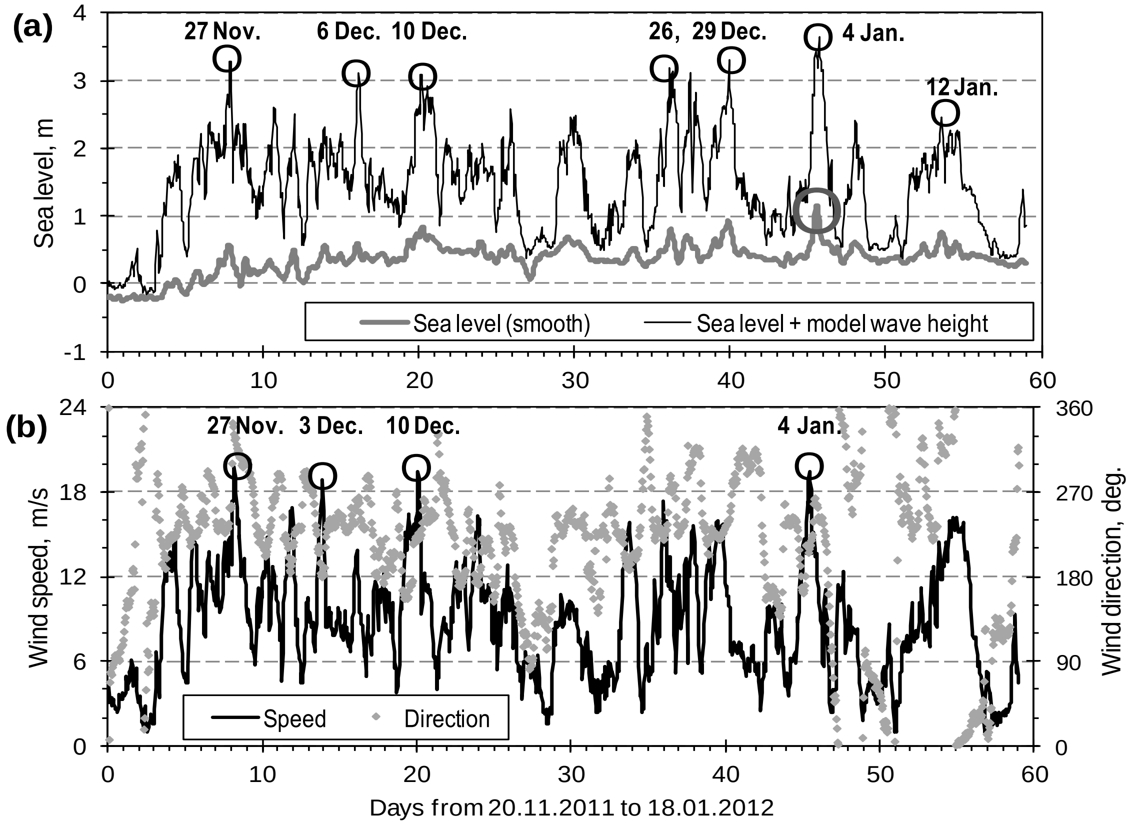

Figure 2. Over the stormy period from 20 November 2011 to 18 January 2012, (a) variations in sea level measured hourly at Ristna (smoothed over 3 h), combined with Ristna sea level and hourly modelled significant wave heights near Kelba Spit; (b) corresponding variations in Vilsandi hourly sustained wind speeds and directions. The prominent peaks are marked with circles.

The measurements are still made according to the Baltic System 1977 with its zero-benchmark reference point at Kronstadt, near St.Petersburg. At present, the Kronstadt zero is nearly equal to the long-term mean sea level for the practically tideless Estonian coastal sea (Suursaar and Sooäär, 2007). Both stations are operated by the Estonian Meteorological and Hydrological Institute (EMHI) and they provide hourly data.

In order to assess variations in forcing conditions for the coasts a wave hindcast was performed using a semi-empirical SMB-type wave model for the location 1.5 km off Kelba Spit. The SMB-model, also known as the significant wave method, is based on the fetch-dependent shallow-water equations by Sverdrup, Munk, and Bretschneider, further modified in the Shore Protection Manuals of the U.S. Army Corps of Engineers (see e.g. USACE, 2002). Based on wind data, the model calculates the significant wave height, wave period and wavelength for a chosen location. As the influence of remotely generated waves (swell) is low and the memory time of the wave fields in the Baltic Sea is relatively short, this fairly simple method can deliver reasonably good results for limited study areas (Suursaar and Kullas, 2009; Suursaar, 2011; Suursaar *et al.*, 2012). The 2011-2012 wave hindcast study was preceded by a wave measurement operation at a location near Kelba Spit. An RDCP-600 oceanographic measuring complex manufactured by AADI Aanderaa was deployed on the seabed at a depth of 14 m between 20 December 2006 and 23 May 2007 (for the details see Suursaar *et al.*, 2008). The instrument was used to measure hourly data on currents, wave parameters, sea level variations and water column properties. It appeared that wave action combined with sea level height were the main hydrodynamic agents for the coasts of Harilaid, while sea current accounted for only minor background drift for material suspended by waves.

Although the RDCP measurements yield non-directional wave data, the directional model calibration scheme itself (see Suursaar *et al.*, 2012) selects out the directions where the highest waves may come to the specific location. The calibration was done mainly by prescribing and modifying fetch distances for different wind directions during the 5-month period. A high correlation coefficient (0.90), low RMSE (0.23 m) and nearly equal average and maximum values of calculated and measured wave properties were obtained. Using the wind forcing from the same source (i.e. Vilsandi station), the calibrated model was then used in hindcast forecasts at a 1h interval.

Coastal Changes

Shorelines, scarp positions and beach profiles were measured at the end of summer 2011 at all of the study sites (Harilaid, Küdema and Sõrve). The same measurements were carried out in Harilaid Peninsula on November 27th and 28th as storm Berit passed over west Estonia. As storm Ulli passed over the study sites, changes in shoreline, scarp positions and beach profiles were measured again at the Harilaid (Figure 3) and Sõrve study sites. The changes in Küdema were measured in summer 2012 (Figure 4).

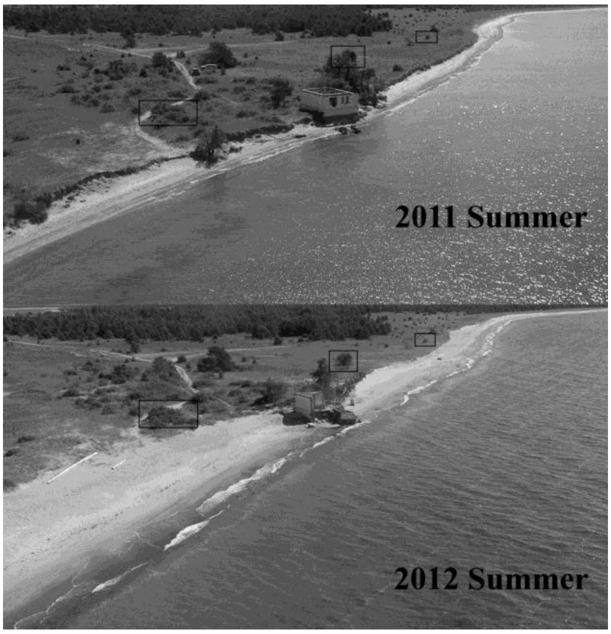

Figure 3. View to the lighthouse keeper´s house at Cape Kiipsaare before and after extreme storms in winter 2011/2012.

Wave run-up and sea-levels were also *in situ* recorded during, and where possible after, the storms, by reference to the location of physical manifestations of the storms' presence (e.g., ridges of debris, fresh sediments etc.). All the measurements were carried out using Trimble and Leica RTK-DGPS devices with an accuracy of 1 cm in vertical and horizontal scale. Sea levels were measured several times during storms Ulli and Berit in Haagi Lõugas Bay on the southern coast of Harilaid. This location was ideal for such measurements due to its position in the shelter of the Kelba Spit.

Studies on historical coastal geomorphic changes are based on the maps, aerial photographs, orthophotos and photographs, which date back to 1900. GPS measurements and precise leveling studies have been performed since 2000 to assess short-term changes in shoreline position. Garmin devices (accurate to within 3 m), and after 2010 the Leica GS09 (accurate to within 1–2 cm), have been used for these purposes. MapInfo software was used to analyse the shoreline changes and calculate the extent of erosion and accumulation.

RESULTS AND DISCUSSION

Meteorological and Hydrodynamic Conditions

Storm Ulli mostly influenced the south-western and western coast of Estonia. Travelling east, it lost its strength and the effects on the northern coast of Estonia were not significant.

Although storms Berit (on 27 November) and Ulli (on 4 January) had somewhat different wind directions (respectively, NW and SW), the direction of the highest waves reaching the Kelba study site (the embayed configuration of which is not quite visible on the small scale sketch-map of Figure 1) were probably not that different because the waves from different directions reach the study site selectively. The dominant westerly direction of wave loads over a longer period of time is also attested to by the shape of the Cape Kelba (Figure 5). According to the wave hindcast, during Ulli significant wave height (Hs) 1.5 km off the Cape Kelba study site was 2.8 m on 4 January and corresponding maximum waves reached 4.2 m. The combined sea level and Hs reached to maximum 3.65 m (Figure 2, Table 1). The wind speed during Ulli reached 20 m/s (with gusts up to 28 m/s). A maximum height of wave run-up reaching 3.2 meters in the proximal part of the Kelba Spit was observed at 12:00 PM (UTC) on 4 January. At the beginning of the storm, at around 06:00 UTC on 4 January, the sea level was already +60 cm at Ristna, and it climbed to 120 cm by the peak of the storm. A maximum sea level (1 m) at the site (Haagi Lõugas Bay) was recorded at 12:00 pm (UTC).

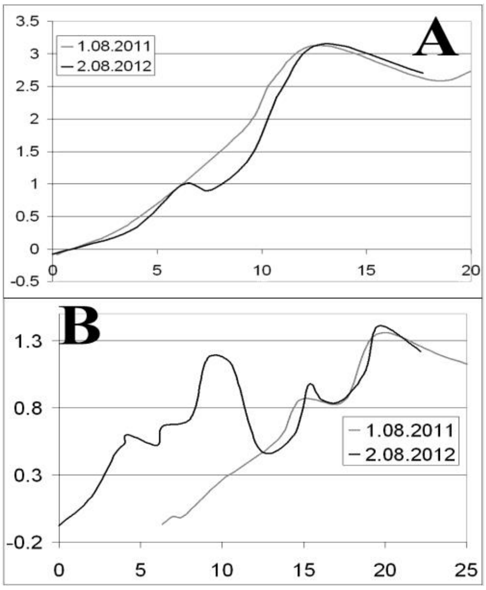

Figure 4. Levelling survey reveals that the sections more exposed to the storm waves (A – proximal part of Küdema Spit) experienced significant erosion from the elevation 1.0 to 2.5 m while notable accumulation appeared on the distal parts located more or less protected from the direct wave impact (B – distal part of the Küdema Spit). Both axes units in metres.

The sea-level rise during Ulli was nearly the same as during Berit (Tõnisson *et al*., 2012). But the initial sea-level just before the storm was zero before Berit and already around +60 cm just before Ulli. Therefore, the consequences of Ulli were more serious. Hs during Berit was nearly the same as in 4 January (2.8 meters) but the combined sea level and Hs reached only 3.3 m in November. As a result of higher sea-level in January the wave run-up reached 3.22 m at Kelba compared to 2.90 m during Berit. It should also be noted that the wave run-up in Cape Kiipsaare (where a 2 m isobath lies more than 100 m from the shoreline) reached 2 m. Waves broke through the foredunes and caused extensive flooding, as the water-level behind the foredunes reached 120 cm. At times during the storm, the water-level on land was 20 cm higher than sea level.

Coastal Changes

The largest changes on Cape Kiipsaare were measured south of the former lighthouse keeper's house, which today is located directly on the beach (Figure 3). Southerly and south-westerly winds and waves predominated for the duration of Ulli. The recession of the sandy scarp north of the old house reached only 3 m during Ulli, whereas it reached 6 m during Berit. Most of that erosion took place at an elevation of nearly 2 m and therefore the height of the scarp was mostly below 0.5 m.

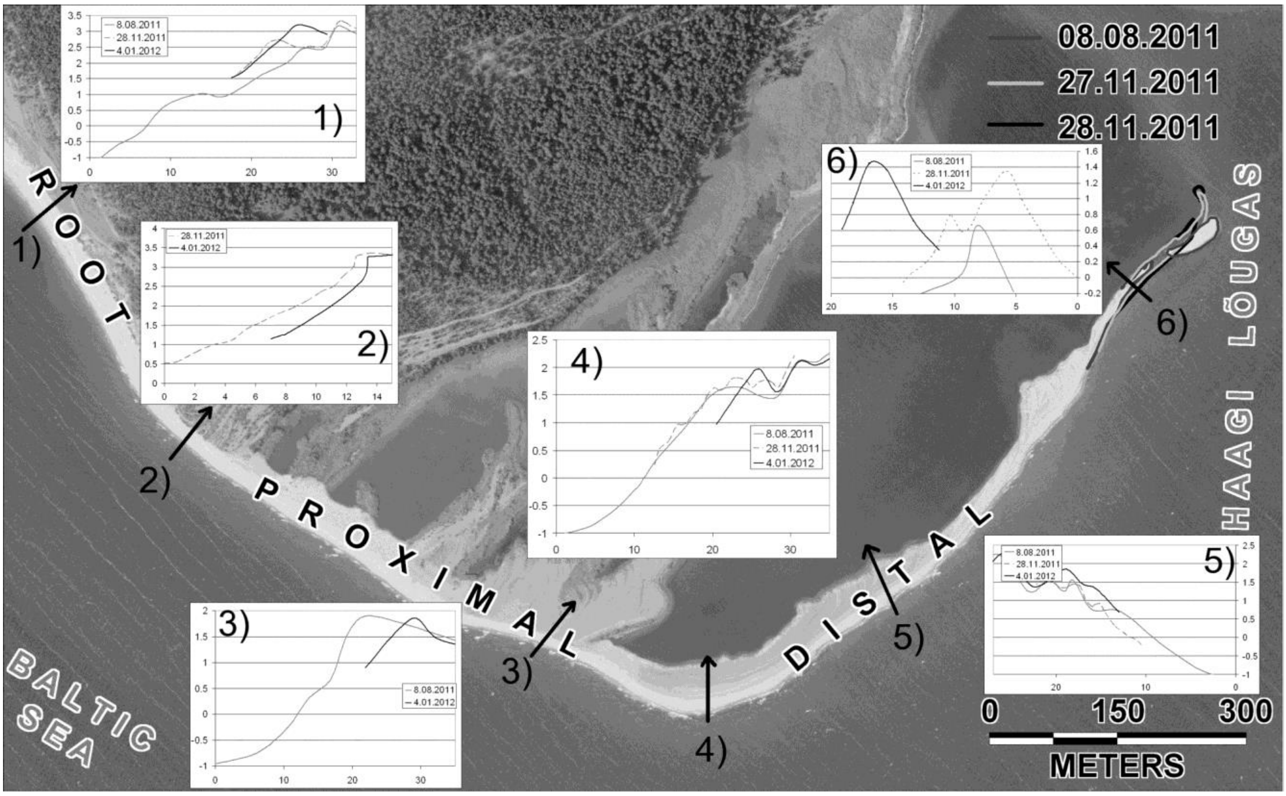

Figure 5. Shoreline changes in the distal part of Kelba Spit and profile changes during the winter 2011/2012. 28.11.2011 indicates the changes caused by the storm Berit while 04.01.2012 reflects the results of the measurements carried out after the storm Ulli.

Some of those eroded sediments were washed over the smaller dunes. As a result, a 20 cm thick fresh layer of sand extending 10-20 m inland was measured on top of the former coastal vegetation after the storm. Recession of the scarp was much quicker south of the old house reaching 8-9 m just 20 m from there. The loss of sand can be estimated at 4-5 m^3 per 1 m of shoreline. The speed of recession reached 0.9 m/h during the peak of the storm – 0.3 m more than during Berit. However, the base of the eroded scarp was at an elevation of 1.8-2.0 m and the amount of eroded sediments was comparable to that of Berit. The area of intensive erosion extended about 400 m south of the house. In total during Ulli the amount of eroded sediments from the western coast of Cape Kiipsaare reached around 3,000 m^3. Those sediments were probably carried around Cape Kiipsaare and accumulated on the leeward side of the peninsula. Periodic measurements along the transect on the eastern coast showed accumulation of 2-4 m^3 of fresh sand on the vertical elevations between 1-2 m. Even on the leeward side of the peninsula, overwash appeared at an elevation of 1.85 m. It destroyed the coastal road on the narrow section between Laialepa Bay and Uudepanga Bay. The measurements taken in summer 2011 and repeated in summer 2012 revealed approximately 1 m of freshly accumulated sand on the coastal sea and on the beach on the western side of Cape Kiipsaare. The edge of the scarp has receded up to 12 m and the total loss of the sediments on the western coast of the cape is approximately 5,000 m^3 (approximately 10 m^3 of sand per meter of shoreline). Some of the sand stayed on the coastal sea due to the short duration of the winter storms and is now coming back to the shore.

Both intensive erosion as well as accumulation was recorded on the gravel-pebble spit at Kelba on the southern part of Harilaid. New gravel ridges in the root area of the spit (i.e., the area before the lagoons and increments of the spit) reached 3.22 m (Figure 5). It was impossible to carry out field measurements at the shoreline due to very strong wave activity. The most intensive accumulation of sediment occurred at the elevations from 1 to 3 m a.s.l. A 2-3 m layer of freshly accumulated gravel and pebble was deposited on the seaward slope of the spit and about 0.5-1 m of sediment accumulated on the top of ridges above a height of 2 m. As the waves approached the shore at a right angle, we assume that the deposits originated from the near-shore seabed and accumulated as a result of onshore drift.

In the proximal part of the spit, the waves approached the shore at less of an angle, thereby changing the character of shore processes. Intensive erosion occurred in places well exposed to the open sea. The most intensive erosion took place at 1-2.5 m above sea level where about a 2-3 m wide and 1 m thick layer of gravel and pebble was removed from the seaward slope of the spit. The wave run-up reached over 2.5 m a.s.l. here causing some sediments to be transported on top and across the spit. The eroded sediment probably drifted along the shore towards the distal part of the spit. The character of processes had changed again from the point where the spit turns NE and the shore becomes less exposed to the waves. The measurements along the transect crossing the spit at the distal section show the accumulation process from 0.85 m up to 1.85 m of height (Figure 5). The last transect crossing the spit a few hundred meters from its tip shows that the distal section of the spit has shifted over 10 m landward as a result of overwash. The height of the freshly formed beach ridge is indicating that the wave run-up reached over 1.5 m here. We may assume that those final 200 m of the spit were shifted landward as well, but due the fact that this formation was constantly underwater the changes in its location have not yet been measured.

The changes registered at the Küdema study site were very similar to the ones measured in Kelba (Figure 4). At the elevation of 1-3 m, a 0.5-1m thick layer of sediments was eroded from the proximal part of the spit, which was well exposed to the storm waves. Intensive accumulation (5-10 m^3 of fresh sediment per one meter of shoreline) was registered on the distal part of the spit and on the sections less exposed to the dominating direction of the storm waves. Cape Sõrve, which is relatively well exposed to both westerly and easterly wave directions, showed surprising results. There were no significant changes despite very strong storms accompanied by very high sea-level. The only notable changes were marginal erosion on the eastern side of the cape, nearly 0.5 km from its tip, and marginal accumulation (a new layer about 0.4 m thick) at the distal section of the eastern side of the cape.

CONCLUSION

Ulli struck Estonian shores on 1 April 2012. Although preceded by other storms, it had the greatest impact in terms of maximum sea-levels and wave parameters during the 2011/2012 storm season. Sea-levels reached 120 cm at Ristna, nearshore wave heights reached 4.2 m and on-site wave run-up was recorded as high as 3.22 m. The high waves combined with high sea levels to cause extensive erosion on the shores exposed to the prevailing wind direction, while rapid accumulation was recorded on the leeward shores. The erosion caused by storm Ulli was mostly visible at elevations between 1-3 m above mean sea-level. In spite of the fact that the 2011/2012 storm season brought many strong storms, including storm Berit, and that each contributed to such coastal erosion, it can be concluded on the basis of real-time field work and successive analysis that due to the high sea-level present during storm Ulli nearly two-thirds of coastal erosion registered at the study sites during the stormy season 2011/2012 was caused by Ulli.

ACKNOWLEDGEMENT

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