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SHORELINE DYNAMICS IN ESTONIA ASSOCIATED WITH CLIMATE CHANGE

Abstract

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Publication III: The author is partly responsible for the parts concerning coastal and shoreline changes. He also made most of the figures and participated in the preparation of the manuscript.
Publication IV: The author is partly responsible for the analysis of shoreline changes data. He also made most of the figures and participated in the preparation of the manuscript.
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Publication VI: The author is principally responsible for the data collection and analysis of data (landscape map, landscape profile, land cover changes). He also made all of the figures and participated in the preparation of the manuscript.
Publication VII: The author is partly responsible for the parts concerning shoreline changes. He also made one of the figures and participated in the preparation of the manuscript.
Publication VIII: The author is principally responsible for the data collection and analysis (landscape map, landscape profile, land cover changes, landscape diversity). He also made all of the figures and participated in the preparation of the manuscript.

PREFACE

This thesis focuses on changes in shoreline position and configuration in Estonia over the past 100 years.

Most coastal areas in Estonia are flat and low-lying. The shoreline is very sinuous with many peninsulas and bays. Estonia is also rich in different geomorphic types of shores.

Fourteen shore areas with dissimilar geomorphic structure and exposure to the open sea were studied. Topographic maps and aerial photographs from different times (1900–1998) and data obtained from direct observations (2000–2003) were used to identify changes in shoreline contour and position. A cartographic method of comparison was used to analyse shoreline changes between different time intervals.

The most detailed studies were carried out in the West-Estonian Archipelago: on Harilaid Peninsula, and on Luidja and Tareste sandy beaches. The database of these areas contains 5–10 shoreline positions from different times (whereas other areas feature 3–6 shoreline positions).

Some of the time series of shoreline changes were related to storm data to analyse the expected activation of shore processes and their relationships with climatic changes. The main purpose of this study was to analyse shoreline changes and determine their relationships with particular storm parameters (e.g. number of stormy days and sea level during storm events).

These results can be used as a basis for predicting shoreline changes during the next 100–300 years. The prediction of possible shoreline changes resulting from global sea-level rise using an algorithm of shoreline retreat (according to the Bruun Rule) comprises an integral part of this study.

1. INTRODUCTION

1.1. CLIMATE CHANGE

Global climate undergoes continuous change. Many colder (glaciations) and warmer (interglacial) epochs have been distinguished in geologic history. Climatic fluctuations in the past 100 years and the prognosis for the next 100 years are the major topics of interest in this study.

From the beginning of the 20th century until 2000, global warming has been 0.6 ± 0.2°C (Folland et al., 2001). 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 (Heino, 1994; Moberg & Alexandersson, 1997; Balling et al., 1998; Jaagus, 1998).

This increase in mean air temperature has been induced mostly by changes in atmospheric circulation (Fu et al., 1999; Serres et al., 2000; Giorgi, 2002 and others). Warming during the cold period in the Baltic Sea region is closely related to intensified westerly winds. More intense westerly winds are a consequence of low pressure above the northern Atlantic Ocean. These weather conditions are characterised by intense cyclonic activity and frequent storms (Orviku et al., 2003).

Variations in surge statistics can also be inferred from analysis of meteorological data. E. Kass et al. (1996) and the WASA (Waves and Storms in the North Atlantic) Group (1998) showed that there were no significant overall changes in windiness and cyclonic activity over the North Atlantic and northwest Europe during the past century, although major variations have occurred on decadal timescales. An increase in storminess in the northeast Atlantic during the last few decades (Schmith et al., 1998) and a recent trend towards higher storm surge levels on the German and Danish coasts (Langenberg et al., 1999) is consistent with natural variability over the last 150 years. However, some research has suggested an increase in storminess in the northeast and northwest Atlantic during the last 10–20 years (Carter & Draper, 1988; Van Hooff, 1994; Schmith et al., 1998; Shaw et al., 1998; Langenberg et al., 1999;

Alexandersson et al., 2000). Important changes have been detected in wind regime in the Baltic Sea area (Ekman, 1999; Pryor & Barthelmie, 2003).

Climate change induces global sea-level variations and increasing cyclonic activity, which results in much stronger short-term sea-level fluctuations between storm periods (primarily caused by winds blowing from a single direction).

All else being equal, future mean sea level rises will result in the present extreme levels occurring more frequently (Church et al., 2001). This could lead to a significant increase in the area threatened with inundation (e.g. Hubbert & McInnes, 1999) and an increased risk within the existing flood plain. These effects can be estimated from information of the current frequency of occurrence of extreme levels (e.g. Flather & Khandker, 1993; Lowe et al., 2001).

Changes in sea ice cover are also affected by climate change. Ice-free nearshore and offshore areas and unfrozen sediments favour intense erosion and transport of sediments during stormy periods. This study stems from observations that clearly show a decrease in both ice cover extent and duration in the Baltic Sea during the last hundred years (Jevrejeva, 2002; Jaagus, 2003b) and an increase in storminess over the last twenty years.

1.2. SEA LEVEL FLUCTUATIONS

Different rates of sea-level rise have been recorded in different parts of the world. Changes in sea level fluctuations have been measured more precisely during the last century.

Many analyses have addressed changes in global sea level. Research during the last decades show that the relative sea-level rise during the last century has been 1–3 mm/yr (mean 1.5–1.7 mm/yr) (Gornitz & Lebedeff, 1987; Barnett, 1988; Peltier & Tushingham, 1989, 1991; Douglas, 1997; Peltier & Jiang, 1997).

Analysis of different climate change scenarios data indicates that the global sea-level rise will be 10–90 cm during the next century, although the latest studies suggest a lower sea-level rise (10–50 cm during the next century, mostly 40–50 cm) (Warrick et al., 1996; Church et al., 2001; Dawson, 2004).

Changes in the mean sea level affecting the Baltic Sea are better represented by those in the North Sea area beyond the Baltic entrance, which might deviate from the global mean sea level (Johansson et al., 2004). Observations from the European tide gauges, as presented by V. Gornitz (1995), might represent this kind of mean sea level. These observations suggest an estimate of 1.5 mm/yr mean sea-level rise during the 20^{th} century.

Sea-level rise scenarios for the next century and their impact on the Estonian shoreline form the most important aspect of this study.

1.3. COASTAL PROCESSES

Coastal processes involve agents at work in coastal waters, including winds, waves, tides and currents, which shape and modify a coastline by eroding, transporting and depositing sediment (Bird, 2000).

Wind-generated waves serve as important energy-transfer agents – first obtaining energy from the wind, which is transferred across the expanse of the sea and finally delivered to the coastal zone, where the energy can be the primary cause of erosion or may generate a variety of nearshore currents and sediment transport patterns (Komar, 1998). Waves are the main forces that modify coastlines. The heights and periods of waves are governed by wind velocity and the duration or time that the wind blows. Wave energy is also influenced by the fetch, the distance over which the wind blows (Bird, 2000).

The activity of coastal processes and storm impact also depend on coastal geomorphology (nearshore topography, sediments etc.) and exposure to the waves. Changes in coastal processes resulting from global climate change deserve particular analysis (Bird, 1985; Leatherman & Nicholls, 1995; Nicholls et al., 1995; Shindell et al., 2001). The anticipated sea-level rise and increased storminess (Church et al., 1996; Ulbrich & Christoph, 1999) intensify coastal processes, which in turn may lead to considerable ecological change and economic damage to coastal zones.

If the global sea continues to rise, coastal erosion will accelerate and become more widespread with declines in compensating sedimentation. Revival of features similar to those now on the world's coastline at higher elevations – with some parts eroding while others are stable or prograding – requires a pause in sea level change (Bird, 2000).

This study focuses on wave-induced shore processes because of their great impact on shoreline changes in Estonia.

1.4. SHORELINE CHANGES

Shorelines change in response to coastal processes at varying rates, with sudden changes during storms and more gradual changes over quieter intervening periods (Bird, 2000). Storm surges occur when strong onshore winds amass coastal water to an exceptionally high level over a few hours or days. Strong onshore winds also generate large waves accompanying the raised sea-level, which overwash beaches, flood low-lying coastal areas and cause extensive changes in a short period.

An increase in the frequency and severity of storms in coastal waters may result in the erosion of beaches that previously have been stable or retreating. Storm waves cut back and steepen beaches until they attain a concave profile adjusted to the augmented wave energy. A series of storms in quick succession is particularly destructive because the second and subsequent events occur on beaches already reduced to a concave eroded profile (Zenkovich, 1967; Bird, 2000).

Shores are classified by age into two types: ancient shores and contemporary shores. Contemporary shores are subdivided by activity of coastal processes into active shores and non-active (geologically "dead") shores. On active shores, the shore platform is narrow and the wave breaker zone lie near the shoreline. On non-active coasts, the shore platform is low and wide and the waves brake far from the shoreline. The active shores differ from the non-active by the occurrence of a variety of coastal processes, whereas inundation during high sea level is the only process on non-active coasts. Active shores occur either as advancing (accretional or depositional) or retreating (erosional) shores.

Owing to its flat and low-lying morphology, climate change could affect many coastal areas in Estonia. The shoreline of Estonia (*ca* 3.800 km) is strongly indented by peninsulas and bays with many islands in the coastal zone. Therefore, coastal areas form a considerable part of Estonia's landscapes where the development of nature complexes proceeds on the borderline of the land and the sea. This zone may be regarded as an ecotone where exchange processes occur at high rates of intensity (Ratas et al., 1999). Coastal landscapes are diverse and rich in natural and cultural dimensions. Their ecosystems comprise a large diversity of habitats and rich flora and fauna. The topography, deposits and the regime of substance movement affect landscape structure development on coastal areas. Landscape types, especially their vegetation and overall biological diversity, are largely influenced by peculiarities of local climatic conditions (VIII; Ratas et al., 1997, 1999).

The most detailed observations on and measurements of Estonian coasts (shoreline changes on contemporary shores) have been carried out during the last about 30 years (Orviku, 1974, 1988, 1992; Raukas et al., 1994; I; II; V; Kask & Kask, 2002, 2003).

This study focuses on shoreline changes on active coasts during the last century.

1.5. OBJECTIVES

The **aim** of this thesis was to analyse quantitatively shoreline changes and estimate their relationships to climatic change.

The objectives were:

- to estimate quantitatively shoreline changes (displacement and configuration) in study areas in Estonia during the 20th century;
- to analyse relationships between shoreline changes (shore processes), frequency and magnitude of storms and sea levels during stormy periods;
- to determine how coasts of different geomorphic types in Estonia would react to sea-level rise.

Hypothesis:

Changes in shoreline position and contour during the last 100 years have been caused by changed climatic conditions and increased activity of shore processes.

2. STUDY AREA

2.1. THE BALTIC SEA

The Baltic Sea is a small semi-closed inland sea in northern Europe (total area with Denmark Straits is 420 000 km^2). Own to its geographical position the Baltic Sea region differs essentially from other regions in the world at the same latitude. Annual mean air temperature has increased by 1.0–1.7 ^{o}C in Estonia during 1951–2000; considerable warming has taken place primarily during winter (with the greatest warming in March, 3–5 ^{o}C) (Jaagus, 2003a). The decrease in the duration of ice cover in the Baltic Sea (Haapala & Lepparanta, 1997; Haapala et al., 2001; Jevrejeva, 2002; Jaagus, 2003b) is a clear consequence of increasing mean air temperature.

The most important factor affecting the mean sea level on the Finnish, Swedish and Estonian coasts is land uplift. The current uplift in Estonia ranges from 1.0 to 3.5 mm/yr with maximum uplift on the north-western coast (Vallner et al., 1988). Thus, the impact of sea-level rise would be compensated by land uplift in major coastal areas in Estonia. The actual rise of the sea would be noticeable only in regions where the annual mean velocity of uplift is less than 1.5 mm/yr, i.e. in north-eastern (east of Kunda) and south-western (south of Häädemeeste) parts of the coast. The data on sea level fluctuations on the southern coast of Finland over the last 100 years (Johansson et al., 2004) coincide with the data on global sea-level rise (Gornitz, 1995) and land uplift in Estonia (Vallner et al., 1988).

Short-term sea-level fluctuations along the Estonian coast are caused primarily by winds blowing from a single direction. Maximum storm surges reaching 2.65 m above the Kronstadt mean sea level (the local benchmark for the eastern Baltic Sea) have been recorded in Pärnu and Matsalu Bay, whereas the highest water level in the open sea rarely exceeds +2.0 m. Minimum water levels usually attain minus 0.5–0.7 m (Orviku et al., 2003).

2.2. VARIETY OF SHORE TYPES AND THEIR RESISTANCE TO WAVE ACTIVITY

Coastal zone topography, sedimentary rocks, unconsolidated deposits and offshore hydrology have resulted in the formation of a diverse range of shore types. Each shore type responds differently to global climate change and concurrent activation of coastal processes.

Estonia is rich in different geomorphic types of shores. K. Orviku (1992) distinguished eight major shore types based on geology, the slope of the primary relief, and the prevailing shore processes: cliff and rocky shore (5% of all shorelines), scarp shore (less than 1%), till shore (35%), gravel–pebble shore (11%), sandy shore (16%), silty shore (30%), and artificial shore (2%).

Changes in shoreline position and backshore area are very slow on cliff and rocky shores. Cliffs are cut back mainly during storms, largely by wave action (mostly lower layers are softer – glauconitic sands, shale etc.). Sunamura (1992) estimates the average rates of recession of limestone cliff to be 1–10 mm/yr and 10 mm/yr on shale cliffs. Therefore, changes on cliff and rocky shores (during the past 100 yr and the future 100 yr) were not considered in this study.

The till shore is the most extensive shore type in Estonia. The nearshore area of this shore type is low and wide. The till is washed out both on the shore and the nearshore. A protective cover of boulders or pebbles is established, which retards considerably the washout process and largely inactivates coastal processes (Orviku, 1974). Therefore, the shoreline position is highly irregular. Shingle, pebble and gravel accumulate in the foreshore and backshore at irregular intervals, brought by the onshore movement between inundation (Orviku, 1974, 1992).

Estonian coasts have been classified into three accumulative shore types: gravel–pebble, sandy and silty shores.

Gravel–pebble and sandy shores (both also known as beaches) are more sensitive to wave activity than other shore types. The wave activity of coastal processes depends on nearshore topography and exposure of the shore to the waves. Some beaches that have been fairly stable over periods of decades undergo rapid changes, especially in stormy weather. Coastal processes are more active in areas exposed to the open sea where the wave-breaking zone is located near the shore. Semi-closed bays and flat coasts with low nearshore area are well protected against wave-induced erosion. On coasts where the nearshore zone is broad and shallow, wave energy is attenuated and breaking waves diminish. In general, accretion dominates in the heads of the bays and erosion in the other sides.

Silty shores are characterised by a protracted amassment of fine-grained deposits. Silty shores in Estonia are very flat and the wave activity is low even at high sea level. There are no erratic boulders and the shore is covered with plants (primarily reed bed). The underwater shore platform is also flat and covered by fine-grained deposits.

2.3. CHARACTERISATION OF THE STUDY AREAS

Two types of study areas were selected (Fig. 1):

- 6 study areas on the west Estonian archipelago, where detailed shoreline changes were estimated (average shoreline length 4 km). Two areas on Hiiumaa Island (Tareste and Luidja), three on Saaremaa Island (Harilaid, Küdema and Järve) and one on Ruhnu Island.
- 8 study areas in other parts of Estonia, where changes in shoreline position and possible responses to global sea-level rise were examined in lesser detail.

2.3.1. Detailed studies

The most detailed studies were carried out on Harilaid Peninsula. Harilaid is a small peninsula (4.3 km^2 in area) on the north-western coast of Saaremaa (Fig. 2 and detailed map in Paper I, Fig. 1). The development of the peninsula began approximately 2000 years ago during the latest phases of the Limnea Stage of the Baltic Sea when the highest parts of Harilaid rose above sea level. On a map dating back to the 17th century, Harilaid is depicted as an island. It was situated 2 km from Saaremaa and was subjected to strong winds and storm waves. Today, Harilaid is an elongated peninsula with a core of NW–SE trending glaciofluvial ridge eroded by seawater. The peninsula is connected to Saaremaa Island by a 300-m-wide tombolo (Ratas et al., 1999).

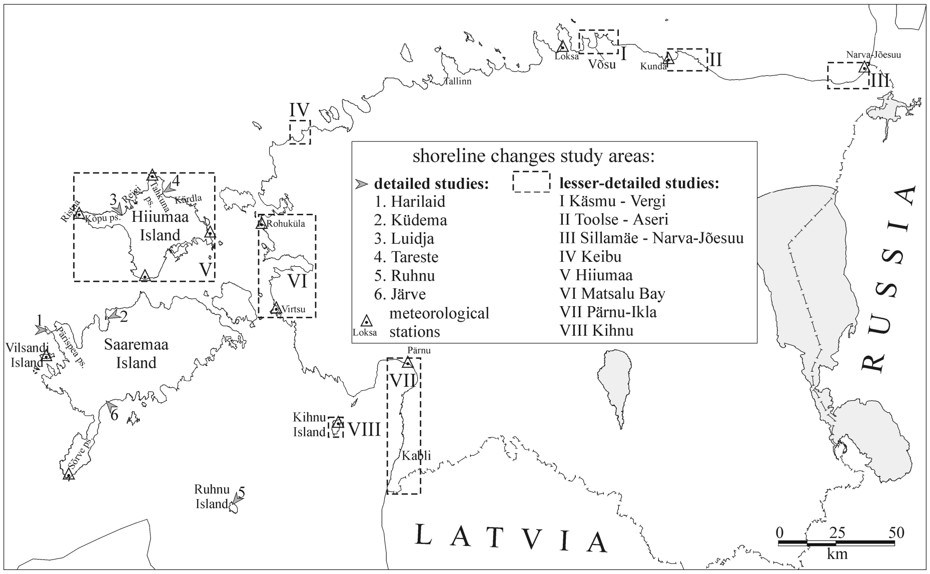

Figure 1. Location of study areas (detailed maps of some areas show figure 2).

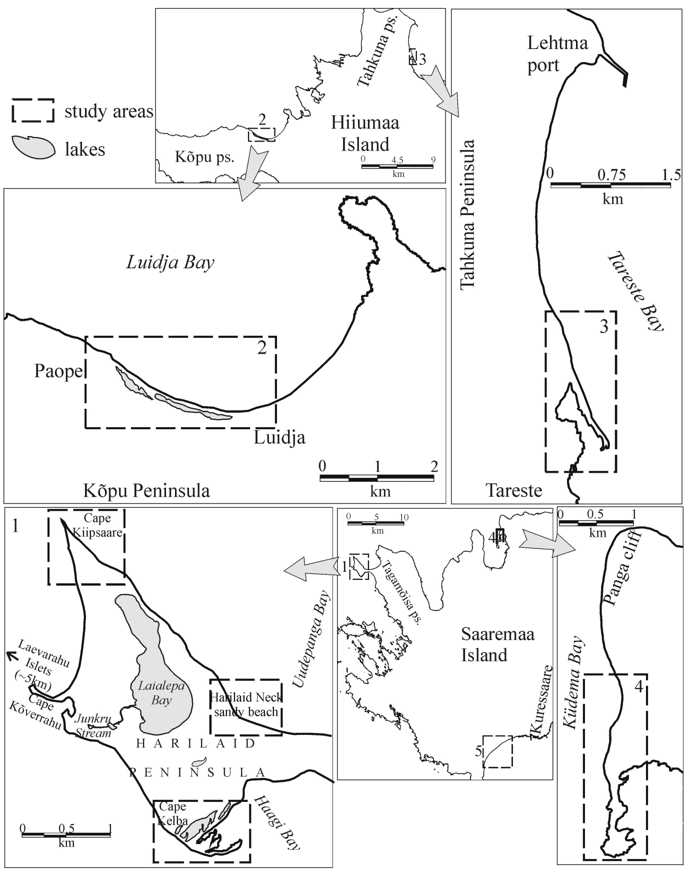

Figure 2. Detailed maps of Harilaid Peninsula, Luidja, Tareste and Küdema study areas.

The shoreline of the peninsula is 13.8 km long and shore area is flat and low (I, Fig. 1). Harilaid borders with the Baltic Proper to the west, Uudepanga Bay to the east and Haagi Bay to the south. The shores on the northern part of the peninsula feature sandy beach ridges and coastal foredunes (up to 4.5 m above sea level) with sparse vegetation, whereas those in the south contain pebble or gravel beach ridges and accumulation plains covered with forest. Some coastal lakes are located in the middle of the peninsula and a number of small bays and coastal lakes are found between the gravel beach ridges in the south.

Harilaid peninsula is a recreation area within the Vilsandi National Park.

Three study sites of dissimilar exposure and structure were chosen at different localities on Harilaid:

1. Cape Kiipsaare – a sandy beach on the northern part of Harilaid (shoreline length 1.8 km)
2. Cape Kelba – pebble and gravel beach ridges on the southern part of Harilaid (contemporary shoreline length 3.5 km)
3. Harilaid neck (tombolo) – a sandy beach in the south-western part of Uudepanga Bay (shoreline length 0.7 km).

The Luidja study area is located on the north-eastern coast of Kõpu Peninsula on Hiiumaa Island between the villages of Luidja and Paope (shoreline length 3.5 km; Fig. 2). The study area borders Luidja Bay to the north and the nearshore area is shallow (the 2-m isobath lie 350–450 (E-part 100–250) m from the shoreline). Sandy beaches dominate the study area. Gravel–pebble beaches can be found only near Paope village. Coastal foredunes, sandy beach ridges and dunes (up to 2–3 m above sea level) separate the beach from land. The study area contains two small coastal lakes, which formed behind the sandy beach ridges. The shores of the lakes are covered by reed beds. The landward side of the study area is covered by persistent vegetation. The Luidja beach is a recreation area.

The Tareste study area (shoreline length 2.5 km and together with spit 5 km) is situated on the south-eastern coast of Tahkuna Peninsula (Hiiumaa Island), 3.5 km south of Lehtma port (Fig. 2). The study area borders Tareste Bay to the east. The nearshore area is shallow – the 2-m isobath lie 150–300 m from the shoreline. Sandy beaches dominate the study area. There is a ca 1.5-km-long and narrow sandy spit in the southern part of the area. An overgrown (reed bed) lagoon is behind the spit. Older coastal formations (up to 2–3 m above sea level) and areas beyond the wave action zone are covered by persistent vegetation. There are some elongated paludified depressions parallel to the current shoreline about 150 m inland. The northern part of this study area is Tareste beach (the most popular recreation area in NE Hiiumaa).

The Küdema study area (shoreline length 4.5 km) is situated on the northern coast of Saaremaa Island at the mouth of Küdema Bay (Fig. 2), which is more than 10 m deep. The nearshore area is also deeper (particularly its western part). A complex accumulative coastal formation with a distal spit (nearly 3 km long and up to 0.5 km wide) is the main changing relief structure whose formation and development depend strongly on erosion of the Panga cliff to the north. The 2.5-km-long cliff (21 m above sea level) consists of Silurian limestone and is well exposed to waves.

The Järve study area (shoreline length 8 km) is located on the southern coast of Saaremaa Island, a few kilometers west of Kuressaare, the largest urban area on Saaremaa (Fig. 2). The nearshore area is shallow (the 2-m isobath lie 150–300 m from the shoreline). This part of the coast is a typical sandy beach with dunes behind the shore area. The dunes were formed during the Limnea Sea stage. The dune ridge (up to 5.8 m above sea level) is 8 km long. The waves have eroded a scarp in marine sediments that is slowly migrating inland. Järve beach is most popular summer recreation area in Saaremaa.

The Ruhnu study area is located on a small oval island with actively changing coasts in the middle of the Gulf of Riga. The island is exposed to wind and waves from all directions. The nearshore area is shallow (the 2-m isobath lie 200–300 m from the shoreline). The study area (shoreline length 4 km) is located on the north-eastern coast. Sandy beaches with dunes dominate the southern part of the study area (the highest dunes are up to 10 m above sea level), whereas the northern part features a sandstone scarp.

2.3.2. Lesser-detailed studies

North Estonia

Käsmu–Vergi, Toolse–Aseri, and Sillamäe–Narva-Jõesuu study areas (Fig. 1), which reflect minor differences in shore types along the northern coast of Estonia, are located in north-eastern Estonia, where the coastline (190 km) is straight in the east and more indented by peninsulas and bays in the west. Most of the area consists of the Baltic Glint, a limestone cliff a up to 56 m a.s.l., which divides the north Estonian coastal plain from the Harju–Viru limestone plateau. The north Estonian coastal plain, which lies between the cliff and the sea, contains peninsulas and headlands stretching far offshore. The glint headlands feature partly the cliff shore type, mostly gravel–pebble and sandy shores. Abraded till shores with boulders and sandy shores with coastal ridges and dunes are characteristic where the coastal plain is wider.

Keibu study area is located in NW Estonia and borders Keibu Bay to the north. This part of the northern coast of Estonia is a typical sandy beach with dunes behind the shore area.

West Estonia

Hiiumaa Island is located in the northern part of the west Estonian archipelago and is surrounded by nearly 200 small islands (Fig. 1). The principal shore types are abraded till shores and silty shores surrounding shallow bays and sandy beaches. There are also gravel shores with beach ridges, sandy beaches with beach ridges and dunes behind.

The 200-km-long Matsalu Bay study area (Fig. 1) from Virtsu (in the south) to Haapsalu (in the north) typifies the most characteristic shore types of the west Estonian plain. The central part of the study area, which encompasses Matsalu Bay, is composed of a low-lying varved clay plain with silty shores covered by reed beds and sea-shore meadows. One of the most important wetlands in Estonia, Matsalu Bay is a part of Matsalu National Park. The southern and northern parts of the area feature mainly abraded till shores with erratic boulders, although some limited sections of the coast near Virtsu have rocky shores.

The Pärnu–Ikla study area is located in south-western Estonia on the western coast of the Gulf of Riga (Fig. 1). The 150-km-long coastline is fairly straight. Most of the area consists of sandy beaches with an extensive ridge of coastal formations covered by foredunes and dunes, the highest of which (40-m a.s.l.) are situated in the central part. The area includes the inhabited island of Kihnu (16.4 km^2) and other smaller islands.

3. METHODS AND DATA

3.1. ANALYSIS OF HYDRO-METEOROLOGICAL DATA

The database of long-term changes in storminess and storm climatology was compiled by J. Jaagus (II). The observation data were obtained from the Estonian Meteorological and Hydrological Institute. Detailed databases of storms were created for three coastal stations (Kihnu, Sõrve and Vilsandi; Fig. 1) near the study areas of detailed shoreline changes. All three are located near lighthouses and exposed to the open sea. Vilsandi and Sõrve stations are situated on the coast of the Baltic Sea proper and Kihnu station on an island in the Gulf of Riga. The database of storminess consists of the data since 1948. Earlier data is incomplete and, therefore, insufficient for such studies.

A storm is defined when the mean the wind speed during one observation (10 minutes) exceeds 15 m/s. A storm day is recorded if a storm is measured during at least one observation. The storm database records contain observation date, the highest mean wind speed, wind direction and duration. Maximum sea level height and sea ice data observed at the same stations during each storm are also included.

In this study the frequency of storm days was used to measure storminess. This simple variable, easily derived from the database, depicts general storminess well but does not reflect storm intensity. The storm data of the three meteorological stations were correlated with shoreline change events in Harilaid, Luidja and Tareste study areas. Annual and monthly frequencies of storm days at three coastal stations in west Estonian archipelago during 1950–2001 have been analysed in this study. As there are no local obstacles, the wind speeds measured at these stations are the highest in Estonia. The locations of these stations have not changed during the observation period.

Long-term changes in storminess were analysed using the Mann-Kendall test referred to by C. Libiseller and A. Grimvall (2002) (II). This test does not require normal distribution of initial data. The annual frequency of storm days is normally distributed, whereas the monthly frequency is not. Observations in Sõrve and Vilsandi have short interruptions for some months, but the test allows for gaps in time series. Compared to linear regression analysis, the Mann-Kendall test is less sensitive to abrupt breaks in time series.

Severe coastal damage in Estonia is usually caused not by a single storm, but rather by extremely stormy periods, which occur for several weeks or even months. A list of extremely stormy periods was composed to collate it with major events of coastal erosion.

An extremely stormy period in this study was defined by the following criteria: (1) the storm must exceed two weeks (15 days as a minimum); (2) storm days must account for at least 20% of all days during the period, and (3) maximum wind speed must exceed 20 m/s or higher for at least three days.

To assessment possible rates of erosion and inundation for the whole Estonian coast for a global sea-level rise of 1.0 m, the data of sea-level fluctuations were obtained from 12 meteorological stations (Tahkuna, Ristna, Sõru, Heltermaa, Pärnu Kihnu, Rohuküla, Keemu, Virtsu, Loksa, Kunda and Narva-Jõesuu; Fig. 1).

3.2. TOPOGRAPHIC AND GEOMORPHIC ASSESSMENT OF SHORELINE CHANGES

Topographic maps and aerial photographs from different times were used to identify changes in shoreline contours and position:

- Topographic maps from the beginning of the 1900s, 1950s, and from the end of the1980s;
- Aerial photographs from the 1950s, the beginning of the 1980s and the end of the 1990s.

The scale of all maps was 1:10 000 except for the oldest one from 1900, which was 1:42 000, and a large-scale map compiled in the 1920s, which was 1:25 000. Maps and aerial photographs were registered by *MapInfo* using control points (location of lighthouses, shorelines of lakes, crossroads *etc*) and their Cartesian co-ordinates. Shoreline contours and the nearest scarps were digitised and analysed using *MapInfo*. Total accuracy of this analyse is between 2–14 meters[1].

Field measurements in relation to local benchmarks and topographic survey of coastal formations were carried out to determine changes in shoreline position. The measurements and survey were repeated at the same study areas at irregular time intervals depending on specific tasks in the framework of different studies. The photographs were compared using the same topographic elements as for maps. Additional information was obtained from several specific small-scale maps (geologic maps, land-use maps etc.), which, due to different projections and relatively limited information, were not digitised.

Shoreline positions were determined 2–3 times a year since 2001 using a Garmin 12 GPS personal navigator with a maximum horizontal accuracy of 3 meters. The attainable accuracy in the field was 3–5 meters. Sea level fluctuations during the aerial photography and GPS measurements were up to 15–20 cm above or below the Kronstadt 0, the local benchmark for the eastern Baltic Sea. Due to the steep nearshore topography of most study areas (50-cm isobaths lay 1–15 m from shoreline), these sea level variations were unimportant. Nevertheless, the data resulting from multiple measurements provided, in addition to qualitative assessment, a rough estimate of the amount of sediment displaced on the coast over a given time interval (1900–2003).

The database of shoreline changes consists of the measured variables on shoreline movements over different time intervals (example: 1900–1955; 1955–1981; 1981–1988; 1988–1998; 1998–2001; 2001–2002 etc.).

Field observation records and photos taken at identical locations at the study areas during the last 35 years (Orviku et al., 2003) provide another means with which to assess shoreline displacement.

3.3. CALCULATION OF SHORELINE CHANGES AND STORM SURGE

Many large-scale transects along and across the coastal formations were compiled and were later extrapolated over the whole study area. These transects were compiled mainly at the sites where detailed

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[1] Printing accuracy of the linear objects in the hardcopy maps is 0.1 mm (i.e. 1m on the scale 1:10 000 or 4.2 m on the scale 1:42 000). Accuracy of map registration and digitising is about 1–10 meters (the lowest accuracy on the oldest map). Summary accuracy of digitising of shorelines from hardcopy maps is maximally 2 m (the newest maps) and minimally 14 m (the oldest map).

description of shore processes was needed. Changes in morphological features of coastal formations were modelled on the basis of these transects. The volumes of coastal formations and the overall amounts of sediment were calculated to determine changes over particular time intervals.

Shoreline changes over a given time interval (from map to map) is expressed in meters, changes in shore areas are expressed in square meters. In some areas the rates of erosion and accumulation are calculated precisely and are expressed in cubic meters.

In the anomalous areas of stable shoreline dynamics, the changes are expressed in mean annual characteristics. The mean annual parameters usually contain inadequate information about the processes but give an explicit overview of changes.

The relationships between storm data and shoreline changes between 1957–2001 were examined using a simple method of comparison. As the time series of storm data is continuous but the data on shoreline changes are irregular, the correlation between storm events and shoreline changes were based on time intervals whose start and end dates were determined either on the maps or using GPS. The shoreline changes in a given time interval were compared with the number of storm events and sea level measurements over the same period, whereas the estimates were based on the storms of 2001/2002 (the baseline period of storms), during which shoreline changes were measured precisely. For other stormy periods, the number of storms with particular parameters (wind direction and duration, sea level fluctuation) was compared to the shoreline changes evident from comparison of maps from different times.

3.4. SEA-LEVEL RISE IMPACT ASSESSMENT FOR THE ESTONIAN COAST

Detailed measurements were made using 1:25000 topographic maps from the 1970s and 1980s and geomorphic maps. The rate of erosion and the shoreline recession were calculated along the coastline at 200 m intervals according to the Bruun Rule (Bruun, 1962). This rule assumes that sea-level rise will cause the equilibrium profile of the beach and shallow offshore to move upward and landward. The analysis is two dimensional and assumes: (1) the upper beach is eroded due to the landward translation of the profile; (2) the material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; (3) the rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in the offshore (Komar, 1998). Application of the Bruun Rule for the Estonian coast was not without complications. Firstly, shoals off the Estonian coasts reduce wave energy and partly protect the shore from erosion. Secondly, the Bruun Rule was designed to calculate erosion on sandy beaches, yet it was used to calculate erosion on other depositional shore types (gravel, pebble and till). However, the overfill ratio of 1.0 for sandy shores has been modified for other shore types: gravel and pebble – 0.7; till – 0.4; and limestone – 0.1 (Kont et al., 1996). The results of calculations on rocky limestone shores are less reliable, because erosional processes are aided by strong karstification. The Bruun Rule was inapplicable on very low and flat silty shores and in the coastal zone of the west Estonian plain, which consists of varved clay. The calculations of land loss in these regions were based solely on the degree of inundation following a "bath-tub" approach.

Based on the measurements, calculations, and field observations, new shoreline positions were drawn on topographic maps. Field observations were used to compare the calculated results with the topographic and current land use situation, and to make corrections where necessary. Coastline positions were drawn for both typical weather conditions and potential storm surges based on the maximum observed event. Both zones were assessed for land loss and temporary damage. (IV)

The Estonian vulnerability assessment considered a hypothetical 1.0-m sea-level rise from 1990 to 2100 with land uplift taken into account in land loss estimates in each study area. For instance, the uplift on the northern coast of Hiiumaa is 100 cm – 31 cm = 69 cm per 110 years (uplift velocity 2.8 mm/yr), and on the southern coast 100 cm – 27 cm = 73 cm (uplift velocity 2.5 mm/yr). Thus, different rates of uplift would cause the estimated sea-level rise to vary from 0.9 m (SW Estonia) to 0.7 m (NW Estonia).

The anticipated shoreline changes resulting from this sea-level rise were compared to the actual shoreline changes that have taken place over the last 100 years at the same sites. Comparison of maps from different times was used for that purpose. As the comparable sites are rather large in area, some smaller-scale maps (1:42 000 and 1:50 000) from three periods (beginning of the 20th century, beginning of the 1950s, and end of the 1990s) were also analysed.

4. SUMMARY OF THE RESULTS AND DISCUSSION

4.1. SHORELINE CHANGES DURING THE LAST CENTURY

Shoreline changes in the study areas were recorded in different periods at different time intervals. The most detailed observations were carried out on Harilaid Peninsula (I, II). Detailed changes at three sites (Cape Kiipsaare, Cape Kelba and Harilaid tombolo) on Harilaid Peninsula are given in Figures 3–5 and in Tables 1–3.

Shore processes during the last century on Harilaid Peninsula have caused the north-westernmost point of the peninsula to migrate to the north-east and to become longer and narrower (Fig. 3). The process itself has accelerated substantially in recent decades. In the first half of the 20th century, Cape Kiipsaare migrated to the north-eastern by 30–35 m and about 75–90 m during the second half of the 20th century. The western coast has receded about 32.5 m during the last 7 years due to erosion (Table 1). In general, accumulation has prevailed on the eastern coast of the cape but the last 15 years has seen significant coastal erosion (a shoreline retreat of *ca* 26 m). Similar changes have also taken place in the development of the scarp retreating up to 50 m from the 1950s until the 1980s, and 50–70 m during the last 20 years.

The shape and position of the shoreline of Cape Kiipsaare is influenced more by westerly and north-westerly and less by northerly and south-westerly winds and waves (I). Southern and eastern winds have little affect at this study site.

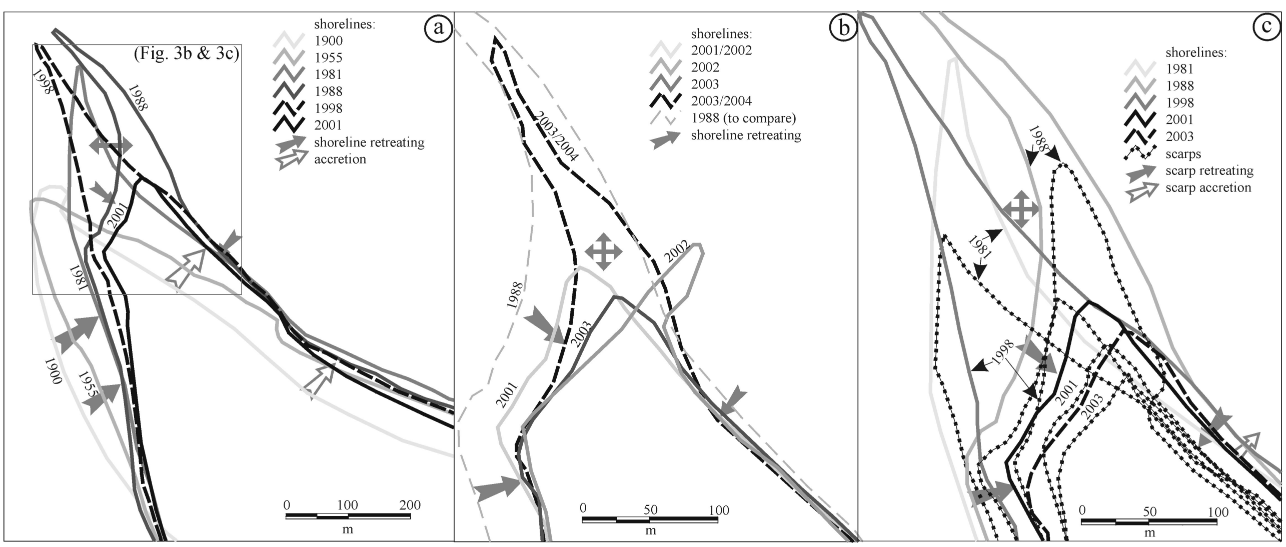

Figure 3. Map of shoreline changes on Cape Kiipsaare 1900–2001 (a), detailed 1998–2003 (b), and with changes of position of inland scarp 1981–2003 (c).

Table 1. Shoreline and scarp movements on Cape Kiipsaare and number of storms with respect to the baseline period 2001–2002 ("-" erosion, "+" accretion, "±" partly accretion and partly erosion)

Period	Shoreline movement, m		Area change of NW-point, m^2	Number of analogue storms	Scarp movement, m		Area change of old beach ridges, m^2
	W-shore	E-shore			W-shore	E-shore	
1900–1955	-23.5	+44	–	–	–	–	–
1955–1981	-38.5	+25.5	–	6	-45	+85	–
1981–1988	-8	+10	±13000	1.5	-10	-10	±7700
1988–1995	-12	-10	±10000	2.5	-25	+15	-5700
1995–1998	-2.5	-1.5		0.5			
1998–2001	-24	-9.5	-16500	3	-17	+2	-3000
2001–2002	-6	-5	-4000, +1500	1	-1	-7	-1900
2002–2003	-4	+2	-1400, +8400	–			

Continuous accumulation of new beach ridges on Cape Kelba has elongated the spit. At the beginning of the 20th century the cape consisted of two small systems of pebble beach ridges (Fig. 4). During the first half of the 20th century, the south-western part of the spit became wider and the area increased by 6 800 m^2 (Table 2). From 1955 to 1981 new beach ridges were formed and the increase of the spit was about 18 500 m^2. The last 20 years suggests an expansion of Cape Kelba by about 56 000 m^2, varying greatly from year to year.

Table 2. Area changes (accretion and erosion) of Cape Kelba and number of storms with respect to the baseline period of 2001–2002

Period	Accretion in the distal part of the spit, m^2	Erosion in the proximal part of the spit, m^2	Number of analogue storms
1900–1955	6800	0	–
1955–1981	18500	500	5
1981–1988	10500	400	3
1988–1995	28500	4300	4
1995–1998	4600	4600	1
1998–2001	5800	7000	1.5
2001–2002	5000	5000	1
2002–2003	4500	1200	–

The south-western coast of Cape Kelba started to erode during the second half of the 20th century. If only approximately 900 m^2 were eroded in 1955–1988, the rate of erosion increased by *ca* 22 000 m^2 by the end of the century (1988–2003).

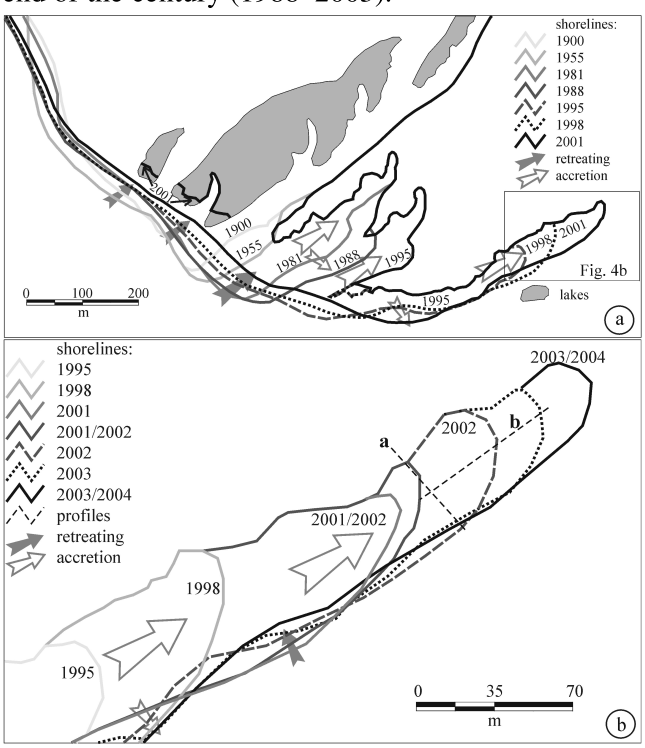

Figure 4. Map of shoreline changes on Kelba spit (a) and detailed changes on distal part of the spit (b).

The development of Cape Kelba is determined more by westerly or north-westerly and less by southerly winds (I). The direction of sediment movement at the study site is dependent on northerly and westerly winds, whereas the direction of the position of the distal part of the spit mostly depends on southerly winds. Strong and lasting southerly winds cause the distal part of the spit to turn to the north.

On the eastern coast of the Harilaid Peninsula, (Harilaid neck) there is a 120-m-wide accumulative plain with a sandy beach (Fig. 5). Active shore processes – mainly sand accumulation – are occurring currently in the seaward half of the beach. These accumulating sediments originate primarily from Cape Kiipsaare but also from the eastern coast of Harilaid (Fig. 2; I, Fig. 1). The rates of accumulation are higher in the central and eastern parts of the study site and lower in the north. The total displacement of the shoreline during the last century has been about

150 m (Table 3). The enlargement of the beach at the Harilaid tombolo study site has increased from 1 m/yr during the first half of the last century to 1.5–13 m/yr during the last 20 years.

Table 3. Shoreline movements ("-" partly erosion) and area increase on sandy shore in Harilaid neck

Period	Shoreline movement, m	Increase in area, m^2
1900–1955	40	30000
1955–1981	10	11500
1981–1988	10	10800
1988–1995	30	16400
1995–1998	35 (-15)	13160
1998–2001	30 (-5)	7650
2001–2002	20 (-15)	2300
2002–2003	15 (-5)	3000

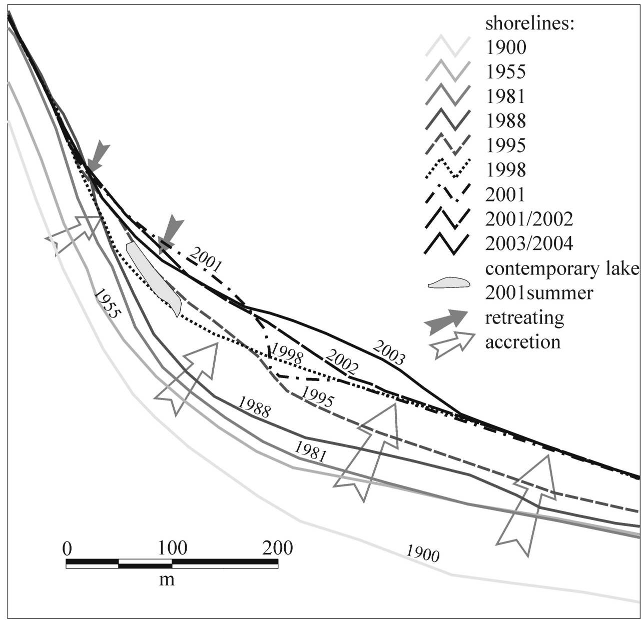

Figure 5. Map of shoreline changes on Harilaid neck.

Analysis of the shoreline changes on Harilaid Peninsula shows that shore processes have become more intensive over the last 20 years. The position of the shoreline of Harilaid neck is influenced more by northerly and north-easterly and less by easterly winds and waves.

Similar changes to those on Harilaid Peninsula have taken place also at the Luidja and Tareste study areas where field experiments have been carried out in lesser detail.

The shoreline in Luidja was rather straight at the beginning of the 20th century (Fig. 6). From 1900 to 1957 the western part of the Luidja sandy beach broadened by about 100 m as a result of the transport of sand from the east and accumulation at the study area. The total increase in beach area was nearly 19 hectares (Table 4). Most of the new terrain came from a 600-m-long arch-shaped spit and a lagoon behind it that was formed during the first half of the 20th century. At the same time accumulation took place at the eastern part of the beach widening it by 20 m. A 1-km-long central section of the beach was subjected simultaneously to erosion and became narrower by about 10 m. From 1957 to 1984 the spit became longer and the lagoon lost its connection to the sea. A new 1.3-km-long and 40-m-wide incremental formation had formed on the seaward slope of the spit during the same period. The overall expansion of the study area during 1957–1984 reached 11 hectares (Table 4). The spit became even longer during the last decade of the previous century and a narrow lagoon formed behind it.

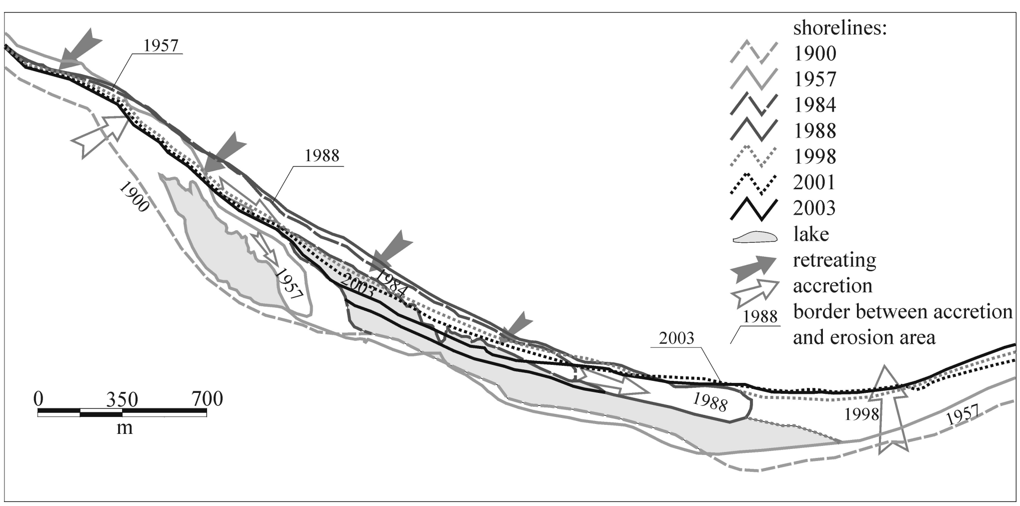

Figure 6. Map of shoreline changes in Luidja study area.

Table 4. Shoreline movements and area changes ("-" erosion) on Luidja study area

Period	Shoreline movement, m		Area changes, m^2	
	E-part	W-part	increasing	decreasing
1900–1957	70 (-10)	120	209000	22000
1957–1984	60 (10-100)	-35	114000	2200
1984–1988	10	10	46000	0
1988–1998	50 (150)	-70 (-20 -80)	92500	87500
1998–2001	20 (15-25)	-15 (-5 -25)	18500	23000
2001–2003	20	-25 (-5 -40)	9500	38500

Analysis of shoreline changes during the last 50 years suggests that erosion of sediments has been dominant in the western part and deposition in the eastern part of the Luidja study area. The sand accumulated in this area was derived mainly from the west and the area of erosion has been constantly shifting to the east. The area of major erosion is currently located at the central part of the biggest lagoon. This is also confirmed by the seashore monitoring results of 2002 (Kask & Kask, 2003). Due to the dominance of erosion in recent years, the spit between the lagoon and the sea has become narrow and is shifting to the south. This, in turn, has made the western part of the lagoon narrower by 40–60 meters. Continuing intensive erosion and migration of the area of erosion may cause the biggest lagoon to fill completely with sediments or rejoin the sea in the next decade.

The position of the shoreline of Luidja study area is influenced more by north-westerly and northerly and less by north-easterly winds and waves.

The Luidja study area has expanded by about 30 hectares during the last 100 years, during which the rate of increment has been ca. 50 ha and erosion ca. 20 ha. Deposition was the dominant process in the earlier years (1900–1984) of its development. Erosion and deposition have achieved near equilibrium during the last 10 years while the activity of sediment transport, shoreline changes and shore processes in general have increased many times.

Like Luidja, the Tareste study area can be also characterised by the formation of a long sandy spit.

The development of the Tareste spit is more complicated. The shores north of the study area have been eroding since a harbour was constructed at Lehtma (Fig. 2) in the NE corner of Tahkuna Peninsula in 1914. The eroded deposits had been transported partly to the south before the groins were erected. After the erection of harbour facilities at Lehtma the main routes of sediment transport were cut off and the sand was trapped between the groins and the shoreline. At the same time, a noticeable deficit of sand became evident and active erosion started south of the harbour (Raukas et al., 1994). The most intensive erosion is currently a 1.5-km-long section of shoreline immediately north of the Tareste Spit, where the shoreline has retreated an average of 25–40 m during the last 15 years. This is evident by repeated topographic surveys at Tõrvanina showing a disappearance of a 40-m-wide strip of land during 1976–1998. This land formerly consisted of beach ridges that were covered with vegetation. There is now a scarp eroded into the old shore deposits on the landward edge of the former shore. A forest stands on top of the scarp (VI). The Tareste Spit, a complex system of erosion and accretion and strongly subjected to human impact, is currently the most thoroughly investigated site along the study areas.

The development of the Tareste Spit has been rapid – the shoreline changes in the last hundred years are clearly visible. There was a very small spit at the end of the 1880s (Tiismann, 1924). The existence of the spit at that time and even earlier are confirmed by a chain of shore lakes parallel to the shoreline on topographic maps from the beginning of the 20th century (Fig. 7).

These lakes were probably separated from the sea as a result of transport and deposition of sand in a north-south direction. Analysis of a map from 1900 show that the separation process of the lakes from the sea had ended by that time and a new incremental formation on the seaward side of the spit had accumulated as a result of longshore transport of sediments. This new formation consisted of two parts: the northern part was 750 m long and 35 m wide and the southern part was 250 m long and 40 m wide.

The topographic map from 1957 shows that the study area had a fairly straight shoreline and the coastal sea off the area was very shallow with a number of sandy shoals. The northern part of the spit from the beginning of the 20th century had eroded completely by the middle of the century. In contrast, the landward side of the spit, which had formed earlier, became wider and longer due to intense deposition. At the end of the 1980s a new incremental formation could be delineated. A lagoon behind it was partly overgrown by aquatic plants (an area between the 1957 and 1988 shorelines in Fig. 7). The new spit is over 1 km long and 60–80 m wide (Table 5). The spit had elongated by 350 m by 2001 and had become narrower (by 20–30 m) from the eastern side because of erosion. From 2001 to 2003 the increment of the spit was about 100 m and its total length is currently 1.5 km. At the same time intensive erosion continued. The spit became even narrower (10–15 m) and the area of the study site decreased by 8400 m^2.
The position of the shoreline of the Tareste spit is influenced more by northerly and north-easterly and less by easterly winds and waves.

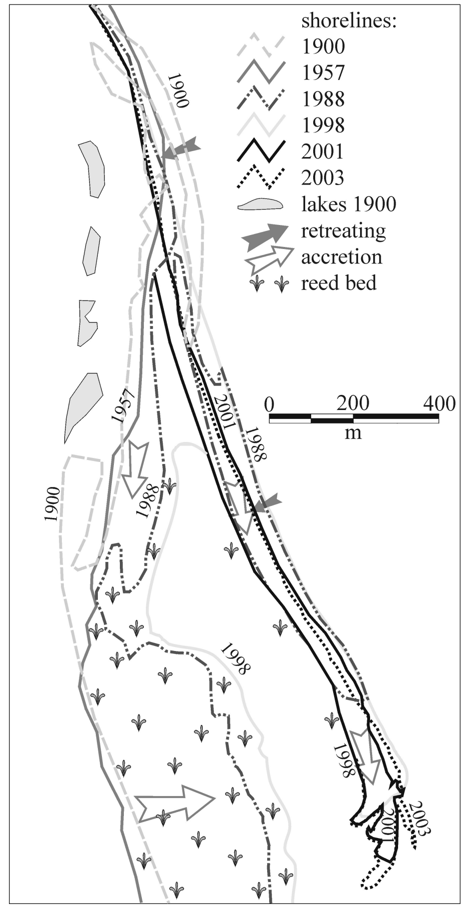

Figure 7. Map of shoreline changes in Tareste study area.

Table 5. Development of Tareste spit

Period	Accretion in the distal part of the spit, m^2	Erosion in the proximal part of the spit, m^2	Elongate of the spit, m	Wideness of the spit, m
1957–1988	58600	0	1030	60–80
1988–1998	20500	1500	230	60–80
1998–2001	6500	32500	100	40–60
2001–2003	6000	8500	100	30–50

The analysis of shoreline changes at both the Luidja and Tareste study areas (as at Harilaid) indicate continuous increasing activity of shore processes over the last 15–20 years.

Field measurements and a topographic survey were made at the Küdema, Ruhnu and Järve study areas (II). Noticeable changes in shoreline and scarp positions have also taken place in these study areas during the last century. Increasing activity of coastal processes and shoreline changes is clearly evident over the last 20–25 years.

Comparison of maps from different times gives an impression of the disposal of huge amounts of sediments. A map dating from the end of the 1980s shows a low (20–30 cm) and wide (30–150 m) sandy beach on the eastern coast of the Ruhnu Island. However, this wide beach is found on no other map.

Changes in shoreline position and contours during the last 100 years on geologically active coasts are noticeable also in the study areas that were investigated in lesser detail (Table 6). Based on the analysis of all study areas, it can be concluded that the greatest shoreline changes during the last century have taken place in NW Estonia and in the West Estonian Archipelago.

Table 6. Average shoreline changes in ("-" retreat, "+" accretion) study areas investigated in lesser detail

Study area	Shoreline movement (1900–2000), m
Narva-Jõesuu	-35 … -40
Võsu	+70 … +90
Keibu	+110 … +130
Pärnu	+90 (+200)
Kabli	-30 … +30

Analysis of shoreline changes on active coasts in different regions of Estonia revealed the following:

- The greatest changes occurred in the areas of the most rapid land uplift.
- The greatest changes have been observed on coasts that are directly exposed to the Baltic Sea proper.

4.2. CHANGES IN HYDRO-METEOROLOGICAL CONDITIONS DURING THE PAST 60 YEARS

Changes in meteorological conditions along coastal areas of western Estonia are given and discussed in Paper II. Long-term changes in storminess and storm climatology were analysed by J. Jaagus (II).

Time series of annual frequency of storm days at the three coastal stations (Kihnu, Vilsandi and Sõrve) indicate high temporal variation and a general increase in storminess (II, Fig. 2, 3 and 4; I, Fig. 2). Mean annual frequency of storm days is 20 in Vilsandi, 14 in Sõrve and 13 in Kihnu. There have been some periods with a maximum number of storm days and a long minimum during the 1960s.

Results of the Mann-Kendall test indicate that in many cases the increasing trend in storminess is statistically significant ($P<0.05$). Change in annual frequency of storm days is significant at every station but changes in monthly values are of different magnitude. In general, increases in winter are most substantial. Storms in summer months are very rare. Therefore, changes in summer storminess have no practical importance.

The frequency of storm days in Estonia has varied remarkably during the second half of the 20th century, especially during the last two decades. An increase in mean sea levels during storm events has also been recorded in the last 20 years (I, Fig. 2).

A list of extremely stormy periods is presented in Paper II Table 2. The strongest storms over the observation period were recorded in 1967 with a maximum mean wind speed of 29 m/s in Kihnu. The storm of August 6th and 7th devastated forests in many regions in Estonia. Many storms have been recorded during mild winters at the end of the 1980s and the beginning of the 1990s. The last three extremely stormy periods were observed at the end of 1999, in November 2001 and in February 2002. During these stormy periods the water level on the western coast of Estonia rose significantly. There was no ice cover near the coast during these extremely stormy periods.

4.3. RELATIONSHIP BETWEEN CHANGES OF HYDRO-METEOROLOGICAL CONDITIONS AND SHORELINE POSITION

Relationships between changes of hydro-meteorological conditions and shoreline position are given and discussed in Papers I and II.

Major coastal changes in Estonia, expressed as both shoreline displacement and the structure of coastal formations, have taken place during extremely stormy periods (I, II), as attested by detailed investigations carried out on Harilaid Peninsula.

Erosion has dominated on the western coast of Cape Kiipsaare since at least the beginning of the 20th century, correlation between shoreline changes and some storm parameters (number of stormy days, sea level and wind direction) during the last 50 years remains unclear. The strongest correlation is between the number of storms analogous with the baseline period storms (2001–2002) and the shoreline movements on the western coast (II, Table 1). A similar correlation on the eastern coast is less significant due to the replacement of accumulation by erosion about 15 years ago. As a result of the migration of Cape Kiipsaare the current coastal scarp crosses the beach ridges of different age (I, Fig. 3). The shore profiles show a flat and uniform both nearshore as well as foreshore relief. The topography of backshore area with foredunes and beach ridges is also relatively flat and uniform. The main shore process in the western and northern sides of the cape is erosion, as evident by a scarp formed as a result of extremely stormy periods at the end of 1999 and 2001 (15 and 12 storm days, maximum wind speed 25 and 30 m/s, SW and W, maximum water level +132 cm). The scarp, particularly its north-western side, receded 25–35 m inland during this stormy period. The shape and position of the shoreline is influenced more by westerly and north-westerly and less by northerly and south-westerly storms.

The development of the Kelba spit was related to the number of storms in different periods, which were analogous with the baseline period storms of 2001–2002. The results revealed a strong correlation (II, Table 2). The increment of the spit during 1988–1995 does not correspond to the number of strong storms (four analogous storms) over the same period and, thus, provides an exception. The calculated number of analogous storms should have been at least twice as high. This phenomenon probably arises from changes in the nearshore topography in the area of accumulation. The deposits 16–10 years ago were accumulated on a submarine shoal that was *ca* 0.5–1 m below sea level. Currently accretion is occurring in much deeper (4–5 m) water (Fig. 8, coastal profiles). Therefore, the expansion of the spit in 1988–1995 has been less dependent on the amount of deposits and the number of favourable storms than either before and after that period.

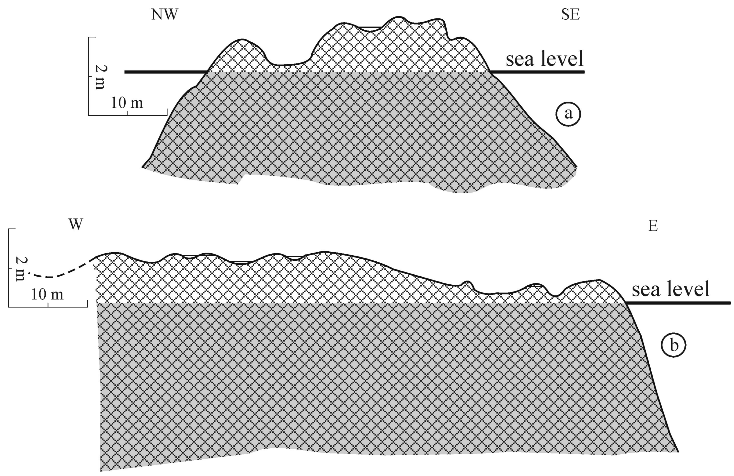

Figure 8. Profiles from Kelba spit (location see figure 4).

Similar analysis on the impact of a single stormy period on shoreline dynamics have been done also at other study areas, such as Ruhnu Island and Järve beach.

A comparison of topographic surveys made before and just after the stormy period in winter 1990 (8 storm days, maximum wind speed 25 m/s, S, water level +171 cm) at the Järve site shows that a 4-km-long scarp in sands receded by 4–5 m. Over 6,500 m^3 of sand per kilometer of beach eroded, of which about 2/3 was eroded from the scarp (II).

Strong southerly storms at the end of February 1990 (according to the Kihnu station, 6 storm days, maximum wind speed 19 m/s, S and SW, water level +143 cm) caused a reversal in sediment erosion, transport and deposition processes on Ruhnu Island. An extensive fresh scarp eroded into the foredunes in the SE, and the sand was transported along the shore to the north. A 1.5-km-long and 15–20 m-wide beach was formed in the long-term area of erosion. During the next five years, the newly formed beach was completely eroded away by northerly storms. The sand was transported southwards, and accumulated on a 10–15 m-wide active beach to form a series of young foredunes (II).

Although no direct measurements have been made on the impact of extremely stormy periods at the Luidja and Tareste study areas, their impact is believed to be significant. Only one extremely stormy period (2001–2002) was observed during the GPS measurements between summer 2001 and spring 2003. This stormy period caused the western part of the Luidja study area to recede an average of 60 m with the maximum recession (100 m) exceeding the shoreline recession during the previous 21–26 years. The shoreline changes during 2001–2003 were substantial also at the Tareste study area (Table 5).

An increase in storminess might affect the coastal study areas in different ways depending on the prevailing wind directions during stormy periods. The importance of prevailing wind direction on the magnitude and character of shoreline changes can be determined by the following circumstances:

- Exposure of shoreline causing the dominance of longshore or onshore movement of sediment;
- Location of coastal formations in relation to shoreline and storm surge direction;
- Location of sediment supply in relation to shoreline and storm surge direction.

4.4. SHORELINE CHANGES INDUCED BY ANTICIPATED SEA-LEVEL RISE

Research on future sea level change has been inconclusive, although most studies suggest rising sea levels by the end of the century. According to different scenarios the sea level will rise about 0.5 m by the end of the 21st century, which exceeds the compensating effect of the land uplift in Estonia. Therefore, the impact of a hypothetical 1-m sea-level rise represents the worst possible scenario for the coastal areas of Estonia. The impact of a 0.5 m rise – as discussed in papers III and IV – might occur after about 300 years on most Estonian coasts and about 200 years in NE and SW Estonia.

The impact of anticipated sea-level rises on the coastal areas of Estonia is estimated and discussed in Papers III, IV and VI.

The results of analysis and a number of theoretical discussions reveal a simple and linear character of the Bruun Rule equation that was used to assess the impact of sea-level rise. Hence, the calculated predictions of shoreline changes according to the Bruun Rule may differ greatly from actual changes. There are many reasons to express caution in applying the Bruun Rule without corrections:

- The Bruun Rule applies only to sandy shores. Without experimental work it is difficult to determine if the applied overfill ratio coefficients were correct when assessing possible change on Estonian coasts consisting of other types of deposits and rocks.
- Accurate measurement of the lengths and depths of coastal profiles from topographic maps is difficult because the Estonian coast is abundant in shoals.
- The Bruun Rule deals only with sediment interchange between the beach face and the nearshore sea floor, and omits gains or losses resulting from longshore drift, and their effects on beach profiles. Therefore, the rule is better suited to swash-dominated rather than drift-dominated beaches. Many beaches also lose sediment blown to backshore dunes, washed into tidal inlets, or swept over barriers or spits into lagoons and swamps (Bird, 2000).
- If climatic changes accompanying a sea-level rise lead to increased rainfall, beaches may receive more sand or gravel washed down coastal slopes, and changes in coastal wind regimes may increase sand blown from hinterland dunes to beaches, or modify incident wave regimes to increase longshore drift. An abundant supply of sediment from a longshore could maintain or prograde beaches during a phase of rising sea level, either directly, or by shallowing the nearshore zone so that shoreward drifting ensues (Bird, 2000).

The impacts of accelerated sea-level rise in Estonia might vary greatly with the type of coasts. Clearly, the most vulnerable coasts are low and flat depositional shores consisting of sand and gravel and the most resistant are cliff and rocky shores.

It is worth mentioning that till shores in Estonia are erodable to the extent that the fine-grained fractions are washed out. The remaining shingle ridges and boulder fields prove to be extremely resistant to further erosion. The results of calculations on rocky shores consisting of limestone are unreliable, because erosional processes are affected strongly by solution of limestone. The Bruun Rule was inapplicable on very low and flat silty shores and in the coastal zone of the west Estonian plain, which consists of clay. The calculations of land loss in this region were based solely on the degree of inundation. (IV)

A 1.0-m global rise in sea level would greatly affect the coastal platform and a number of small islands. Part of the islands would be inundated. The most significant changes would occur on the western coast, including the Matsalu Bay study area. Due to the compensating effect of land uplift, the actual sea-level rise would vary from 72 to 80 cm. As this area is low-lying and flat and consists of varved clay, the dominant processes would be inundation and temporal flooding. A 350–400 m-wide shore area would be inundated (reed bed area of Matsalu Bay is an exception, where about 2.8 km (average and max. 6.5 km) would be inundated) and 500-m-wide area would be under the storm surge at the Matsalu Bay study area (III, IV, VI).

On Hiiumaa Island, 38 km^2 of the coastal area would be eroded and inundated and the most extensive coastline recession (about 1500 m) would be on the silty shores near Kõrgessaare–Reigi, Kärdla–Hellamaa and Käina. Loss estimates indicate that all reed beds and 80% of coastal meadows (salt marshes) would be at direct risk (III, IV).

The area least vulnerable to ASLR (accelerated sea-level rise) is the eastern part of the north-Estonian coastal plain, although the relative sea-level rise would be among the highest in Estonia. The study area is a narrow strip of land between the Baltic Glint and the sea. Unfortunately, the excellent sandy beaches between Narva-Jõesuu and Meriküla, which would be eroded (about 100–200 m-wide area) in case of sea-level rise, have already suffered from strong storms in recent decades.

The territories most vulnerable to sea-level rise in the Pärnu–Ikla study area are located both in the north, where silty shores dominate, and in the south on a densely populated Island of Kihnu. During the most recent powerful storms, the waves reached dwellings 300-m inland. A 1.0-m sea-level rise would inundate over 22 km^2 of coastal territory, including almost 2.5 km^2 of Pärnu and 3.8 km^2 of Kihnu Island. The greatest shoreline recession (500–1000 m) would occur in the central part of the study area where flat coastal areas are covered with reed. The land uplift in this area is the slowest in Estonia (about 1.0 mm/yr), resulting in a relative sea-level rise from 85 cm in Pärnu to 95 cm near the Latvian border.

In addition to possible changes in shoreline positions and contours resulting from a hypothetical sea-level rise, the actual shoreline changes during the last century in the same study areas were also investigated. The greatest changes have been observed in the areas with flat topography and most rapid land uplift, for instance, in Matsalu, Häädemeeste, north-western Hiiumaa and Keibu. The shoreline changes over the last hundred years and those expected to occur over the next 200–300 years are in good correlation. The areas expected to retreat the most as a result of ASLR have been emerging intensively during the last century. In general, the territory that has emerged during the last 100 years constitutes about 40–60% of the territory that would likely be inundated or eroded as a result of a 1.0 m sea-level rise by 2200–2300 (Table 7). The Pärnu–Ikla study area is an exception where the potentially inundated coastal territory exceeds over 5 times the territory that has emerged during the last century. This phenomenon is a result of slow land uplift and extremely flat topography. To conclude, a 1.0-m sea-level rise by 2200–2300 would result in the coastline of Estonia being located in roughly the same position as 200–250 years ago.

Table 7. Increased coastal area during the last 100 y and potential inundation area during the next 2–3 centuries.

Study area	increased area (km^2)	decreasing area (km^2)
Reigi	2.1	5
Kärdla	0.2	0.5
Matsalu Bay	35.6	76.6
Pärnu – Ikla	3.3	18.4
Kreibu	0.7	1.2
Käsmu – Vergi	1.7	2.7
Toolse – Aseri	1.2	2.1
Sillamäe – Narva-Jõesuu	0.45	1.1

5. CONCLUSIONS

Taking into account general tendencies in storminess (WASA Group, 1998) it is likely that storminess in Estonia has increased, especially during the 1980s and 1990s. In a wider time frame, this change is only a phase within long-term fluctuations.

The relationship between storminess and shoreline changes in study areas and particularly on Harilaid Peninsula is quite strong. Analysis of the shoreline changes at the study areas shows that shore processes have become more intensive over the last 20 years, of which most changes occur during stormy periods. The shoreline changes are 4–10 times greater in recent decades than before. Intensification of shore processes is well correlated with increased annual storminess and higher sea levels but also with the absence of ice cover near the coast in recent decades. This combination induces intense erosion and transport of sediments above the mean sea level and inland the mean shoreline, and leads to substantial changes in coastal morphology that persist for years or even decades.

Changes in shoreline position and contours are greater at the study areas that are well exposed to the open Baltic Sea and to the dominating stormy wind sectors. In general, changes in shoreline position and contours are also greater in areas with more rapid land uplift. The least changes in shoreline position and contours occur on active coasts in NE and SW Estonia.

The last studies show an expected mean global SLR by about 40–50 cm during the next century. This scenario would not affect the Estonian coast greatly during the next 100 years.
A 1 m rise in sea level rise over the next 200–300 years would cause the Estonian coastline to retreat to the position of about 200–250 years ago. A 1.0-m sea-level rise would result in considerable change in coastal ecosystems and would lead to significant economic risk, the degree of which would vary in different regions of Estonia.

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RANNAJOONE MUUTUSED EESTIS NING NENDE SÕLTUVUS KLIIMAKÕIKUMISTEST

Kokkuvõte

Eesti rannajoon on umbes 3800 km pikk, kohati liigestatud poolsaartest ja nende vahele jäävatest lahtedest. Rannikumeres on üle 1500 saare. Looduslike protsesside ja inimmõju tõttu on rannajoonega piirnevad alad pidevas muutuses, mis mõnikord võivad olla väga kiired. Looduslikud protsessid ja nende aktiviseerumine mõjutavad rannikualade ökosüsteeme ning seavad kindlad piirid alade majandamisele. Rannas asetleidvate muutuste kindlakstegemiseks on mitmeid võimalusi, üks neist on rannajoone asendi muutuste hindamine ajas.

Mere mõju rannale ja rannajoonele sõltub rannaprotsesside iseärasustest ning nende aktiivsusest. Rannaprotsessidest on põhilised setete ärakanne, transport ja kuhjumine. Rannaprotsesside aktiivsus sõltub peamiselt ranna geoloogilis-geomorfoloogilistest omadustest ning lainetusest, eriti murdlainetusest. Lainete jõud on seda suurem, mida pikem on laine hoovõtumaa ja mida suurem on tuule kiirus. Mida suurem on randa jõudva laine energia, seda aktiivsemad on rannaprotsessid. Kõige suurem mõju on seega tormilainetel. Madala veeseisuga mõjutavad lained rohkem rannakut, sest laine murdumise ala on keskmisest rannajoonest mere pool. Kõrge veeseisuga, kui laine murdumise ala nihkub keskmisele rannajoonele lähemale, mõjutatakse enam aga randa.

Käesoleva töö ülesandeks oli hinnata kvantitatiivselt rannajoone muutusi 20. sajandil ja 21. sajandi alguses ning seostada neid mõningate kliimanäitajate muutustega. Eelnevast lähtudes püstitati eesmärgid:

- rekonstrueerida uurimisaladel rannajoone asendi ja konfiguratsiooni muutused;
- analüüsida rannajoone (rannaprotsesside) muutuste ja mõningate tormiparameetrite (tormide arv ja sagedus, veetase tormide ajal) omavahelist seost;
- selgitada välja võimaliku meretaseme tõusu mõju erinevat tüüpi randadele.

Rannajoone asendi ja konfiguratsiooni muutusi uuriti kokku 14 rannikualal. Kõige detailsemad uuringud tehti Lääne-Eesti saarestikus kuuel aktiivse rannaga alal ning vähemdetailsemad kaheksal uurimisalal Eesti eri piirkondades.

Rannajoone asend saadi peamiselt eriaegsetelt kaartidelt ning aerofotodelt, millele alates 2001. a lisandusid GPS-ga määratud rannajoone muutuste andmed. Välitööde käigus looditi rannaprofiile ning tehti kindelpunktidest korduspildistusi. Põhiliseks uurimismeetodiks oli kaartide, skeemide ja profiilide võrdlev analüüs.

Rannajoonte asendites toimunud muutusi võrreldi J.Jaaguse (Orviku, et al., 2003) poolt koostatud tormide andmebaasiga (aluseks EMHI andmed Vilsandi, Sõrve ja Kihnu ilmajaamadest alates 20. sajandi keskpaigast). Kuna rannajoonte andmebaas ja tormide andmebaas on erineva tihedusega (rannajoonte oma diskreetne, tormide oma pidev), siis detailsemaid seoseid analüüsiti kõige tihedama andmereaga uurimisaladel – Harilaiu poolsaarel, Luidjas ja Tarestes.

Antud töö tulemusel võib järeldada, et rannajoone asendi ja konfiguratsiooni muutused on kõige ulatuslikumad suurema maakerke kiirusega aktiivsetes randades, mis on eksponeeritud avamerele ning valitsevatele tormituultele. Rannaprotsesside aktiivsus sõltub veel rannaprofiilist ning rannamoodustiste ekspositsioonist, morfoloogiast ja settebaasi olemasolust.

Detailsemal rannajoonte asendite analüüsil tehti kindlaks, et uurimisaladel on rannaprotsessid viimase 20 aasta jooksul, võrreldes 20. sajandi varasemate aastakümnetega, muutunud aktiivsemaks, mille tulemusel on intensiivistunud setete ärakanne, ränne ja kuhjumine. See väljendub eeskätt rannajoone asendi ja konfiguratsiooni muutustes, mis on viimastel aastakümnetel kõigil uurimisaladel olnud 4–10 korda ulatuslikumad. Sama kehtib ka rannaastangute pervede asendite muutuste kohta uuritud liivarandades.

Tormiandmete ja rannajoonte asendite vahelised seosed ei ole alati üks-ühesed. Tugevama seose leidmist takistab andmete vähesus ja rannaprotsesside keerukas toimemehhanism. Kõige selgemini avalduvad seosed sellistes piirkondades, kus rannaprotsesside iseloom on ajaliselt täpsemini teada ja rannajoone asendi andmeid erinevatest aastakümnetest on rohkem (Kiipsaare uurimisala läänerand ja Kelba maasäär). Suur osa rannajoone ja -astangu perve asendi muutusi leiab uuritavatel aladel aset eriti tormistel perioodidel, kusjuures neid muutusi suurendavad keskmisest kõrgem veetase ja jää puudumine rannikumeres.

Võimaliku meretaseme tõusu mõju uuringud näitasid, et Eesti rannaalad ei ole kuigi haavatavad, sest maakerge kompenseerib selle osaliselt või täielikult. Kõige suuremad rannajoone asendi muutused leiaksid aset aeglasema maakerkega madalates ja laugetes kamardunud randades.

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